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A General Methodology for Evaluation of Carbon Sequestration Activities and Carbon Credits

November 2002

Prepared by
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A GENERAL METHODOLOGY FOR EVALUATION OF CARBON SEQUESTRATION ACTIVITIES AND CARBON CREDITS

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CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

A general methodology was developed for evaluation of carbon sequestration technologies. In this document, we provide a method that is quantitative, but is structured to give qualitative comparisons despite changes in detailed method parameters, i.e., it does not matter what "grade" a sequestration technology gets but a "better" technology should receive a better grade. To meet these objectives, we developed and elaborate on the following concepts:

- All resources used in a sequestration activity should be reviewed by estimating the amount of greenhouse gas emissions for which they historically are responsible. We have done this by introducing a quantifier we term Full-Cycle Carbon Emissions, which is tied to the resource.
- The future fate of sequestered carbon should be included in technology evaluations. We have addressed this by introducing a variable called Time-adjusted Value of Carbon Sequestration to weigh potential future releases of carbon, escaping the sequestered form.
- The Figure of Merit of a sequestration technology should address the entire life-cycle of an activity. The figures of merit we have developed relate the investment made (carbon release during the construction phase) to the life-time sequestration capacity of the activity. To account for carbon flows that occur during different times of an activity we incorporate the Time Value of Carbon Flows.

The methodology we have developed can be expanded to include financial, social, and long-term environmental aspects of a sequestration technology implementation. It does not rely on global atmospheric modeling efforts but is consistent with these efforts and could be combined with them.

ACKNOWLEDGMENTS

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1. INTRODUCTION

Nowadays the U.S. is focusing attention nationally on processes and activities that mitigate the release of CO_2 to the atmosphere and in some cases may remove CO_2 from the atmosphere. As we invest national resources to these ends, it is important to evaluate options and invest wisely. How can we evaluate and compare various CO_2 sequestration technologies on a common basis? A standard methodology that considers all the carbon impacts is needed. This would be useful for policy makers to understand the range of options, and for technology developers and investors to guide investment decisions. It would also serve as a source of information for calculations in support of international agreements and for estimations of carbon credits in a future credit trading system.

Decisions on national policy and strategy for carbon management must take into account a variety of factors dealing with economic, environmental, and social impacts of carbon management. Many people are already pursuing several of these issues from a global perspective.

This report outlines a contribution to the toolbox for these carbon management analyses. We describe a methodology for assessing the merit of technologies that sequesters carbon (and other greenhouse gases) according to a standard set of criteria that can be applied to a wide variety of technologies for comparative purposes. Obviously, the ability to sequester carbon is an important parameter in any higher-level analysis pertaining to global warming. A standard methodology for comparative purposes does not exist today.

2. DEVELOPMENT OF A UNIFORM APPROACH FOR EVALUATION OF CARBON SEQUESTRATION ACTIVITIES

Our operating definition of carbon sequestration derives from the fact that we are focusing on engineered processes over which we have some control in their design and operation. Naturally occurring processes that influence carbon flows are not within our scope.

In our context of engineered processes, carbon sequestration means that less carbon dioxide is added to the atmosphere relative to an appropriate baseline case. A variety of technologies fall within this definition of CO_2 sequestration.

- Process improvements that reduce the net release of CO_2 to the atmosphere.
- New processes (e.g., in manufacturing) that replace existing processes.
- Processes whose main purpose is extraction of CO_2 from the atmosphere or capturing CO_2 prior to release to the atmosphere.

We so far have spoken only of CO_2, which in many cases exists in conjunction with other important greenhouse gases (GHGs). The Kyoto protocol states that carbon dioxide equivalence should be used when reviewing emission/sequestration of other GHGs. The GHGs are listed in Table 1 along with their carbon dioxide and carbon equivalence [1].

Table 1. Carbon equivalence of selected greenhouse gases (100 year basis).

GHG	CO_2 equivalent (g/g)	Carbon equivalent (g/g)
Carbon dioxide (CO_2)	1	0.27
Methane (CH_4)	21	5.7
Nitrous oxide (N_2O)	310	84.5
Hydrofluorocarbons (HFCs)	140-11,700	38.2–3,190
Perfluorocarbons (PFCs)	6,500-9,200	1,770–2,510
Sulfur hexafluoride (SF_6)	23,900	6,520

Thus, when we speak of carbon sequestration, we really mean all GHG sequestration measured in carbon dioxide or carbon equivalence. The carbon dioxide equivalence is also called the Global Warming Potential (GWP). A complete list of GWP values has been listed by the Intergovernmental Panel on Climate Change (IPCC) [1]. The calculation of a carbon equivalent (CE) from gas emission (or in our case sequestration) information may be calculated from the following relationship [2]:

$$CE = (mass\ amount\ of\ gas\ emitted) \times GWP \times \left(\frac{12}{44}\right) \tag{1}$$

Throughout this report, we use the term carbon (C) as the equivalent of CE. For example, 5 Mt C means 5 megatons of carbon equivalents.

2.1 CARBON ACCOUNTING STRATEGY FOR NATIONAL SEQUESTRATION ACTIVITIES

Debate on carbon credits is meaningful when discussed in conjunction with improvements from a base line of emissions. For example, the Kyoto protocol calls for nations to reduce their carbon dioxide equivalent emissions to less than 1990 levels. Carbon credits, on an international basis, will not come into effect before these levels have been reached for a nation. If a greater reduction can be achieved, a carbon credit is available to trade with other countries. To reduce emissions, a nation can engage in several activities, e.g., reduction of fossil fuel use, increase in forested areas, reduction in cement production, etc. Other activities may in the future include carbon sequestration activities. To calculate the national emissions, the IPCC has established a methodology for emissions calculations [3]. Based on this methodology, the nation is divided into several industrial categories (energy production, cement production, ammonia production, etc.), all of which are activities that significantly contribute to carbon emissions. Carbon sequestration activities (except for forestry/land use) are not yet part of the accounting methodology.

We propose that the following general accounting method can be used if carbon sequestration becomes a real industry, representing a significant contribution to the total national carbon balance:

1. Establish a measurable quantity of “product” related to a sequestration activity. This, for example, could be “mass of dry ice” (generation of dry ice for deep ocean disposal has been proposed as a sequestration technology [4]) or “mass of fertilizer” (production of ammonium carbonate has been proposed as a sequestration technology [5]).
2. Calculate the annual amount of carbon equivalence the technology sequesters using the following general equation:

   $$carbon\ sequestered = (sequestration\ factor) \times (quantity\ of\ product) - adjustments, \tag{2}$$

   where the *sequestration factor* depends on the carbon content in the product and any conversion factors that must be applied to convert units and address carbon equivalence. The *adjustments* that must be made are to account for those activities related to the sequestration that may have emissions, but which are not accounted for by any other industry (e.g., emissions from energy needed to freeze CO_2 would be accounted for in the energy category). In the case of dry ice generation, there may be some CO_2 evaporation during storage and transportation that is not accounted for in other categories. In the case of ammonium fertilizer, perhaps some ammonium carbonate decomposes before packaging.

In general, we propose four types of adjustment (some of which may be time dependent):
(a) Those proportional to the quantity of product (e.g., evaporation in storage).
(b) Those proportional to some other quantity (maybe the number of farmers who use the fertilizer). The quantity of product may also be important in this type of adjustment.
(c) Emissions related to prior year sequestration activities, if sequestration was not permanent. For example, we may hypothesize that every year a fraction of the dry ice in the deep ocean evaporates and affects the atmospheric CO_2 levels. We incorporate this knowledge into the adjustment. The quantity of product may also be important in this type of adjustment.
(d) Those adjustmenst that relate to international imports or exports of the product.

2.2 DEVELOPMENT OF A GENERAL METHODOLOGY FOR EVALUATION OF CARBON SEQUESTRATION ALTERNATIVES

The above proposed sequestration accounting method represents a general strategy that follows the same approach as for emissions accounting proposed by IPCC. It accounts only for the annual carbon sequestration (and emissions) in the process represented by sequestration activities. Carbon emissions related to energy use, transportation, raw materials, etc., to accomplish the sequestration are accounted for by other industries on a national basis. However, in order to compare different sequestration technologies, a more complete assessment methodology must be developed to assist in future decision-makings. For example, if a coal fired steam plant is considering implementation of either an off-gas CO_2 scrubbing technique or an algal pond strategy to reduce its CO_2 emissions in order to get favorable treatment from a regulatory agency, the evaluation approach may be considerably different than the national accounting approach—especially if these sequestration technologies are moderate in size and do not influence significantly, on an individual basis, national accounting calculations. Even if the national accounting strategy were used on a localized zone, there is still not a clear method by which sequestration technologies should be compared when it comes to their effectiveness in achieving long-term sequestration. For example, is a method that sequesters CO_2 for an average of 200 years, twice as good as a method sequestering it for 100 years?

Ideally, we would like to evaluate each sequestration technology based on the global impact on atmospheric CO_2 levels or on global warming. This, however, may not be a practical method for many activities. It is also likely that short-term or smaller activities, not globally implemented, will not significantly alter the result predicted by global modeling efforts. Thus, we should develop more of a generic approach that would be less labor intensive, yet provide some indication of technology benefits. To assist in the evaluation, we propose that a general object function can be used for a life-cycle assessment of a proposed technology. The object function for the technology value may look something like this:

$$figure\ of\ merit = \int_0^\infty f(V_1, V_2, .., V_n)\,dt \ , \qquad (3)$$

where the variables V_1, V_2, etc., correspond to environmental, economical, and social effects, etc., over time. Currently, the scope of this project only deals with the life-cycle carbon flows. Thus, the metric we have developed is a simplified methodology that later may be incorporated into a complete objective function.

The performance objective for a sequestration technology is not necessarily zero emission of CO_2, but a care must be taken to make sure that there are no hidden emissions when making an alteration from the baseline. The fundamental question running through an analysis of merit of a process, or alteration of a process, is

> —***How much CO_2 is generated as a result of the operation (or change) of this process, and what is its ultimate fate?***

Both inputs and outputs must be considered to obtain a total picture. To make sure that all emissions are accounted for in a process, we introduce a property we call *latent emissions content*, or *full-cycle carbon emissions*, FCCE for short. The FCCE is a value that is expressed in mass of carbon and corresponds to historic and future emissions for a "stream." We will use the FCCE in addition to actual carbon content of streams to help assess a process. Mass and energy balances and FCCE are discussed in the next sections.

2.3 MASS AND ENERGY BALANCES

2.3.1 Mass Balances

In Figure 1 we have depicted a schematic process in the shape of a factory for sequestering carbon dioxide. One form of carbon sequestration is the removal of CO_2 from the atmosphere (① in Figure 1). However, there may also be technologies that prevent CO_2 release, by interception of the waste gas or by process improvement. We call this type of activity process sequestration (② in Figure 1).

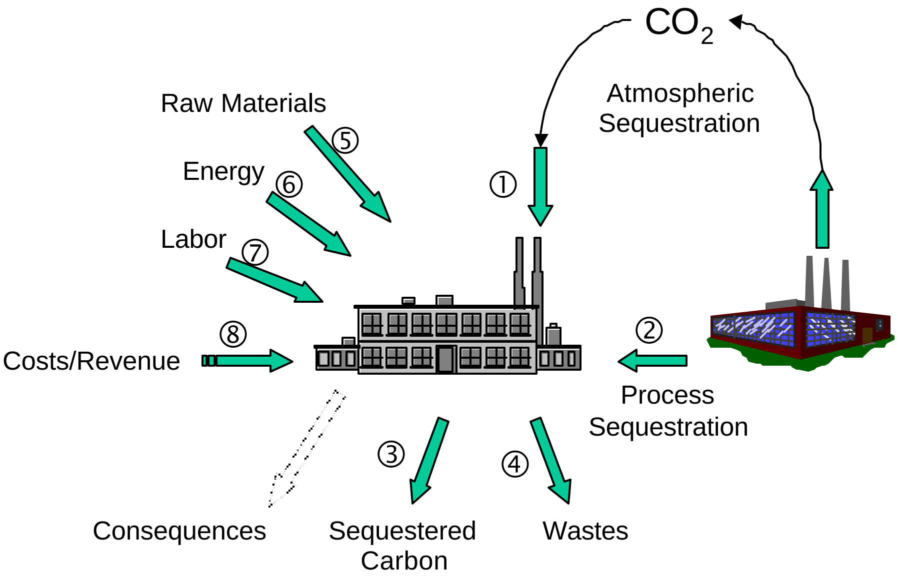


Figure 1. Conceptual flow model for sequestration activities.

The sequestration activities are likely to generate two "product" streams: the sequestered carbon stream (③) and waste streams (④). To accomplish the sequestration, the activity may need raw materials (⑤), energy (⑥), and labor (⑦). A process such as this is likely to cost money or it may generate revenue (⑧). A simple carbon balance around the boundary of the sequestration factory requires that the mass of carbon in flows ①, ②, and ⑤ will equal the mass of carbon in flows ③ and ④ plus whatever has accumulated in the "factory." The carbon balance is a strict mass balance of carbon, but the carbon equivalence may not be balanced. We may capture hydrofluorocarbons with a high carbon equivalence value, but there is not much carbon in the stream.

The amount of carbon sequestered in the activity should be calculated from the mass of carbon in stream ③.

The amount of carbon sequestered in the activity should be calculated from the mass of carbon in stream ③. The amount of carbon equivalence sequestered should be calculated by analyzing the carbon and the GHG content in streams ① and ②, and accounting for any immediate emissions. As an alternative, we can multiply the amount of carbon in steam ③ with the *sequestration factor* (see Equation 2).

2.3.2 Energy Balances

A traditional energy balance calculation over the system will reveal if the process will require or generate energy. Also it is important to identify and quantify what type of energy is needed (or generated) in the process. For example, the process may use electricity from a coal-fired power plant but it may generate steam that may be used by the local community, which now needs less power from the power plant. The energy flow in Figure 1 (⑥) corresponds to the net energy required for the process. If the plant requires a fossil fuel for energy generation on-site, it should be included as a separate stream in the mass balance to the process.

2.3.3 Full-Cycle Carbon Emissions (FCCE) of Streams

In a life cycle approach to the sequestration activity, we should also consider the historic as well as the future fate of streams. To illustrate this, we can consider an example that advocates sequestering CO_2 from stack gases by combining the gas stream with ammonium hydroxide to produce an ammonium carbonate fertilizer. First we will consider the ammonium hydroxide, which is a **raw materials** stream (⑤). The full-cycle carbon emissions (FCCE)for this stream must be found by answering the question:

> ***—How much CO_2 (or more correctly, carbon equivalents of CO_2 and GHG) was generated in the production and distribution of the ammonium hydroxide?***

If a considerable amount was generated, we must now capture enough CO_2 (or carbon equivalences) to offset the amount released during the making/storage/transportation of the ammonium hydroxide.

The sequestration process may also use a type of **energy**, which may have generated some CO_2 and other GHGs in its generation and distribution. Thus, the energy streams in and out of the process will have associated FCCE. Unless a technology uses a type of energy that cannot be easily distributed to someone else (e.g., excess heat in a process), the energy will have an associated FCCE value. Hydropower electricity does not generate many emissions, but diverting a large portion of this type of energy for sequestration would only result in someone else using more fossil fuel generated electricity.

The future of the **sequestered carbon** is of equal importance. In the fertilizer example, it is important to estimate what will happen to the carbon in the fertilizer once it is applied to the growing area. If the fertilizer remains in storage for a long time, will carbon be released to the surroundings due to breakdown? The FCCE of the fertilizer (product) includes the handling and transportation of the material to its final disposition, as well as long term releases of the GHG from this stream.

The fate of the **waste** should also be considered as having latent emissions content due to possible GHG emissions related to its handling and disposal. The FCCE of this stream may be related to the transport and disposal of the waste as well as long term releases.

The **labor** associated with the sequestration activities was included in Figure 1 for completeness; however, it is very unlikely that the CO_2 generation by human breakdown of food during the activities is worth considering. One may also argue that this CO_2 would be generated regardless of what the work force is doing. Thus, we will eliminate further discussion the generation of CO_2 by the work force due to its existence. There are other aspects we will consider later as part of the costs.

The **costs** of implementing a sequestration are important and a low cost is preferred and we will discuss it later in detail.

So far we have addressed only the more obvious material and energy flows that contribute to changes in carbon dioxide (or equivalent) release. We have done so by looking at direct effects through mass balances and indirect effects through full-cycle carbon emissions discussions (e.g., in energy use). Further details about the materials and energy use will be covered in the Discussion section and in Appendix A.

For every action, there is a reaction – a sequestration activity is likely to have positive and negative **consequences** apart from what can be estimated from the approach presented in this paper. Environmental issues have not been addressed in the current approach, nor have employment, land use, public perception, etc. For the approach to be consistent with the Kyoto protocol, the sequestration accounting method should be quantifiable and verifiable. Thus, we will not include these currently non-quantifiable consequences in the approach, other than to note that they are important factors to consider, but unless there is a clear link between consequences and CO_2, we will leave them out of our discussion.

2.4 TIME-ADJUSTED VALUE OF CARBON SEQUESTRATION

In discussing the activity of sequestration, we introduced the concept of FCCE mainly from the aspect of resource utilization. When a sequestration technology uses a resource such as energy, we are saying that somewhere in the world, this results in emissions and that these emissions are occurring (or are accounted for) at the same time we are carrying out the sequestration. For the waste and product stream however, emissions may occur in a distant future depending on the fate of these streams. In order to assign a FCCE estimate to these streams we propose to introduce the *Time-adjusted Value of Carbon Sequestration* (TVCS). We would like this property to indicate that a technology that sequesters carbon and does not release it for circulation in the atmosphere is more valuable than an alternate technology that releases it after a short time. Ideally, the techniques would sequester the carbon indefinitely; however, it is clear that many of the proposed technologies do not accomplish this.

How does one estimate the *Time-adjusted Value of Carbon Sequestration*? One way would be to employ our global climate models to predict changes in atmospheric CO_2 levels as a result of sequestration and future release from sequestered carbon. This would be a labor-intensive task, and if an individual sequestration effort is moderate, it will be considered noise in the global models. We propose another approach—we will start by defining a sequestration duration goal that will serve as a metric for future reference. For instant, we may choose to use 100 years as our goal for sequestration. This would mean that if we sequester 2 megaton of carbon (2 Mt C = 7.4 Mt of CO_2) today and we are able to keep it sequestered for at least 100 years, we are doing well and we should get 100% credit value for the activity. If we had partial or full release in fewer than 100 years, we are not doing as well and the value is less. The question is; how do we evaluate different carbon release profiles and determine their proper value?

Consider the graphs in Figure 2, where several value curves have been constructed based on the instantaneous release of 2 Mt sequestered carbon sometime in the future. Later we will consider partial release over time. In Figure 2a the graph shows a scenario that does not give any value (or credit) to a sequestration amounting to fewer than 100 years at which time we get full value of our activities (2 Mt C). Figure 2b takes a more gradual approach by applying a straight-line model. Here, if we instantaneously release all the carbon at any time before 100 years (e.g., 75 years), we would get fractional credit (e.g., 75/100×2=1.5 Mt C). If we would like to give proportionally more credit to longer sequestration periods, we can construct a curve as in Figure 2c. Here we are emphasizing that there is increasingly more value in focusing on technologies that will keep the carbon sequestered longer, thus discouraging activities with potential quick release. It is clear that this third approach is very sensitive to prior knowledge about the future potential quick release. It is clear that this third approach is very sensitive to prior knowledge about the future release, especially for the years close to year 100. To counter this, we may choose to use a fourth approach (Figure 2d) that suggests that we should consider short-term solutions favorably while realizing that future predictions are hard. In all the cases, we have chosen to give full credit, or value, to sequestration past 100 years (or whatever goal metric we select).

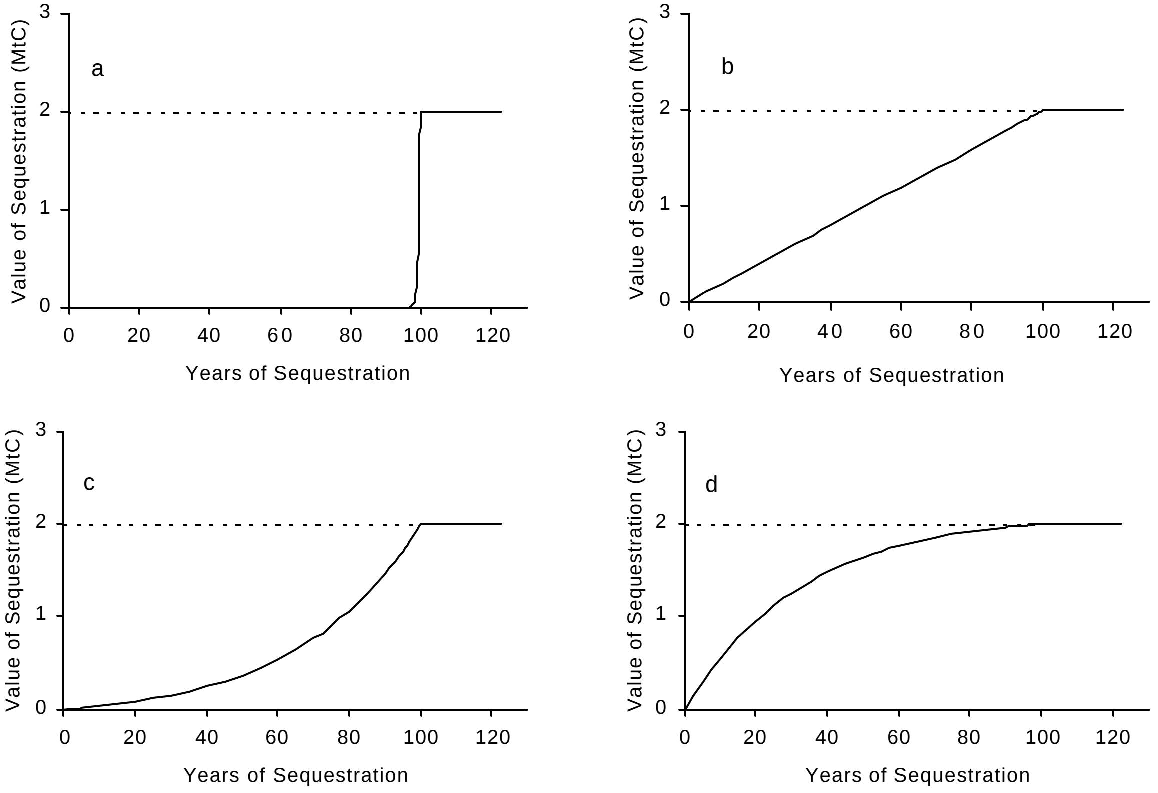


Figure 2. Several potential profiles for calculation of the time value of sequestration.

