

A General Methodology for Evaluation of Carbon Dioxide Sequestration Activities

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Abstract

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.

To do this we have 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 does not rely on global atmospheric modeling efforts and can be expanded to include financial, social, and long-term environmental aspects of a sequestration technology implementation.

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Introduction

The United States may soon be focusing national attention on processes and activities that mitigate the release of CO₂ to the atmosphere and, in some cases, may remove CO₂ from the atmosphere. As we invest national resources to these ends, it is important to evaluate options and invest wisely. How can we apply consistent standards to evaluate and compare various CO₂ sequestration technologies? 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 or 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. Several of these issues are already pursued from a global perspective.

Traditional carbon accounting methods follow the approach for emissions accounting that is proposed by the Intergovernmental Panel on Climate Change (IPCC). Similar national accounting methods could be developed for carbon sequestration activities. These methods account only for the annual carbon emission reduction represented by sequestration activities. Carbon emissions that relate 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-making processes. For example, if the operators of a coal-fired steam plant are considering implementation of either an off-gas CO₂ scrubbing technique or an algal pond strategy to reduce CO₂ emissions in order to get favorable treatment from a regulatory agency, the evaluation approach may be considerably different from the national accounting approach—especially if these sequestration technologies are moderate in size and do not significantly influence, on an individual basis, the national accounting calculations. Even if a national accounting strategy were used on a very localized zone, no clear method exists by which sequestration technologies should be compared regarding their effectiveness in achieving long-term sequestration. For example, is a method that sequesters CO₂ for an average of 200 years twice as good as one that sequesters it for 100 years?

Ideally, we would like to evaluate each sequestration technology based on the global impact on atmospheric CO₂ levels or on global warming. This, however, may not be a practical method for many

activities. It is likely that short-term or more-limiting activities, not globally implemented, will not significantly alter the result predicted by global modeling efforts. Thus, we should develop a more generic approach that would be less labor intensive and 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 should look something like this:

$$figure\ of\ merit = \int_0^{\infty} f(V_1, V_2, \dots, V_n) dt , \quad (1)$$

where the variables V_1 , V_2 , etc., correspond to environmental, economic, and societal effects, etc., over time. Currently, the scope of this project deals only with life-cycle carbon flows. Thus, the metric we have developed is a simplified methodology that later may be incorporated into a complete objective function. This paper outlines a contribution to the set of tools available for carbon management analyses. We describe a methodology for assessing the merit of technologies that sequester 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.

Objective

Our objective was to develop a general methodology for evaluation of carbon sequestration technologies. We wanted to provide a method that was quantitative but that was structured to give qualitative robust comparisons despite changes in detailed method parameters—that is, it does not matter what “grade” a sequestration technology gets, but a “better” technology should always get a better grade.

The performance objective for a sequestration technology is not necessarily zero emission of CO₂ but rather a reduction compared with the baseline of current practice. To make sure that all carbon aspects are considered, care must be taken to ensure that there are no hidden emissions when making an alteration from the baseline. The fundamental question underlying an analysis of merit of a process or alteration of a process is as follows:

How much CO₂ 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. When we speak of carbon sequestration in this manuscript, we refer to all greenhouse gas sequestration measured in carbon dioxide or carbon equivalence (CE). The carbon dioxide equivalence is also called the Global Warming Potential (GWP). A complete list of GWP values has been prepared by IPCC [1].

Approach

To address our objective, we have developed and elaborated 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* (FCCE), 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* (TVCS) 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 lifetime 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*.

To demonstrate the methodology, we have decided to use a general example and describe in steps how we approach the task of assigning an overall figure of merit to a sequestration project. We gradually progress from an overall visual representation, through detailed review of the individual parts, to the point at which all the information can be consolidated to one or two figures of merit. The steps may be summarized as follows:

1. First, we show the carbon flows occurring as part of an imagined sequestration activity.
2. Then, we show how these flows would be estimated based on the resources used to accomplish the sequestration.
3. This is followed by an inspection of the annual sequestration accomplishment and assigning a value to the activity depending on future carbon flows (e.g., releases) related to the sequestered carbon.
4. Lastly, we discuss how these carbon flows may be used in carbon credit calculations and how to develop the overall figure of merit for the activity based on life-cycle carbon flows.

