Source-Gap Analysis: A New Method for Analyzing Environmental Problems

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Abstract

Life Cycle Assessment (LCA), a well-established method of assessing environmental impacts across the entire production cycle, is vital for comparing the actual impacts of different products, but it is not designed for comparing strategies to reduce such impacts. This paper proposes a new method, called Source-Gap Analysis (SGA), which breaks the life cycle down into sources whose impacts and incentives can be analyzed from an actor-centered perspective. The new method is applied to cattle farming as a case study, highlighting major gaps in either effectiveness or incentive for commonly proposed mitigation techniques. This case study demonstrates the usefulness of SGA as a method of environmental analysis to focus on difficulties that are overlooked in traditional LCA.

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Introduction

There is an urgent need to reduce the many costs we place on the environment, from emissions to land use to loss of biodiversity (World Economic Forum 2022). Life Cycle Analysis (LCA) is a rigorous, impartial evaluation of such costs for a particular product across its entire production cycle (US EPA 2022). LCA's focus on the full cycle allows accounting for production and disposal costs that might otherwise go unnoticed, thus giving a more accurate picture of environmental impacts. The method has even been extended to cover social impacts (Garrido 2017), monetary valuation (Weidema, Pizzol and Brandao 2013), natural capital (Weidema 2016), and market dynamics (Gong and You 2017). The results can be summed conveniently in "footprints".

However, with the simplicity of footprints, the uncertainty and complexity inherent in LCA results is "not usually communicated effectively to wider audiences, in particular policy makers" (Salemdeeb et al. 2021, Grant and Hicks 2018). Those seeking to solve environmental problems are confronted with sums rather than breakdowns of individual sources (GSA 2022); thus "footprints" are visible, but the "feet" are not. To estimate the impacts of particular solution strategies, it is possible to compare full LCA results between configurations of scenarios until a minimum is found (Felseghi et al 2022, Contreras et al 2009), but this brings up a different issue with system boundaries.

LCA begins by defining clear boundaries around costs that will be included in the study. This requirement can be quickly understood by imagining a hypothetical study without boundaries, focused on *Product A.* Product A must have a life cycle involving resource extraction, assembly and production, use, and disposal. But, at each of these stages, the producers and users involved might be operating machinery or consuming resources which themselves have life cycles of extraction and production attached — and so would the producers and users involved in those life cycles, and so on until the entire global economy is included. To avoid this problem, LCA researchers effectively create a model of the production cycle within a clearly defined boundary, outside which environmental costs are assumed to be negligible (US EPA 2022). Differences in the choices of boundaries can lead to widely varying, or even directly contradictory, LCA results, making the task of comparing studies to determine a solution extremely difficult.

Both the footprint issue and the boundary issue are clearly demonstrated in LCA studies of beef cattle farming. Cattle are a well-known source of environmental costs, especially methane emissions, which are relatively predictable and well-understood (IPCC 2019). But in terms of mitigating these environmental costs, LCA results lead to unclear conclusions.

The difficulty of comparing scenarios between LCA studies, compounded by differing choices of boundaries, is exemplified in the choice between pasture-fed and feedlot cattle. A whole-farm approach finds trade-offs to either method (Klopatek et al. 2022), but in terms of greenhouse gasses per kilogram of product, increased efficiency is often strongly emphasized as a primary mitigation strategy (DeRamus et al. 2003). Similar logic recommends moving cattle from pastures to feedlots as much as possible because of the increased efficiency (Pelletier et al. 2010). However, efficiency increases on their own could lead to increased livestock numbers overall and thus a net increase in emissions (Rolfe 2010), and countries which already have highly efficient cattle production, such as the United States, have much less room to improve in terms of emissions per product (Cusack et al. 2021). Moving from feedlot back to pasture would make cattle less productive and require more in total to meet the same level of demand (Hayek & Garrett 2018) — and yet, LCA studies whose boundaries include offsets from carbon sequestration show large reductions in emissions if more extensive pasture-fed techniques are used (Stanley et al. 2018), even mitigating cattle greenhouse gas emissions entirely (Reyes-Palomo et al. 2022). These techniques are not necessarily sustainable on a global scale due to land use requirements (Cusack et al. 2021), but creative use of system boundaries to include carbon absorbed by live tree fences and not the re-release of carbon at the end of the trees' lives shows that similar offsets are possible even for intensive cattle systems (Brook et al. 2022).

An even bigger issue than comparison between cattle LCA results is the obfuscation of direct sources within those results. One meta-analysis found that 71% of emissions totals from beef production LCA studies could not be broken down into individual sources (Lynch 2019). While it is clear and widely understood that the majority of emissions impacts come from enteric emissions, or gasses released in the stomachs of cattle during digestion, reporting emissions as a combined total makes it difficult to determine the relative impacts of strategies that mitigate enteric emissions. Assuming that such strategies would lead to a net reduction is often false – the various gasses produced during the cattle life cycle can have complex interactions or even swap magnitudes when different mitigation techniques are used (Gerber et al. 2013).

Thus, adding up costs obscures solutions and makes their comparison difficult. With clear emissions and unclear solutions, many have concluded that abandoning beef is the best option, but the continual forward march of beef demand indicates that such a strategy is not yet working (Schulz 2021). In the US, where mask and vaccine requirements during the pandemic resulted in protests (BBC 2020), expecting the public to make a much more culturally impactful change in moving away from beef may not be reasonable in the short term — especially when a quarter of Americans already believe there is a movement to ban meat under way (Ipsos 2021). Alternative plant-based beef products are becoming a promising competitor, but LCA results are mixed (Good Food Institute 2023), and it is unclear how well plant-based meats will be able to catch on (Osaka 2023).

