A Potential Error Associated with Using Chemical and Equipment Sales Data To Estimate Greenhouse Gas Emissions from Long-lived, Pressurized Equipment

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Abstract

This paper discusses and quantifies a potential error associated with using information on sales of chemical and equipment to estimate emissions of greenhouse gases from long-lived, pressurized equipment, such as air-conditioning and refrigeration equipment, fire suppression equipment, and SF_6-containing electrical equipment. In the Good Practice Guidance issued by the IPCC (*Reference 1*), the sales-based, or mass-balance, method is recommended as a relatively accurate method for estimating emissions from these types of equipment. Indeed, as will be shown, the sales-based method yields a very good estimate of emissions when equipment stocks are growing (or declining) at a steady pace. However, the sales-based approach should be applied carefully when equipment stocks are growing or declining very rapidly. This is because many types of equipment may leak for more than one year before they must be refilled with gas, and therefore demand for new gas lags actual emissions. The error resulting from this lag is most pronounced during the first few years after a chemical is introduced into the equipment, when much of the equipment has leaked, but none (or very little) has required refilling. In general, the error decreases as more equipment containing the new chemical is introduced into the field, finally reaching a constant, low level when the equipment containing the new chemical begins to retire.

Introduction

As concerns about global climate change prompt more countries to develop estimates of the quantities of greenhouse gases emitted from their equipment, it has become increasingly important to have a straightforward estimation method that can be applied in a wide range of regions with a relatively high degree of accuracy in each one. Traditionally, emissions from pressurized equipment have been calculated based on the stock of equipment in the field and estimated release rates from this stock. The drawbacks of the stock-based approach are that the stock and its release rates are difficult to estimate directly, and both quantities vary considerably over time and between regions. Thus, estimates developed using the stock-based approach are subject to considerable uncertainty, especially if they rely on emission factors developed years ago or outside of the region being studied.

One method that overcomes these drawbacks is to use data on current and historical sales of gas and equipment to directly calculate the share of gas consumption that replaces gas released to the atmosphere in the region being studied. This method is discussed in detail in the IPCC's Good Practice Guidance and elsewhere (*Reference 2*). In brief, the method is based on the idea that an industry's demand for new gas comes from four sources: (1) the need to replace emissions from the current equipment stock, (2) net changes in the size of the operating gas bank, that is, in the total charge of the equipment stock (which may come from changes in the number of individual pieces of equipment and/or from changes in the charge size of equipment), (3) the need to replace destroyed gas, and (4) stockpiling of gas. The method systematically accounts for the last three sources of demand, leaving an estimate of emissions. The method uses the following equation:

Emissions = Annual sales of new gas – Total charge of new equipment + Original total charge of retiring equipment – Gas destroyed – Gas stockpiled + Gas drawn from stockpiles

where:

Annual sales are the annual sales of gas for filling or refilling equipment, both in bulk and in equipment.

New gas means newly produced gas. Recycled gas is not "new gas."

Total charge of new equipment means the sum of the full charges of all the new equipment that is sold in a year, including both equipment that is filled in the factory before shipment and equipment that is filled after installation. It does not include charging emissions.

Original total charge of retiring equipment means the sum of the original full charges of all the equipment that is retired in a year, including both equipment that was filled in the factory before shipment and equipment that was filled after installation. It does not include charging emissions, and it does not exclude gas lost to the atmosphere after the equipment was installed.

New/retiring equipment includes imported equipment and excludes exported equipment.

Estimating the Potential Error in the Sales-Based Method

The sales-based method is designed to yield an excellent estimate of the quantity of chemical used to replace emitted chemical in a given year. However, because some equipment may leak but nevertheless continue to run with less than a full charge, emitted chemical is not always replaced during the year that it leaks. Thus, to some extent, demand for recharges "lags" actual emissions. This means that when the equipment stock is either growing or shrinking, the sales-based method may either under- or overestimate actual emissions.

The precise relationship between the amount of chemical being recharged and actual emissions depends upon (1) the frequency with which the equipment is serviced, (2) the growth rate of the equipment stock, (3) the length of time the chemical has been used in the equipment (i.e., less vs. more than the equipment lifetime), and (4) the fraction of emissions represented by leaks (as opposed to installation, servicing, and disposal emissions, which are detected the year that they occur).