The methodology we suggest does not rely on global atmospheric modeling efforts and can be expanded to include financial, social, and long-term environmental aspects of a sequestration technology implementation.

Project Description

Assume that we have the pieces to construct a life-cycle carbon-flow diagram for a particular sequestration activity. The time scale for the carbon flow should begin at conception of the idea and end many years after completion of the activity. An example of such carbon flows for an imagined activity may be seen in Figure 1.

To illustrate the carbon flows in Figure 1, we can visualize a sequestration project beginning with research and development, releasing CO₂ in the process. A few years before the construction of the processing plant, we clear some land and burn the tree stumps [2 metric tons of carbon (MtC) released]. In the year just before we open our plant, we build on the land, generating 5 MtC in energy use and latent CO₂ emission associated with the construction, capital equipment and structures. The plant begins operation by ramping up the sequestration capacity over the first 8 years of operation, and capacity then remains constant. During these later years, we sequester a net amount of carbon (about 2 MtC) each year but we also have slow releases from the captured carbon. During the processing plant's last year (year 40), 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 in 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 1, values above the *x*-axis correspond to a net flux of carbon being removed from the atmosphere by the sequestering technology, while negative values correspond to a net release of carbon.

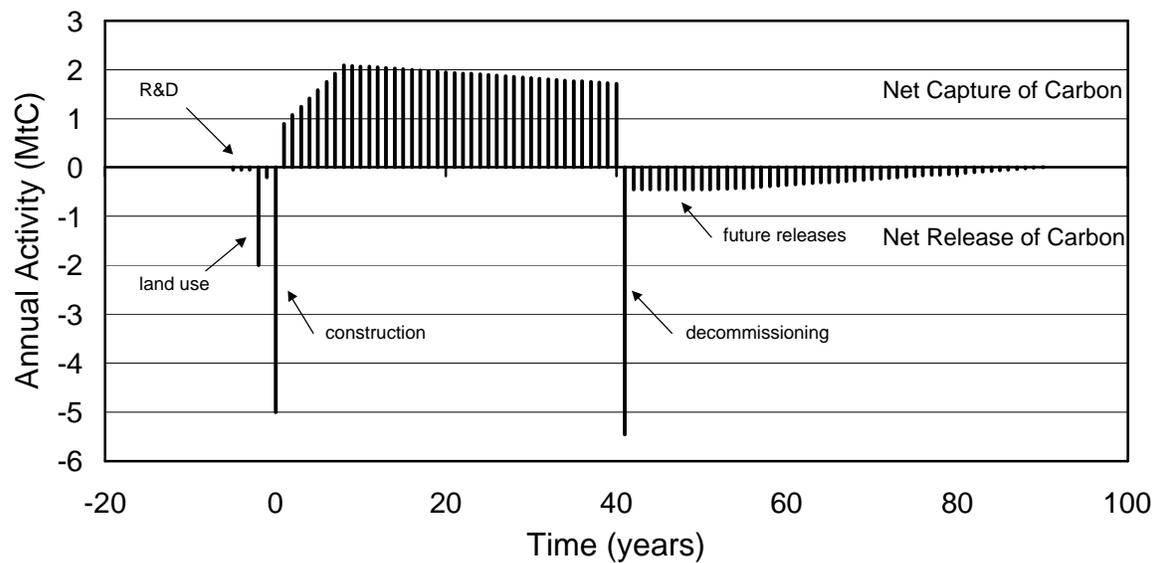


Figure 1. Life-cycle carbon flow for a sequestration activity, including anticipated releases from the sequestered carbon.

Our goal has been to develop an evaluation methodology that addresses life-cycle metrics as well as the annual (carbon) value (or credit) of a sequestration activity. In a carbon trading system, national or international, we must keep in mind that a credit can only be assigned in a year in which sequestration activity occurs—in other words, during the active life of the sequestration plant. Any emissions occurring outside this time frame must be accounted for through another process. To do this, one may choose to assess a “penalty” to account for future releases of carbon from the sequestered form.