There is a need for rigorous and comprehensive studies of ways to reduce such costs in terms of individual sources, but without sacrificing the larger perspective that LCA affords.

Motivation

The problems associated with LCA result from the method being stretched to something it was never intended to do. LCA is meant to assess entire impacts to comprehensively understand environmental costs (US EPA 2022), not to compare solutions and their individual impacts. In fact, LCA has been described as aiming "to be a neutral basis to measure sustainability impacts without having a vision for a desired future" (Ebrary 2022). While this neutral basis is a vital part of the picture, it is not, on its own, a solution analysis method.

While there are plenty of studies on individual environmental solutions to be found, there is no general method that analyzes proposed solutions or alternatives without abandoning the big-picture perspective that LCA affords. This especially affects interested non-scientists who need to find solutions; currently, they must either rely only on footprints, piece together data on solutions themselves, or hire consultants such as "life cycle hotspot" analysts to do it for them (Sustainability Consortium 2022). A new source-focused method with clear results similar to LCA-based footprints would thus be useful not only to professional scientists, but to the many problem-solvers from all backgrounds who are and will be involved in fighting climate change.

This paper presents such a method of studying environmental costs which combines source-focused LCA techniques with a general focus on the gaps between the current situation and an idealistic goal of zero environmental impact. The proposed method, called Source-Gap Analysis (SGA), is demonstrated by applying its framework to environmental costs associated with beef cattle farming.

Method: Source-Gap Analysis

This new method breaks the life cycle process into well-defined sources and analyzes the trade-offs associated with alternatives and solutions to each source in terms of environmental costs, financial burdens and other qualitative risks. A central focus of the method is to identify gaps — both in the literature related to costs, as per a regular gap analysis, and in terms of gaps which are preventing the widespread adoption of proposed alternatives. Thus the method can be called "Source-Gap Analysis" (SGA), and the goal is to analyze environmental solutions in terms of their varying impacts and gaps.

The techniques used in this method are not particularly revolutionary or new, and similar cost comparisons have even been applied directly to cattle enteric emissions (Knapp et al. 2014) and emissions from manure management (Montes et al. 2013). However, SGA is unique in its well-defined combination of existing approaches, its clear separation from usual LCA methods, and especially its treatment of system boundaries.

Sources and Boundaries

In regular LCA, system boundaries are an important way to avoid having to consider an exponentially increasing number of product cycles while still accounting for total impacts. In SGA, where the focus is on individual sources and mitigation techniques, the exponentiation problem is potentially even worse, since each mitigation technique might bring its own product cycle into the picture.

To solve this problem, the SGA method proposes taking the perspective of a single actor or group of actors at one stage of the life cycle. This separates costs naturally into three categories: costs associated with inputs the actor uses, costs the actor produces directly, and costs associated with use of the product after it leaves the actor. For simplicity, these can be called *inherited*, *produced* and *induced* costs respectively.

This separation makes clear the method for studying each cost. Produced costs can be assessed in direct physical terms based on the method of production. Inherited costs, on the other hand, cannot be directly influenced by the actor of focus, and so can be accounted for either using existing LCA results up to the point of purchase or in terms of input amounts if such a breakdown of LCA results is not available. Finally, induced costs could be assessed in a similar way to inherited costs, but they could also be left for other SGA studies to examine if their overall share of the costs is comparatively low.

Cautions

The focus on a particular actor should not be interpreted as recommending a particular point of view on environmental responsibility or solutions — it is merely an analysis approach. For any environmental cost, the general options are to get rid of the source, replace the source, or modify the source so that it no longer exacts a toll. The first option needs no further analysis than LCA, and the second can be studied by effective comparison LCA results which use the same boundaries, but the third option — modifications at the source — heavily involves direct impacts to the person managing the source, so it is simply easier to consider these impacts at that point rather than some other approach like a whole-system model. The SGA approach does not preclude the possibility of removing or replacing the product of focus, but the barriers to implementing such strategies are much more obvious (especially from the point of view of a producer) and do not need to be rehashed in the SGA framework.

The purpose of a method like SGA is to supplement and clarify LCA results to better understand proposed mitigation techniques. It should not be seen as a replacement for sturdy LCA; the intention is to add holistic considerations of alternatives within processes to already existing footprint metrics so that interested problem solvers are equipped with all of the information they need to decide on a strategy.

Suggested Steps

To conduct an SGA, an analyst could follow these steps:

1. Choose an actor or group of actors for the focus of the study.
2. Based on existing LCA research, break the entire life cycle down into each individual source of environmental costs.
3. Based on the chosen actor, determine which sources have primarily produced costs and which have primarily inherited or induced costs. Decide whether or not to include induced costs in this study.

4. For sources with primarily inherited (or induced, if included) costs, use existing LCA studies to assess impacts before (or after) the actor of focus. These results should be in terms of units used (or produced) by the actor so that mitigation strategies which require more or less of the source can be effectively compared. If LCA results are not available, such costs should simply be included as units used (or produced).
5. For produced costs, use physical models to predict these costs in terms of basic variables. Use known configurations of variables to compare the produced costs of alternative production processes. Combining produced costs across different sources in terms of "CO2 equivalent" emissions or other similar metrics should be avoided, if breakdowns can be determined. There is no benefit to combining breakdowns, and it makes later research more difficult (Lynch 2019)
6. Examine proposed mitigation techniques for each produced cost and predict their effects on the base physical model, using either an adjusted model or existing predictions from the literature. Note which impacts are currently unknown and what effects are hypothesized. Combinations of strategies should not be assumed to directly add in effects.
7. Study and list qualitative considerations of each mitigation technique and alternative to each source, including financial impacts to the actor (both up-front and per-product), likely impacts on demand, and any other important difficulties or side effects.