<u>Four Scenarios</u>

The relationship between the amount of chemical being recharged and actual emissions is clarified by examining four scenarios. The two simplest scenarios are those in which the stock of equipment (1) is serviced at least annually or (2) does not change in size. In these scenarios, there is no lag error. If a type of equipment is serviced and recharged once a year or more, then emissions from leaks are detected almost as soon as they occur. If the equipment stock neither grows nor shrinks, then the equipment being recharged will be representative of the equipment stock as a whole, and again, the amount of chemical being recharged will be the same as actual emissions.[1]

However, it is often the case that equipment is serviced less frequently than once a year, and that the equipment stock is either growing or shrinking. In this case, the amount of chemical being recharged will be either smaller (if the stock is growing) or larger (if the stock is shrinking) than the annual emissions from the stock.

Figure 1 shows the relationship between apparent and actual emissions in equipment whose sales are growing exponentially at a rate of 5% per year. The equipment is assumed to have a lifetime of 15 years and to be serviced every 5 years, reasonably common characteristics for the types of equipment for which the sales-based method is designed. The first year shown in the graph is the year when the chemical of interest is first introduced into the equipment. For illustrative purposes, leaks are assumed to make up 100% of emissions.

As can be seen from Figure 1, after a chemical is first introduced into a type of equipment, emissions ("Actual Leaks") grow rapidly as the bank of chemical in the equipment stock approximately doubles in the second year, triples in the third, etc. However, sales of the chemical for recharging ("Apparent Leaks") do not reflect emissions from the equipment until the equipment is recharged for the first time, in this case, five years after installation. Thereafter, the relationship between chemical sales and actual emissions varies periodically, as cohorts of equipment sold over five-year periods are serviced for the first and second times. (In reality, the equipment is likely to vary somewhat in the frequency with which it must be recharged, smoothing out the curve.) Once the chemical of interest has been used in the equipment for the lifetime of the equipment, the relationship between sales for recharging and actual emissions stabilizes to a constant, equilibrium value. For this scenario, that value is 0.88.

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1 For example, suppose that a type of equipment must be recharged every three years, and that the quantity of equipment sold each year has been steady at 100 units per year for at least the lifetime of the equipment. In a given year, the emissions from the equipment sold during any three-year period will be EF x 100 x 3, where EF is an emission factor equal to the annual leak rate of the equipment. At the same time, in any given year, one third of the equipment sold during any three-year period (1/3 x 300) will have to be recharged to replace the chemical lost over the last three years (3 x EF). The amount that it will have to be recharged will be EF x 100 x 3. In this situation, demand equals emissions.

Figure 2 illustrates the relationship between chemical sales for recharging and actual emissions in equipment that is serviced every 3 years, has a lifetime of 12 years, and whose sales grow at a rate of 2% per year. Once again, the relationship between chemical sales and actual emissions oscillates on an upward trend until the equipment containing the chemical begins to retire, at which point an equilibrium value is reached. For this scenario, that value is 0.97.

In general, for exponentially growing equipment stock, the equilibrium ratio between apparent and actual leaks can be estimated using the following expression:

$$\frac{\text{Apparent Leaks}}{\text{Actual Leaks}} = \frac{R[\ln(1+g)]}{(1+g)^R - 1}$$

Where

R = number of years between recharges, and
g = the annual growth rate of equipment sales (Note that this is the same as the growth rate of the stock once equilibrium has been reached.)

The derivation of this expression is discussed below.

<u>Explaining the Behavior of the Curve</u>

Behavior of the Curve at the Beginning and End of Chemical Use

The relationship between apparent and actual leaks varies in a complex fashion during the period when a chemical is first introduced into equipment, making it difficult to characterize the relationship during that period with a simple mathematical expression. Nevertheless, the dynamics of the curve can be understood by considering how emissions and sales of chemical for refilling grow at that time. The behavior of the curve during the earliest years is easy to understand: clearly, sales for refilling (and therefore the ratio between sales and leaks) will be close to zero until the equipment installed during the first year is serviced for the first time. At that point, the ratio between sales and leaks rises sharply.