It should be pointed out that all the curves drawn in Figure 2a–2d were constructed using the same basic equation, namely

$$value\ of\ carbon\ sequestration = (amount\ of\ carbon\ released) \times \left[\frac{(1+i)^{y} - 1}{(1+i)^{Y} - 1} \right] \qquad \text{(for y} \leq \text{Y)}, \quad (4)$$

where i is the penalty interest rate, y is the number of years sequestered, and Y is the number of years for maximum value. Equation 4 is of the same type as interest rate functions but has been normalized by the expression in the denominator so that the function takes a value of 1 (one) when $y = Y$. The different curve shapes constructed in Figure 2a–2d were obtained by changing the penalty interest rate from 500% to 0.01% to 3% to –3% for 2a, 2b, 2c, and 2d, respectively. Using short-hand, we propose the following expression for the modifier:

$$V = R \times TVCS(i, y, Y) \ , \qquad (5)$$

where V is the *value of carbon sequestration* and R is the *amount of carbon released.*

example of this may be sequestered carbon stock that is suddenly being used for fuel. Other scenarios may call for estimating the periodic release of small amounts of the sequestered carbon. We can help visualize this with a carbon release profile. The time scale begins when sequestration takes place, and in this example we have chosen to sequester 2 Mt C. According to our example (Figure 3), we anticipate a release of 0.5 Mt in year 20, 0.2 Mt in year 60, and 0.1 Mt in year 80.

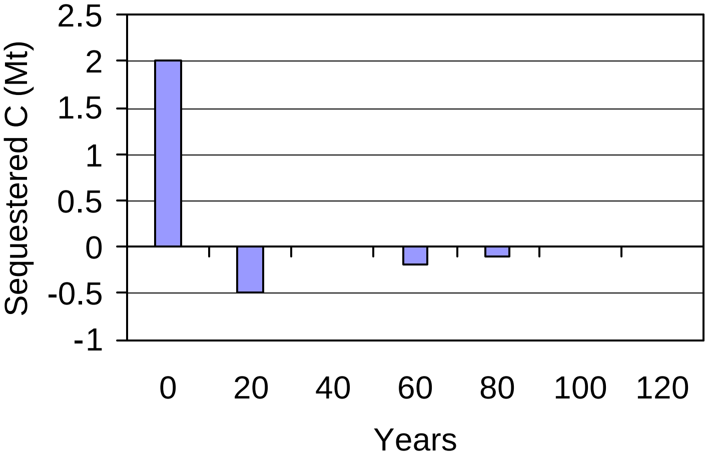


Figure 3. Example of periodic release of sequestered carbon.

To calculate the value or credit for this activity we would just add the individual release values, realizing that 1.2 Mt of the sequestered carbon remains unreleased for more than 100 years. The calculation will take the form of Equation 6, where we have chosen to use 100 years is the goal for sequestration (Y = 100).

$$\begin{aligned} V = 0.5\times TVCS(i,20,100) + 0.2\times TVCS(i,60,100) + 0.1\times TVCS(i,80,100) + \\ (3.7-0.5-0.2-0.1)\times \underbrace{TVCS(i,>100,100)}_{=1} \end{aligned} \tag{6}$$

Equation 6 can be simplified and generalized to yield Equation 7,

$$V = S_C - \sum_{j=1}^{Y} R_j \times \left(1 - TVCS(i, y_j, Y)\right) \ , \tag{7}$$

where the maximum sequestration value (S_C = net amount of carbon initially sequestered) is reduced (or penalized) by the value of the carbon released each year until the year, Y, is reached.

The above example shows how to discount the maximum sequestration value for discrete releases of the sequestered carbon; however, it is more likely that future carbon release from an activity is predicted via a mathematical expression, e.g., a half-life constant. In this case Equation 7 is modified to yield the integral form

$$V = S_C - \int_0^Y R(y) \times \left(1 - TVCS(i, y, Y)\right) dy \ . \tag{8}$$

which may, or may not, be solved analytically depending upon the complexity of the carbon release profile, $R(y)$. An example of a case where the carbon release profile might be available is the ammonium carbonate fertilizer, which may partially decompose with time in the soil.

2.5 TIME-ADJUSTED VALUE OF ENERGY AND MATERIAL USE RELATED TO SEQUESTERED CARBON

We have discussed the future release of carbon from a sequestration activity. We should also consider that energy and materials might be needed in the future for “maintenance” to retain the carbon in its sequestered form. Intuitively, we can say that the use of energy and materials in the future should be limited. Because we expect that their use generates CO_2, we need to incorporate this knowledge in the value of sequestration. To keep with the approach we have taken on the time-adjusted value of carbon sequestration, we would value delayed use of energy more than early use. The easiest way of visualizing this it to realize that any maintenance in the future will generate CO_2, and this amount must be added to any amount of CO_2 that might be released from the sequestered carbon. Thus, the R_j and $R(y)$ in Equations 7 and 8 represent the total CO_2 (or CE) released in the future, whether the release is from captured CO_2 or from any CO_2-generating activity associated with the captured carbon. The result of incorporating maintenance activities will create a situation that would cause some sequestration technologies to have a negative value, indicating a poor carbon management strategy. To demonstrate how the time-adjusted value of energy is used in conjunction with the time-adjusted value of sequestration we can review the release profile example in Figure 4. Here we have labeled the CO_2 released directly from the sequestered carbon with “Product” and CO_2 released from auxiliary activities has been labeled with “Operation.”

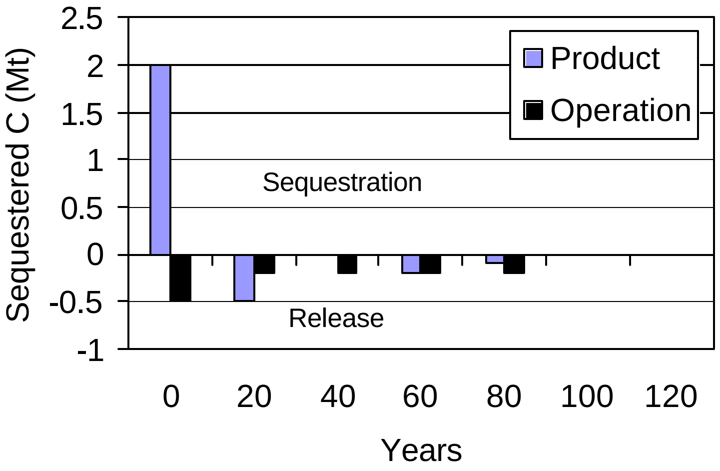


Figure 4. Carbon release profile in the case of auxiliary GHG-generating activities.

It should immediately be noted that we release 0.5 Mt C from the operation (in year 0) when we initially capture 2 Mt C. Thus, the maximum value of the sequestration is the net amount, or 1.5 Mt C. The reduced value due to early release may be calculated from Equation 7 as

$$V = (2-0.5) - \begin{bmatrix} (0.5+0.2)\times(1-TVCS(i,20,100)) + 0.2\times(1-TVCS(i,40,100)) \\ +(0.2+0.2)\times(1-TVCS(i,60,100)) + (0.1+0.2)\times(1-TVCS(i,80,100)) \end{bmatrix}. \qquad (9)$$

The total carbon release in out-years (1–100 years) for this example is 1.6 Mt C, which is slightly higher than the net amount initially sequestered. Even without a value function (adjusting for time), this technology may not represent the best alternative. Using a penalty rate of –3%, the value of the sequestration with this release profile is 1.02 of a maximum of 1.5 Mt C.

2.6 CORRELATION BETWEEN FULL-CYCLE CARBON EMISSIONS AND VALUE OF CARBON SEQUESTRATION

The FCCE of the waste and the sequestered carbon streams is the amount of carbon equivalents of future emissions related to these streams. In introducing the *Time-adjusted Value of Carbon Sequestration*, we have acknowledged that emissions may occur in the future from the sequestered carbon and we have also incorporated a value metric to address when in the future releases happen. Thus, the time-adjusted FCCE is the right portion of the expressions in Equations 7 and 8,

$$FCCE = \sum_{j=1}^{Y} R_j \times \left(1 - TVCS(i, y_j, Y)\right) \quad \text{or} \quad \int_{0}^{Y} R(y) \times \left(1 - TVCS(i, y_j, Y)\right) dy \ , \tag{10}$$

with R_j and $R(y)$ as defined in the preceding section.

3. THE LIFE-CYCLE CARBON FLOW CONCEPT

In the discussions above we have limited ourselves to look at a one-time sequestration activity and then evaluating its effectiveness with time. Just doing that is a very practical tool for evaluation of different sequestration technologies. In practice, a sequestration technology will sequester carbon each year it is operational and some of the carbon may be released during the life of the project or after the project is completed. Maybe a sequestration processing plant is only operational 40 years before major renovation and new capital equipment are needed. Any engineered approach used for sequestration will also require extensive research, development, and construction of equipment and facilities to carry out the sequestration. For example, the pipeline to transport CO_2 to the bottom of the ocean must be built and the CO_2 separations technology must be developed and installed in the coal-burning power plants. All these activities represent carbon investments in the technology, because they generate CO_2 in the process. There may also be activities at the end of the project cycle that also generate CO_2. For example, the sequestration processing plant may need decommissioning, etc.

Assume we have the pieces to construct a life-cycle carbon flow diagram for a particular process. The time-scale for the carbon flow should begin at conception of the idea and end many years after the completion of the activity. An example of such carbon flows may be seen in Figure 5.

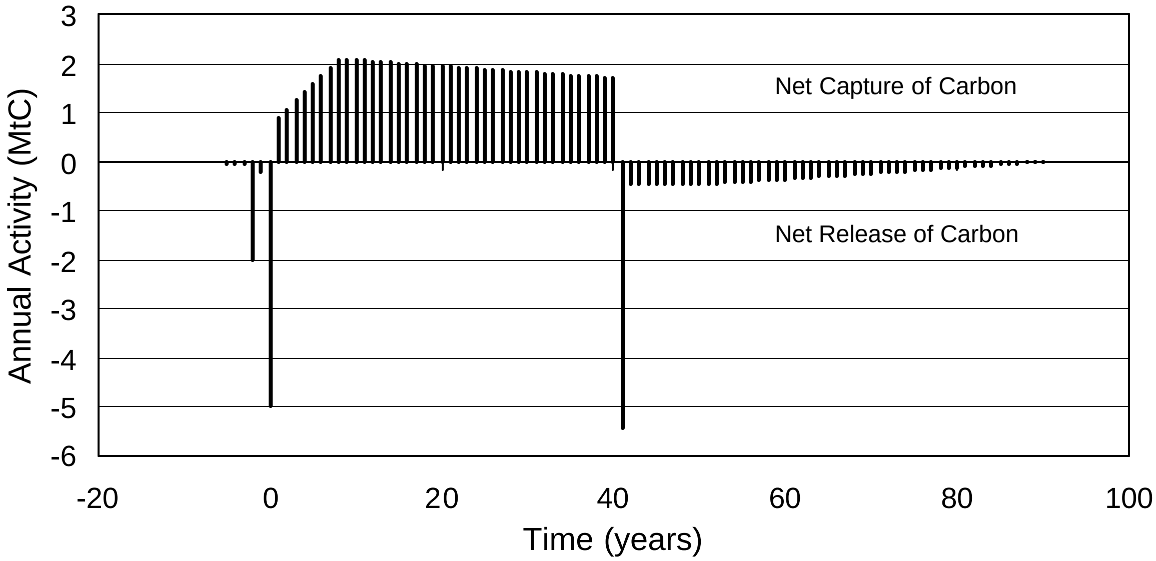


Figure 5. Life-cycle carbon flow for a sequestration activity, including anticipated releases from the sequestered carbon.

To illustrate the carbon flows in Figure 5, we can visualize a sequestration project beginning with research and development, releasing a little CO_2 in the process. A few years before the construction of the processing plant we clear some land and burn the tree stumps (2 Mt C released). In the year just before we open our plant, we build on the land, generating 5 Mt C in energy use and latent CO_2 emission associated with the capital equipment and structures. The plant begins operation by ramping up the sequestration capacity over the first eight years of operation, and then capacity remains constant for the rest of the time. At these latter years, we sequester a net amount of carbon (about 2 Mt C) each year but we also have slow releases from the captured carbon. During the processing plant's last year, we must decommission and demolish our facility, thus generating some carbon emission in the process. In the out-years, there is a small annual net release from the sequestered carbon. In our example, we assumed a release profile, by which 25% of the sequestered carbon is released during its first 50 years of sequestration. The remaining 75% will stay sequestered "forever," or longer than our target goal. In Figure 5, values above the X-axis correspond to a net flux of carbon being removed from the atmosphere, while negative values correspond to a net release of carbon. The data in Figure 5 can also be plotted in a cumulative plot (Figure 6).

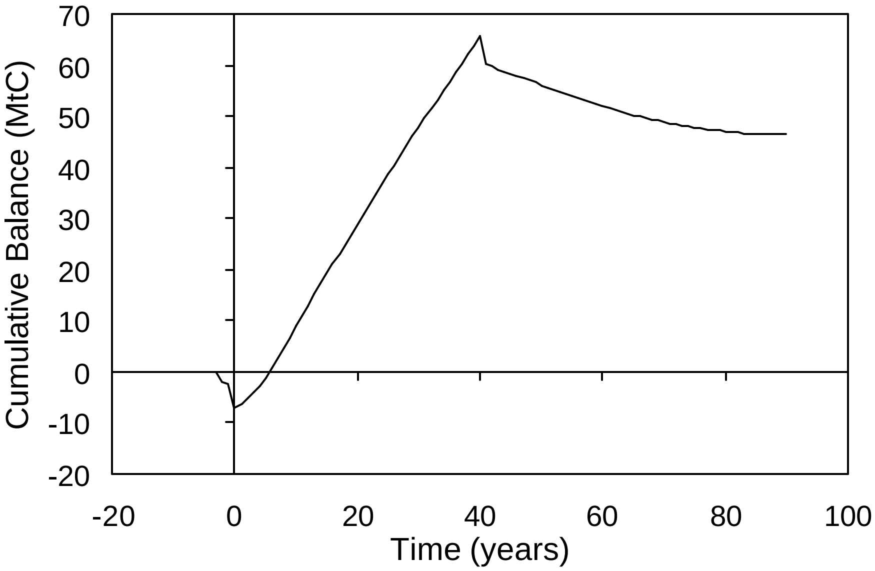
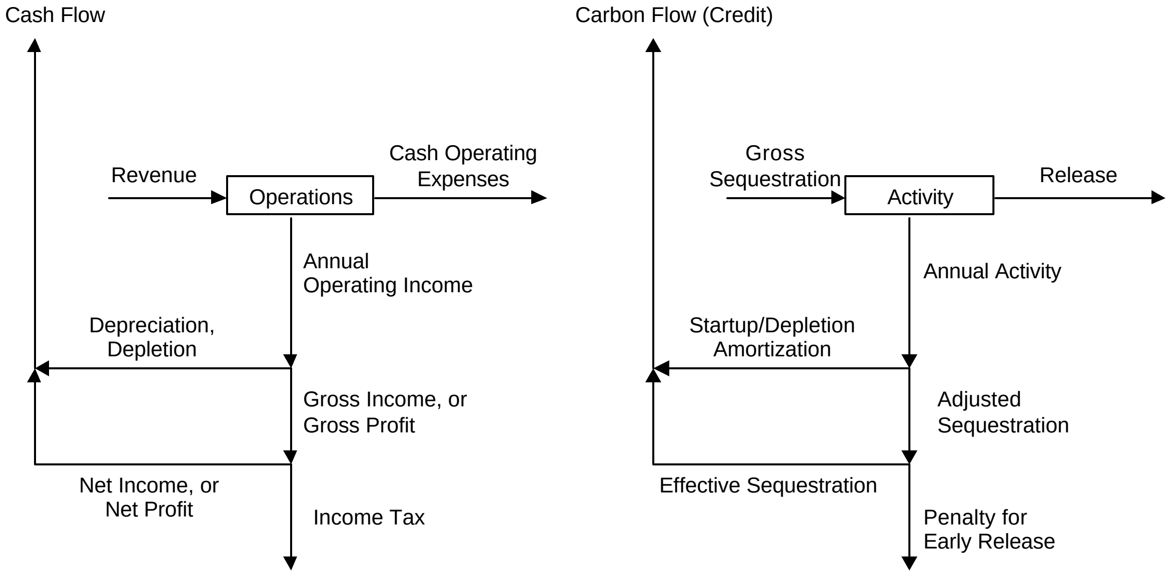


Figure 6. Cumulative carbon flow for a sequestration activity.

The overall life-cycle result of the sequestration activity presented in Figure 5 and 6 is that a balance of approximately 46 Mt C was captured. In order to assign carbon value and compare alternative sequestration schemes, we have to expand discussions about the carbon flows over the time of the activity.

By looking at the life-cycle carbon flow concept as being analogous to the cash flow concept discussed in economic analysis of chemical processing plants, we can gain more insight. The discussion of startup carbon release is analogous to investment capital and thus “amortization” of start-up carbon release becomes analogous to capital cost depreciation in the economic analysis. In Figure 7 we show the cash flow concept and the carbon flow concept.

In the example presented in Figure 5 and 6, we presented flows related to the activity, wherever they may occur. In Figure 7, we take a slightly different approach to address the value of a technology. In the true cash flow concept, depreciation and income tax reduce the annual activity (or Annual Operating Income) before the net income is calculated. We propose the same visualization can used in the value calculations in the carbon flow concept where the carbon emissions related to project startup and sequestration efficiency (*Time-adjusted Value of Carbon Sequestration* discussed above) can be brought into the evaluation. When this is done, any carbon emissions occurring past the demolition of the sequestration plant are accounted for in the “Penalty for Early Release” (see Figure 7), and any startup or demolition emissions are accounted for in the “Amortization.” Thus, the life cycle of the project is reduced to focusing on the time-valued carbon flows during the active life.



Cash Flow Concept

Carbon Flow Concept

Figure 7. Cash flow and carbon flow concepts compared.

We have listed the numerical values for the annual carbon flows around our plant in Table 2. The data in Figure 5 included releases from carbon captured, while Table 2 only focuses on the sequestration process ("Activity" box in Figure 7). The amount of carbon "invested" in the activity is 7.35 Mt C [cumulative flow at end-of-year (EOY) 0, Table 2] and in the year past the end of the activity (year 41) we anticipate a release of 5 Mt C related to the demolition of the sequestration plant. The project is ramping up the sequestration capacity over the first eight years of operation and then remains constant for the rest of the time. The operation of the plant requires materials and energy, which has associated carbon equivalence release ("Operational Release") calculated via the FCCE concept. For brevity purpose, there is no listing in Table 2 for carbon release from the sequestered material or any maintenance activity related to the sequestered material.

Table 2. Example of carbon flows associated with a sequestration acitivty. The annual activity for years 11 through 39 remains the same as in year 10.

	EOY	Sequestration (MtC)	Operational Release (MtC)	Annual Activity (MtC)	Cummulative (MtC)
Research	-5	0	0.05	-0.05	-0.05
	-4	0	0.05	-0.05	-0.1
	-3	0	0.05	-0.05	-0.15
Land use	-2	0	2	-2	-2.15
Equipment	-1	0	0.2	-0.2	-2.35
	0	0	5	-5	-7.35
Activity	1	1	0.1	0.9	-6.45
	2	1.2	0.12	1.08	-5.37
	3	1.4	0.14	1.26	-4.11
	4	1.6	0.16	1.44	-2.67
	5	1.8	0.18	1.62	-1.05
	6	2	0.2	1.8	0.75
	7	2.2	0.22	1.98	2.73
	8	2.4	0.24	2.16	4.89
	9	2.4	0.24	2.16	7.05
	10	2.4	0.24	2.16	9.21
	↓	↓	↓	↓	↓
	40	2.4	0.24	2.16	74.01
Demolition	41	0	5	-5	69.01

3.1 AMORTIZATION OF CARBON INVESTMENT

To make things simple, we illustrate the most common method of amortization, the straight line, where the carbon investment is spread evenly over the operational life of the activity. In the example above, the carbon investment was 7.35 Mt C plus the final release of 5 Mt C. Spread over 40 years, this calculates to 0.309 Mt C per year. The amortization may for some scenarios be more of an academic exercise, but it helps in the visualization and discussions.

3.2 PENALTY FOR EARLY CARBON RELEASE

We have already discussed the time-adjusted value of sequestration and how to calculate the "penalty" for releasing the sequestered carbon before our goal of Y years is reached. In the example above we assumed that 25% of the gross sequestered carbon in any one year is released during its first 50 years of sequestration, but that the remainder stays sequestered for more than Y years. Thus, the annual release of carbon in the first 50 years is calculated as

$$R = \frac{amount\ C\ sequestered \times 0.25}{50} \quad , \tag{11}$$

and the value of the activity is derived from Equations 7 or 8. In our example, it turns out that it is easier to use Equation 8 and we get the following expression for activities at the end of year j:

$$V_j = S_j - \frac{(amount\ C\ sequestered)_j \times 0.25}{50} \times \int_0^{50} \left(1 - \frac{(1+i)^y - 1}{(1+i)^Y - 1} \right) dy \quad . \tag{12}$$

Equation 12 appears somewhat complicated but it can easily be solved analytically.

3.3 CREDIT FOR ANNUAL CARBON SEQUESTRATION ACCOMPLISHMENTS

Our goal has been to develop an evaluation methodology by assigning (carbon) value (or metric) to a sequestration activity. The reason for the discussions above has been to lay the foundation for a technique that can assign a fair value to a claimed accomplishment. In a carbon trading system, national or international, we must keep in mind that a credit can only be assigned in a year where there is sequestration activity—in other words, during the active life of the sequestration facility. Any emissions occurring outside this time frame must be accounted for in the form of a penalty as we described above or through another process. Since it is not clear what type of carbon accounting system will be implemented for trading purposes, it is not possible to predict how true carbon credits are to be calculated for a sequestration activity. It may be that the product (sequestered carbon) may serve as the basis for the activity, as we proposed on page 2, or it may be that carbon flows to and from the atmosphere will be considered. In the examples above we have tried to develop a methodology for sequestration evaluation purposes, not for carbon accounting purposes.

Consider that some regulatory agency gives the fossil fuel power industry an emission reduction goal to be achieved by year 2010. This assumed agency further stipulates that the reduction can be accomplished either through process changes, by engaging in sequestration activities, or by acquiring carbon sequestration credits from the new carbon sequestration industry. If purchasing credits is the choice, it is important that these credits have a fair value in representing the emissions reduction accomplishments. To demonstrate what credits could be claimed, let us continue with our example. For the sequestration scenario we have created, the carbon flows are listed in Table 3; e.g., in year 6, we anticipate that our plant will remove 2 Mt C from the atmosphere, but that it will have an annual activity of 1.8 Mt C. (We sequester 2 Mt C in a product, but we emit 0.2 Mt C to accomplish it.) However, the fair amount of carbon credit that could be claimed in that year is 1.56 Mt C because of the anticipated future release of some of the sequestered carbon. The amortization does not affect the value of the carbon flow (credit), but may serve a purpose for overall figure of merit of sequestration processes.