Case Study: Beef Cattle Farming

In this section, I apply the SGA approach outlined above to four environmental costs associated with beef cattle farming in the United States: methane emissions, nitrous oxide emissions, water use, and land use. The actor of focus is a beef cattle farmer, assumed to oversee each of the stages of cattle herd operation; in reality, these stages are often separated under several different farmers, but the costs facing each are similar. The study and its conclusions are confined to the United States and should not be assumed to apply elsewhere due to wide differences in cattle management between countries.

Life Cycle and Source Breakdown

Several LCA studies of beef cattle were consulted to determine the main sources of environmental costs involved in the beef life cycle. These sources include power consumption, fuel combustion, feed, cattle, manure, and induced costs related to slaughter, processing and consumption. Other costs, such as the costs associated with the construction of farm buildings, are negligible in comparison (Lupos et al. 2013) and are not included in this analysis.

All life cycle analyses consulted agree with IPCC recommendations in placing most of the environmental costs involved with beef cattle on the cattle themselves (IPCC 2019). Induced costs from processing and cooking are not treated in this analysis. Each of the other sources is treated separately, except for feed, which is included as a cost when considering cattle as a source — this simplifies the cattle model for the purposes of this case study, while still allowing costs associated with feed (especially land use and water use) to be generally tracked between alternatives by noting increases or decreases in feed requirements.

Power Generation

Table 1 shows produced and inherited costs associated with power generation. The table presents alternatives for beef cattle farmers who are allowed by their state to choose their method of power generation (ACCES 2023) or elect to generate power themselves; for the latter, produced costs are also listed in terms of fuel. It is important to note, however, that this table reflects choices that are entirely out of the control of the rest of American cattle farmers who do not generate their own power or have choice over power methods.

Inherited costs were assessed with LCA methods over an entire lifetime, whereas produced CO2 is predicted on a per-use basis using physical parameters from sources cited in the table. This means that combustion-related generation methods place increased cost on the generator owner compared to renewable energy; a farmer considering a biodiesel generator may end up generating much more than 0.840 kg CO2 equivalent emissions, for example, whereas one who installs solar panels will be unlikely to increase their life cycle impacts beyond 0.028 kg.