The life-cycle evaluation methodology should take into account all emissions in a process. To do this, we introduce a property we call Full-Cycle Carbon Emissions, or FCCE. The FCCE is a value that is expressed in mass of carbon and corresponds to historic and future emissions for a “stream.” When a sequestration technology uses a resource such as energy, we are indicating that this results in emissions somewhere in the world and that these emissions are occurring (or are accounted for) at the same time we are carrying out the sequestration. The FCCE is related to the amount of resource through the FCCE Factor. The FCCE factor is analogous to standard emissions factors used in carbon accounting but specifically addresses life-cycle emissions. For the waste and product streams, however, emissions may occur in the distant future, depending on the fate of these streams. In order to assign an FCCE to these streams, we propose to introduce the Time-Adjusted Value of Carbon Sequestration, or TVCS. In addition to simply accounting for future emissions, we would like this property to indicate that a technology that sequesters carbon and does not rapidly release it for circulation in the atmosphere is more

valuable than an alternate technology that releases it after a short time. Ideally, a technology should sequester the carbon indefinitely; however, it is clear that many of the proposed technologies do not accomplish this.

Results

Full-Cycle Carbon Emissions from Resource Use

One of the most obvious emissions in a proposed sequestration approach is related to the energy used in sequestration activities and subsequent activities for keeping the carbon sequestered. For the United States, which represents limited energy diversity, the CO₂ emissions factor for energy use in 1997 was 15.7 MtC/EJ [$1.57 \cdot 10^{-5}$ gC/J (grams of carbon per joule)] [2]. It includes sources other than fossil energy that do not have CO₂ emissions. The use of fossil energy also generates other greenhouse gas emissions, such as CH₄, N₂O, and CO. These should also be considered and have been quantified by EPA [2]. 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 GWP), which contributes an additional 6.2% to the regular CO₂ emissions. These emissions are all process-related—they do not take into account factors such as constructing power plants and building infrastructures. Attempts have been made to estimate what has been termed *Full-Energy-Chain* (FENCH) *Emissions Factors* of greenhouse gases for electricity use [3]. These emissions factors are in the range of $3.52 \cdot 10^{-5}$ to $4.21 \cdot 10^{-5}$ g CE/J for electricity produced from mixed sources within a region. 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.

Table 1. Full-Energy-Chain Emissions Factors for Electricity use.

Source of Electricity	FENCH Emissions Factor (g CE/J)
Coal	
Lignite [3]	$8.81 \cdot 10^{-5} - 1.00 \cdot 10^{-4}$
hard coal [3]	$7.22 \cdot 10^{-5} - 9.68 \cdot 10^{-5}$
Gas	
natural gas [3]	$5.79 \cdot 10^{-5}$
liquid natural gas [3]	$4.90 \cdot 10^{-5}$
Nuclear power [3]	$7.50 \cdot 10^{-8} - 1.93 \cdot 10^{-6}$
Hydro power [3]	$1.35 \cdot 10^{-6}$
Solar photo voltaic [3]	$4.28 \cdot 10^{-6} - 2.09 \cdot 10^{-5}$
Wind power [3]	$1.20 \cdot 10^{-6} - 9.00 \cdot 10^{-6}$
Biomass [4]	$2.78 \cdot 10^{-6} - 1.35 \cdot 10^{-5}$
Electricity mix [3]	$3.52 \cdot 10^{-5} - 4.21 \cdot 10^{-5}$

A general methodology to determine the FCCE in materials may be to divide this estimation into four different categories of latent emissions that arise from using materials in the process:

1. Process emissions related to the stream. For example, ammonia has been proposed as a CO₂ absorbent for combustion gas, producing a fertilizer. Thus, we would have to account for CO₂ generation from process methane used in ammonia production.
2. Indirect or direct emissions from the use of energy. For example, the energy requirement for ammonia production is 29 MJ/g NH₃ [5].
3. Emissions from transportation fuel used to get the “stream” to or from our sequestration location.
4. All 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.