4. FIGURE OF MERIT FOR CARBON SEQUESTRATION ACTIVITIES

To this point we have introduced methods to estimate

- the net amount of carbon sequestered by taking into account both actual mass flow of carbon and latent emissions,
- the time-adjusted value of sequestration be assigning a function to account for early release and the use of energy/material in the future to keep the carbon captured,
- the concept of carbon investment that occurs as a result of activities even before carbon sequestration is realized, and
- the carbon flow concept, which addresses the life-cycle carbon flows and may serve as a basis for carbon credits calculations for a sequestration activity.

Table 3. Carbon flows on an annual basis.

EOY	Sequestration (MtC)	Annual Activity (MtC)	Amortization (MtC)	Penalty (MtC)	Carbon Flow (MtC)
-5	0	-0.05			-0.05
-4	0	-0.05			-0.05
-3	0	-0.05			-0.05
-2	0	-2			-2
-1	0	-0.2			-0.2
0	0	-5			-5
1	1	0.9	0.309	0.120	0.780
2	1.2	1.08	0.309	0.144	0.936
3	1.4	1.26	0.309	0.168	1.092
4	1.6	1.44	0.309	0.192	1.248
5	1.8	1.62	0.309	0.216	1.404
6	2	1.8	0.309	0.241	1.560
7	2.2	1.98	0.309	0.265	1.715
8	2.4	2.16	0.309	0.289	1.871
9	2.4	2.16	0.309	0.289	1.871
10	2.4	2.16	0.309	0.289	1.871
↓	↓	↓	↓	↓	↓
40	2.4	2.16	0.309	0.289	1.871
41	0	-5			-5

What is needed to complete the methodology is an overall figure of merit for the technology based on the carbon flow concept. We propose that the same approach used in chemical plant economics is useful when evaluating sequestration activities. Many of the most recently developed figures of merit (e.g., performance measures or profitability) used in the evaluation of industrial processes are based on different types of cash flow. Some of the measures include depreciation, with or without tax, with or without discounting.

The word ‘profitability’ implies that we are now interested in how well our activity is doing compared with the investments we made. When we look at ‘profitability,’ we can compare other investment alternatives. When alternatives are compared (in our carbon sequestration case), it is very likely that the carbon flows for different projects will be dissimilar, both in their magnitude and when they occur. When flows occur at different times this detail is corrected by introducing the time value of carbon. There have been discussions about carbon flows and whether or not there is such a concept of time value of carbon. One argument is that for most cases the time interval often looked at is too short for the flows to be time dependent—the time dependency may exist if we look at flows in terms of millenniums, but maybe not on a decade or century basis. We have selected to treat the value of carbon flows as time dependent to allow for a complete analysis. The methodology can easily be modified if the time dependency is to be ignored.

There are two types of figure of merit we propose are useful and these are discussed in detail in the Discussion section. To summarize, the first method looks at the cumulative carbon flows over the life of the project and compare them to the carbon flow of the initial carbon investment. The second type compares the average sequestration of carbon per year to the emissions from initial investment plus demolition, averaged over the active sequestration facility life.

5. DISCUSSION

Above we have developed a general methodology for carbon accounting in sequestration activities on a national basis in support of IPPC general methodologies. We have also developed a more detailed, yet general, methodology for evaluation of proposed individual sequestration technologies, and part of this approach may be used in assessing credits. In this section we plan to discuss and elaborate on the following topics:

- selection of sequestration goal, e.g. 100 years;
- the penalty interest;
- the latent emissions content in energy and materials used for sequestration or equipment construction and the data sources that may be available or techniques for estimation; and
- sequestration costs and how these may be used as a evaluation tool.

5.1 SELECTION OF SEQUESTRATION GOAL AND PENALTY INTEREST

Intuitively, it makes sense that there should be a goal with sequestration efforts. Clearly our objective is to reduce global warming by reducing GHG concentrations in the atmosphere. In our methodology development we arbitrarily chose 100 years of sequestration as a goal and if we can sequester carbon (equivalents) for at least this amount of time, we equate this with perfection. Clearly, this goal value is important and some of the aspects that should be considered when choosing this goal might be:

1. U.S. policy on carbon emissions. Are we trying to capture carbon to satisfy international agreements?
2. Should the goal be tied to the estimated time left of fossil fuels, so that future emissions will come after all fossil fuel emissions have taken place?
3. Should we strive to become at least as good as managed forests; e.g., let us grow trees, harvest them and bury them? How long does it take for most of the carbon to return to the atmosphere?
4. Should we consider using global climate models to get guidance of an appropriate time scales? For example, the life of CO_2 in the atmosphere is 100–200 years.

Aspects 2, 3, and 4 suggest a goal of a century or greater. The same aspects might also be considered when selecting a penalty interest rate, which, together with the sequestration time goal, suggests how much we value the duration of sequestration. Selection of a penalty interest may be policy setting or may have its roots in science.

5.2 FULL-CYCLE CARBON EMISSIONS FROM ENERGY USE

One of the most obvious latent emissions in a proposed sequestration approach is related to the energy used in the sequestration activities or subsequent activities for keeping the carbon sequestered. For a slightly energy-diverse U.S., the CO_2 emissions factor for energy use in 1997 was 15.7 Mt C/EJ ($1.57 \cdot 10^{-5}$ g C/J) [6]. This value also includes other-than-fossil energy sources that do not have CO_2 emissions. The use of fossil energy also generates other greenhouse gases emissions, such as CH_4, N_2O, CO and others. These should also be considered and have been quantified by EPA [6]. For example, the emission from fossil burning and losses (such a as methane generation in coal mining, natural gas flaring in oil recovery, etc.) amount to approximately 91.2 Mt C (based on GWP), which contributes an additional 6.2% to the regular CO_2 emissions. These emissions are all process-related emissions—they do not take into account that we must construct power plants and build infrastructure, etc. Attempts have been made to estimate what has been termed *Full-Energy-Chain Emissions Factors* (*FENCH Emission Factors*) of green house gases appropriate for energy use [7]. These emissions factors are in the range of $3.55 \cdot 10^{-5}$ to $4.25 \cdot 10^{-5}$ g C/J for electricity use from mixed sources. Thus, it is important to accurately determine the amount and type of energy a sequestration activity requires and to apply the appropriate emissions factors. A table of FCCE for different types of energy may be found in Appendix A

5.3 FULL-CYCLE CARBON EMISSIONS FROM MATERIALS USE

A general methodology to determine the FCCE related to raw materials may be to divide this estimation into four different categories of latent emissions that arise from the production of these materials:

(a) process emissions related to the stream (e.g., CO_2 generation from process methane used in ammonia production),
(b) indirect or direct emissions from the use of energy (e.g., the energy requirement for ammonia production is 29 MJ/g NH_3 [8]),
(c) emissions from transportation fuel used to get the "stream" to, or from, our sequestration location, and
(d) all other emissions.

As noted, the fourth category is a catch-all group, which includes the emissions related to ammonia plant construction, labor force transportation, etc. If we desire to estimate this catch-all group of indirect emissions, a possible method may be to look at the market price of the raw material. In the case of ammonia, the cost in 1997 was \$227/ton (short) not including transportation [9], which translates to \$$2.5 \cdot 10^{-4}$/g NH_3. We can use this cost in two ways,

1. assume that all of this cost will ultimately be applied to some type of energy use in society, and then convert the cost to carbon emission by using the energy price in 1997 (adjusted with gross domestic product implicit price deflators), which was \$8.99/MBtu (\$$8.52 \cdot 10^{-9}$/J) [10], and emissions factors based on general energy use ($1.062 \times 1.57 \cdot 10^{-5}$ g C/J). This would give us an estimated cost emissions factor of 1960 g C/\$.
2. or, we can use the gross domestic product (GDP) and its correlation to carbon emission. In 1997 the GDP was $8300 \cdot 10^{9}$ dollars [11], and the estimated emissions were 1800 Mt C ($1.8 \cdot 10^{15}$ g C), including all GHGs [12]. This would lead to a cost emissions factor of 217 g C/\$.

The first method will most likely result in an overestimation of latent emissions because part of the cost of the materials includes energy (and sometimes transportation) already accounted for in (b). We may thus refine our general FCCE estimation methodology to:

(a) Determine process emission factor and calculate the GHG emissions. There are several sources for this such as IPCC [3], EPA [6], and others [13].
(b) Determine the energy use for the production and transportation of the raw material to the sequestration plant. Convert the energy to carbon emissions using the appropriate emissions factors for energy.
(c) Determine the delivered product cost and use the GDP/emission relationship to estimate all other indirect emissions. This will lead to a somewhat conservative estimate as part of the product costs is associated with energy and materials use.

As an alternative, we could use an even more simplified approach based on process emissions and cost, but not the energy use for the materials production. Instead one could assume that the entire material cost is associated with energy use.

In addition to the raw material used in the sequestration process, the capital equipment, buildings, and other items will have associated FCCE. As with the materials used in construction, the same methodology developed above for raw materials may be used once the amount of construction materials has been estimated. Van de Vate has summarized some process emission and energy intensity values for common building materials [14]. It should be pointed out that none of these generalized methods have been tested, and that detailed estimation of true FCCE is preferred whenever possible. A detailed discussion, as well as our calculated FCCE values for different materials, may be found in Appendix A.

5.4 COST OF CARBON SEQUESTRATION

We have, in the sections above, introduced cost as a method of estimating some indirect emissions contained in the FCCE. We could potentially extend this to the entire sequestration process. By doing this we only look at materials streams in and out of the "sequestration factory" and their associated process emissions factors. Then we use the cost of land, capital equipment, and operation to estimate all other carbon emissions. The use of cost in this manner would also include the labor cost, thus providing an estimate of carbon emissions from labor. It is very speculative, but also very interesting how this approach would compare with detailed emissions estimation.

6. FIGURE OF MERIT FOR CARBON SEQUESTRATION ACTIVITIES

Figure of merit (or 'profitability') for a carbon sequestration activity must be developed so that different activities can be compared. We propose that the approach used in chemical plant economics is useful when evaluating sequestration activities. Rather than presenting each analogous figure of merit for carbon sequestration, we will only discuss a few that are especially applicable.

The word 'profitability' is used in terms of return on investment. We have already made a case that carbon release will occur as part of development and construction of sequestration facilities or modification of processes. It is logical that we compare our reward (future carbon sequestration) to our initial releases. As previously mentioned, there have been arguments against using time value of carbon. We have selected to treat the value of carbon flows as time dependent to allow for a complete analysis. The methodology can easily be modified by assuming an interest rate of 0%, if the time dependency is to be ignored.

6.1 TIME VALUE OF CARBON FLOWS

The time value of carbon flows may be handled using the single payment compound amount factor, $(P / F\ I, n)$ (15), which is described by

$$(P / F\ I, n) = (1 + I)^{-n} \ , \tag{13}$$

where P is the present worth, F is the future worth, I is the discrete compound interest rate, and n is the years between P and F. If the carbon flows are not time dependent, I is zero and $(P/F\ I, n)$ is always one. To determine the present worth of, for example, 1.56 Mt C in year 6 (Table 3) with a 10% interest rate we can calculate this to be

$$P = 1.56 \times (P / F\ 10\%, 6) = 1.56 \times (1 + 0.1)^{-6} = 1.56 \times 0.5645 = 0.88 \ . \tag{14}$$

One way to view this information is to say that, we can either capture 0.88 Mt C today, or we must capture 1.56 Mt C in year 6—time is of the essence.

6.2 PRESENT-WORTH INDEX AS FIGURE OF MERIT

The present-worth index appears to be a useful figure of merit for comparisons of alternatives and relates the overall present worth of all the carbon flows (Annual Activity minus Penalty) to the present worth of the initial 'investment' (flows for year ≤ 0). Thus, it addresses the overall merit of the 'investment,' and we want the present worth index to be as large as possible for a project. In Table 4 we have expanded the result presented in Table 3 to include the present worth. The calculated present worth index (PWI) for our example process is 0.89 as calculated by Equation 15.

$$PWI = \frac{present\ worth\ of\ all\ carbon\ flows}{present\ worth\ of\ initial\ 'investment'} = \frac{7.02}{7.86} = 0.89 \tag{15}$$

In addition to using PWI as a figure of merit, the present worth for all the carbon flows (also known as net present worth) may be used as an indicator when comparing alternatives. This was 7.02 Mt C in our case.

6.3 ANNUAL WORTH AS FIGURE OF MERIT

In this method, present worth (or value) of the flows during the <u>active</u> life of the sequestration activities is averaged out over the active life of the sequestration plant. Similarly, the present worth of the initial investment and the demolition carbon flows are also averaged out. It should be noted that these are not straight averages, but that a uniform series capital recovery fund factor is used to calculate the average (15). This factor is used to spread a present worth over future years, while still maintaining the time worth of carbon at the set interest rate. Then, the two averages (investment versus carbon flow for active plant life) are compared. The (uniform series capital recovery fund) factor that the present worth should be multiplied by is

$$(A/P\ I,\ N) = \frac{I \times (1+I)^N}{(1+I)^N - 1}\ , \tag{16}$$

where *A* is the annual average we are calculating and *N* is the life expectancy in years for the plant. The average worth for our example is

$$A_{investment+demolition} = 7.96 \times (A/P\ 10\%, 40) = 7.96 \times \frac{0.1 \times (1+0.1)^{40}}{(1+0.1)^{40} - 1} = 0.814 \text{ and} \tag{17}$$

$$A_{carbon\ flow} = 14.98 \times (A/P\ 10\%,\ 40) = 14.98 \times 0.1023 = 1.532\ . \tag{18}$$

This means that we are sequestering on average 0.718 Mt C per year above the recovery of the carbon emissions related to initial activities and demolition, even if we expect a 10% return on the ‘investment.’

Other figures of merit used in applied finance and economic analysis are in some cases using cash flows without depreciation/depletion, sometimes with depreciation/depletion. This is why we included the concept of amortization for completeness.

Table 4. Present worth calculation based on carbon flow. (The present worth for the flows for year 11 through 39 have been left out for brevity.)

EOY	Sequestration (MtC)	Annual Activity (MtC)	Amortization (MtC)	Penalty (MtC)	Carbon Flow (MtC)	Present Worth (MtC)
-5	0	-0.05			-0.05	-0.08
-4	0	-0.05			-0.05	-0.073
-3	0	-0.05			-0.05	-0.067
-2	0	-2			-2	-2.42
-1	0	-0.2			-0.2	-0.22
0	0	-5			-5	-5
1	1	0.9	0.309	0.120	0.780	0.709
2	1.2	1.08	0.309	0.144	0.936	0.773
3	1.4	1.26	0.309	0.168	1.092	0.820
4	1.6	1.44	0.309	0.192	1.248	0.852
5	1.8	1.62	0.309	0.216	1.404	0.871
6	2	1.8	0.309	0.241	1.560	0.880
7	2.2	1.98	0.309	0.265	1.715	0.880
8	2.4	2.16	0.309	0.289	1.871	0.873
9	2.4	2.16	0.309	0.289	1.871	0.794
10	2.4	2.16	0.309	0.289	1.871	0.722
↓	↓	↓	↓	↓	↓	↓
40	2.4	2.16	0.309	0.289	1.871	0.041
41	0	-5			-5	-0.100
			Interest =	10%	Sum of flows	7.02

7. CONCLUSIONS

Our objective was to develop a general methodology for evaluation of carbon sequestration technologies. We wanted to provide a method that was quantitative, but would be structured to give qualitative comparisons despite changes in detailed method parameters—i.e., it does not matter what "grade" a sequestration technology gets but a "better" technology should get a better grade. We think that the developed methodology provides this capability. Our methodology can be defined by "What it is" and by "What it is not." We have found that in some of our discussion groups it is useful to explain the scope of the methodology by reviewing both these terms.

7.1 WHAT IT IS

- This is a methodology that will assist evaluation and comparison of well-defined sequestration activities.
- This is a methodology that should be used prior to engaging in an activity to address long-term merit.
- This is a methodology that treats a sequestration activity as an engineering activity over which we have control and knowledge.
- This is a methodology that addresses carbon sequestration in life-cycle terms.

7.2 WHAT IT IS NOT

- This is not a global climate model.

- This is not a model to predict sequestration impact on carbon dioxide levels in the atmosphere.
- This is not an approach to estimate environmental impact.
- This is not a model that addresses a trading mechanism of carbon credit; however, portions of the methodology may be used to determine a carbon credit value for a sequestration activity.

We feel that the methodology presented in this report is ready for input from an extensive scientific community. We would encourage workshops for discussions on FCCE calculations, penalty interest rate, time value of carbon, and figure of merit. Ultimately, the methodology must be put through rigorous testing with different sequestration approaches. In Appendices B and C, we elaborate on the typical calculations needed for the methodology.

8. ABBREVIATIONS, NOMENCLATURE, AND CONVERSION FACTORS

A = annuity
Btu = energy, British thermal unit
C = carbon (or carbon equivalent)
CE = carbon equivalent
EOY = end-of-year
EPA = U.S. Environmental Protection Agency
F = future value
FCCE = full-cycle carbon emissions
FENCH= full-energy chain emissions
g = gram = $2.2046 \cdot 10^{-3}$ lb
GDP = gross domestic product
GHG = greenhouse gases
GWP = Global Warming Potential
HFC = hydrofluorocarbons
i = penalty interest rate
I = periodic (annual) interest rate
IPPC = Intergovernmental Panel on Climate Change
J = energy, Joule = 0.0009486 Btu
j = index counter (= year of activity)
J(e) = electric energy, Joule
kg = kilogram = 1,000 g
kWh = kilowatt hour ($3.6 \cdot 10^{6}$ J(e))
M = mega (million) = 10^{6}
Mt C = mega (metric) ton carbon = 10^{9} kg
N = number of periods (years) for interest rate calculations
P = present value
PFC = perfluorocarbons
PWI = present worth index
R = amount carbon released
S_C = net amount carbon sequestered
t = metric ton, 1000 kg, 10^{6} gram, 2204.6 lb
TVCS = time-adjusted value of carbon sequestration
V = value variable
Y = sequestration duration goal, in years
y = years of sequestration before release

9. REFERENCES

1. *Climate Change 1995-The Science of Climate Change*, Houton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., eds., Cambridge University Press, pp. 21–22 (1996).
2. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–1996*, EPA 236-R-98-006, U.S. Environmental Protection Agency Office of Policy, Planning and Evaluation, p. ES-6 (1998).
3. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Workbook*, Intergovernmental Panel on Climate Change, (1996).
4. Rawls, R.L., “Sequestering CO_2,” *C&EN*, (September 18, 2000).
5. Lee, J.W., “A New Strategy for Global CO_2 Sequestration,” presented at the 22nd Symposium on Biotechnology for Fuels and Chemicals, Gatlinburg, TN, (May 2000).
6. *Inventory of U.S. Greenhouse Gas Emissions and Sinks:* 1990–1997, EPA 236-R-99-003, U.S. Environmental Protection Agency Office of Policy, Planning, p. 2-12 (1999).
7. *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emissions Factors of Greenhouse Gases*, IAEA-TECDOC-892, International Atomic Energy Agency, Vienna, Austria, p. 9 (1996).
8. *Kirk-Othmer Encyclopedia of Chemical Technology,* 4th ed., vol. 2, John Wiley & Sons, New York, p. 655 (1992).
9. *Chemical Market Reporter*, (December 29, 1997).
10. *Annual Energy Review 1999*, DOE/EIA-0384(99), U.S. Department of Energy, Office of Energy Markets and End Use, Energy Information Administration, p. 67 (July 2000).
11. Reference 10, p. 347.
12. *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98), Energy Information Administration, Office of Energy Markets and End Use, U.S. Department of Energy, p. x (October 1999).
13. Van de Vate, J.F., “Comparison of Energy Sources in Terms of their Full Energy Chain Emission Factors of Greenhouse Gases,” *Energy Policy* **25** (1), 1–6 (1997).
14. Van de Vate, J.F. “Full Energy Chain Analysis of Greenhouse Gas Emissions from Different Energy Sources,” in *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emissions Factors of Greenhouse Gases*, IAEA-TECDOC-892, International Atomic Energy Agency, Vienna, Austria, pp. 11–17 (1996).
15. Couper, J.R. and Rader, W.H., *Applied Finance and Economics for Scientists and Engineers*, Van Nostrand Reinhold Co., New York, p. 136 (1986).

APPENDIX A: FULL-CYCLE CARBON EMISSIONS (FCCE) FACTORS FROM RESOURCE USE IN CARBON SEQUESTRATION ACTIVITIES

A-1. FCCE FOR ENERGY AND ELECTRICITY USE

In a proposed sequestration, one of the most obvious emissions is related to the energy used in sequestration activities and subsequent activities for keeping the carbon sequestered. For the United States, which represents a certain energy diversity, the average CO_2 emissions factor for energy use in 1997 was 15.7 Mt C/EJ [$1.57\cdot10^{-5}$ g C/J (grams of carbon equivalents per joule)] [A1]. Other countries would have different averages as it includes energy sources (other than fossil) that do not have CO_2 emissions. The use of fossil energy also generates other greenhouse gas emissions, such as CH_4, N_2O, and CO. These should also be considered and have been quantified by U.S. Environmental Protection Agency (EPA) [A1]. For example, the emission from fossil burning and losses (such as methane generation in coal mining and natural gas flaring in oil recovery) amount to approximately 91.2 MtC (based on global warming potential, GWP), which contributes an additional 6.2% to the regular CO_2 emissions. This would suggest that the emissions factor for general use energy is $1.67\cdot10^{-5}$ g C/J. These emissions are all process-related—they do not take into account factors such as constructing power plants and building infrastructures.

To get an estimate of the indirect emissions related to energy use we could use the cost of energy, which was \$8.82/MBtu (\$$8.36\cdot10^{-9}$/J) [A2], and the gross domestic product (GDP) and its correlation to carbon emission. In 1997 the GDP was $8300\cdot10^{9}$ dollars [A3], and the estimated emissions were 1800 Mt C ($1.8\cdot10^{15}$ g C), including all GHGs [A4]. This would lead to a cost emissions factor of 217 g C/\$. This in turn would suggest an indirect emissions factor of $1.81\cdot10^{-6}$ g C/J and an overall emissions factor of $1.85\cdot10^{-5}$ g C/J for general energy use.