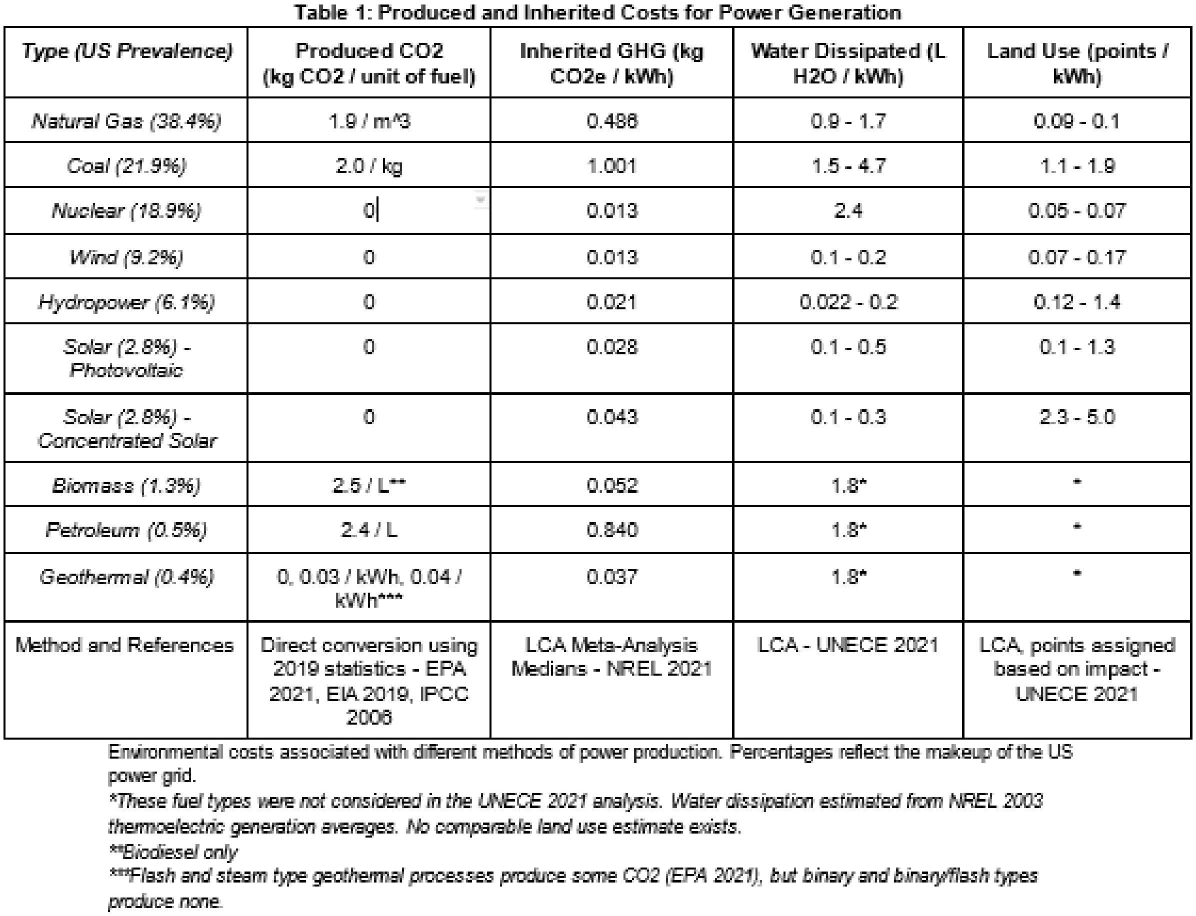


Table 1: Produced and Inherited Costs for Power Generation

Type (US Prevalence)	Produced CO2 (kg CO2 / unit of fuel)	Inherited GHG (kg CO2e / kWh)	Water Dissipated (L H2O / kWh)	Land Use (points / kWh)
Natural Gas (38.4%)	1.9 / m^3	0.486	0.9 - 1.7	0.09 - 0.1
Coal (21.9%)	2.0 / kg	1.001	1.5 - 4.7	1.1 - 1.9
Nuclear (18.9%)	0	0.013	2.4	0.05 - 0.07
Wind (9.2%)	0	0.013	0.1 - 0.2	0.07 - 0.17
Hydropower (6.1%)	0	0.021	0.022 - 0.2	0.12 - 1.4
Solar (2.8%) - Photovoltaic	0	0.028	0.1 - 0.5	0.1 - 1.3
Solar (2.8%) - Concentrated Solar	0	0.043	0.1 - 0.3	2.3 - 5.0
Biomass (1.3%)	2.5 / L**	0.052	1.8*	*
Petroleum (0.5%)	2.4 / L	0.840	1.8*	*
Geothermal (0.4%)	0, 0.03 / kWh, 0.04 / kWh***	0.037	1.8*	*
Method and References	Direct conversion using 2019 statistics - EPA 2021, EIA 2019, IPCC 2006	LCA Meta-Analysis Medians - NREL 2021	LCA - UNECE 2021	LCA, points assigned based on impact - UNECE 2021

Environmental costs associated with different methods of power production. Percentages reflect the makeup of the US power grid.

**These fuel types were not considered in the UNECE 2021 analysis. Water dissipation estimated from NREL 2003 thermoelectric generation averages. No comparable land use estimate exists.*

***Biodiesel only*

****Flash and steam type geothermal processes produce some CO2 (EPA 2021), but binary and binary/flash types produce none.*

There are clear environmental advantages to renewable energy compared to fossil fuels across all categories, especially from the point of view of a power operator. However, there are also trade-offs to consider, especially for water and land use. Nuclear energy has the lowest effect on land and inherited GHG emissions, but has a higher water use cost than all other energy sources except some coal power.

Tables 2 and 3 consider the prevalence of farmers who generate their own power and some financial costs for doing so. This data is not specific to cattle farmers, but still gives a rough idea of the costs they face. Total farm operations producing energy were first reported in the 2007 Agricultural Census, found to be 23,451 (U.S. Census 2007). A follow-up survey in 2009 assessed costs and savings for 8,569 farmers who reported using wind turbines, methane digesters or solar panels. These farmers are summarized in Table 2.

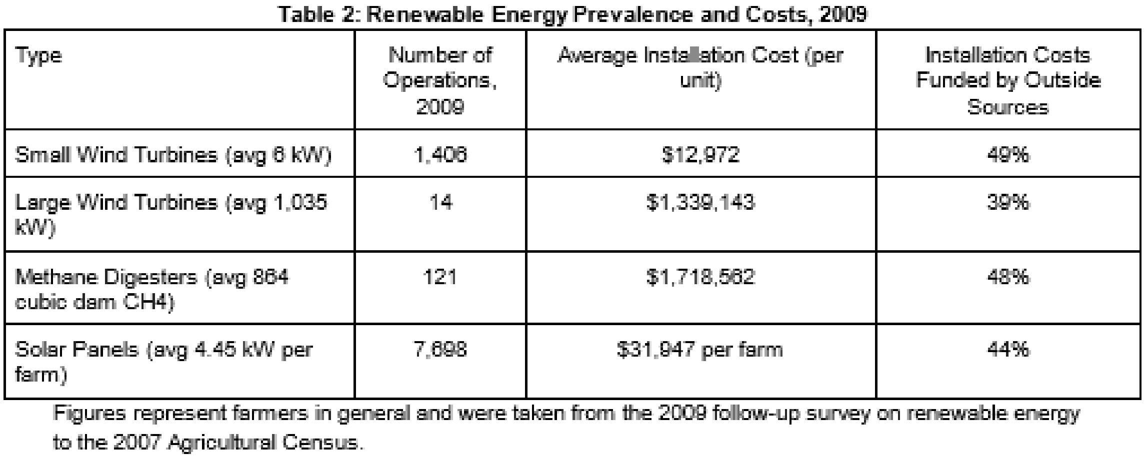


Table 2: Renewable Energy Prevalence and Costs, 2009

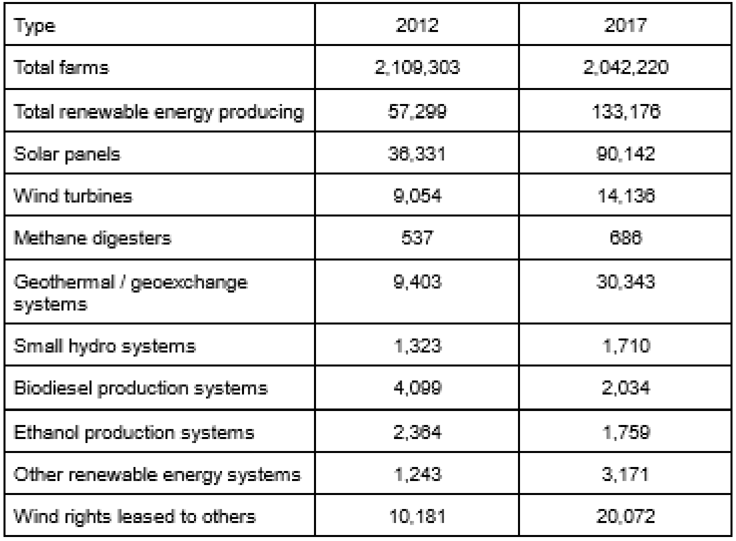
Type	Number of Operations, 2009	Average Installation Cost (per unit)	Installation Costs Funded by Outside Sources
Small Wind Turbines (avg 6 kW)	1,406	$12,972	49%
Large Wind Turbines (avg 1,035 kW)	14	$1,339,143	39%
Methane Digesters (avg 864 cubic dam CH4)	121	$1,718,562	48%
Solar Panels (avg 4.45 kW per farm)	7,698	$31,947 per farm	44%