The fourth category is a catchall group, which includes the emissions related to ammonia plant construction, etc. To estimate emissions represented in this group, a possible method is to look at the market price of the raw material and assign an FCCE factor for cost. In the case of ammonia, the cost in 1997 was \$227/ton (short), not including transportation [6], which translates to $\$2.5 \cdot 10^{-4}/\text{g NH}_3$. We can use this cost in one of two ways:

- 4a. Assume that all of this cost will ultimately be applied to some type of energy use. Then convert the cost to carbon emission by using the energy price in 1997 [adjusted with gross domestic product (GDP) implicit price deflators], which was \$8.99/MBtu ($\$8.52 \cdot 10^{-9}/\text{J}$) [7], and emissions factors for general energy use ($1.062 \times 1.57 \cdot 10^{-5} \text{ gC}/\text{J}$). This would give us an estimated cost emissions factor of 1960 gC per dollar.
- 4b. We can use the GDP and its correlation to carbon emission. In 1997 the United States GDP was $8300 \cdot 10^9$ dollars [8], and the estimated emissions were 1800 MtC ($1.8 \cdot 10^{15} \text{ gC}$), including all greenhouse gases [9]. This would lead to a cost emissions factor of 217 gC per dollar.

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 emissions type 2 above. We may thus refine our general FCCE estimation methodology to the following:

1. Determine the process emission factor and calculate the greenhouse gas emissions. Several sources (e.g., IPCC [10], EPA [2], and others [11]) provide relevant information.
2. 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.
3. Emissions from transportation fuel used to get the “stream” to or from our sequestration location.
4. Determine the cost of the undelivered product less energy cost and use the GDP/emission relationship to estimate all other indirect emissions.

In addition to materials used in the process, the capital equipment, buildings, and other items needed for carbon sequestration have associated FCCEs. Once the amount of construction materials has been estimated, the same methodology developed above for raw materials may be used. Some process emissions and energy intensities of common building materials have been summarized by Van de Vate [12].

The above examples attempt to capture the life-cycle emissions of a resource used for carbon sequestration. There are other methods that have been used for the same purpose. 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 [13]. For instant, spending \$1.00 on plastics in 1972 require 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 CE/\$ [14]. The categories presented in reference 13 are somewhat broad and a

more detailed categories are available for 1967 data [15]. For more recent data, Carnegie Mellon University has combined this type of industry input-output information with emissions information. One dollar of plastic spent in 1992 would accordingly generate 5.15 g CE of emissions [16].

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 (BEA Sector/ Input Output Code 07) is shown for the industries Livestock and Livestock Products (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 is sold. To calculate the energy intensities, 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 [17]. The natural gas and crude petroleum use in 1997

was 22.53 and 36.266 quadrillion Btu [ref. 7, 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 [18]. 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) [18].
3. Convert the nuclear- and hydro-electric power to equivalent fossil-electric power using $1.0927 \cdot 10^7$ J(fossil)/kWh(e) (3.035 J/J(e)) [18].
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 gas emissions, but are incorporated into products as carbon compounds. For example, plastics contain a lot of carbon. Also, all the products or infrastructure 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 effect the primary energy use. The BEA sectors are broad and may not provide the detail needed for some activities.

Full-Cycle Carbon Emissions from Sequestered Carbon

Future carbon emissions occurring from sequestered carbon should be considered when evaluating different sequestration approaches. To determine the FCCEs for streams that will cause carbon emissions in the future, we introduce the Time-Adjusted Value of Carbon Sequestration (TVCS). One way to estimate this value is to employ our global climate models to predict changes in atmospheric CO₂ levels as a result of sequestration and future release from sequestered carbon. This would be a labor-intensive task. Moreover, if an individual sequestration effort is moderate, it will be considered merely as noise in existing global models. We propose another approach—to start by defining a sequestration duration goal that will serve as a metric for future reference. For example, we may chose to use 100 years as our goal for sequestration. In this scenario, if we sequester 2 megatons of carbon (2 MtC = 7.4 Mt of CO₂) today and are able to keep it sequestered for at least 100 years, we should receive full value (100%) for the activity. If we have partial or full release in less than 100 years, we are not doing as well and the value is

less. The question is this; how do we evaluate different carbon release profiles and determine their proper values?