Attempts have been made to estimate what has been termed *Full-Energy-Chain* (FENCH) *Emissions Factors* of greenhouse gases for electricity use [A5]. These emissions factors are in the range of $3.52\cdot10^{-5}$ to $4.21\cdot10^{-5}$ g C/J(e) for electricity produced from mixed sources within a region (see table below). Thus, it is important to accurately determine the amount and type of energy that a sequestration activity requires and to apply the appropriate emissions factors. The FENCH Emission Factor represents the same concept as the FCCE Factor but differs in the development. In the FCCE concept, we often use cost as a method for estimating indirect emissions.

Source of Electricity	FENCH Emissions Factor (g C/J(e))
Coal	
Lignite [A5]	$8.81\cdot10^{-5} – 1.00\cdot10^{-4}$
hard coal [A5]	$7.22\cdot10^{-5} – 9.68\cdot10^{-5}$
Gas	
natural gas [A5]	$5.79\cdot10^{-5}$
liquid natural gas [A5]	$4.90\cdot10^{-5}$
Nuclear power [A5]	$7.50\cdot10^{-8} – 1.93\cdot10^{-6}$
Hydro power [A5]	$1.35\cdot10^{-6}$
Solar photo voltaic [A5]	$4.28\cdot10^{-6} – 2.09\cdot10^{-5}$
Wind power [A5]	$1.20\cdot10^{-6} – 9.00\cdot10^{-6}$
Biomass [A6]	$2.78\cdot10^{-6} – 1.35\cdot10^{-5}$
Electricity mix [A5]	$3.52\cdot10^{-5} – 4.21\cdot10^{-5}$

Industry also uses a substantial amount of fossil fuel for heating, e.g., steam generation via coal combustion. We must realize that there are several types of emissions with this type of energy use. Because its use is prevalent in industry, we will look at them each in detail.

A-1.1 EMISSIONS FROM INDUSTRIAL COMBUSTION OF COAL

IPCC lists the following equations for combustion of coal for industrial purposes [A7, p. 1.24–42]:
CO_2 emissions (g C) = (net J) × $25.8\cdot10^{-6}$ × 0.98
CH_4 emissions (g C) = (net J) × $10\cdot10^{-9}$ × 5.7, with 5.7 as the CE GWP [A8]
N_2O emissions (g C) = (net J) × $1.4\cdot10^{-9}$ × 84.5, with 84.5 as the CE GWP for N_2O [A8]
NOx emissions (g C) = (net J) × $300\cdot10^{-9}$ × 0.2 × 10.9, with 10.9 as the CE GWP for NO_2 [A9]
CO emissions (g C) = (net J) × $150\cdot10^{-9}$ × 0.513, with 0.513 as the CE GWP for CO [A10]
NMVOC emissions (g C) = (net J) × $20\cdot10^{-9}$ × 1.11, with 1.11 as the CE GWP for NMVOC [A10]

Net J (net joules) of energy value for bituminous coal is 28,700 J/g [A7, p. 1.62]. The emissions of CH_4 from mining and post-mining, and other activities may be calculated as
CH_4 emissions (g C) = (g coal) × (17.5+2.45) × $0.67\cdot10^{-3}$ × 5.7 for underground coal [A7, p. 1.105 & 1.110] and
CH_4 emissions (g C) = (g coal) × (1.15+0.1) × $0.67\cdot10^{-3}$ × 5.7 for surface coal [A7, p. 1.108 & 1.110],

or in terms of energy value:
CH_4 emissions (g C) = (net J) × $3.48\cdot10^{-5}$ × (17.5+2.45) × $0.67\cdot10^{-3}$ × 5.7 for underground coal and
CH_4 emissions (g C) = (net J) × $3.48\cdot10^{-5}$ × (1.15+0.1) × $0.67\cdot10^{-3}$ × 5.7 surface coal.

In the US, 61.4% of coal comes from surface mining [A1, p. 2.27]. There is also a small amount of CO_2 released from coal burning during mining. The amount can be estimated from [A7, p. 1.112–113] as
CO_2 emissions (g C) = (g coal) × 0.003 × 0.75 × 0.5 or
CO_2 emissions (g C) = (net J) × $3.48\cdot10^{-5}$ × 0.003 × 0.75 × 0.5.

Accounting for above, we get can calculate a process emissions factor of $27.4\cdot10^{-6}$ g C/net J:

$$\begin{aligned}
25.8\cdot10^{-6} \times 0.98 &= 25.3\cdot10^{-6}\\
10\cdot10^{-9} \times 5.7 &= 0.057\cdot10^{-6}\\
1.4\cdot10^{-9} \times 84.5 &= 0.118\cdot10^{-6}\\
300\cdot10^{-9} \times 0.2 \times 10.9 &= 0.654\cdot10^{-6}\\
150\cdot10^{-9} \times 0.513 &= 0.077\cdot10^{-6}\\
20\cdot10^{-9} \times 1.11 &= 0.022\cdot10^{-6}\\
3.48\cdot10^{-5} \times (17.5+2.45) \times 0.67\cdot10^{-3} \times 5.7 \times 0.386 &= 1.02\cdot10^{-6}\\
3.48\cdot10^{-5} \times (1.15+0.1) \times 0.67\cdot10^{-3} \times 5.7 \times 0.614 &= 0.102\cdot10^{-6}\\
3.48\cdot10^{-5} \times 0.003 \times 0.75 \times 0.5 &= 0.039\cdot10^{-6}\\
\hline
\textbf{Total} \quad & \mathbf{27.4\cdot10^{-6}}
\end{aligned}$$

A-1.2 EMISSIONS FROM INDUSTRIAL COMBUSTION OF PETROLEUM PRODUCTS

IPCC lists the following equations for combustion of oil for industrial purposes [A7, p. 1.24–42]:
CO_2 emissions (g C) = (net J) × $20\cdot10^{-6}$ × 0.99
CH_4 emissions (g C) = (net J) × $2\cdot10^{-9}$ × 5.7, with 5.7 as the CE GWP [A8]
N_2O emissions (g C) = (net J) × $0.6\cdot10^{-9}$ × 84.5, with 84.5 as the CE GWP for N_2O [A8]
NOx emissions (g C) = (net J) × $200\cdot10^{-9}$ × 0.2 × 10.9, with 10.9 as the CE GWP for NO_2 [A9]]
CO emissions (g C) = (net J) × $10\cdot10^{-9}$ × 0.513, with 0.513 as the CE GWP for CO [A10]
NMVOC emissions (g C) = (net J) × $5\cdot10^{-9}$ × 1.11, with 1.11 as the CE GWP for NMVOC [A10]

Net J (net joules) of energy value for oil is 40,900 J/g [A7, p. 1.62]. Emission of CH_4 from a variety of sources such as field production, storage, refining, and transportation is hard to estimate since it depends on the source of oil and the product produced. A rough estimate may be obtained by summing the amount of CH_4 emissions reported by EPA [A1, p. F.3–F.5] and dividing by the total number of energy units consumed [A1, p. A.4].
CH_4 emissions (g C) = $(23.35+1.70+9.19+5.5) \times 10^9 \times 5.7$ for year 1997
Energy consumption = $36961.9\cdot10^{12}$ Btu = $3.90\cdot10^{19}$ J

Using these values we can construct the following equation:
CH_4 emissions (g C) = (net J) $\times 1.02\cdot10^{-9} \times 5.7$

Adding all these emissions together, we get a process emissions factor of $20.3\cdot10^{-6}$ g C/ net J.

$$\begin{aligned}
20\cdot10^{-6} \times 0.99 &= 19.8\cdot10^{-6}\\
2\cdot10^{-9} \times 5.7 &= 0.011\cdot10^{-6}\\
0.6\cdot10^{-9} \times 84.5 &= 0.051\cdot10^{-6}\\
200\cdot10^{-9} \times 0.2 \times 10.9 &= 0.436\cdot10^{-6}\\
10\cdot10^{-9} \times 0.513 &= 0.005\cdot10^{-6}\\
5\cdot10^{-9} \times 1.11 &= 0.006\cdot10^{-6}\\
1.02\cdot10^{-9} \times 5.7 &= 0.006\cdot10^{-6}\\
\hline
\textbf{Total} \quad & \mathbf{20.3\cdot10^{-6}}
\end{aligned}$$

A-1.3 EMISSIONS FROM INDUSTRIAL COMBUSTION OF NATURAL GAS

IPCC lists the following equations for combustion of natural gas for industrial purposes [A7, p. 1.24–29]:
CO_2 emissions (g C) = (net J) $\times 15.3\cdot10^{-6} \times 0.995$
CH_4 emissions (g C) = (net J) $\times 5\cdot10^{-9} \times 5.7$, with 5.7 as the CE GWP [A8]
N_2O emissions (g C) = (net J) $\times 0.1\cdot10^{-9} \times 84.5$, with 84.5 as the CE GWP for N_2O [A8]
NOx emissions (g C) = (net J) $\times 150\cdot10^{-9} \times 0.2 \times 10.9$, with 10.9 as the CE GWP for NO_2 [A9]
CO emissions (g C) = (net J) $\times 30\cdot10^{-9} \times 0.513$, with 0.513 as the CE GWP for CO [A10]
NMVOC emissions (g C) = (net J) $\times 5\cdot10^{-9} \times 1.11$, with 1.11 as the CE GWP for NMVOC [A10]

Net J (net joules) of energy value for natural gas is 52,300 J/g [A7, p. 1.62]. The emissions of CH_4 from gas production may be obtained by summing the amount of CH_4 emissions during production reported by EPA [A1, p. 2.28] and dividing by the total number of energy units consumed [A1, p. A.4].
CH_4 emissions (g C) = $5.9\cdot10^{12} \times 5.7$, for year 1997
Energy consumption = $22575\cdot10^{12}$ Btu = $2.38\cdot10^{19}$ J

Using these values we can construct the following equation:
CH_4 emissions (g C) = (net J) $\times 0.248\cdot10^{-6} \times 5.7$

Adding all these emissions together, we get a process emissions factor of $17\cdot10^{-6}$ g C/ net J.

$$\begin{aligned}
15.3\cdot10^{-6} \times 0.995 &= 15.2\cdot10^{-6}\\
5\cdot10^{-9} \times 5.7 &= 0.028\cdot10^{-6}\\
0.1\cdot10^{-9} \times 84.5 &= 0.008\cdot10^{-6}\\
150\cdot10^{-9} \times 0.2 \times 10.9 &= 0.327\cdot10^{-6}\\
30\cdot10^{-9} \times 0.513 &= 0.015\cdot10^{-6}\\
5\cdot10^{-9} \times 1.11 &= 0.006\cdot10^{-6}\\
0.248\cdot10^{-6} \times 5.7 &= 1.41\cdot10^{-6}\\
\hline
\textbf{Total} \quad & \mathbf{17.0\cdot10^{-6}}
\end{aligned}$$

A-1.4 EMISSIONS FROM INDUSTRIAL COMBUSTION OF 'AVERAGE' FOSSIL FUEL

The above calculations are helpful if the usage of a particular type of fossil fuel is known. A weighted average may be used if such details are not known. The 1997 industrial use of fossil energy (other than for electricity production) in the U.S. was 10.5% coal, 46.9% natural gas, and 42.6% petroleum (based on energy value) [A2, p. 37]. Using the emissions factors described in the text we can calculate this to be: $0.105\times27.4\cdot10^{-6} + 0.469\times17\cdot10^{-6} + 0.426\times20.3\cdot10^{-6} = 1.95\cdot10^{-5}$ g C/J.

The above emissions factors are based on energy content in the fuel even though most industrial processes where these fossil energy sources are used for combustion do not operate at 100% efficiency. For most industrial processes, the energy requirement is rarely listed as fuel energy value but rather energy consumption, which corresponds to the effective use of energy. The above does not take into account many indirect emissions for distribution of the consumable fuel. One way of approaching this is to use the indirect emissions factor of $1.81\cdot10^{-6}$ g C/J, developed earlier [page 25], provided that this does not result in double accounting.

A-1.5 EMISSIONS FROM USE OF ELECTRICITY

The FCCE factor for electricity production at electrical power plants in the U.S. would be $5.80\cdot10^{-5}$ g C/J(e) using our proposed methodology [A11], taking into account the emissions from the fossil fuel and considering that fossil fuel was used for 69% of the electricity production. Others have made similar estimates for carbon emissions from electricity use in the U.S. West and Marland use a value of 0.18 kg C/kWh ($5\cdot10^{-5}$ g C/J(e)) for electricity use in the U.S. [A12]. This number includes carbon dioxide emissions from production and transportation but does not include other GHG emissions.

A-1.6 EMISSIONS FOR INDUSTRIAL USE OF GENERAL UTILITIES

Steam generation and use in an industrial setting is common for heating requirement of various processes. Most of this steam is generated from the combustion of fossil fuel. If the overall efficiency of the conversion can be considered to be 80%, then the following values can be used for the FCCE:

Utility	Useful heating value [A13]	Energy use	Cost [A14]	FCCE factor [A15]
Low pressure steam, 6.8 ata (100 psig)	$2.34\cdot10^3$ J/g	$2.93\cdot10^3$ J(fossil)/g	$\$5.98\cdot10^{-6}$/g	0.058 g C/g
High pressure steam, 34 ata (500 psig)	$2.38\cdot10^3$ J/g	$2.98\cdot10^3$ J(f)/g	$\$8.76\cdot10^{-6}$/g	0.060 g C/g

A-2. FCCE FOR THE USE OF RAW MATERIALS IN SEQUESTRATION ACTIVITIES

Sequestration activities may depend on the use of raw materials as part of the sequestration activity. These may be one-time acquirement, e.g., a recyclable solution for flue gas scrubbing, or be a "disposable" material used in the process, e.g., ammonia in the case of sequestering CO_2 to produce an alternative fertilizer (e.g., NH_4HCO_3). To demonstrate the concept of FCCE we will show ammonia as an example of a raw material.

The greenhouse emissions from ammonia production and use can be divided into four parts.

1. ***Process emissions.*** These are estimated based on the chemical reactions that take place in the production of ammonia and the emissions resulting from these reactions. Ammonia production

usually involves the use of natural gas (or other fossil fuel) to generate hydrogen, which then is combined with nitrogen to form ammonia. The carbon in the natural gas is released as CO_2 in the process. The individual reactions and the overall reaction are listed below.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$N_2 + 3H_2 \rightarrow 2NH_3$$

(for all practical purposes, the CO produced in the first reaction will be oxidized to CO_2 at some later point in the process)

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$
$$\text{(overall) } CH_4 + N_2 + \tfrac{1}{2}O_2 \rightarrow CO_2 + 2NH_3$$

Thus, on a theoretical basis, ½ mol of CO_2 is generated for each mol of NH_3 produced. Based on weight the ratio is 1.3 g CO_2/g NH_3. The production of ammonia usually involves scrubbing of CO_2 from the gas with a carbonate solution that later is regenerated to release the absorbed CO_2 with some loss of carbonate. To account for this, the IPCC has proposed the process emission factor for ammonia production to be [A16]:

CO_2 emissions (g C) = (g NH_3) × 1.5 × 0.272 with 0.272 (=12/44) as the CE GWP for CO_2
CO emissions (g C) = (g NH3)× $3{\cdot}10^{-5}$ × 0.513 with 0.513 as the CE GWP for CO [A10]
TOC emissions (g C) = (g NH_3) × $4.7{\cdot}10^{-3}$ × 1.31 with 1.31 as the CE GWP for TOC [A17]
SO_2 emissions (g C) = (g NH_3) × $3{\cdot}10^{-5}$ × 0 with 0 as the CE GWP for SO_2 [A18]

To keep the spirit of FCCE, we should also include the process emissions that took place to produce the raw materials for the ammonia process. Of these, only methane is important. Methane production releases some methane and the emissions may be calculated based on the energy value of the methane used and the CE GWP for methane (page 27). It takes 0.47 g of process methane for production of 1 g NH_3.

CH_4 emissions (g C) = (g NH_3) × 0.47 × 52,300 × $0.248{\cdot}10^{-6}$ × 5.7

2. ***Direct and indirect emissions from the use of energy.*** It takes 28.45 kJ/g NH_3 of energy to produce ammonia [A19]. This energy includes both energy for heat and methane for the process. Using the stoichiometry from Equation (4), we need 0.5 mol CH_4 for each mol of NH_3. That coupled with the heating value of CH_4, 891.4 kJ/mol, it is estimated that the energy use for the process is 2290 J/g NH_3. This is equivalent to 0.038 g C/g NH_3, using $1.67{\cdot}10^{-5}$ g C/J as emissions factor assuming general energy use. We did not use the FCCE factor for energy that included indirect emissions, because we will address the indirect emissions for the overall process in the last step.
3. ***Transportation emissions.*** Transportation emissions are variable and hard to predict since they depend on the mode of transportation and the distance. Direct emissions for heavy-duty diesel engines with moderate emissions control are [A7, p. 1.75]:

CO_2 emissons (g C) = (km) × 1011 × 0.272 with 0.272 (=12/44) as the CE GWP for CO_2
CH_4 emissions (g C) = (km) × 0.05 × 5.7, with 5.7 as the CE GWP [A8]
N_2O emissions (g C) = (km) × 0.025 × 84.5, with 84.5 as the CE GWP for N_2O [A8]
NO_X emissions (g C) = (km) × 7.96 × 10.9, with 10.9 as the CE GWP for NO_2 [A9]
CO emissions (g C) = (km) × 5.01 × 0.513, with 0.513 as the CE GWP for CO [A10]
NMVOC emissions (g C) = (km) × 1.13 × 1.11, with 1.11 as the CE GWP for NMVOC [A10]

The cost of transportation may be used to estimate the indirect emissions from transport. Costs are typically $\$3.65{\cdot}10^{-8}$/(g·km) [A20]. We can use the cost emissions factor of 217 g C/\$ to calculate the transportation indirect emissions to be in the range of $7.9{\cdot}10^{-6}$ g C/(g NH_3·km). With typical tanker size of 42,000 lb (7,000 gal = $1.905{\cdot}10^{7}$ g), the overall transportation emissions from transporting ammonia in full tanker diesel trucks is 518.5 g C/km or $2.72{\cdot}10^{-5}$ g C/(g·km). For transportation 150 miles (241 km) this amounts to 0.0066 g C/g NH_3.

4. ***Other indirect emissions.*** We can attempt to estimate all other emissions for ammonia production by using detail analysis of the process. This type of analysis may involve the estimation of emission stemming from construction of the plant from the use of concrete, steel, etc. In practice, this task may be quite challenging. As an alternative, we may be able to consider the cost of the ammonia. In 1997 the cost for ammonia was \$227/ton (short) not including transportation [A21], which translates to $\$2.50 \cdot 10^{-4}$/g NH_3. We can use the cost emissions factor of 217 g C/\$ to calculate the other indirect emissions to be in the range of 0.054 g C/g NH_3.

This leads us to an overall FCCE factor for ammonia equal to 0.54 g C/g NH_3, plus transportation emissions.

$$
\begin{array}{rl}
1.5 \times 0.272 = & 0.408 \\
3 \cdot 10^{-5} \times 0.513 = & 15.4 \cdot 10^{-6} \\
4.7 \cdot 10^{-3} \times 1.31 = & 6160 \cdot 10^{-6} \\
0.47 \times 52{,}300 \times 0.248 \cdot 10^{-6} \times 5.7 = & 34700 \cdot 10^{-6} \\
0.038 = & 38000 \cdot 10^{-6} \\
0.054 = & 54000 \cdot 10^{-6} \\
\hline
\textbf{Total} & \textbf{0.541}
\end{array}
$$

A-3. FCCE FOR USE OF BUILDING AND OTHER MATERIALS

In addition to the raw material used in the process, the capital equipment, buildings, and other items have associated FCCE. As with the materials used in construction, the same methodology developed above for raw materials may be used once the amount of construction materials has been estimated. Van de Vate has summarized some process emission and energy intensity values of common building materials [A22, A23]. Considering the process emissions and the process energy intensities, the FENCH Emissions Factors are shown in the table below. Also shown are our own calculations of the FCCE factor for selected materials. As noted, our calculated FCCE factors are slightly different than the FENCH emissions factors because of differences in reference sources. We feel that the emissions factors used by the IPCC should be used to the largest extent possible and augmented with process knowledge. The high value of the FENCH emissions factor for steel-reinforced concrete is likely due to calculation error by a factor of 10 in reference A22.

Material or Product	FENCH Emission Factor (g C/g) [A23]	FCCE factor (g C/g)
Cement	0.21–0.26	0.34 [A24]
Concrete	0.04	0.06 [A25]
steel-reinforced	0.53	0.09 [A26]
Steel		
unalloyed	0.66	0.47 [A27]
low alloyed	0.54–0.82	0.48 [A28]
high alloyed	1.95	1.39 [A28]
Aluminum		
virgin	3.51–9.18	8.7 [A29]
recycled	0.35	0.56 [A29]
Copper	0.73–2.38	
Silicon	48.8	
Plastics	0.37–2.13	
Ammonia		0.54
Nitric acid	0.16–0.38	1.14 [A30]
Fertilizer	3.24	0.98 (g C/g N) [A31]

A-4. FCCE FROM INPUT-OUTPUT INDUSTRY DATA BASED ON COST

The Bureau of Economic Analysis (BEA) publishes the interactions between different industries in our economy and tabulates the flow of resources between industries. Such data can be used to find labor and energy intensities of different industrial sectors [A32]. For instance, spending $1.00 on plastics in 1972 required 223,654 Btu (236 MJ) of primary energy (fossil fuel). If we used the process emissions factors for fossil fuel use and national fossil fuel usage data from 1972, we can calculate emissions resulting from spending $1 in 1972 to be 4,480 g C/$ [A33] (if all the fossil fuel was combusted). The categories presented in reference A32 are somewhat broad; more detailed categories are available for 1967 data [A34]. For more recent data, Carnegie Mellon University has combined this type of industry input-output information with emissions information. One dollar spent on plastics in 1992 should accordingly generate 5.15 g C of emissions [A35].

To use more recent information on the resource use (e.g., energy) by different industries we may develop a procedure directly from the BEA data on commodity use by industry. This type of data is presented below, describing total requirements coefficients. These values show the direct and indirect commodity production required for the industry named in the first column per dollar of delivery to final use of the industry named in the second column.

Commodity Code	Industry Code	Year	Table	Commodity Input/Industry Output ($/$)
		↑		
07	01	1997	8	0.0029869
07	02	1997	8	0.0013641
07	03	1997	8	0.0008265
07	04	1997	8	0.0008933
		↓		

In the abbreviated table (above) the use of the commodity resulting from Coal Mining (Commodity Code 07) is shown for the industries Livestock and Livestock Products (Industry Code 01), Other Agricultural Products (02), Forestry and Fishery Products (03), and Agricultural, Forestry, and Fishery Services (04). The same information is available for the commodity industry Crude Petroleum and Natural Gas (08) and Electric Services (Utilities) (68A). So for example, the Plastics and Synthetic Materials industry (28) spent \$0.0044989, \$0.0859971, and \$0.032044 (directly or indirectly) in the Coal Mining, Crude Petroleum and Natural Gas, and Electric Services industries for every dollar of product that was sold.