Figures represent farmers in general and were taken from the 2009 follow-up survey on renewable energy to the 2007 Agricultural Census.

Specific savings were not reported for each type of energy in the 2009 survey, but overall, the average utility bill savings reported was $2,406. In addition, 1,101 reported receiving federal funding.

Table 3 shows raw numbers of renewable energy operations on farms in 2012 and 2017. Detailed data on costs and benefits of renewable energy operations on farms has not been assessed in these censuses or subsequent surveys. The most popular type of renewable energy, solar installations, currently average $20,020 for home owners after applying the federal solar credit (EnergySage 2023), which might indicate a falling price compared to $31,947 for farms in 2009 in table 2.

Table 3: Operations with Renewable Energy Producing Systems



Type	2012	2017
Total farms	2,109,303	2,042,220
Total renewable energy producing	57,299	133,176
Solar panels	36,331	90,142
Wind turbines	9,054	14,136
Methane digesters	537	686
Geothermal / geoexchange systems	9,403	30,343
Small hydro systems	1,323	1,710
Biodiesel production systems	4,099	2,034
Ethanol production systems	2,364	1,759
Other renewable energy systems	1,243	3,171
Wind rights leased to others	10,181	20,072

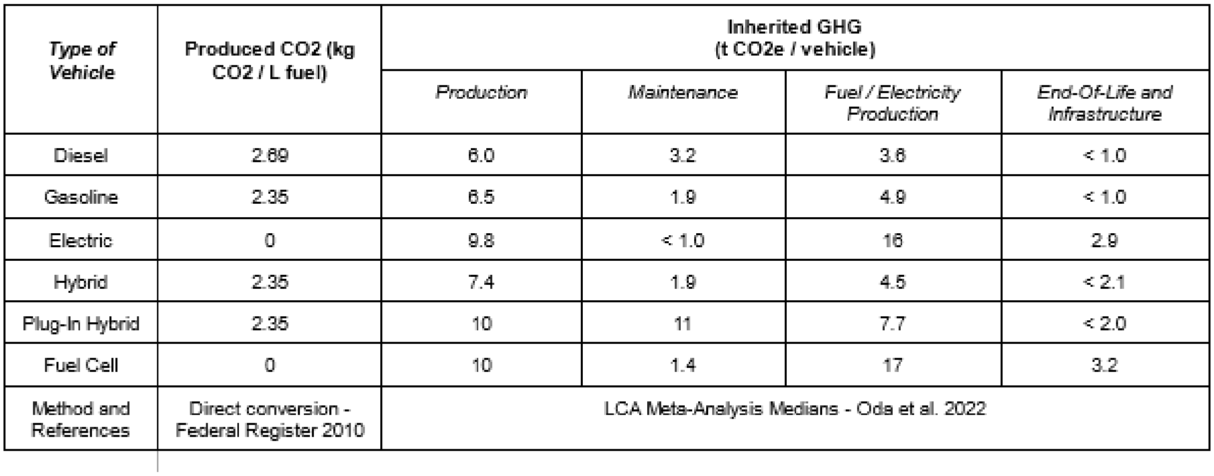
Of the 133,176 farms reporting renewable energy production in 2017, 100,653 were family farms making less than $150,000 a year (USDA 2017). This category of farmer represents 81.7% of all US farms but only 75.6% of renewable energy producing farms. This difference, together with fairly to ludicrously high costs of renewable energy, low total numbers of farmers using renewable energy compared to all farmers, prevalent use of federal funding, and large proportions of installation costs being paid from outside farms, suggests that the main barrier preventing farmers from generating their own power is financial.

Altogether, the comparison of power methods that could be available to cattle farms shows that although there are clear ways to reduce all of the environmental costs associated with power generation, consumers of power like cattle farmers face difficult financial barriers to installing their own generators. The burden for mitigating emissions from power generation falls much more on the American power grid and all of the governments and companies involved in supporting it.

Fuel Consumption

Table 4 shows inherited and produced emissions associated with transportation of any kind. Land use and water use were not considered in the sources consulted, but are likely not a very large part of the total costs. Estimates for inherited costs, listed in terms of tons of equivalent CO2 emissions, were taken from an extensive meta-analysis of LCA studies on vehicles. These results are global in scope and predicted for lifetime use of the vehicle assuming current power generation methods, so they should be interpreted with caution when considering drivers in the United States alone. Produced costs are based entirely on physical characteristics of fuel and don’t account for efficiency of using such fuel; hybrid vehicles and diesel vehicles would be expected to use less fuel than gasoline vehicles in reality.