Consider the graphs in Figure 2, in which several value curves have been constructed based on the instantaneous release of 2 Mt of sequestered carbon sometime in the future. We will later consider partial release over time. Figure 2a shows a scenario that does not give any value (or credit) to a sequestration of less than 100 years. 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., $75/100 \times 2 = 1.5$ MtC). To give proportionally more credit to longer sequestration periods, we can construct a curve as in Figure 2c. Here we emphasize 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 release, especially for the years close to year 100. To counter this, we may choose to use a fourth approach (Figure 2d) which suggests that we should consider short-term solutions favorably while recognizing that future predictions are hard to make. In all the cases, we have chosen to give full credit, or value, to sequestration past 100 years (or whatever metric we select as a goal).

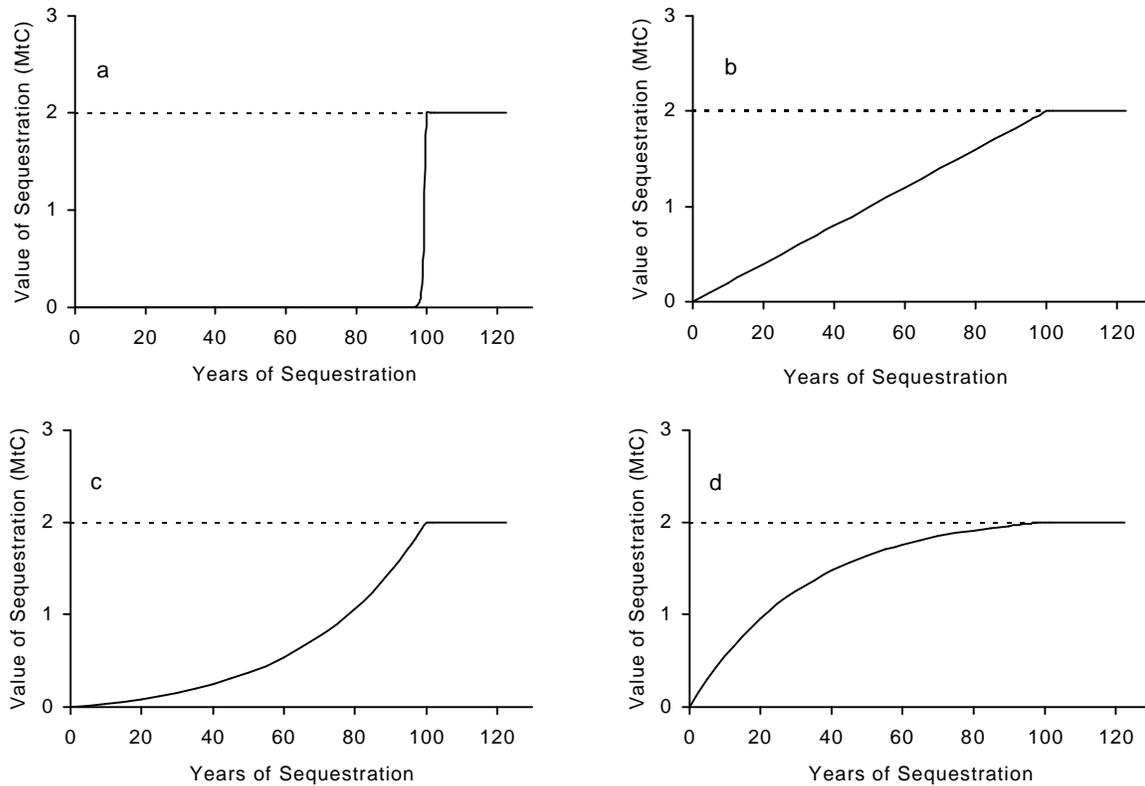


Figure 2. Several potential profiles for calculation of the time value of sequestration.

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

$$\text{Value of Carbon Sequestration} = (\text{Amount of Carbon Released}) \times \left[\frac{(1+i)^y - 1}{(1+i)^Y - 1} \right] \quad (\text{for } y \leq Y), \quad (2)$$

where i is the penalty interest rate, y is the number of years sequestered, and Y is the sequestration goal (expressed in years). Equation 2 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 2 were obtained by changing the penalty interest rate from 500% to 0.01% to 3% to -3% for Figure 2a, 2b, 2c, and 2d, respectively. We propose the following abbreviated expression for the modifier:

$$V = R \times TVCS(i, y, Y), \quad (3)$$

where V is the Value of Carbon Sequestration and R is the Amount of Carbon Released.