To calculate the energy intensities for the Plastics and Synthetic Materials industry, the first two coefficients can be used together with the cost of fossil energy. The Electric Service industry provides electricity as a commodity and part of this electricity is produced via nuclear- and hydro-electric power—we need to include this fraction of electric energy but not the other fraction that is accounted for in the fossil energy. To calculate the primary energy intensities of an industry output, we can use the following approach:

1. Determine the cost of fossil energy. This was $1.24 \cdot 10^{-9}$, $4.38 \cdot 10^{-9}$, and $4.33 \cdot 10^{-9}$ \$/J for coal, natural gas and crude petroleum, respectively in 1997 [A36]. The natural gas and crude petroleum use in 1997 was 22.53 and 36.266 quadrillion Btu [A2, p. 9]; thus, the weighted price for combination of natural gas and crude petroleum is $4.35 \cdot 10^{-9}$ \$/J.
2. Determine the fraction of electricity produced from nuclear- and hydro-electric power. This was 31% in 1997 [A11]. Thus, the fraction of electric utility cost from nuclear- and hydro-electric power was \$0.0099336. The consumer (industry) cost of electricity in 1997 was $\$1.91 \cdot 10^{-8}$/J(e) [A11].
3. Convert the nuclear- and hydro-electric power to equivalent fossil-electric power using $1.0927 \cdot 10^{7}$ J(fossil)/kWh (3.035 J/J(e)) [A11].
4. Now calculate the energy intensity from each fraction and make summation.
   Contribution from coal: $0.0044989 \div 1.24 \cdot 10^{-9} = 3.628 \cdot 10^{6}$ J/\$
   Contribution from crude petroleum and natural gas: $0.0859971 \div 4.35 \cdot 10^{-9} = 1.977 \cdot 10^{7}$ J/\$
   Contribution from nuclear- and hydro-electric power: $0.0099336 \div 1.91 \cdot 10^{-8} \times 3.035 = 1.578 \cdot 10^{6}$ J/\$
   Total Primary Energy Intensity = $2.50 \cdot 10^{-7}$ J/\$

Converting primary energy intensities to carbon emissions may appear straight forward as we have discussed and developed process emissions factors for fossil energy use. However, it turns out that it is more complicated as we must consider the fate of primary energy use. Part of the energy used does not end up as GHG emissions, but are incorporated into products as carbon compounds. For example, plastics contain a lot of carbon. Also, all the products or infrastructures that were used in the production of the plastics may contain carbon. Regardless, the Input-Output analysis is a useful tool when reviewing alternative approaches on a global scale and how changes may affect the primary energy use. We have calculated the primary energy intensities for all BEA sectors on page 33 for 1997 data and also included calculations of emissions cost factors for all the categories based on the primary energy use, not taking into account carbon content in products. The BEA sectors are broad and may not provide the detail needed for some activities. More details are available using Standard Industrial Classification (SIC) codes; SIC codes roll up into the more global IO codes.

IO-Code	Commodity =>> Industry	Coal ($/$)	Crude Petroleum & Natural Gas ($/$)	Refined Petroleum ($/$)	Electric Services (Utilities) ($/$)	Gas Utilities ($/$)	Primary Energy Intensity (Btu/$)	Primary Energy Intensity (MJ/$)	GHG Emissions (g CE/$)
01	Livestock and livestock products	0.0029869	0.0374507	0.0348495	0.0309184	0.0114604	11887	12.54	248
02	Other agricultural products	0.0013641	0.0408703	0.0346709	0.0124843	0.0119215	10531	11.11	210
03	Forestry and fishery products	0.0008265	0.0274171	0.0286051	0.0066966	0.0055753	6919	7.30	138
04	Agricultural, forestry, and fishery services	0.0008933	0.0241807	0.0166246	0.0074803	0.0068267	6301	6.65	126
05+06	Metallic ores mining	0.0078456	0.0455212	0.0390466	0.0708202	0.0210065	19223	20.28	424
07	Coal mining	1.1152199	0.0397879	0.0439309	0.0298129	0.0094261	98137	103.53	2737
08	Crude petroleum and natural gas	0.0022442	1.3576369	0.0159707	0.0205026	0.0772782	80602	85.04	1548
09+10	Nonmetallic minerals mining	0.0071424	0.049796	0.0403415	0.0428574	0.0309141	18311	19.32	401
11	New construction	0.0018467	0.0205269	0.0202757	0.0109523	0.0073106	6396	6.75	135
12	Maintenance and repair construction	0.0015973	0.0266479	0.0290646	0.0103239	0.0066519	7510	7.92	155
13	Ordnance and accessories	0.0016436	0.0105021	0.0078678	0.0134128	0.0059764	4171	4.40	92
14	Food and kindred products	0.0026819	0.0265106	0.0208989	0.0207764	0.0137348	8797	9.28	187
15	Tobacco products	0.0014067	0.0093498	0.007857	0.0064304	0.0036773	3413	3.60	75
16	Broad and narrow fabrics, yarn and thread mills	0.004003	0.0368563	0.0229944	0.0355725	0.0187086	12752	13.45	272
17	Miscellaneous textile goods and floor coverings	0.0038843	0.0442003	0.0269661	0.0292737	0.0222804	13967	14.74	294
18	Apparel	0.0027559	0.0228399	0.014828	0.0243862	0.0141346	8222	8.67	177
19	Miscellaneous fabricated textile products	0.0024781	0.0244399	0.0156573	0.0221284	0.0141405	8253	8.71	175
20+21	Lumber and wood products	0.001882	0.020115	0.0183051	0.0181561	0.0081917	6669	7.04	141
22+23	Furniture and fixtures	0.0027827	0.0184328	0.0141083	0.0176496	0.0102653	6968	7.35	153
24	Paper and allied products, except containers	0.0060106	0.0353058	0.0220524	0.0301678	0.0238236	13696	14.45	305
25	Paperboard containers and boxes	0.0042401	0.0310179	0.0241178	0.0235292	0.0161155	11099	11.71	243
26A	Newspapers and periodicals	0.001161	0.0094227	0.0073456	0.008758	0.0049343	3350	3.53	72
26B	Other printing and publishing	0.0017071	0.0148443	0.0104886	0.0132751	0.0084444	5159	5.44	111
27A	Industrial and other chemicals	0.0048932	0.1299026	0.0520355	0.0319842	0.0427027	33540	35.38	674
27B	Agricultural fertilizers and chemicals	0.0038822	0.1537486	0.0327349	0.0241576	0.0527382	37597	39.67	743
28	Plastics and synthetic materials	0.0044989	0.0859971	0.0484705	0.032044	0.0341774	23674	24.98	483
29A	Drugs	0.0015318	0.0135355	0.009245	0.0124138	0.0076566	4700	4.96	101
29B	Cleaning and toilet preparations	0.0020878	0.0365911	0.0292873	0.0152929	0.0129108	10283	10.85	211
30	Paints and allied products	0.0025389	0.0558776	0.0403611	0.0183701	0.0177016	14974	15.80	303
31	Petroleum refining and related products	0.0024621	0.8035384	1.1188285	0.0238465	0.0651267	23801	25.11	471
32	Rubber and miscellaneous plastics products	0.0031294	0.0366069	0.0231371	0.0278109	0.0169126	11667	12.31	245
33+34	Footwear, leather, and leather products	0.0024528	0.0306971	0.0226772	0.0195555	0.015186	9477	10.00	198
35	Glass and glass products	0.008263	0.0376127	0.0205596	0.0334636	0.0312065	16075	16.96	368
36	Stone and clay products	0.0082549	0.0391264	0.0248337	0.0290275	0.031169	16191	17.08	370
37	Primary iron and steel manufacturing	0.0202106	0.0327534	0.0176351	0.041622	0.0309486	24530	25.88	619
38	Primary nonferrous metals manufacturing	0.0043154	0.0264196	0.0183226	0.0409436	0.0181935	10967	11.57	241
39	Metal containers	0.0072152	0.031096	0.0200075	0.0395778	0.0230708	14139	14.92	323
40	Heating, plumbing, and fabricated structural metal products	0.0046734	0.0182751	0.012002	0.0201795	0.0135615	8497	8.96	197
41	Screw machine products and stampings	0.006211	0.0192386	0.0119773	0.0255176	0.0156566	10131	10.69	239
42	Other fabricated metal products	0.0044225	0.0198381	0.0123348	0.0230467	0.0153957	8779	9.26	200
43	Engines and turbines	0.0050617	0.0164412	0.0108909	0.021219	0.0126512	8442	8.91	198
44+45	Farm, construction, and mining machinery	0.0038284	0.0149196	0.0100683	0.0175713	0.0110089	6998	7.38	162
46	Materials handling machinery and equipment	0.0038316	0.0162706	0.0118085	0.0173009	0.0112726	7282	7.68	167
47	Metalworking machinery and equipment	0.0030096	0.013537	0.0095132	0.0167031	0.0093633	6030	6.36	137
48	Special industry machinery and equipment	0.0029455	0.0136463	0.009794	0.0167118	0.0093345	6005	6.34	136
49	General industrial machinery and equipment	0.003165	0.0140111	0.0097379	0.0177955	0.0101355	6303	6.65	144
50	Miscellaneous machinery, except electrical	0.0031083	0.0125324	0.008395	0.018216	0.0096899	5957	6.29	137
51	Computer and office equipment	0.0021715	0.0133335	0.0100605	0.020112	0.0077492	5504	5.81	121
52	Service industry machinery	0.0030951	0.0149352	0.0102513	0.0179098	0.0103184	6457	6.81	146
53	Electrical industrial equipment and apparatus	0.0029417	0.0184653	0.014616	0.0185907	0.0110045	7140	7.53	158
54	Household appliances	0.0036847	0.0232694	0.0162916	0.0218442	0.0137362	8907	9.40	197
55	Electric lighting and wiring equipment	0.0028324	0.0178428	0.0121562	0.0191455	0.0117347	6947	7.33	153
56	Audio, video, and communication equipment	0.0018703	0.0113951	0.0083209	0.0164867	0.0067716	4682	4.94	103
57	Electronic components and accessories	0.0024754	0.0149397	0.0103817	0.0229279	0.0087603	6218	6.56	137
58	Miscellaneous electrical machinery and supplies	0.002601	0.017782	0.012251	0.0212414	0.0105791	6855	7.23	150
59A	Motor vehicles (passenger cars and trucks)	0.0033415	0.020037	0.0146837	0.0203866	0.011681	7872	8.31	175
59B	Truck and bus bodies, trailers, and motor vehicles parts	0.0046554	0.0199406	0.0137286	0.0251543	0.0134948	9078	9.58	207
60	Aircraft and parts	0.0018002	0.0103355	0.0079938	0.0134433	0.0059886	4256	4.49	94
61	Other transportation equipment	0.0029971	0.0146486	0.0108913	0.0153566	0.0093346	6200	6.54	140
62	Scientific and controlling instruments	0.0019574	0.0099403	0.0073469	0.0139663	0.0057917	4314	4.55	97
63	Ophthalmic and photographic equipment	0.0020154	0.0141497	0.00965	0.0113867	0.0078238	5155	5.44	113
64	Miscellaneous manufacturing	0.0020189	0.0175164	0.0129999	0.0148018	0.0093466	6051	6.38	130
65A	Railroads and related services; passenger ground transportation	0.0010008	0.0481432	0.0591326	0.0068756	0.0060212	11576	12.21	227
65B	Motor freight transportation and warehousing	0.001234	0.0445404	0.0534028	0.0119767	0.0068583	11208	11.82	222
65C	Water transportation	0.0015553	0.0219945	0.0242423	0.0108789	0.0050481	6489	6.85	135
65D	Air transportation	0.000881	0.0768203	0.0959581	0.0084692	0.0077013	17808	18.79	345
65E	Pipelines, freight forwarders, and related services	0.001319	0.0148549	0.0096481	0.0141845	0.0030954	4907	5.18	103
66	Communications, except radio and TV	0.000826	0.0060893	0.0054797	0.007727	0.0028625	2319	2.45	50
67	Radio and TV broadcasting	0.0014247	0.0074719	0.0064529	0.015662	0.0036753	3448	3.64	76
68A	Electric services (utilities)	0.0756859	0.0351392	0.018148	1.0049547	0.0361242	65743	69.36	1822
68B	Gas production and distribution (utilities)	0.0018259	0.7821844	0.0171316	0.0156117	1.3158835	172563	182.05	
68C	Water and sanitary services	0.0017259	0.0517987	0.0386089	0.012821	0.0358397	13205	13.93	264
69A	Wholesale trade	0.0011143	0.0105919	0.0094804	0.0109135	0.005262	3669	3.87	78
69B	Retail trade	0.0019539	0.0100117	0.0090524	0.0220479	0.0049936	4705	4.96	104
70A	Finance	0.0009461	0.0053031	0.0044873	0.0061225	0.0030072	2165	2.28	48
70B	Insurance	0.0006661	0.0046811	0.0043217	0.0049925	0.0021026	1762	1.86	38
71A	Owner-occupied dwellings	0.000166	0.0020422	0.0019193	0.0012109	0.0006849	628	0.66	13
71B	Real estate and royalties	0.0009949	0.0061074	0.0047263	0.0103625	0.0038987	2575	2.72	56
72A	Hotels and lodging places	0.0033888	0.0147998	0.0089703	0.039011	0.0124577	7637	8.06	170
72B	Personal and repair services (except auto)	0.001482	0.0119641	0.0086356	0.0147313	0.0083526	4428	4.67	95
73A	Computer and data processing services, including own-account software	0.0008313	0.0053756	0.0046106	0.0074867	0.0026797	2156	2.27	47
73B	Legal, engineering, accounting, and related services	0.0007192	0.0042555	0.0037191	0.0064856	0.0021839	1780	1.88	39
73C	Other business and professional services, except medical	0.0006737	0.0077051	0.0074049	0.0058486	0.0029917	2467	2.60	52
73D	Advertising	0.0006456	0.003939	0.0033743	0.0060341	0.0019616	1634	1.72	36
74	Eating and drinking places	0.002305	0.0149739	0.0109699	0.0242638	0.009777	6158	6.50	134
75	Automotive repair and services	0.0019589	0.0200854	0.0190032	0.0158584	0.008577	6614	6.98	140
76	Amusements	0.0017746	0.0089005	0.0072397	0.0199997	0.0048262	4230	4.46	94
77A	Health services	0.0016167	0.0112883	0.008094	0.0162115	0.0066314	4452	4.70	97
77B	Educational and social services, and membership organizations	0.0014292	0.011899	0.010184	0.0135904	0.0063714	4320	4.56	93
78	Federal Government enterprises	0.0118332	0.0268244	0.0278626	0.0097293	0.0094807	15345	16.19	381
79	State and local government enterprises	0.013064	0.06832	0.0424156	0.0357257	0.0428345	26541	28.00	603
80	Noncomparable imports	0.013064	0.06832	0.0424156	0.0357257	0.0428345	26541	28.00	603
81	Scrap, used and secondhand goods	0.013064	0.06832	0.0424156	0.0357257	0.0428345	26541	28.00	603

A-5. ABBREVIATIONS, NOMENCLATURE, AND CONVERSION FACTORS

BEA = Bureau of Economic Analysis
Btu = energy, British thermal unit
C = carbon, carbon equivalence
CE = carbon equivalence
EJ = exajoules (= 10^{18} J)
EPA = (U.S.) Environmental Protection Agency
FCCE = Full Cycle Carbon Emissions
FENCH = Full-Energy-Chain Emissions
g = gram
GDP = gross domestic product
GHG = greenhouse gas
GWP = global warming potential
IO = Input-Output
IPCC = Intergovernmental Panel of Climate Change
J = energy, Joule = 0.0009486 Btu
J(e) = electric energy, Joule
J(f) = fossil energy, Joule
km = kilometer (=0.621 miles)
kWh = electric energy, kilowatt hours (=$3.6 \cdot 10^6$ J)
MBtu = million British thermal units
MJ = megajoules (= 10^9 J)
Mt = megaton
NMHC = non-methane hydrocarbons
NMVOC = non-methane volatile organic compounds
SIC = Standard Industrial Classification
TOC = total organic carbon

A-6. REFERENCES

A1. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–1997*, EPA 236-R-99-003, U.S. Environmental Protection Agency, Office of Policy Planning, pp. 2.12 (1999).

A2. *Annual Energy Review 1999*, DOE/EIA-0384(99), U.S. Department of Energy, Office of Energy Markets and End Use, Energy Information Administration, p. 67 (July 2000).

A3. Reference 2, p. 347, converting 1996 nominal dollars to 1997 dollars as described on the same page.

A4. *Emissions of Greenhouse Gases in the United States 1998*, DOE/EIA-0573(98), Energy Information Administration, Office of Energy Markets and End Use, U.S. Department of Energy, p. x (October 1999).

A5. *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emissions Factors of Greenhouse Gases*, IAEA-TECDOC-892, International Atomic Energy Agency, Vienna, Austria, 7–10 (1996).

A6. Van de Vate, J.F., "Overview of Existing Studies on Full-Energy-Chain (FENCH) Emissions of Greenhouse Gases," in *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emissions Factors of Greenhouse Gases*, IAEA-TECDOC-892, International Atomic Energy Agency, Vienna, Austria, 77–84 (1996).

A7. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Reference Manual*, Intergovernmental Panel on Climate Change, (1996).

A8. *Climate Change 1995-The Science of Climate Change,* Houton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., eds., Cambridge University Press, pp. 21–22 (1996).

A9. El-Fadel, M. and Bou-Zeid, E., "Transportation GHG Emissions in Developing Countries. The Case of Lebanon," *Transp. Res. Part D* **4**, 251–264 (1999).

A10. Streets, D.G. and Waldhoff, S.T., "Greenhouse-Gas Emissions from Biofuel Combustion in Asia," *Energy* **24**, 841–855 (1999).

A11. Electric utilities produced a net $3.123\cdot10^{12}$ kWh in 1997, of which $1.788\cdot10^{12}$ came from coal, $7.8\cdot10^{10}$ came from petroleum, $2.84\cdot10^{11}$ came from natural gas, $6.29\cdot10^{11}$ came from nuclear, $3.41\cdot10^{11}$ from hydro, and the rest from geothermal and other renewables [A2, p. 215]. To back-calculate the fossil energy usage, these numbers may be multiplied by the electrical heat rate ($1.0927\cdot10^{7}$ J/kWh) [A2, p. 332]. This leads to a fossil energy use of $1.954\cdot10^{19}$ J coal, $8.53\cdot10^{17}$ J petroleum, and $3.103\cdot10^{18}$ J natural gas. Using the GHG emissions factors developed in the text, the emissions would be $6.055\cdot10^{14}$ g C or, spread over the total net production, 194 g C/kWh [$5.39\cdot10^{-5}$ g C/J(e)]. With a cost of \$20.15/MBtu [$\$1.91\cdot10^{-8}$/J(e)] [A2] and an indirect emissions factor of 217 g C/\$, the FCCE factor for U.S. electricity would be $5.80\cdot10^{-5}$ g C/J(e).

A12. West, T.O. and Marland, G., "A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States," *Agric. Ecosys. Environ.* **1812**, 1–16 (2001).

A13. *Perry's Chemical Engineer's Handbook*, 6th ed, McGraw-Hill, New York, pp. 3.237–239 (1984). Assuming that the return steam is saturated liquid at 1 atm with a heating value of 419.1 J/g. 100 psia steam has a heating value of and 2762 J/g and 500 psi steam has a heating value of 2801 J/g.

A14. Steam cost in January 1979 was $\$4.85\cdot10^{-6}$/g (500 psig) and $\$3.31\cdot10^{-6}$/g (100 psig) [Peters, M.S. and Timmerhaus, K.D., *Plant Design and Economics for Chemical Engineers*, 3rd ed., McGraw-Hill, New York, p. 881 (1980)]. Using Marshall & Swift Cost Index for steam power this translates to $\$8.76\cdot10^{-6}$/g and $\$5.98\cdot10^{-6}$/g, respectively in 1997.

A15. Using the process emissions factor for average fossil energy use [page 28], and the cost emissions factor [page 25] to account for indirect emissions the low pressure steam would have an FCCE factor of $2.93\cdot10^{3}\times1.95\cdot10^{-5} + 5.98\cdot10^{-6}\times217 = 0.058$ g C/g and the high pressure steam would have an FCCE factor of $2.98\cdot10^{3}\times1.95\cdot10^{-5} + 8.76\cdot10^{-6}\times217 =$ 0.060 g C/g.

A16. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Workbook*, Intergovernmental Panel on Climate Change, pp. 2.12–15 (1996).

A17. CE $GWP_{TOC} = 1.31$ based on CO_2 GWP_{NMHC} of 4.1 [A10] and the assumption that NMHC=1.17×TOC.

A18. *Climate Change -The IPCC Scientific Assessment*, Houton, J.T., Jenking, G.J., and Ephraums, J.J., eds., Cambridge University Press, pp.41–68 (1990).

A19. *Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 2, John Wiley & Sons, New York, p. 655 (1992).

A20. Reference A19, p. 681.

A21. *Chemical Market Reporter*, (December 29, 1997).

A22. Van de Vate, J.F., "Full Energy Chain Analysis of Greenhouse Gas Emissions from Different Energy Sources," in *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emissions Factors of Greenhouse Gases*, IAEA-TECDOC-892, International Atomic Energy Agency, Vienna, Austria, 11–17 (1996).

A23. Van de Vate, J.F., "Comparisons of Energy Sources in Terms of their Full Energy Chain Emission

Factors of Greenhouse Gases," *Energy Policy* **25**(1), 1–6 (1997).

A24. Cement production releases 0.4985 g CO_2/g cement [A7, p. 2.5–7], which is equal to 0.136 g C/g. There are also 0.3 mg SO_2 emissions per g cement, but SO_2 has no current GWP. The production process requires 5.7 MJ/kg (or 5700 J/g), of which 10.3% (or 587.1 J(e)/g) is electricity [*Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 5, John Wiley & Sons, New York, pp. 591–592 (1992)]. The remainder (5112.9 J/g) is from the use of fossil fuels; 84.2% from coal/coke, 9.3% from natural gas, 1.3% from petroleum, and 5.2% from waste fuel. Assuming the waste fuel has the same makeup as the rest of the fossil fuels, the emissions related to the process and energy requirements are: $0.136 + 587.1 \times 5.80 \cdot 10^{-5} + 5112.9 \times (1+0.052) \times (27.4 \cdot 10^{-6} \times 0.842 + 17 \cdot 10^{-6} \times 0.093 + 20.3 \cdot 10^{-6} \times 0.013) = 0.3041$ g C/g. To include other factors from capital equipment and other factors we can use the cost relationship. The cost of cement in 1997 was approximately $\$1.60 \cdot 10^{-4}$ per g of cement [www.state.nj.us/transportation/cpm/AsphaltCementFuelPriceIndex/acfpi1997.htm]. Using a cost emissions factor of 217 g C/$, we can calculate indirect emissions to be 0.0347 g C/g. This suggests an FCCE factor of 0.3041+0.0347, or 0.339 g C/g cement.