Table 4: Fuel and Vehicle Costs



Type of Vehicle	Produced CO2 (kg CO2 / L fuel)	Inherited GHG (t CO2e / vehicle)			
		Production	*Maintenance*	*Fuel / Electricity Production*	*End-Of-Life and Infrastructure*
Diesel	2.69	6.0	3.2	3.6	< 1.0
Gasoline	2.35	6.5	1.9	4.9	< 1.0
Electric	0	9.8	< 1.0	16	2.9
Hybrid	2.35	7.4	1.9	4.5	< 2.1
Plug-In Hybrid	2.35	10	11	7.7	< 2.0
Fuel Cell	0	10	1.4	17	3.2
Method and References	Direct conversion - Federal Register 2010	LCA Meta-Analysis Medians - Oda et al. 2022			

The results in table 4 lead to similar conclusions as were reached in the power consumption section. Electric vehicles have high electricity and fuel production costs, but this may be partly or entirely due to current power generation methods in an economy heavily dependent on fossil fuels. Production costs are the highest category overall and place at least second-highest for every type of vehicle, suggesting that there is more to be done at the beginning of the vehicle life cycle than the end. In addition, buyers of electric vehicles cannot increase their carbon footprint much after purchase, but those driving fuel-based vehicles could cause a much larger environmental impact than what is listed above if their habits exceed the assumptions of LCAs considered in the meta-analysis.

As far as incentives are concerned, electric cars are increasing in popularity and can cost much less than gasoline vehicles in the long term, but their adoption is currently driven more by social or moral motives than for economic reasons (Bobeth & Kastner 2020)

Cattle Life Cycle Costs

Table 5 shows the baseline costs associated with raising cattle according to the Regular Operations Model and proposed alternatives. Cattle in the United States grow in three stages; calves are born in a breeding operation until weaning, then raised up to a certain weight in a backgrounding operation, then sent to a finishing lot where they are fed a highly concentrated diet without as much physical activity to achieve market weight in a short period. The Regular Operations Model, based on lifespans and weights in an extensive LCA study of cattle in the Northern Great Plains area (Lupos et al. 2013) and assessed using Tier 2 IPCC 2019 methodology, assumes calves are weaned after 200 days, proceed to backgrounding upon reaching 250 kg where they stay for 110 days, and then are finished in a feedlot for 110 days, growing from 385 kg to a final weight of 612 kg. Replacement cows and steers are backgrounded for 210 days before reaching maturity, at which point 700 kg cows breed for 7 seasons and 900 kg bulls for 2. The breeding and replacement herd takes up 17% of the overall herd, and costs are weighted accordingly.

Costs for this stage are displayed in terms of kilograms of live weight at death. Cost per weight is a much more relevant functional unit than costs per day or per farm (Grainger & Beauchemin 2011). Live weight at death is not the same as the amount of beef produced, but it is proportional, so relative costs and benefits will be the same.

Feed inputs are estimated in terms of Dry Matter Intake (DMI), calculated based on IPCC 2019 estimations of DMI required to sustain a particular energy level. These inputs are split into pasture-based DMI, which serves as a proxy for cattle land use costs, and feed or non-pasture DMI, which represents substantial land, water and emissions costs associated with feed production. The Regular Operations Model assumes a 40:60 feed to forage diet during growth and 90:10 during finishing, consistent with Lupo et al. 2013.

Water consumption was modeled based on the BC Livestock Watering Manual (Brown 1990). The likely water *use* is much higher; even though high estimates from the manual were used, which is realistic for beef cattle farmers planning their water delivery systems around peak consumption, this estimate does not account for evaporation that occurs during delivery or wasted water from leaks or drainage.

Alternatives were modeled based on proposals found in various life cycle scenarios, and the qualitative considerations of each are discussed in detail below. Financial impacts for each alternative are based on existing studies where possible, or estimated based on their effects on finishing weight and increases in inputs required to sustain production.

Models Considered

- *Hypothetical Weight Increase* — as a demonstration of the efficiency arguments discussed earlier, this model simply increases the end weight of the beef cattle by 10%. Such an increase would directly benefit producers, but is unlikely to occur in practice without significant innovations.
- *Move finishing to pasture* — this model effectively compares grass-fed beef to feedlot finished beef, removing finishing cows from the regular operations model and extending backgrounding at pasture to a typical grass-fed lifetime of 350 days. Finishing weight is also reduced to 430 kg consistent with grass-fed cattle in Lupo et al. 2013. The reduced weight and increased time to production causes a decrease in productivity compared to regular operations; in addition, regular corn-fed beef is detectably favored over grass-fed beef in terms of flavor (Tatum 2008). However, as discussed earlier in this paper, the potential for carbon sequestration is much higher for a grass-fed beef scenario; this effect, not included in the table because it does not directly decrease methane or nitrogen emissions, could be used by policy makers to create carbon credit incentives for farmers.
- *Increased forage vs. feed* — this model changes growing diet to 20:80 concentrate to feed and finishing diet to 80:20, assuming the same overall weight gains. Such an assumption is unrealistic, but shows the independent effect of diet composition on environmental costs. The reduction in feed input is substantial, which would decrease land use and water use overall, but the increase in methane and nitrogen emissions from

cattle might not be as easily offset as a similar increase in CO2 emissions related to feed production for the regular model, since feed emissions mostly involve power and fuel consumption (Lupos et al. 2013).

