Energy budget of nitrogen use in the United States

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Abstract

The production of Nitrogen Based Fertilizers (NBF) is extremely energy intensive, averaging 32.5 million BTUs/ton of Nitrogen. In 2008, the United States applied 12,561,000 tons of NBF to a variety of crops in the U.S. Agricultural system. The U.S. imports 82% of all NBF it uses, from over 48 countries around the world. Of the facilities that produce NBF worldwide, 73% use natural gas-operated plants and 27% use coal. Since there is a lack of data (or the data is not readily available) to calculate the amount of energy used to transport all of the NBF within the U.S. to the farms, only estimates are provided herein. The energy used to apply all of the NBF to crops within the U.S. is approximately equivalent to 664 million gallons of diesel. The discussion attempts to follow the energy budget used for NBF from its production to crop application within the U.S.

Nitrogen (N) serves as an essential building component of nucleotides and proteins; thus, N is an eminent component to terrestrial life [1]. While nitrogen is present in our atmosphere and soils in various organic and inorganic forms (e.g. N_2, NO_3, N_2O, NO_3^-, NH_3), its natural cycle is extremely complex. Nitrogen constitutes between 1 and 5% of a plant's weight, while at the same time the biological availability of natural nitrogen is scarce; thus, our agricultural system is heavily dependent on synthetic nitrogen fertilizers, most commonly NH_3, $CO(NH_2)_2$, NH_4NO_3 to sustain our urban lifestyles [1, 2]. From the late 1950s to 2008, global application of synthetic nitrogen fertilizer has increased by a factor of 10, from ~10 Tg (1 Tg = 1 million metric tons) N/year in the late 1950s to ~100 Tg N/year in 2008 [1].

Today, the industrial production of ammonia (NH_3) is used as both the main source of nitrogen fertilizer and the base for other synthetic nitrogen-based fertilizers [3]. Fritz Haber [4] discovered the extremely energy intensive process of combining free nitrogen gas from the air (N_2) with hydrogen (from natural gas). Today, natural gas still serves as both primary feedstock, or source of hydrogen, and fuel source for the Haber-Bosch process, requiring 34.5 GJ/mt (Giga Joules per metric ton) of N (or 32.3 million BTUs/mt N) and 47.0 GJ/mt N (or 44.5 million BTUs/mt N) using modern nitrogen plants and nitrogen plants during the 1980s, respectively [5]. The energy budget for production does not include the amount of energy used for nitrogen fertilizer packaging, transportation, and application (including on-farm energy use). Thus, a comprehensive energy budget of the use of nitrogen is needed to assess the energy efficiency of the United States' industrialized agri-monoculture.

Energy of Production

In 2008, the U.S. used a total of 12.561 Tg of nitrogen-based fertilizer [6] including: anhydrous ammonia, urea, and UAN solutions, among others, 10.300 Tg N (82%) of which was imported [5]. The production of NBF takes an average of 32.3 million BTUs/mt N, based on the production of ammonia, urea, and urea ammonia nitrate in modern plants using natural gas (Table 1) [1]; nitrogen fertilizer plants that run off of coal use roughly 56.9 million BTUs/mt N [5]. Internationally, NBFs are produced using ~73% natural gas

Table 1. Energy required to manufacture nitrogen fertilizer by type using natural gas. Energy for coal-based production is shown for comparison. (*mt=metric ton*)

N Production Type	Millions of BTUs/mt N
Ammonia	29.7
Urea	35.9
Urea ammonium nitrate	31.4
NBF average – Natural Gas	**32.3**
Coal	**56.9**

Table 2. Total energy of nitrogen production, based on 2008 U.S. consumption of 12.561E6 metric tons of NBFs and average energy usage of modern production facilities.

Production Source	Percentage from Natural Gas	Percentage from Coal	Total BTUs	Total Joules	Total gallons Diesel Fuel
Imported	73%	27%	4.0E14	4.2E17	2.9E+09
Domestic	100%	0%	7.3E13	7.7E16	5.7E+08
Total	-	-	4.7E14	5.0E17	3.4E+09

and 27% from coal [7]. (In the U.S., all NBF are produced using natural gas.) The total energy budget for production, 4.7E14 BTUs, is shown in Table 2 as expressed in total BTUs, total Joules, and total gallons of diesel fuel equivalent, based on modern production methods and U.S. consumption in 2008.