A25. Assuming that there is 18% cement in concrete [A22].

A26. Assuming that there is 7% steel in reinforced concrete [A22].

A27. Iron (pig iron) production releases 1.6 g CO_2/g product from the coke/tar oxidation by iron ore and 0.11 g CO_2/g from the $CaCO_3$ addition, which is equal to 0.466 g C/g. There is also 0.12 mg NMVOC, 1.442 mg CO, and 0.076 mg NO_X emissions from the blast furnace charging and pig iron tapping per g product [A7, p. 2.27–29]; this corresponds to 0.0017 g C/g. There is no substantial energy requirement other than the coke/tar used in the process. The pig iron, together with recycled products, is converted to various iron and steel products by re-smelting, which requires 450 kWh/metric ton [1620 J(e)/g] of electrical energy in the electric furnace [*Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 22, John Wiley & Sons, New York, pp. 765–832 (1992)]. Other furnace types do not use electric energy but are powered by fossil fuels or chemical energy in the form of pure oxygen. If we assume that 60% of the steel is made from recycled product and the rest from pig iron [*Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 20, John Wiley & Sons, New York, pp. 1092–1106 (1992)], the process emissions from steel are: $(0.466+0.0017) \times 0.6 + 1620 \times 5.80 \cdot 10^{-5} = 0.375$ g C/g steel. Cost of steel is $\$4.4 \cdot 10^{-4}$/g; using a cost emissions factor of 217 g C/$, we can calculate indirect emissions to be 0.0955 g C/g. This suggests an FCCE factor of 0.375+0.0955, or 0.470 g C/ g steel.

A28. Using the FENCH emissions factors as guidelines for the increase in emissions for higher grade steels, the FCCE for the alloyed were estimated from the FCCE for unalloyed steel.

A29. Production of virgin aluminum releases 1.8 g CO_2, 15.1 mg SO_2, 2.15 mg NO_X, 535 mg CO, 1.4 mg CF_4, and 0.2 mg C_2F_6 per g product in direct process emissions [ref. A7, p. 2.32–37], which is equal to 3.77 g C/g $(1.8 \times 0.272 + 0.00215 \times 10.9 + 0.535 \times 0.513 + 0.0014 \times 1770 + 0.0002 \times 2500)$ [A8]. This value is extremely sensitive to the CF_X emissions. Without considering CF_X emissions the value is 0.787 g C/g. Overall energy requirements for aluminum production (not including anode) is 49,000 J fossil energy/g and 17,310 kWh/metric ton (62,316 J(e)/g) [*Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 2, John Wiley & Sons, New York, pp. 195–200 (1992)]. Using the emissions factors described in the text we can calculate this to be: $49{,}000 \times 1.95 \cdot 10^{-5} = 0.955$ g C/g. The emissions from electricity usage would be $62{,}316 \times 5.81 \cdot 10^{-5} = 3.621$ g C/g. The cost of aluminum in 1997 was \$0.771/lb (\$0.0017/g); using a cost emissions factor of 217 g C/$, we can calculate indirect emissions to be 0.369 g C/g. This suggests an FCCE factor of 3.77+0.955+3.621+0.369 = 8.715 g C/g aluminum. Recycled aluminum production requires much less energy, only 10,000 J/g [*Kirk-Othmer Encyclopedia of Chemical Technology*, 4th ed., vol. 20, John Wiley & Sons, New York, pp. 1110–1111 (1992)] for smelting purposes using fossil energy. This energy use would release 0.195 g C/g. The FCCE factor would be 0.195+0.369, or 0.564 g C/g, because the emissions associated with primary production are avoided.

A30. Production of nitric acid from the oxidation of ammonia releases 2–9 mg N_2O and 12 mg NO_X per g product [A7, p. 2.17–18] in process emissions, which is equal to 300–890 mg C/g ((2 to 9)×84.5 + 12×10.9) [A8, A9]. The ammonia and energy requirements are 0.282 g/g, 30.6 J(e)/g, 0.1 g/g low pressure steam, 0.87 g/g high pressure steam [*Ullmann's Encyclopedia of Industrial Chemistry*, 5th ed., vol. 17, VCH Verlagsgesellschaft mbH, Weinheim, Germany, pp. 320–321 (1987)]. This translates to 0.137 and 0.057 g C/g $[0.282 \times 0.487$ and $30.6 \times 5.39 \cdot 10^{-5} + 0.1 \times 0.058 + 0.87 \times 0.060]$ from the ammonia production and process energy requirement. The cost of nitric acid in 1997 was 0.108 \$/lb (\$0.00024/g) for 100% nitric acid [A21]. Using a cost emissions factor of 217 g C/$, we can calculate indirect emissions to be 0.051 g C/g. This suggests an FCCE of 0.89+0.137+0.057+0.051 = 1.14 g C/g HNO_3 (=1.09 g C/96% HNO_3).

A31. See Appendix B.

A32. Hannon, B. and Casler, S., "Updating Energy and Labor Intensities for Non-Input-Output Years," *Energy Sys. Policy* **9**(1), 27–48 (1985).

A33. The 1972 industrial, residential, and transportation use of fossil energy (not including electricity) in the U.S. was 8.2%

coal, 34.3% natural gas, and 57.5% petroleum (based on energy value) [A2, p. 37]. Using the emissions factors described in the text we can calculate this to be:$0.082 \times 27.4 \cdot 10^{-6} + 0.575 \times 17 \cdot 10^{-6} + 0.343 \times 20.3 \cdot 10^{-6} = 1.90 \cdot 10^{-5}$ g C/J. This results in a plastics emissions factor of 4,480 g C/$ plastics.

A34. Bullard, C.W., Penner, P.S., and Pilati, D.A., “Net Energy Analysis, Handbook for Combining Process and Input-Output Analysis,” *Resources and Energy* **1**, 267–313 (1978).

A35. Carnegie Mellon University Green Design Initiative, *Economic Input-Output Life Cycle Assessment (EIO-LCA) model [Internet]*, available from: <http://www.eiolca.net/> [Accessed 18 Oct, 2001].

A36. The cost for production of coal and natural gas in 1997 as $0.85 and $2.10 per million Btu [A2, p. 63]. The consumer prices were $1.31 and $4.62 per million Btu ($1.24 \cdot 10^{-9}$ and $4.38 \cdot 10^{-9}$ $/J). The production cost for crude petroleum was $2.97/MBtu. Assuming a 54% margin, the consumer price is $4.57/MBtu ($4.33 \cdot 10^{-9}$ $/J).

APPENDIX B: EVALUATION OF A CARBON DIOXIDE SEQUESTRATION ACTIVITY BASED ON PRODUCTION OF CARBON-RICH FERTILIZERS

B-1. A SEQUESTRATION TECHNOLOGY EXAMPLE

The substitution of ammonium nitrate (NH_4NO_3) by urea [$(NH_2)_2CO$] or ammonium bicarbonate [NH_4HCO_3] has been proposed as a methodology for sequestering carbon dioxide [B1, B2]. Of the two suggested, urea is the most common solid fertilizer in the world today, the second suggestion is not a common fertilizer in most countries because of technical concerns regarding stability. It does however account for half of the fertilizer production in China [B2]. Production of ammonium nitrate is based on production from ammonia and nitric acid (which in turn is produced from ammonia). The carbon-rich fertilizers are based on reaction between carbon dioxide and ammonia. Ammonia production is based on reaction between diatomic hydrogen and diatomic nitrogen. The hydrogen in ammonia production typically comes from methane conversion. The over-simplified chemical process diagrams for the three fertilizers are shown in Figure 1–3.

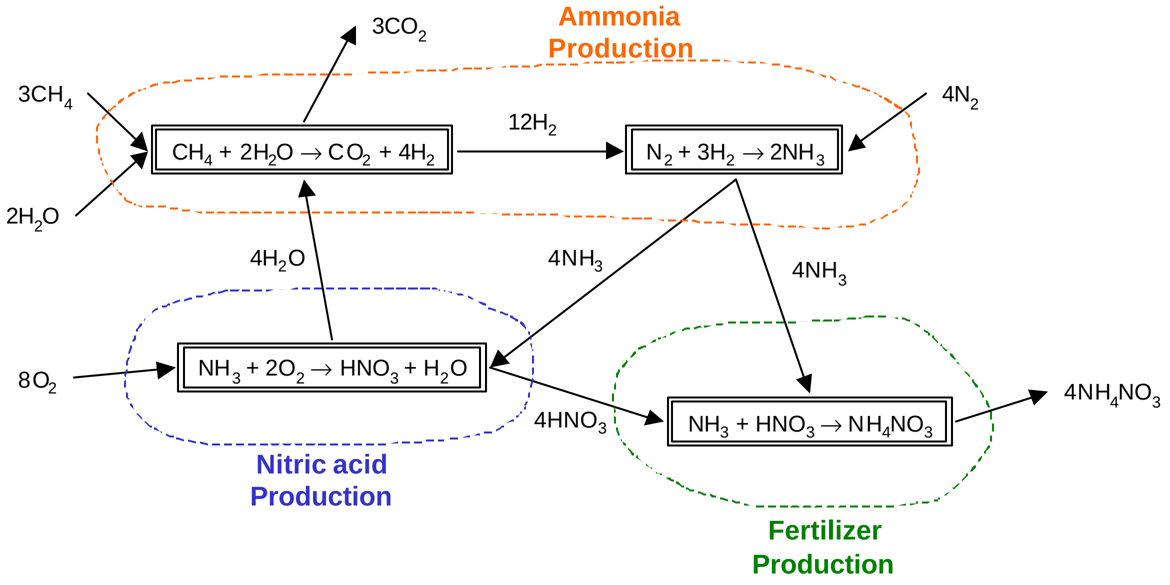


Figure 1. Production of ammonium nitrate from ammonia and nitric acid.

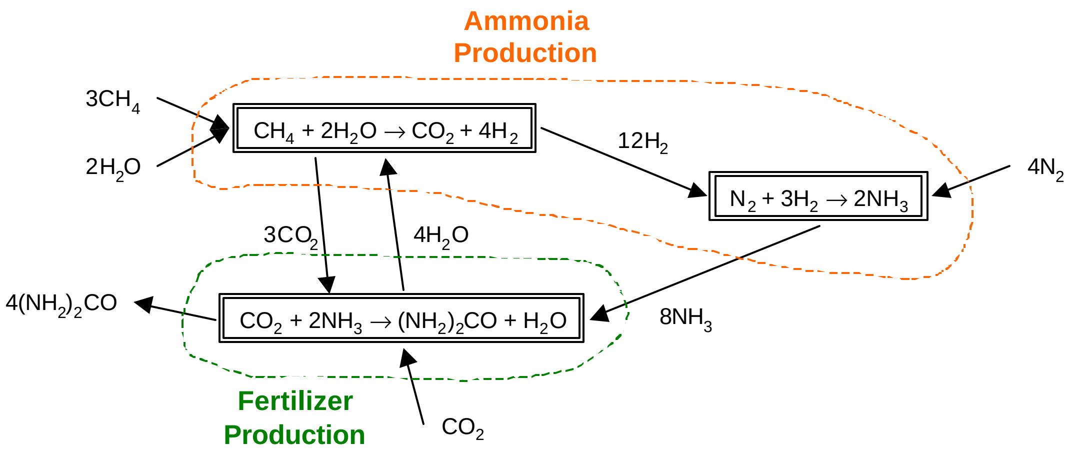


Figure 2. Production of urea (carbamide) from ammonia and carbon dioxide.

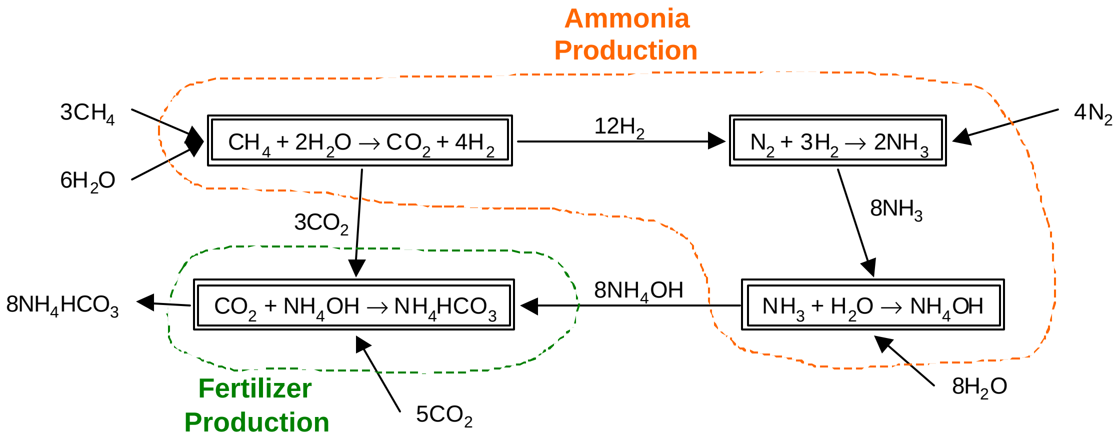


Figure 3. Production of ammonium bicarbonate from ammonia and carbon dioxide.

Based on the chemistry, the overall reactions for the three types of fertilizers with their associated standard heat and energy of reaction is shown in Equations B-1 to B-3.

$$3CH_4(g) + 2H_2O(l) + 4N_2(g) + 18O_2(g) \rightarrow 4NH_4NO_3(s) + 3CO_2(g) \quad \Delta H° = -1846.7 \text{ kJ} \quad \Delta G° = -1220.1 \text{ kJ} \quad \text{(B-1)}$$

$$3CH_4(g) + CO_2(g) + 4N_2(g) + 2H_2O(l) \rightarrow 4(NH_2)_2CO(s) \quad \Delta H° = -144.44 \text{ kJ} \quad \Delta G° = 303.46 \text{ kJ} \quad \text{(B-2)}$$

$$3CH_4(g) + 5CO_2(g) + 4N_2(g) + 14H_2O(l) \rightarrow 8NH_4HCO_3(s) \quad \Delta H° = -601.6 \text{ kJ} \quad \Delta G° = 116.6 \text{ kJ} \quad \text{(B-3)}$$

From the overall stoichiometry, the production of ammonium nitrate releases 0.75 mol CO_2/mol NH_4NO_3, the production of urea captures 0.25 mol CO_2/mol $(NH_2)_2CO$, and the production of ammonium bicarbonate captures 0.625 mol CO_2/mol NH_4HCO_3. The stoichiometry only tells part of the story and one should be very careful about how these are used. Rather that using the product stoichiometry (mol CO_2/mol product), one could use a nitrogen stoichiometry (mol CO_2/mol N) and the assumption that all carbon fixed in a fertilizer will be released very quickly to the atmosphere. In that case, overall CO_2 emissions based on theoretical stoichiometry is the same for all cases, 0.375—it takes 3 methane carbons to bind 8 nitrogen. From a transportation and production standpoint, urea is the best fertilizer as it contains the highest percent nitrogen per weight, generating the least amount of transportation emissions per amount of nitrogen fertilizer. CO_2 is only one of the greenhouse gases—a more complete picture is necessary.

B-1.1 AMMONIUM NITRATE PRODUCTION

As mentioned before and as described in Figure 1, ammonium nitrate (AN) is produced by reaction between ammonia and nitric acid. Nitric acid production is based on oxidation of ammonia with oxygen, and ammonia is produced from methane and nitrogen. To calculate the FCCE for ammonium nitrate we simply take into account the FCCE from ammonia, the FCCE from nitric acid, and add emissions from the process of making the fertilizer. The production of the fertilizer does not have appreciable emissions, but requires 90–216 J(e)/g AN and 0–0.05 g steam/g AN [B3]. Using emissions factors previously developed [B4], this energy requirement corresponds to $14.4 \cdot 10^{-3}$ g C/g AN [B3].

An estimate for indirect emissions can be found by considering that the cost of ammonium nitrate (fertilizer grade) was \$0.076/lb (\$$1.68 \cdot 10^{-4}$/g) in 1997 [B5]. This corresponds to an indirect emissions factor of 0.036 g C/g ($1.68 \cdot 10^{-4} \times 217$). It should be noted that this indirect emissions factor includes all other indirect emissions including those from ammonia, nitric acid, and methane production.

The FCCE (less indirect) for the raw material ammonia is 0.487 g C/g NH_3, and the FCCE (less indirect) for the raw material nitric acid is 1.09 g C/g HNO_3 [B4]. Ammonium nitrate production requires 0.217 g NH_3 and 0.792 g HNO_3 per g product produced. This includes estimated process losses of 6 mg NH_4NO_3 and 3 mg NH_3 per g product [B3]. Thus, we can calculate the FCCE for ammonium nitrate as $0.217 \times 0.487 + 0.792 \times 1.09 + 14.4 \cdot 10^{-3} + 0.036 = 1.02$ g C/g AN (= 2.91 g C/g N)

This is almost 300% more than that predicted by the stoichiometry of Equation B-1, which is 0.11 g C/g AN (0.32 g C/g N). The substantial emissions of nitrogen oxides during nitric acid production contribute to the higher value.

B-1.2 UREA PRODUCTION

Urea is produced by the reaction of carbon dioxide and ammonia to form ammonium carbamate (NH_2COONH_4), which in turn can decompose to ammonia and carbon dioxide or, if the operating conditions are correct, can release water and form urea. Because these two reactions compete, there are several types of processes for urea production that differ in the recovery of unreacted materials for re-reaction. All the different processes are very efficient in converting the raw materials to product. The overall process was described in Figure 2 and Equation B-2. As is shown in Figure 2, 75% of the carbon dioxide used in the process comes from the manufacturing of ammonia and 25% of the CO_2 comes from another source. In the U.S., all the urea produced is manufactured using CO_2 from ammonia production. Because ammonia is produced for other reasons than urea production, more CO_2 is produced than is needed for urea production and is most often sold for soft drink manufacturing or as dry ice. Let us first consider emissions under the current production methods.

The raw materials for urea are ammonia and carbon dioxide. The FCCE (less indirect) for ammonia is 0.487 g C/g NH_3 [B4]. We cannot really use an FCCE for CO_2 as a raw material as it is produced as a byproduct from ammonia production, instead we just use the carbon content of CO_2, 0.27 g C/g CO_2. The stoichiometric requirement for urea production is 0.733 g CO_2/g urea (0.2 g C/g). In practice 0.74–0.75 g CO_2/g urea is used because some of the CO_2 is lost in the process [B6]. This loss translates to a process emission of $3.2 \cdot 10^{-3}$ g C/g urea [B7]. The average ammonia requirement for urea production is 0.57 g NH_3/g urea [B6].

The overall energy use for urea fertilizer is not very dependent on manufacturing process type. Typical energy requirements are 582 J(e) and 1.47 g steam per g urea, using average values of the different synthesis and granulation processes [B6]. Using emissions factors previously developed [B4], this corresponds to $582 \times 5.39 \cdot 10^{-5} + 1.47 \times 2.83 \cdot 10^{3} \times 1.95 \cdot 10^{-5} = 0.11$ g C/g.

The cost of urea fertilizer in 1997 was about \$0.096/lb (\$$2.12 \cdot 10^{-4}$/g) [B5]. This leads to other indirect emissions for urea production of 0.046 g C/g urea ($217 \times 2.12 \cdot 10^{-4}$). We can now come up with an expression for emissions related to urea production. This would be:
$0.745 \times (-0.27) + 3.2 \cdot 10^{-3} + 0.57 \times 0.487 + 0.11 + 0.046 = 0.236$ g C/g urea (= 0.506 g C/g N)

This value is not a true FCCE but is for production only; it does not include future emissions from the use of urea as a fertilizer, but would correspond to FCCE urea as a permanently stored form of carbon. When urea is used as a fertilizer we must answer the question about what happens to the carbon in urea. The proponents of sequestration via urea production suggest that the carbon gets incorporated into the soil or at least subsurface [B1]. However, the use of urea as fertilizer in forestry did not increase the amount of carbon stored in the soil as much as did ammonium nitrate [B8]. Furthermore, in the development of the FCCE for ammonium nitrate, it was assumed that all the CO_2 generated in the ammonia production escaped as emissions, which is not true as it is incorporated into urea but the IPCC does not acknowledge the carbon content in urea for sequestration purposes [B9]. Thus, we must assume that all of the carbon dioxide is released soon (within a year) after the fertilizer is spread, generating 0.200 g C/g urea in CO_2 emissions. This allows us to calculate the FCCE (less transportation) for urea fertilizer as 0.436 g C/g urea (0.935 g C/g N).

B-1.3 AMMONIUM BICARBONATE PRODUCTION

Although ammonium bicarbonate (AB) is not used as a fertilizer in the U.S., China has been using this formula as a nitrogen fertilizer for 40 years [B2]. There are multiple technical issues for using AB as a fertilizer. They include [B10]:

- Decomposition of AB to CO_2 and NH_3 at 38–60°C.
- Leaching of NH_4^+ to groundwater.
- Low nitrogen content.

However, let us look at this from an emissions standpoint. The overall reaction (Equation B-3) and Figure 3 show that we need an extra five moles of carbon dioxide, which must come from somewhere else than ammonia production (e.g., from flue gases). There is very little or no information about energy requirement for the production of AB in China. Production of AB in U.S. for fertilizer is not performed but a feasibility study was performed of an ammonia scrubbing scheme. Electricity use was anticipated to be 34.8 J(e)/g AB for the whole process [B11]. This ammonia scrubbing scheme does rely on carbonate solution for scrubbing and thus the ammonia production portion of this approach is anticipated to only generate stoichiometric amounts of CO_2 (1.3 g CO_2/g NH_3) but all the other emissions are assumed to be the same [B4]. This leads to process emissions of 0.394 g C/g NH_3 from the ammonia production. As in the case of urea, we use 0.27 g C/g CO_2 to account for the CO_2 as a raw material. Assuming little loss of ammonia in the scrubbing process, we need 0.254 g NH_3 and 0.656 g CO_2 to produce 1 g of AB (Figure 3). This translates to process emissions of –0.077 g C/g AB ($0.394 \times 0.254 - 0.27 \times 0.656$), indicating a net capture. Emission from process energy use is 0.0019 g C/g AB. The cost of AB fertilizer is not available, but in China the cost of AB is 40% that of ammonia [B2]. Assuming that this cost basis holds in the U.S., the cost of competitively priced AB would be on the order of \$$1.0 \cdot 10^{-4}$/g AB. This corresponds to an indirect emissions factor of 0.022 g C/g AB. The FCCE for production is thus –0.053 g C/g AB (–0.077 + 0.0019 + 0.022), suggesting a net capture of carbon. Assuming all the carbon is released when the fertilizer is used this value becomes 0.099 g C/g AB (0.55 g C/g N).