- *Increased feed vs. forage* — this model changes growing diet to 60:40 concentrate to feed and finishing diet to 95:5, assuming the same overall weight gains, similar to the above increased forage model. Such an increase is suggested in Lupos et al. 2013 as one way to lower methane emissions. However, there is a definite trade-off between land and water increases in terms of feed inputs and emission decreases to the cattle themselves. In practice, cattle weight might increase, which could offset the cost of additional feed to the farmer, but if such an increase was possible, the Regular Operations Model would likely include it already, since that model's diet assumptions were developed based on feedback from farmers in the Northern Great Plains area (Lupo et al. 2013).
- *Extended grain finishing* — motivated by Beauchemin et al. 2011, this model decreases time spent in backgrounding and increases time spent in finishing. Financial impacts are unclear from a model point of view, but have been estimated as leading to an overall decrease in profit (Modongo & Kulshreshtha 2018).
- *All cattle fed concentrate* — in the regular model, breeding cattle are fed entirely forage from pasture; this model changes their diet to the same as growing cattle, or 40:60 concentrate to feed. The motivation in this model is to cut down on pasture space, but the substantial increase in feed required to sustain this change makes it an unreasonable option for farmers, who have little economic reason to shrink the size of their pastures. The next few models examine other suggestions to manage the costs of the breeding herd.
- *Increased forage quality for breeding stock* — this model, suggested by Beauchemin et al. 2011, raises the digestibility (DE) of forage for the breeding herd to the maximum suggested value in the IPCC recommendations (2019). In practice, this would require breeding cattle to be located on the freshest, greenest pastures available at all times, which is a difficult task for the farmer. The benefits in terms of production or livestock health are unclear.
- *Increased longevity of breeding stock* — in this scenario, hypothesized in Beauchemin et al. 2011, the effect of cows breeding for 8 seasons instead of the regular model of 7 would be to require ⅞ as many cows to maintain the same amount of breeding; this model adjusts the proportion of breeding cattle accordingly, while also increasing their lifespan. The increase in pasture DMI suggests that the effort for the farmer required to sustain these longer lifespans would be substantial, and the overall impact on cattle emissions is small.
- *Increased calves per cow* — similarly, also suggested by Beauchemin et al. 2011, the effect of increasing calves per cow by 10% would be to reduce the proportion of breeding cows by 10%, but without an increased lifespan per cow. This change would be much more environmentally beneficial, but it is unclear how such a result would occur in practice.
- *Increased fat content in diet* — this model shows the estimated effect of switching to a higher-fat diet, based on estimates from Granger & Beauchemin (2011) scaled to the

regular operations model. Two other studies found possible increases in nitrogen output, large enough to offset the GHG reduction from methane with an overall 5-6% increase in GHG (McGinn et al. 2009, Hunerberg et al. 2014). Effects on water consumption are unknown. The cost to the farmer would depend on the relative costs of feeds with higher fat content.

- *Lowered CP content* — crude protein, or CP, affects the nitrogen output in cattle manure and thus has a direct effect on nitrogen emissions (Todd et al. 2006). CP is an input in the tier 2 IPCC calculations, so this model simply decreases the CP by 1.5% for all cattle except calves as suggested in Todd et al. 2006, and the result agrees with studies listed. Generally, feeds with lowered crude protein are cheaper, so profits to the farmer would increase, but there is a limit to the amount of reduction possible, and the example in this model may be near the maximum (Ndwega et al. 2008). Water consumption should decrease with decreasing crude protein content (Winchester & Morris 1956).
- *Defaunation* — Reducing the amount of bacteria in the rumen through additives has been hypothesized to reduce methane emissions. The listed results are based mainly on Tekle (2016); methane also includes estimates from Bird et al. 2008, Hegarty 1999, and Nguyen & Hegarty 2016. The effect on water consumption is unknown.
- *Intensive Grazing Management*, or *Best Management Practices* (BMPs) — these figures come from studies on such practices in specific locations; overall effects on DMI and water consumption were not included (DeRamus et al. 2003, Boody et al. 2005, Allard et al. 2007, Luo et al. 2010). Such practices are hypothesized to increase production and thus profit (DeRamus et al. 2003) but have been shown to have little to no impact on farm income (Boody et al. 2005).

Several proposed methods to mitigate enteric emissions were not included in Table 5 because the results are still too uncertain. Yeast strain additives might lower methane output by 7%, but increase risk of acidosis, with unknown impacts on the other costs (Grainger & Beauchemin 2011); bacterial direct-fed microbials (DFMs), already used for their positive effects on productivity and health (Jeyanathan et al. 2013), might decrease methane depending on the diet (Philippeau et al. 2017) or have no effect at all (Jeyanathan et al. 2019 & Oh et al. 2019).

Table 5: Costs Associated With Cattle

Baseline Model ***Alternatives***	**Non-pasture DMI (kg)**	**Pasture / Grazing DMI (kg)**	**Produced CH4 Emissions (kg)**	**Produced N2O Emissions (g)**	**Water Consumption (L)**	**Estimated Impact on Profit**
Regular Operations Model	7.77	74.25	0.23	4.98	76.7	*Baseline*
(Hypothetical) Weight Increase	-1.8%	-0.3%	-1.7%	-0.9%	-2.9%	Slight Increase
Move Finishing	-29.8%	+5.2%	+8.0%	+0.7%	+9.7%	Decrease

to Pasture						
Increased Forage vs. Feed	-6.3%	+0.7%	+1.6%	+1.8%	No change	Slight increase
Increased Feed vs. Forage	+5.1%	-0.6%	-1.2%	-1.3%	No change	Slight decrease
Extended Grain Finishing	+8.4%	-0.8%	-2.1%	+3.1%	+1.5%	Overall decrease
All Cattle Fed Concentrate	+375%	-39.3%	-10.1%	-9.4%	No change	Decrease
Improved Forage Quality for Breeding Stock	No change	No change	+4.4%	-15.1%	No change	Slight decrease
Increased Longevity of Breeding Stock	No change	+10.7%	-0.6%	-0.2%	-0.1%	Unclear
Increased Calves per Cow	No change	No change	-6.8%	-6%	-6.8%	Unclear
Increased Fat Content in Diet	No change	No change	-0.45% / g fat added -31.8% maximum	Large increase		Unclear
Lowered Crude Protein	No change	No change	No change	-12.9%	Decrease	Increase
Defaunation	No effect	No effect	0 to -13%	Decrease		Increase
Intensive Grazing Management (BMPs)			-22%	-17% to -55%		No effect