The preceding discussion addressed instantaneous release of the entire amount of sequestered carbon. An example of this scenario is that of sequestered carbon stock that is suddenly being used for fuel. Other scenarios may need to address periodic release of small amounts of the sequestered carbon. We can use a carbon release profile (Figure 3) to visualize this phenomenon. The timescale begins when sequestration takes place. In this example, we have chosen to sequester 2 MtC. 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.

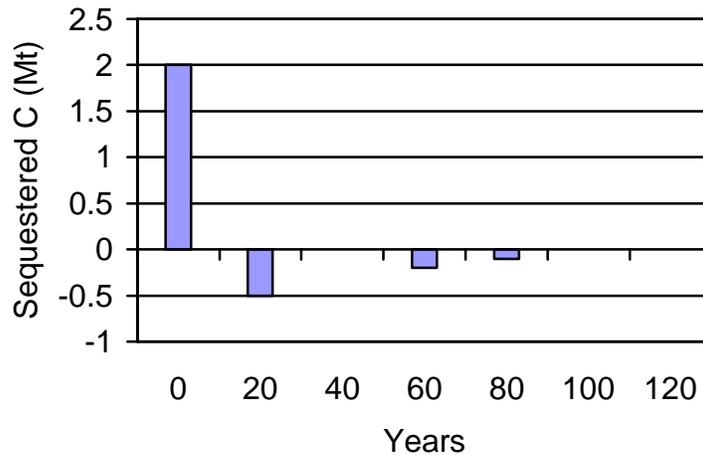


Figure 3. Example of periodic release of sequestered carbon.

To calculate the value or credit for this activity, we would simply add the individual time-adjusted 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 4, in which we have chosen to use 100 years as the goal for sequestration ($Y = 100$):

$$V = 0.5 \times TVCS(i, 20, 100) + 0.2 \times TVCS(i, 60, 100) + 0.1 \times TVCS(i, 80, 100) + \underbrace{(3.7 - 0.5 - 0.2 - 0.1) \times TVCS(i, > 100, 100)}_{=1} \quad (4)$$

Equation 4 can be simplified and generalized to yield Equation 5:

$$V = S_C - \sum_{j=1}^Y R_j \times (1 - TVCS(i, y_j, Y)) \quad (5)$$

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

The preceding example showed how to penalize (or 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 5 is modified to yield the integral form

$$V = S_C - \int_0^Y R(y) \times (1 - TVCS(i, y, Y)) dy \quad , \quad (6)$$

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

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 generate CO_2 , we need to incorporate this knowledge in the value of sequestration. To keep with the approach that we have taken concerning TVCS, we would value delayed use of energy more than early use. The easiest way to visualize this it to realize that any maintenance in the future will generate CO_2 , and this amount must be added to that potentially released from the sequestered carbon. Thus, R_j and $R(y)$ in Equations 5 and 6 represent the total CO_2 (or CE) released in the future, whether from captured CO_2 itself or from any CO_2 -generating activity associated with the captured carbon. Incorporating maintenance activities into the projected scenario creates a situation that would cause some sequestration technologies to have a negative value, indicating a poor carbon management strategy.

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 TVCS, we have acknowledged that emissions may occur in the future from the sequestered carbon and we have also incorporated a projected value to address future releases. Thus, the time-adjusted FCCE is the right-hand part of the expressions in Equations 5 and 6,

$$FCCE = \sum_{j=1}^Y R_j \times (1 - TVCS(i, y_j, Y)) \quad \text{or} \quad \int_0^Y R(y) \times (1 - TVCS(i, y, Y)) dy, \quad (7)$$

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

Credit for Annual Carbon Sequestration Accomplishments

In a carbon credit–trading scenario, carbon credits must be calculated. 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 2. For example, in year 6, we anticipate that our industrial facility will remove 2 MtC from the atmosphere but that it will have an annual activity of 1.8 MtC. (We sequester 2 MtC in a product, but we emit 0.2 MtC to accomplish this.) The fair amount of carbon credit (carbon flow) that could be claimed in that year is 1.56 MtC because of the anticipated future release of some of the sequestered carbon.