This value is about 36% lower than that for urea (a similar fertilizer). However, energy requirements proposed for the production of AB are highly speculative [B12] and do not, for example, include granulation.

B-1.4 TRANSPORTATION EMISSIONS FOR FERTILIZERS ON A NITROGEN BASIS

As these fertilizers contain different amounts of nitrogen, the transportation requirement will be different for each case on a nitrogen basis. The emissions from transportation via diesel truck have previously been discussed as 368 g C/km for emissions associated from the burning of fuels and $7.9 \cdot 10^{-6}$ g C/(g·km) for indirect emissions [B4]. Assuming that the average truck can hold 47,500 lb ($2.16 \cdot 10^{7}$ g) and that the average distance for transporting the fertilizer is 150 miles (241 km), we can calculate an overall emissions factor of 0.006 g C/g fertilizer, which is not a significant contribution to the emissions associated with manufacturing. When the nitrogen content is incorporated into the calculations, we can estimate the transportation emissions as:

Ammonium nitrate: 0.017 g C/g N
Urea: 0.013 g C/g N
Ammonium bicarbonate: 0.029 g C/g N

B-2. CONCLUSIONS

The estimated carbon emissions from production of different nitrogen fertilizers are summarized in the table below.

	Based on Fertilizer Weight (g C/g fertilizer)				Based on Nitrogen Content (g C/g N)			
	Production	Transportation	Use	Total	Production	Transportation	Use	Total
Ammonium nitrate	1.02	0.006	0	1.03	2.91	0.017		2.93
Urea	0.24	0.006	0.20	0.45	0.51	0.013	0.43	0.95
Ammonium bicarbonate	–0.053	0.006	0.15	0.11	-0.29	0.029	0.86	0.60

Based on the above results, ammonium bicarbonate has an advantage over the other fertilizers from a carbon management assessment; however, since the production emissions for this fertilizer are highly speculative, further information about this aspect is desired.

B-3. ABBREVIATIONS, NOMENCLATURE, AND CONVERSION FACTORS

$\Delta G°$ = Gibbs standard free energy
$\Delta H°$ = standard enthalpy
AB = ammonium bicarbonate
AN = ammonium nitrate
C = carbon, carbon equivalent
g = gram
J = energy, Joule = 0.0009486 Btu
J(e) = electric energy, Joule
kJ = kilojoules

km = kilometer (=0.621 miles)
lb = pounds (= 453.6 grams)

B-4. REFERENCES

B1. Lee, J. W. and Li, R., "A Novel Strategy for Global CO_2 Sequestration and Clean Air Protection," proceedings of the First National Conference on Carbon Sequestration (paper P.12), Washington, DC, May 14–17, 2001.

B2. Zhou, J., Shang, J., Der, V., Li, Z., Zhang, J, Li, X, and Zhang, Z., "A Feasibility Study on a Two Stage Benefits CO_2 Sequestration Technology for Fossil Fuel Power Generation," proceedings of the First National Conference on Carbon Sequestration (paper P.2), Washington, DC, May 14–17, 2001.

B3. *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry, Production of Ammonium Nitrate and Calcium Ammonium Nitrate, Booklet No. 6 of 8*, European Fertilizer Manufacturers' Association, Brussels, Belgium (2000). The production of ammonium nitrate does not generate appreciable process emissions. The electrical energy requirement is 90–216 J(e)/g and the steam requirements are 0–0.05 g/g. Using emissions factors previously developed [4], this corresponds to (90 to 216)$\times 5.39\cdot10^{-5}$ + (0 to 0.05)$\times 2.83\cdot10^{3}\times 1.95\cdot10^{-5} = 4.9\cdot10^{-3}$–$14.4\cdot10^{-3}$ g C/g.

B4. Appendix A. The FCCE for ammonia is 0.541 g C/g. If the indirect emissions (0.054 g/g) are not included, the value is 0.487 g C/g NH_3. The FCCE for nitric acid is 1.14 g C/g. If the indirect emissions (0.051 g/g) are not included, the value is 1.109 g C/g HNO_3.

B5. *Chemical Market Reporter*, (December 29, 1997).

B6. *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry, Production of Urea and Urea Ammonium Nitrate, Booklet No. 5 of 8*, European Fertilizer Manufacturers' Association, Brussels, Belgium (2000).

B7. The process requires, on average, 0.745 g CO_2/g urea. The stoichiometric requirement is 0.733. The losses are in urea vaporization and as water contaminant. It is assumed that these losses are quickly converted into CO_2 in the environment. The GWP for CO_2 is 0.27 g C/g CO_2. This results in process losses of (0.745–0.733)×0.27 g C/g urea.

B8. Nohrstedt, H.-O., Arnebrant, K. Baath, E., and Soderstrom, B., "Changes in Carbon Content, Respiration Rate, ATP Content, and Microbial Biomass in Nitrogen-Fertilized Pine Forest Soils in Sweden," *Can. J. Forest Res.* **19**, 323–328 (1989).

B9. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Workbook*, Intergovernmental Panel on Climate Change, pp. 2.12–15 (1996).

B10. Yeh, A.-C. and Bai, H., "Comparison of Ammonia and Monoethanolamine Solvents to Reduce CO_2 Greenhouse Gas Emissions," *Sci. Tot. Environ.* **228**, 121–133 (1999).

B11. Athon, A., Behne, K., Davis, D., Delaney, A., Forbes, B., Oswald, R., and Williams, C., "Design Project: CO_2 Sequestration from Coal Fired Power Plant Flue Gas," Chemical Engineering 488 Internship in Industrial Pollution Prevention, University of Tennessee, 2000.

B12. The electricity use for the AB process appears very low (34.8 J/g) in reference B11, as ammonia production alone consumes 2300 J/g NH_3.

APPENDIX C: EVALUATION OF A CARBON DIOXIDE SEPARATION ACTIVITY BASED ON ABSORPTION FROM FLUE GAS STREAMS

C-1. A CO_2 SEPARATION TECHNOLOGY EXAMPLE

Carbon dioxide separation from flue gas streams using reactive absorbents has been the focus of many studies. The conventional absorbents are in the alkanolamine family. Carbonate-based systems are usually not considered for CO_2 capture from flue gas as the operating pressure must be high [C1]. There are also new groups of adsorbents which are based on sterically hindered amines or formulated amines [C2, C3]. Commercial processes exist using monoethanolamine (MEA) formulations and Chapel et al. has proposed design equations for the capture operation [C1]. These are summarized below.

$$D_{\mathrm{A}} = \left(0.6Y_{\mathrm{CO2}} + 0.542\right)\sqrt{\frac{0.01S}{Y_{\mathrm{CO2}}}} \quad \text{[C4]} \tag{C-1}$$

$$D_{\mathrm{S}} = 0.13\sqrt{S} \tag{C-2}$$

$$F_{\mathrm{R}} = 0.71S \tag{C-3}$$

$$P_{\mathrm{B}} = \left(9.6 + \frac{3.936}{Y_{\mathrm{CO2}}}\right)S \quad \text{[C5]} \tag{C-4}$$

$$P_{\mathrm{S}} = 2760F_{\mathrm{R}} \quad \text{[C6]} \tag{C-5}$$

$$L_{\mathrm{S}} = 1.6S \tag{C-6}$$

$$W = 0.075S \tag{C-7}$$

$$C = 6.75S \quad \text{[C7]} \tag{C-8}$$

$$L_{\mathrm{C}} = 0.125S \quad \text{[C8]} \tag{C-9}$$

$$L_{\mathrm{W}} = 75.6S \quad \text{[C8]} \tag{C-10}$$

A simplified flow diagram of the process is shown in Figure 1.

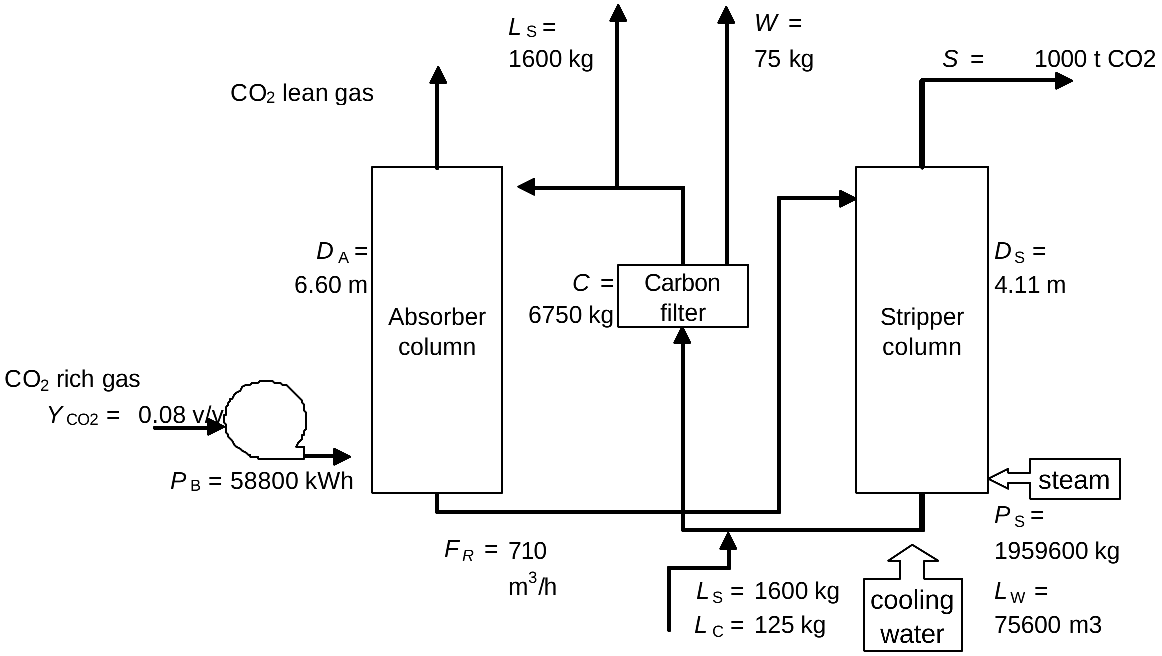


Figure 1. Simplified schematic of CO_2 absorption process using MEA. All flows are on a per day basis, unless otherwise indicated. The carbon filter is given as total size.

To install and operate the 1,000 ton CO_2/day absorption equipment on a flue gas stream with 8 vol. % CO_2, which has been pretreated and cooled by an SO_2 scrubber, the following items are needed [C9]:

Absorber column with support skirt operating under atmospheric pressure	Diameter = 6.6 m. Total height = 14.9 m. Carbon steel construction, 1.25 cm wall thickness. Packed with 5-cm stainless steel pall rings to a total height of 11.8 m in the absorber and water-wash section. Estimated weight of 592,000 kg carbon steel and 135,000 kg stainless steel.
Stripper column with support skirt operating under slight pressure, 0.7 atm	Diameter = 4.11 m. Total height = 33 m. Stainless steel construction, 1.25 cm wall thickness. Packed with 5-cm stainless steel pall rings to a total height of 27.4 m. Estimated weight of 3,800 kg carbon steel and 175,000 kg stainless steel.
Stripper column overhead gas condenser	790 m^2 heat transfer area in tube-and-shell heat exchanger. Stainless steel tubes, carbon steel shell. Estimated weight of 3,200 kg carbon steel and 10,000 kg stainless steel.
Reboiler and reclaimer for stripper column	3,200 m^2 heat transfer area in tube-and-shell heat exchanger for each of the reboiler and relcaimer. Stainless steel tubes, carbon steel shell. Estimated weight of 15,000 kg carbon steel and 40,500 kg stainless steel.

Solvent storage tank and activated carbon filter vessel	Solvent tank to hold up to 185,000 L solvent mixture (30% MEA). Estimated weight of 11,100 kg carbon steel. Activated carbon bed vessel to hold 6,750 kg carbon. Estimated weight of 2,470 kg carbon steel.
Pumps and blowers	Standard construction with an estimated weight of 6,930 kg stainless steel.
Concrete foundation	Size = 26 m × 20 m. Thickness = 15–142 cm. Steel-reinforced with an estimated weight of 437,000 kg.

C-1.1 FCCE FROM MANUFACTURING OF PROCESS RAW MATERIALS AND PROCESS ENERGY USE

C-1.1.1 Monoethanolamine

The solvent MEA circulating through the system must be available at startup and during operation, as some of it is lost in the process. We make the assumption that the loss results in release of the carbon in the MEA as CO_2. This is a fair assumption as the compound leaking is biodegradable and that the byproducts and retained MEA in the carbon filters are incinerated. The manufacturing of MEA takes place via the reaction between ammonia (NH_3) and ethylene oxide (CH_2OCH_2). During this process considerable amounts of di- and tri-ethylamine (DEA & TEA) are also created. In a process optimized for MEA, the product stream consists of 80% (w/w) MEA, 15% DEA, and 5% TEA [10]. DEA and TEA are useful consumer products, appearing in detergents, soaps, makeup, etc. Most of these products are short-lived and we assume here that release of the stored carbon in DEA and TEA is released as CO_2. The reactions involved in MEA/DEA/TEA production are exothermic but require 1.75 g steam and $12.5 \cdot 10^{-5}$ kWh [45 J(e)] per g MEA/DEA/TEA [C11].

Ammonia requirements for the process are 0.316 g NH_3/g MEA [C12]. The release from the production of NH_3 needed for the MEA reaction has previously been covered and it is estimated that 0.487 g C/g NH_3 is released in this process [C13].

Ethylene oxide (EO) requirements for the process are 0.934 g EO/g MEA [C12]. Ethylene oxide is produced via the reaction between ethylene and oxygen (in air or purified) in a process that releases carbon dioxide (0.858 g CO_2/g EO) and requires electrical power (4,500 J(e)/g EO) as well as steam (0.2 g low pressure steam/g EO) and cooling water [C14]. It is estimated that 0.488 g C/ g ethylene oxide is produced in this process [C15]. Ethylene (the raw material for EO at 0.91 g ethylene/g EO) is produced by the cracking of hydrocarbons, which also produces a range of other hydrocarbon products. Depending on the starting hydrocarbon, more or less ethylene is produced and the energy consumption also changes. On average, 168 J(e)/g ethylene is required [C16]. Assuming all the other hydrocarbons generated are burned for their fuel value, we do not have to address any emissions. In addition, the Intergovernmental Panel on Climate Change estimates that there are approximately 0.001 g CH_4 released per g of ethylene produced [C17, p. 2.23]. Thus, emissions for ethylene production are estimated at 0.0148 g C/g ethylene [C18]. Oxygen (the other raw material for EO) production consumes 1,020–1,390 J(e)/g O_2 [C19] and the EO reaction requirements is 1.3 g O_2/g EO [C20]. This allows us to calculate an emissions factor of 0.586 g C/g EO for direct process emissions and energy use (including historic energy use) [C21].

The above numbers allow us to calculate emissions for manufacturing of MEA as 0.945 g C/g MEA [C22]. The loss of MEA in the capturing process is given by Equation 6 as 1.6 kg MEA per ton CO_2 captured (0.0016 g MEA/g CO_2), which based on above emissions would translate to 0.0013 g C/g CO_2.

C-1.1.2 Soda Ash

Soda ash (Na_2CO_3) is added ($1.25\cdot10^{-4}$ g/g CO_2 captured) as an alkali to keep the pH low. The values for the material flows listed in Figure 1 were based on the capture of 1,000 t CO_2/day from the flue gas. We will count the carbon in the carbonate as an emission, which amounts to $1.42\cdot10^{-5}$ g C/g CO_2. Because of the very small amount, we will not estimate any emissions occurring in the manufacturing of soda ash.

C-1.1.3 Energy Demand for Capture

The daily energy demand for the CO_2 capture (1,000 t CO_2/day) is described by Equations C-4 and C-5 and in Figure 1 as 58,800 kWh and 1,959,600 kg steam. This corresponds to 212 J(e)/g CO_2 and 1.96 g steam/g CO_2 [C13]. This can be translated to indirect emissions from energy use of 0.123 g C/g CO_2.

C-1.1.4 Other Indirect Emissions

The other indirect emissions not accounted for in the process and energy use can be estimated from the annual operating expenses associated with running the absorber system. These are estimated at \$19.24/t CO_2 [C1], which using a cost emissions factor of 217 g C/\$, translates to 0.0042 g C/g CO_2.

C-1.2 CARBON INVENTORY AND BALANCE FOR SEPARATION

C-1.2.1 Construction of Separation Equipment and Initial Solvent Inventory

Before the separation facility is operational, the following releases of GHGs have occurred from the manufacturing and installation of equipment:

Resource	Amount	Carbon Equivalent Released (g C)
Carbon steel	$6.28\cdot10^{8}$ g	$2.35\cdot10^{8}$, using an emissions factor of 0.375 g CE/g [C23]
Stainless steel	$3.67\cdot10^{8}$ g	$1.42\cdot10^{8}$, using an emissions factor of 0.386 g CE/g [C24]
Reinforced Concrete	$4.37\cdot10^{8}$ g	$3.32\cdot10^{7}$, using an emissions factor of 0.076 g CE/g [C25]
Monoethanol Amine	2.89·107 g	$2.73\cdot10^{7}$, using an emissions factor of 0.945 g CE/g
Other indirect	\$$3.28\cdot10^{7}$ [C26]	$7.12\cdot10^{9}$, using an emissions factor of 217 g CE/\$
Total		$7.56\cdot10^{9}$

C-1.2.2 Operational Emissions

The operational emissions have been discussed above and it is expected that the process will have emissions of 0.128 g C/g CO_2. For a plant capacity of 1,000 t CO_2/day, the annual amount captured is $3.65\cdot10^{11}$ g CO_2 ($9.96\cdot10^{10}$ g C) and emissions while performing the separation are $4.67\cdot10^{10}$ g C, resulting from the loss of MEA, soda ash consumption, and energy use.

C-1.2.3 Decommissioning Emissions and Credit

After the facility has passed useful life (here assumed 20 years), the MEA and activated carbon are assumed to be incinerated. This results in emissions of $5.68\cdot10^{6}$ g C from the MEA and $5.31\cdot10^{6}$ g C from the activated carbon [C27]. The steel in the construction can be recycled and emissions from the use of iron ore can be avoided. This results in a credit of 0.468 g C/g recycled steel [C28]. The total amount of credit of the equipment then becomes $4.66\cdot10^{8}$ g C. Overall this translates to a net credit of $4.55\cdot10^{8}$ g C. Here, we have neglected any costs associated with the demolition of the facility.

C-2. A CO_2 DISPOSAL EXAMPLE

If we consider an ocean disposal method for our captured carbon dioxide, we will need to review the emissions associated with this activity. It is difficult to get detailed information about the construction requirement of such an ocean disposal activity but the International Energy Agency has published some information[C29]. From this we can estimate the following, assuming 100 km land pipeline followed by 100 km ocean pipeline:

Pipeline from capture to injection nozzle	Diameter = 0.864 m. Total length = 200,000 m. Low alloy carbon steel construction, 3.8 cm wall thickness. Estimated weight of $1.61 \cdot 10^8$ kg steel.
Injection nozzle	Estimated weight = 250,000 kg steel.

This equipment was designed for a much larger flow of CO_2 (52,000 t CO_2/day). If we assume that our model separation system of 1,000 t CO_2/day only provides a 1/52th of the flow, our separations system only has to 'account' for 1/52th of the steel needed for the pipeline/injection system. The calculation of steel requirement does not include other equipment (such as compressors, pumps, structural support, etc.) that we unable to locate information at this time. However, it is likely to be small in comparison to the emissions for the pipeline construction.

It is hard to predict what will actually happen to the disposed carbon dioxide once it has been injected into the ocean as it depends on the injection depth and geographical location [C30, C31]. In our example, we will assume that the injected CO_2 has a half-life of 265 years [C32], which corresponds to a typical decay curve, e.g., the amount retained in the ocean at year j, once injected in year 0, can be described by the expression in Equation C-11.

$$\mathit{retained} = \mathit{initial} \times e^{-j/383} \qquad \text{(C-11)}$$

C-2.1 FCCE FROM PROCESS ENERGY USE AND DISPOSAL

C-2.1.1 Energy Demand for Transport and Disposal

Transportation of liquid CO_2 in pipelines to the coast and into the ocean has been estimated to be an energy intensive task requiring 0.0057 kWh per metric ton and kilometer [C33]. Assuming that the capturing plant is 100 km (about 62 miles) from the coast and we have another 100 km of pipeline in the ocean, we can estimate that energy requirement is 1.14 kWh/t CO_2 (4.1 J(e)/g CO_2). In addition, we must liquefy and inject the CO_2 in the ocean and it is estimated that this will require about 106.5 kWh/t CO_2 (383.4 J(e)/g CO_2) [C34]. This translates into emissions equivalents of 0.021 g C/g CO_2, using an FCCE factor of $5.39 \cdot 10^{-5}$ [C13].

C-2.1.2 Release from Disposed Carbon Dioxide

The information provided in Equation C-11 can be used to estimate how much is released for a specific year. For example, the amount released, R, for initial amount of S carbon equivalents in year j after capture can be described by

$$R = S \times \left(e^{-(j-1)/383} - e^{-j/383} \right) . \qquad \text{(C-12)}$$

To calculate the FCCE from the releases occurring from the disposed carbon, we follow the procedure outlined in Sections 2.4 to 2.6. This calls for defining a duration goal for sequestration as well as a penalty interest rate. For this example, we will use a goal of 100 years and penalty interest rate of 0.01%. Based on this, the FCCE becomes

$$FCCE = \sum_{j=1}^{100} S \times \left(e^{-(j-1)/383} - e^{-j/383}\right) \times \left(1 - TVCS(0.01\%, j, 100)\right) \quad \text{(C-13)}$$

Using the information above, we can calculate a FCCE per g of CO_2 stored in the ocean. To summarize:

Initial sequestration:	1 g CO_2 (= 0.27 g C)
Total release in the first 100 years:	0.23·g CO_2 (= 0.063 g C)
FCCE:	0.12·g CO_2 (= 0.032 g C)
Credit:	0.88 g CO_2 (= 0.24 g C)

C-2.1.3 Other Indirect Emissions

The other indirect emissions not accounted for in the process and energy use can be estimated from the annual operating expenses associated with running the transport/injection system. These are estimated at \$98,000 per year [C35], which using a cost emissions factor of 217 g C/\$ translates to 21,000 g C/year or $5.9 \cdot 10^{-5}$ g C per g captured CO_2.