Energy of Import Transportation

To compute transportation, we assumed that all imported NBF was transported using ocean-going vessels. The number of gallons of diesel fuel needed to transport 1 ton of NBF 1 kilometer was computed as 10.439E-3 [gal/km/ton] – this calculation is based on the available data that it takes ~75 barrels of diesel fuel to ship a 40' container holding 27 tons of NBF from China to the U.S. Table 3 shows the top 10 NBF import countries into the U.S. with the tons of NBF imported per country, an estimated transportation distance, and the equivalent energy of transportation (based on 2008 U.S. NBF import data). The top 10 countries account for 79% of all imported NBF. The energy of transportation per country was computed using:

$$E_{t,i} = \alpha T_i D_i \qquad (1)$$

where $E_{T,i}$ is the transportation energy for country i, T_i is the tons of NBF imported for country i, and D_i is the estimated transportation distance from country i to the U.S. The scalar α is 10.439E-3. For the "Other 38 Countries" from which NBF is imported to the U.S, the distance was assumed to be the average distance of the top10 countries. The total transportation energy for NBF imports was therefore estimated to be 9.69E+13 BTUs, or 1.02E+17 Joules, or 6.98E+08 gallons of diesel fuel, or roughly 20% of the energy of production.

Transportation with the U.S.

In 2007, the U.S. harvested 309,607,601 acres out of a total of 922,095,840 acres of farmland throughout the country [5]. After NBF are produced, the distribution to each individual farm may take many different routes. For example,

Table 3. Estimates, based on 2008 U.S. NBF import data, of the energy required to ship NBF from the top 10 import countries. The travel distance for the remaining 38 countries was estimated to be the average distance to the top 10 countries.

Import Country	Tons of NBF	Distance [km]	BTUs	Joules	Gallons of Diesel
Trinidad and Tobago	4.40E+05	3.22E+03	2.05E+12	2.17E+15	1.48E+07
Canada	3.07E+06	1.32E+03	5.86E+12	6.19E+15	4.23E+07
Russia	1.03E+06	4.56E+03	6.83E+12	7.21E+15	4.92E+07
Kuwait	7.60E+05	1.12E+04	1.23E+13	1.30E+16	8.89E+07
Ukraine	1.73E+05	1.05E+04	2.63E+12	2.78E+15	1.90E+07
China	7.96E+05	1.12E+04	1.29E+13	1.36E+16	9.29E+07
Qatar	5.25E+05	1.67E+04	1.27E+13	1.34E+16	9.14E+07
Venezuela	3.47E+05	2.17E+03	1.09E+12	1.15E+15	7.86E+06
Saudi Arabia	6.02E+05	1.07E+04	9.35E+12	9.87E+15	6.74E+07
Egypt	4.13E+05	9.58E+03	5.73E+12	6.05E+15	4.13E+07
Other 38 Countries	2.16E+06	8.12E+03	2.54E+13	2.68E+16	1.83E+08
Total Imported	1.03E+07		9.69E+13	1.02E+17	6.98E+08

several ammonia pipelines run over 11 states, stretching for more than 2,000 miles [8, 9]. From the terminals of the pipelines, NBF is transferred to a specified carrier for transport to a local destination for consumption. This is just one route NBF's could take; NBF's could be transported down the Mississippi River via barge as well, for example. Due to the complexity of NBF's distribution throughout the U.S and the lack of data on the distribution services, the energy used for distribution was not calculated here. However, with the acquisition of the data, one could approximate the total energy used on the distribution of NBF's per year via equation (2), which accounts for the use of trucks, trains, barges, and pipelines within the United States (Table 4).

$$E_{DT} = \beta_p M_n L_p + G_m L_f D_{BTU} + G_B L_b D_{BTU} + G_T L_T D_{BTU} \quad (2)$$

Application to Crops in the U.S.