We can assign a credit only during the active life of the operating plant; thus, the initial releases do not factor into the credit calculations. However, values from these releases should still be used in the evaluation of the life-cycle activity as described in the following section. The initial releases may be seen as an investment in the technology—we must emit CO₂ in the early stages in order to capture more CO₂ later in the overall activity.

Figure of Merit for Carbon Sequestration Activities

To this point, we have proposed methods to estimate

- the net amount of carbon sequestered by taking into account both the actual mass flow of carbon and latent emissions;
- the TVCS by 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 basis for carbon credit calculations for a sequestration activity.

Table 2. Carbon flows on an annual basis.

End of Year	Sequestration (MtC)	Annual Activity (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	0.120	0.780
2	1.2	1.08	0.144	0.936
3	1.4	1.26	0.168	1.092
4	1.6	1.44	0.192	1.248
5	1.8	1.62	0.216	1.404
6	2	1.8	0.241	1.560
7	2.2	1.98	0.265	1.715
8	2.4	2.16	0.289	1.871
9	2.4	2.16	0.289	1.871
10	2.4	2.16	0.289	1.871
-	-	-	-	-
40	2.4	2.16	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 and with or without discounting. In our case, carbon flow is analogous to cash flow.

The word “profitability” implies that we are now interested in how well our activity is performing compared with the investments (analogous to prestartup releases) we made. When we look at profitability, we can compare other investment alternatives. When such alternatives are compared, it is very likely that the carbon flows for different projects will be dissimilar, both in their magnitude and in the time they occur. When flows occur at different times this detail is corrected by introducing the time value of carbon. Discussions have arisen concerning carbon flows and whether the concept of time value of carbon exists. The argument is that—for most cases—the time interval often examined 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 perhaps not on a decade or even century basis. We have decided 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.

The time value of carbon flows may be handled using the single payment compound amount factor [19],

$$P = F \times (P/F I, n), \quad \text{where} \quad (P/F I, n) = (1 + I)^{-n}, \quad (8), (9)$$

where P is the present worth, F is the future worth, I is the discrete compound interest rate, and n is the number of 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 MtC in year 6 (Table 2) with a 10% interest rate, we can calculate as follows:

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

One way to view this information is to say that we can either strive for a carbon credit of 0.88 MtC today or reach a carbon credit of 1.56 MtC in year 6—time is of the essence.

Two types of figure of merit that we propose are useful. In economic evaluations, these are termed *Present Worth Index* and *Annual Worth*. To summarize, the first method looks at the cumulative present worth of carbon flows over the life of the project and compares this with the present worth of carbon flow by the initial carbon investment. The second type compares the present-worth-corrected average sequestration of carbon per year with the emissions from initial investment plus demolition, averaged over the active sequestration plant life [19].

Conclusions and Future Activities

Our objective was to develop a general methodology for evaluation of carbon sequestration technologies. We wanted to provide a method that was quantitative but also structured to give robust qualitative comparisons despite changes in detailed method parameters—that is, it does not matter what “grade” a sequestration technology gets, but a “better” technology should always achieve a higher score. We think that the methodology we have begun to develop provides this capability.

- This is a methodology that will assist in evaluation and comparison of well-defined sequestration activities.

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

Abbreviations and Conversion Factors

C = carbon

g = gram = $2.2046 \cdot 10^{-3}$ lb

J = joule = 0.0009486 Btu

M = mega = 10^6

t = metric ton = 1000 kg = 10^6 g = 2204.6 lb

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 13. Hannon, B.; Casler, S. Updating Energy and Labor Intensities for Non-Input-Output Years. Energy Systems and Policy 9(1): 27–48; 1985.
 14. 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) [ref. 7, 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 CE/J. This results in a plastics emissions factor of 4,480 g CE/\$ plastics.
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 17. The cost for production of coal and natural gas in 1997 as \$0.85 and \$2.10 per million Btu [ref. 7 .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).

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