C-2.2 CARBON INVENTORY AND BALANCE FOR DISPOSAL

C-2.2.1 Construction of Pipeline and Injection Equipment

Before disposal can be accomplished, we need to build the pipeline and the following releases of GHGs are estimated to occur as part of the construction:

Resource	**Amount**	**Carbon Equivalent Released (g C)**
Carbon steel (low alloy)	$3.1 \cdot 10^9$ g	$1.16 \cdot 10^9$, using an emissions factor of 0.375 g CE/g [C24]
Other indirect	\$$3.61 \cdot 10^6$ [C36]	$7.84 \cdot 10^8$, using an emissions factor of 217 g CE/\$
Total		$1.95 \cdot 10^9$

C-2.2.2 Operational Emissions

The operational emissions have been discussed above and it is estimated that the large energy demand will result in emissions of 0.021 g C/g captured CO_2. The emissions due to maintenance are $5.9 \cdot 10^{-5}$ g C per g disposed CO_2. On an annual basis, we dispose of $3.65 \cdot 10^{11}$ g CO_2. Thus, the estimated operational emissions are $7.69 \cdot 10^9$ g C/year.

C-2.2.3 Release for Sequestered CO_2 in the Ocean

There is release of CO_2 from the disposed CO_2 in the ocean. The time-valued emissions of this are 0.032 g C per g disposed CO_2. On an annual basis, we dispose of $3.65 \cdot 10^{11}$ g CO_2. Thus, the estimated emissions are $1.17 \cdot 10^{10}$ g C/year.

C-2.2.4 Decommissioning Emissions and Credit

After the pipeline has passed useful life (here assumed 20 years), the steel in the construction can be recycled and emissions from the use of virgin iron ore can be avoided. This results in a credit of 0.468 g C/g recycled steel [C28]. Thus, the total amount of credit of the pipeline/injector steel is $1.45 \cdot 10^9$ g C. Here, we have neglected any costs associated with the demolition of the facility.

C-3. LIFE-CYCLE FLOW ANALYSIS

In order to get an overall summary, we can generate annual carbon flow patterns over the life of the project. First we can display this in a simple table on the basis of capturing and disposing of $3.65 \cdot 10^{11}$ g CO_2 ($9.96 \cdot 10^{10}$ g C) per year.

Item	Capture/Separation	Transport/Disposal	Total
Emissions from Capital Investment	$7.56 \cdot 10^{9}$ g C	$1.95 \cdot 10^{9}$ g C	$9.51 \cdot 10^{9}$ g C
Operational Releases			$6.61 \cdot 10^{10}$ g C/year (incl. ocean release)
without ocean release	$4.67 \cdot 10^{10}$ g C/year	$7.69 \cdot 10^{9}$ g C/year	
with ocean release		$1.94 \cdot 10^{10}$ g C/year	
Emissions from Demolition Releases	$-4.55 \cdot 10^{8}$ g C (credit)	$-1.45 \cdot 10^{9}$ g C (credit)	$-1.91 \cdot 10^{9}$ g C (credit)

We can also show this in graphical formats. The gross sequestration is shown in Figure 2 and the net impact of flows is shown in Figure 3. As mentioned in Section 3.3, the net impact is important; however, it does not address the concept of carbon credits. Carbon credits are assumed to only be given in a year of sequestration (or reduction of emissions). At that time we need to account for any future emissions and incorporate this into the given credit. If we do this, the total activity profile is given in Figure 4.

The 'profitability' of the entire activity can now be calculated as described in Section 6. The present worth index for this activity is 199, assuming a 15% expected return on the initial emission we had to occur to construct the facility. If this number was 1, we would meet our expected return. Clearly, we easily exceeded this expected return.

Another measure of 'profitability' is to compare the annual worth for the initial and demolition emissions with the annual worth of the annual credit activities. The method for calculation of these values is described in Section 6. For the above example, these are

$A_{investment+demolition}$ = 1.5 Gg C and

$A_{carbon\ flow}$ = 33.4 Gg C .

This means that we are preventing 31.9 Gg C/year from reaching the atmosphere above and beyond the 15% 'return' on emissions (amounts released during the construction and demolition periods).

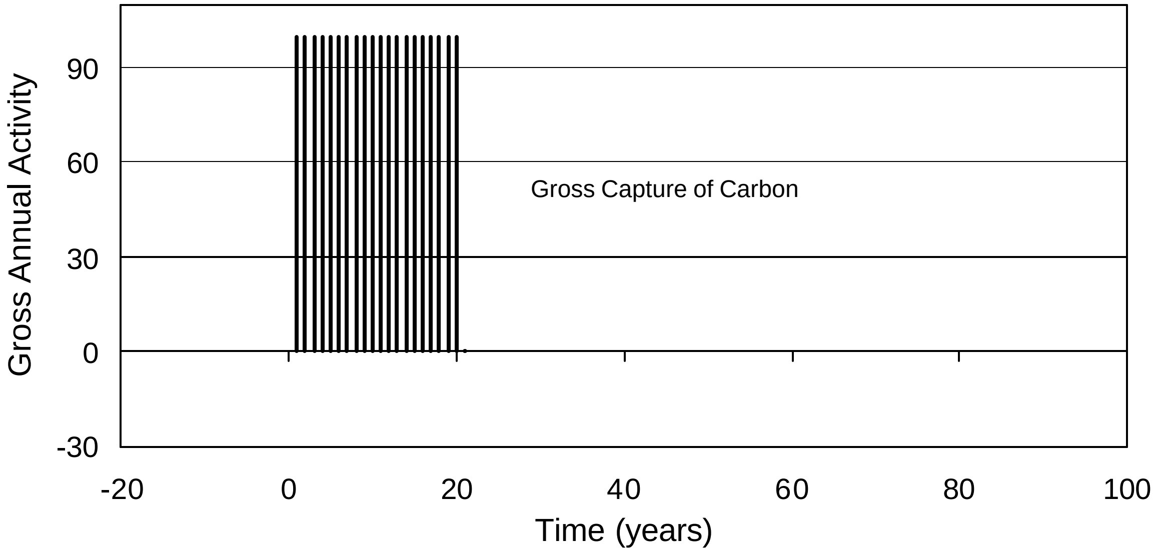


Figure 2. Gross sequstration, reflecting capture and ocean disposal of 99.6 Gg C per year.

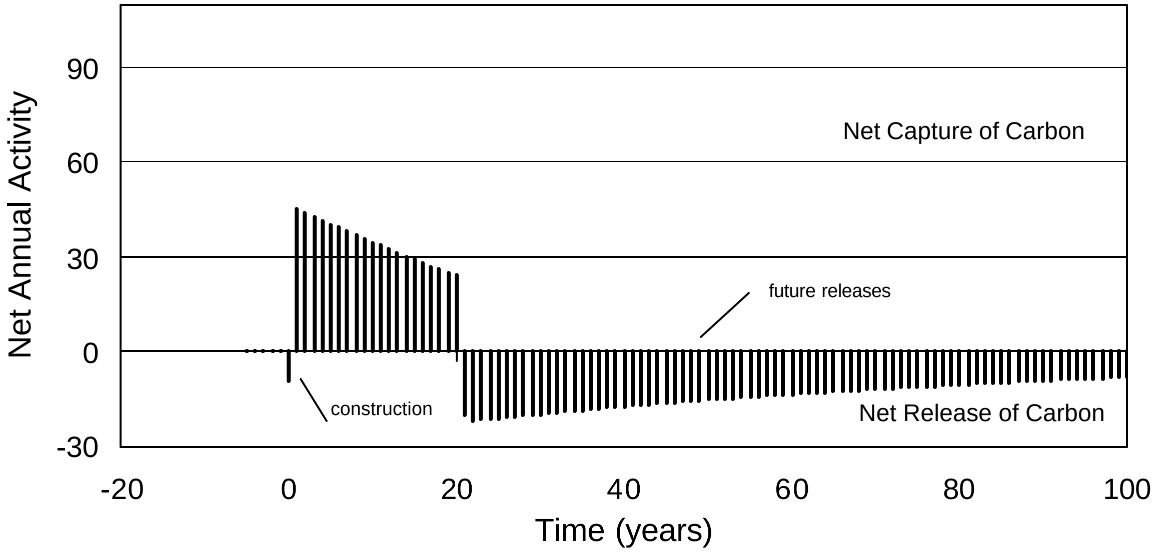


Figure 3. Net carbon flows from an activity for capture and ocean disposal of 99.6 Gg C per year.

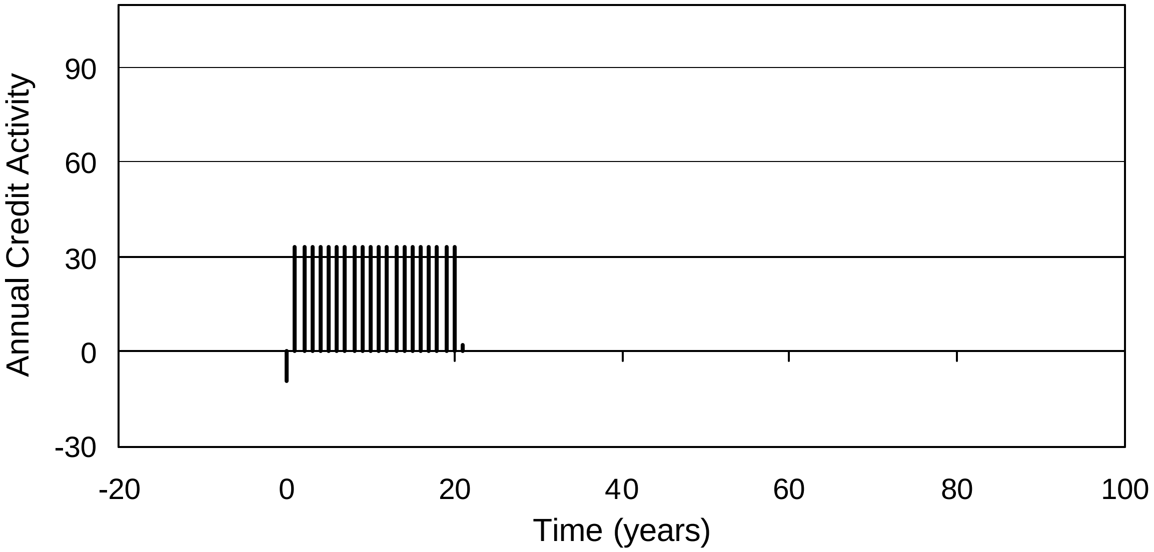


Figure 4. Credit flows for the activity that capture and disposal of 99.6 Gg C per year.

C-4. ABREVIATIONS, NOMENCLATURE, AND CONVERSION FACTORS

C = carbon
C = size of carbon filter (kg)
CE = carbon equivalents
cm = centimeter (= 0.01 m)
D_A = diameter of absorber (m)
DEA = diethylamine
D_S = diameter of stripper (m)
EO = ethylene oxide
FCCE = full-cycle carbon emissions
F_R = circulating flow rate of rich solvent (amine) solution (m^3/h)
g = gram
Gg = gigagram (= 10^9 gram)
j = year
J(e) = electric energy, Joule = 0.0009486 Btu
kg = kilogram (= 1,000 g)
km = kilometer
kWh = kilowatt hours of electricity ($3.6 \cdot 10^{-6}$ J(e))
L_C = makeup of soda ash (Na_2CO_3) (kg/day)
L_S = loss (makeup) of amine (kg/day)
L_W = cooling water (m^3/day)
m = meter
MEA = monoethanolamine
P_B = power consumption of flue gas blower (kWh/day)
P_S = steam requirement (kg/day)

S = amount CO_2 captured/sequestered [t/day]
t = metric ton (1,000 kg, $1\cdot10^6$ g, 2,2,205 lb.)
TEA = triethylamine
ton = metric ton
W = activated carbon for disposal or recycle (kg/day)
Y_{CO2} = volume fraction of CO_2 in flue gas (v/v)

C-5. REFERENCES

C1. Chapel, D.G., Mariz, C.L., and Ernest, J., “Recovery of CO_2 from Flue Gases: Commercial Trends,” proceedings of the First National Conference on Carbon Sequestration (paper 2B.3), Washington, DC, May 14–17, 2001.

C2. Mimura, T., Shimojo, S., Suda, T., Iijima, M., and Mitsuoka, S., “Research and Development on Energy Saving Technology for Flue Gas Carbon Dioxide Recovery and Steam System in Power Plant,” *Energy Convers. Mgmt*. **36**(6–9), 397–400 (1995).

C3. Chakma, A., “An Energy-Efficient Mixed Solvent for the Separation of CO_2,” *Energy Convers. Mgmt*. **36**(6–9), 427–430 (1995).

C4. According to Chapel et al. [C1], the diameter of the absorber column is equal to A×sqrt{(ton/d CO_2)/(%CO_2)}, where A is 0.56 at 3% CO_2 to 0.62 at 13% CO_2. Linear interpolation for intermediate CO_2 concentration and the use of volume fraction instead of percent have been incorporated in Eq. C-1.

C5. According to Chapel et al. [C1], the electric power consumption in kW for blowers and circulating pumps is {0.4 + 16.4/(%CO_2)}× (ton/d CO_2). Converting this in terms of daily power consumption and volume fraction CO_2, results in Eq. C-4.

C6. According to Chapel et al. [C1], the steam consumption is 115 kg steam per m^3 rich solvent. If the flow rate of the solvent is F_R m^3/h, the daily steam consumption is $24\times115\times F_R$.

C7. According to Chapel et al. [C1], the activated carbon must be changed out every 90 days. Thus, the consumption is 0.075 kg/t CO_2. This leads to Eq. C-8, which specifies the size of the carbon filter.

C8. According to Chapel et al. [C1], the cost for cooling water for the plant is \$0.0045/m^3 water, or \$0.34/t CO_2; and the cost of soda ash is \$510/2000 lb soda ash, or \$0.07/t CO_2. This translates to Eqs. C-9 and C-10.

C9. Counce, R.M., University of Tennessee, Knoxville, TN, personal communication, 2002.

C10. *Ullmann’s Encyclopedia of Industrial Chemistry*, 5th ed., vol. A10, VCH Verlagsgesellschaft mbH, Weinheim, Germany, pp. 320–321 (1987).

C11. Bailer, O. Sulzer Chemtech Ltd, Winterthur, Switzerland, personal communication, April 16, 2002.

C12. Assuming stoichiometric conversion of ammonia and ethylene oxide to 80 wt-% MEA, 15% DEA, and 5% TEA, the ammonia requirement is 0.316 g NH_3 and 0.934 g EO per g MEA.

C13. Appendix A. The FCCE for ammonia is 0.487 g C/g NH_3, if the indirect emissions (0.054 g/g) are not included. The FCCE for electricity is $5.39\cdot10^{-5}$ g C/J(e); and for low pressure steam, the value is 0.0571 g C/g steam.

C14. DeMaglie, B., “Oxygen Best for EO,” *Hydrocarbon Process*. **55**(3), 78–80 (1976). The yield of EO from ethylene is reported as 1.099 g EO/g ethylene. Based on stoichiometry, the loss of carbon in this process is 0.234 g C/g EO. All of this release is CO_2 or VOC flared to CO_2 in the oxygen-based process [Gans, M. and Ozero, B.J., *Hydrocarbon Process*. **55**(3), 73–77 (1976)].

C15. Emissions from CO_2 release, electricity use, and steam use corresponds to 0.488 g C/g EO [$0.858\times0.273 + 4500\times5.39\cdot10^{-5} + 0.2\times0.0571$].

C16. *Encyclopedia of Chemical Processing and Design*, vol. 20, McKetta, J.J. and Cunningham, W.A.

(eds.), Marcel Dekker, New York, pp. 88–159 (1984). In the U.S., 44%, 11%, 31%, and 12% of ethylene is produced from ethane, propane, naphtha, and gas oil, respectively; consuming 77.1, 203.2, 217.3, and 343.4 J(e)/g, respectively. This translates to 168 J(e)/g ethylene, or $9.07 \cdot 10^{-3}$ g C/g.

C17. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Reference Manual*, Intergovernmental Panel on Climate Change, (1996).

C18. Emissions from energy and CH_4 during ethylene production correspond to 0.0148 g C/g ethylene [$168 \times 5.39 \cdot 10^{-5} + 0.001 \times 5.7$]

C19. Murata, Y., *Low Purity Oxygen Production Process by Utilizing Liquid Hydrogen Cold Energy*, Nippon Sanso Corp., Kawasaki, Japan, http://www.enaa.or.jp/WE-NET/ronbun/1997/e18/sanso.html (accessed March 2002).

C20. The ethylene oxide production produces CO_2 and water as byproducts. Based on the fact that oxygen and ethylene reacts to form CO_2, H_2O, and EO at a yield of 1.099 g EO/g ethylene [C14]. The oxygen demand is then 1.3 g O_2/g EO.

C21. Emissions from the EO process (including emissions from ethylene and O_2) are 0.586 g C/g C [$0.488 + 0.91 \times 0.0148 + 1.3 \times 1205 \times 5.39 \cdot 10^{-5}$].

C22. Assume a basis of 0.8 g MEA. 0.15 g DEA (or 0.0687 g C) and 0.05 g TEA (or 0.0241 g C) is produced as waste. 0.253 g NH_3 is needed to make the MEA; this releases 0.123 g C. 0.747 g EO is needed to make the MEA; this releases 0.438 g C. Steam, 1.75 g, and electricity, 45 J(e) per g MEA/DEA/TEA are also needed. Thus, the total estimated release is ($0.0687 + 0.0241 + 0.123 + 0.438 + 1.75 \times 0.0571 + 45 \times 5.39 \cdot 10^{-5}$) ÷ 0.8 = 0.945 g C/g MEA.

C23. Appendix A. Unalloyed steel has an FCCE (less other indirect emissions) of 0.375 g C/g steel.

C24. Appendix A. Low alloyed steel has an FCCE (less other indirect emissions) of 0.375 g C/g steel.

C25. Appendix A. Concrete contains 18 wt-% cement with a process emissions factor of 0.3041 g C/g cement and 7 wt-% unalloyed steel with a process emissions factor of 0.375 g C/g steel. This leads to a process emissions factor of 0.076 g C/g reinforced concrete [($0.18 \times 0.3041 + 0.07 \times 0.375$) ÷ 1.07].

C26. According to Chapel et al. [C1], the capital recovery cost (20 year life, 15% ROI) is \$10.83/(t/day) for a 13% flue gas and \$17.85 for a 3% flue gas in 1997. This translates to about \$14.34 for an 8% flue gas stream. On an annual basis, the recovery cost is \$5.23 million. Using capital recovery equation [Cooper, J.R. and W.H. Rader, *Applied Finance and Economic Analysis for Scientists and Engineers*, Van Nostrand Reinhold, New York, p. 240 (1986)], we can calculate an equipment capital cost of \$32.75 million.

C27. MEA has a carbon content of 19.6%. If the carbon stored in the MEA is released, the emissions will be $5.68 \cdot 10^{6}$ g C. Assuming that the activated carbon has the same energy value as coal (28,700 J/g) and that the GHG release from combustion of carbon is $27.4 \cdot 10^{-6}$ g C/J [Appendix A], we can calculate the emissions from 6750 kg activated carbon to be $6750 \cdot 10^{3} \times 28{,}700 \times 27.4 \cdot 10^{-6} = 5.31 \cdot 10^{6}$ g C.

C28. Appendix A. Conversion of iron recyclables to various iron and steel products by re-smelting requires 1620 J(e)/g of electrical energy in the electric furnace. This would indicate a process emissions factor of 0.094 g C/g. If the raw material is pig iron, the process emissions are 0.56 g C/g.

C29. Adams, D., Ormerod, W., Riemer, P., and Smith, A., *Carbon Dioxide Disposal from Power Stations*, IEA Greenhouse Gas R&D Program, Cheltenham, United Kingdom. http://www.ieagreen.org.uk/sr3p.htm (accessed November 2002). The information is given for a 5 nozzle injection at the end of 100 km mild steel pipeline injecting at 500 m.

C30. Nakashike, N. and Hikita, T., "Effectiveness of Ocean Intermediate Depth Injection," *Energy Convers. Mgmt.* **36**(6–), 453–456 (1995).

C31. Dewey, R.D., Stegen, G., and Bacastow, R., "Far-Field Impacts Associated With Ocean Disposal of CO_2," *Energy Convers. Mgmt.* **38**(Suppl.), S349–S354 (1997).

C32. Dewey et al [C31] predicts CO_2 release from ocean sequestration of $4.1 \cdot 10^{11}$ g CO_2/year for 100 years would reach the same level of atmospheric CO_2 100 years after the last year of sequestration as a scenario of annual releases of $3.0 \cdot 10^{11}$ g CO_2/year for 43.4 years without sequestration. This can be used to determine the half-life of CO_2 by finding the value of k in the equation 67.9 = sum{for i=1 to 100 of $e^{-(200-i)/k}$}, which is 383 years.

C33. Haugen, H.A. and Eide, L.I., “CO_2 Capture and Disposal: The Realism of Large Scale Scenarios,” *Energy Convers. Mgmt.* **37**(6–8), 1061–1066 (1996).

C34. Haugen and Eide [C33] estimate that 57.5 MW of electricity is required liquefy, purify, pressurize and inject (into aquifer) CO_2 from a 500 MW coal fired power plant generating 540 t CO_2/hr [Guevel et al., *Energy Convers. Mgmt.* **37**(6–8), 1053–1060 (1996)]. From this we can calculated that it takes 106.5 kWh/t CO_2 [= 57.5×1000÷540], or 383.4 J(e)/g CO_2.

C35. Adams et al. [C29] list the annual maintenance cost for a 52,000 t CO_2/day 100-km ocean disposal pipeline to be \$3.8 million in 1993 (ChE Cost Index_{1993}=359.2). If we interpolate for a 1,000 t/day unit and adjust the cost to 1997 (ChE Cost Index_{1997}=386.5), the value is \$79,000/year. Assuming that the extra 100 km of above ground pipeline will require and additional 25% of maintenance cost, the value becomes \$98,000/year.

C36. Adams et al. [C29] list the cost of pipeline and injection unit to be \$128 million and \$14.5 million in 1993 (ChE Cost Index_{1993}=359.2) for an 100-km ocean pipeline disposing of 52,000 t CO_2/day. If we interpolate for a 1,000 t/day unit and adjust the cost to 1997 (ChE Cost Index_{1997}=386.5), the values are \$2.6 and \$0.3 million. Assuming that the extra 100 km of above ground pipeline will require and additional 25% of pipeline cost, the total capital investment is \$3.61 million.

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