Since there is so much farmland in the U.S. and multiple means of NBF application onto crops, each with varying NBF load requirements, the calculation for the energy required to apply all the NBFs is roughly approximated. According to Haby (2008) [10], it costs $5.00/acre to spread NBF at a rate of 70lbs/acre. Assuming that all NBF consumed in the U.S in 2008 (12.56 Tg = 2.77E10 lbs) was applied to all 9.22E8 acres of U.S farmland, this yields 30 lbs/acre. At $5.00/acre, it is approximated that the U.S. spent $1.98B on the application of NBF to crops in 2008 alone, equivalent to 5.19E8 gallons of diesel fuel (at $3.81 per gallon based on May 2008 average price of diesel), equivalent to 5.19E8 gallons of diesel or 7.60E16 Joules or 7.20E13 BTUs or roughly 15% of the energy of production.

Table 4. Variable definitions, equation 2.

Variable	Definition
E_{DT}	Energy of domestic transportation [BTUs]
β_p	BTU * ton^{-1}_{NBF}*$mile^{-1}_{pipeline}$
M_n	12561000 tons N used in the U.S. (2008)
L_p	Total length of pipeline NBF's travel [mi]
L_f	Total distance traveled by trucks containing NBF's [mi]
L_b	Total distance Barge's Travel with NBF's [mi]
L_T	Total travel distance of trains containing NBF's [mi]
G_m	Average gas mileage of diesel transportation truck
G_B	Avg. gas mileage of Barges [gal/mi]
G_T	average gas mileage of trains (diesel) [gal/mi]
D_{BTU}	138,690 BTU's/gallon of diesel

Results and Conclusion

According to the models used, the total energy budget for the use of NBFs in the United States in 2008, which does not include domestic transportation estimates, was 6.43E14 BTUs (or 6.79E17 Joules), roughly 0.15% of the total worldwide energy consumption of 4.74E20 Joules in 2009 [11] and 0.50% of the total U.S. power consumption in 2008. For perspective, the total NBF budget as calculated is directly comparable to the total electrical energy consumed by the entire country of Nigeria in 2008 and the total energy consumed for transportation in all of China in 2008 [12].

Moreover, the amount of energy used for the production and application of NBF in the U.S only constitutes 22.6% of the total calculated energy used. Ultimately, the production of NBF overseas constitutes 62.4% of the energy used in the U.S. for NBF, 40% of which is produced by coal-burning NBF production facilities.

Note again that these calculations do not take into account the energy for domestic transportation of NBF. Also, not included are the costs associated with NBF packaging or the costs associated with soil degradation and water supply contamination remediation from nitrogen runoff.

We understand that the error is not only unquantifiable in this study, but likely very large, yet we believe that one can extract qualitative understanding of the relative energy budgets necessary for a high level comparison, which is the goal of this investigation.

The production of NBF is an extremely energy intensive process. The cost of energy required to make NBFs increases with the molecular complexity (i.e. ammonia nitrate, ammonia sulfate, sodium nitrate, calcium cyanamid) [3, 13]. A more in-depth analysis of the production facilities abroad, the trade network to the U.S, the transportation of NBF within the U.S, and even the production facilities within the U.S is required to have a better understanding of the true energy cost.

With the exponential growth in worldwide population, the use of NBF is a necessity to sustain the human population [1, 4, 13]. A significant proportion of energy could be saved if the fertilizer was produced locally, within the U.S, or within whichever country used that specific NBF. Various agricultural techniques could also be used (i.e. rotation systems, GMOs, polyculture) together to significantly reduce the amount of NBF used in the production of food commodities [1, 14, 15].

The production and application of synthetic NBF has led to high concentrations of nitrogen being leached into the groundwater, resulting in significant environmental impacts including acidification and depletion of soil, stimulation of algal growth, hypoxia in regions in our oceans, acid rain, as well as a major contributor of green house gas emissions (specifically NOx and CO2) [1, 16]. The U.S agricultural system, as it exists today, would not be able to function without it. Major changes from an agri-monnoculture to a localized model would be necessary to realize dramatic reductions in nitrogan usage worldwide.

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