What is less clear is why that ratio then declines for the next few years. The reason for the decline is that until the equipment begins to retire, the total stock of equipment (and therefore volume of emissions) generally grows much more quickly than the amount of equipment serviced (and therefore sales of chemical for refilling). For example, in Figure 1, the ratio between sales and leaks falls after year 6, because the amount of equipment serviced is only growing at 5% per year at that time, while the total stock of equipment is growing at 21% per year at that time. The curve only recovers in year 11, when, for the first time, *two* sets of equipment (that installed in year 1 and that installed in year 6) are serviced during the same year. This almost doubles the amount of apparent emissions. Again, the ratio between apparent and actual emissions falls after year 11, but less sharply than before. Although the growth rate of the equipment serviced is still just 5%, the growth rate of the total amount of equipment has declined to 12% at that time, narrowing the gap. Finally, when the equipment begins to retire, the growth rates of the equipment serviced and of the total stock become equal, and, as noted above, the relationship between sales for recharging and actual emissions stabilizes to a constant, equilibrium value. The same is true in Figure 2.

Figure 3 shows the growth rates of actual leaks (emissions) and of apparent leaks (sales of chemical for refilling) for the equipment depicted in Figure 1. Note how the growth of emissions at the beginning of the equipment's life starts high and then declines and levels off, equaling the growth rate of apparent leaks once the lifetime of the equipment has been reached. Also note the spikes in the growth rate of apparent leaks in years 6, 11, and 16.

Figure 4 shows the relationship between apparent and actual leaks when use of the chemical in new equipment abruptly stops. As in Figure 1, the equipment has a lifetime of 15 years and is serviced every 5 years. In many ways, Figure 3 is the mirror image of Figure 1, with apparent leaks *exceeding* actual leaks more and more as the equipment ages and retires. This overestimate exactly compensates for the underestimate that occurs earlier in the equipment's life, and it occurs for similar reasons. However, the overestimate does not occur until and unless use of the chemical in the equipment begins to decline.

Behavior of the Curve under Equilibrium Conditions

The expression for the equilibrium ratio between apparent and actual leaks can be derived by considering some general scenarios similar to those depicted in Figures 1 and 2. First, consider the situation in which leaks are the sole source of emissions and in which the equipment leaks at a slow rate, so that it need not be serviced during its lifetime. (The situation in which leaks aren't the sole source of emissions will be discussed below.) Suppose further that apparent and actual leaks have reached their equilibrium ratio; that is, that the chemical of interest has been used in the equipment for at least the lifetime of the equipment. Let L equal the lifetime of the equipment. Let C_r equal the original total charge of the equipment sold L years ago. This is the equipment that will retire this year. Let g be the growth rate and EF be the annual leak rate of the equipment (as a fraction of the charge).

Clearly, leaks from this equipment will not be "caught" until the year the equipment retires, at which time less than the original full charge will be recovered from it. The amount that will be found to be missing at that point is EF x C_r x L. The actual emissions from the equipment during that year will be EF times the total charge of the total stock equipment. The total charge of the total stock actually changes during the year, as new equipment replaces retiring equipment. However, with a constant exponential growth rate, the *average* total charge of the total stock of equipment during the year can be expressed as a function of the total charge of the retiring equipment, as follows:

$$\text{Stockcharge} = \left[C_r \int_{t=0}^{t=L} (1+g)^t \, dt \right]$$

Thus,

$$\text{Emissions} = \text{EF}\times\text{Stockcharge} = EF\times\left[C_r\int_{t=0}^{t=L}(1+g)^t\,dt\right]$$

Solving, one obtains

$$Emissions = EF\times C_r\left[\frac{(1+g)^t}{\ln(1+g)}\right]_0^L = EF\times C_r\left[\frac{(1+g)^L}{\ln(1+g)}-\frac{1}{\ln(1+g)}\right]$$

The ratio between the apparent and actual emissions from leaks will be:

$$\frac{EF\times C_r\times L}{EF\times C_r\left[\frac{(1+g)^L}{\ln(1+g)}-\frac{1}{\ln(1+g)}\right]} = \frac{L\times\ln(1+g)}{(1+g)^L-1}$$

For example, where L=10 and g= 0.05, the ratio between apparent and actual emissions from leaks will be:

$$\frac{\text{Apparent leaks}}{\text{Actual leaks}} = \frac{10\times\ln(1+0.05)}{(1+0.05)^{10}-1} = 0.78$$

If the equipment is serviced and recharged during its lifetime, the analysis above continues to apply, except L is replaced by R, the number of years between recharges. One can see this by dividing the total set of existing equipment (sold over L years) into smaller sets of equipment sold every R years. Clearly, the relationship between the quantity of gas used to recharge the equipment sold R years ago (or aR years ago where a is an integer) and the quantity of gas leaked from the equipment sold over the entire period of R years is analogous to the above relationship between the quantity of gas used to recharge the equipment sold L years ago and the quantity of gas leaked from the equipment sold over the entire period of L years. This yields the following ratio between apparent and actual emissions from leaks:

$$\frac{EF\times C_r\times R}{EF\times C_r\left[\frac{(1+g)^R}{\ln(1+g)}-\frac{1}{\ln(1+g)}\right]} = \frac{R\times\ln(1+g)}{(1+g)^R-1}$$

For example, where R=5 and g= 0.05, the ratio between apparent and actual emissions from leaks will be:

$$\frac{\text{Apparent leaks}}{\text{Actual leaks}} = \frac{5\times\ln(1+0.05)}{(1+0.05)^5-1} = 0.88$$

Note that this is a minimum value where equipment stocks are growing. Unless L is perfectly divisible by R, the disposal of the retiring equipment will reveal that equipment's final leakage emissions before R years have elapsed since the last recharge.

Share of Emissions Accounted for by Leaks

The above ratios are based on the assumption that leaks make up 100% of emissions from equipment. In fact, leaks are likely to make up only a fraction of emissions. Because other emissions, such as releases during installation, servicing, and disposal, are detected as soon as they occur, the ratio between apparent and actual emissions from all sources will be closer to one than are the above ratios.

Specifically, where leaks make up fraction F of total emissions, the ratio between apparent and actual emissions from all sources will be a weighted average of one and the ratio between apparent and actual leaks, as follows:

$$\frac{ApparentEmissions}{ActualEmissions} = F \times \frac{ApparentLeaks}{ActualLeaks} + (1 - F)$$

For example, if the ratio between apparent and actual leaks for a type of equipment is 88%, and leaks make up 40% of the emissions from that type of equipment, then the ratio between apparent total emissions and actual total emissions will be

$$\frac{ApparentEmissions}{ActualEmissions} = 0.40 \times \frac{ApparentLeaks}{ActualLeaks} + (1 - F) = (0.40 \times 0.88) + 0.60 = 0.95$$

Conclusion: Compensating for the Error

Under equilibrium conditions, the relatively small lag-error can be estimated and largely compensated for if the growth rate of the equipment stock, the servicing frequency, and the share of emissions accounted for by leaks are approximately known. Among these three quantities, the most difficult to estimate is probably the share of emissions accounted for by leaks, which requires fairly detailed knowledge of emissions during the life of the equipment. However, even without this information, the maximum possible error can be estimated by assuming that leaks make up 100% of emissions, and this maximum error can be taken into consideration in developing a final emissions estimate.

Under the non-equilibrium conditions that apply when a chemical is first used in equipment (or alternatively, when it is phased out of equipment), the size of the error varies, making it more difficult to compensate for. Nevertheless, some general conclusions can be drawn. First, during the first few years after a chemical is introduced, sales of gas for refilling will be low even if the leak rate of the equipment is relatively high; only when the first cohort of equipment is refilled will sales (as measured by the sales-based method) begin indicating the actual leak rate. (Of course, if the leak rate is high enough, this first refill will come sooner rather than later.) Users of the sales-based method should track demand closely, noting when it increases and levels off. At that time, they may tentatively conclude that the first cohort of equipment has been serviced, although subsequent tracking will be required to confirm this. Until that time, very low sales for refilling should *not* be taken as a confirmation of very low leak rates. Instead, if the tolerance of the equipment for low charge is known, this information can be used to place an upper limit on the leak rate. For example, if it is known that the equipment's performance declines noticeably after the equipment has lost 15% of its charge, and if four years have passed since the chemical was first introduced into the equipment (with little or no refilling during that period), then it can be concluded that the equipment's leak rate is probably below five percent per year.

The second conclusion that can be drawn is that, although the ratio between apparent and actual leaks fluctuates, it tends toward the equilibrium value as the rate of growth of the equipment stock approaches that of equipment sales. Thus, as time passes after the first servicing of the equipment, the sales-based method can be used with increasing confidence to estimate emissions, and the expression for the error at equilibrium can be used to largely compensate for the error that exists before equilibrium is reached.

References

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Key Words

Emissions, measurement, inventory, error, sales, greenhouse gases, hydrofluorocarbons, sulfur hexafluoride, HFCs, SF_6, equipment, air conditioning, refrigeration, electrical equipment, fire suppression equipment, CFC substitutes.