One interesting option currently under study is the addition of seaweed as an additive in cattle diets (Vijn et al. 2020). Preliminary studies show 40% to 98% reductions in methane emissions, but there are many hurdles to consider, including the infeasibility of producing seaweed for the global cattle supply, difficult regulations that create disincentives for using seaweed as feed, and iodine increases in milk. On the upside, seaweed cultivation could benefit ocean environments and decrease eutrophication if the correct cultivation methods are used (Seghetta et al. 2017); it can also help protect shorelines, though the scope to expand seaweed production is limited by space, engineering, and demand (Duarte et al. 2017). Life cycle impacts depend highly on the method of cultivation (Oirschot et al. 2017), but are generally comparable to land-based plants (Taelman et al. 2015). One study projecting the use of seaweed as an additive for cattle forward to 2050 found an overall 10% reduction in emissions compared to business-as-usual (Nin-Pratt et al. 2022).

There are also many hypothesized mitigation techniques that have not been studied well enough to include in any models. Examples include ruminant feed enzymes (Grainger & Beauchemin 2011), precision livestock farming (Lovarelli et al. 2020), tailored nanoparticles (Altermann et al. 2022), vermicomposting (Nasiru et al. 2014), breeding selectively less emissive cattle (Hayes et al. 2013 and Haas et al. 2021), chemical inhibitors (Henderson et al. 2016), agricultural by-products used as feed (Yanti & Yayota 2017), and many, many additives suggested to decrease enteric emissions (Michalak et al. 2021). There is insufficient evidence that any of the most commonly proposed additives increase cattle production (Hegarty et al. 2021), which means they represent an increased cost with no increased benefit to a cattle farmer.

Approaches to reduce water consumption are also under study, but such approaches are unlikely to reduce water consumption below the predictions of the models considered above. Cattle without abundantly available water become stressed and productivity suffers as a result (Wagner & Engle 2021). Water losses to evaporation, waste, or other uses like cooling can be reduced with careful water management (Menendez & Tedeschi 2020) or innovative ways to reduce time spent outputting (Al-Haidary & Al-Hassan 2003). However, Table 5 includes only direct water consumption by cattle, so it is unlikely that any management techniques could reduce consumption below the estimates listed in that table.

Summary

Altogether, this analysis presents a muddy picture for directly reducing the environmental costs of cattle. There are tremendous gaps in research on the effects of various common proposals, and even well-studied techniques show little direct benefit to the producer other than becoming more environmentally friendly. Many promising additives are being studied to reduce methane emissions, but water consumption and land use for cattle is unlikely to decrease under any of these scenarios, and could even increase to sustain the production of additives. More research and more innovations in technology and policy are needed to solve this seemingly unsolvable problem.

Manure Management Costs

The model used in Table 5 accounts for CH4 and N2O emissions from manure as part of total emissions, but there are many techniques specific to manure management that deserve separate consideration.

Table 6 shows costs associated with manure management, calculated using IPCC 2019 Tier 2 methodology for various scenarios. The baseline scenario assumes regular operations, as in Table 5, with manure managed in solid storage, the most common method in North America (IPCC 2019). There are no inherited emissions or costs to consider, and enteric emissions are not considered in this table. Water and land consumption likely differ slightly between management methods, but are not estimated in Table 6.

CH4 emissions from manure depend highly on climate, so estimates in Table 6 are based on a hypothesized cool climate to minimize variation between alternatives. This simplification, and the real-life practice of combining manure management strategies, should lend to caution in interpreting these results; while directions and relative magnitudes should still hold across climates and scenarios, the exact numbers presented do not represent reality.

Qualitative and financial considerations mentioned in studies of manure management methods are listed directly in Table 6. Uncited considerations are general assumptions based on whether or not a cattle farmer would have to increase inputs to the farm in order to apply the technique. In general, there is considerable room for research into the financial impacts of various manure management strategies.

Table 6: Manure Management Costs

Baseline Model ***Alternatives***	**Produced CH4 Emissions**	**Produced N2O Emissions**	**Other Considerations**
Solid Storage, Regular Operations Model	0.22 kg	4.98 g	
Covered / Compacted Solid Storage	No change	-16.7%	
Bulking Agents	-3.4% (modeled)	-25.3%	Underlying mechanism poorly understood May increase CO2 and NH3 emissions while reducing CH4 and N2O (Maeda et al. 2012)
Additives	-2.3%	-53.2%	Increased cost
Uncovered Anaerobic Lagoon	+132%	-76.1%	Work better in warm climates (Rice et al. 2006) Not very effective at reducing antimicrobial resistance and pathogens in manure, unless alternated with storage in covered lagoon (Agga et al. 2022)
Liquid / Slurry	+43.3%	-45.4% Natural cover -59.0% Artificial cover	

		-67.2% Natural cover removed	
Pit Storage	+43.3%	-69.3%	Usually applies to operations with livestock in confined structures, may be unreasonable for farmers
Dry Lot	-2.3%	+58.8%	Very different from confined facilities (Rice et al. 2006)
Daily Spread	-4.33%	-95.2%	Reduces NH3 emissions by 21% to 85% depending on the location (Carew 2010), but injection into the soil is much better (Kirchmann & Lundvall 1998)
Anaerobic Digestion / Biogas	-2.3% to +23.1%	-78.9%	Expensive both up-front and to maintain, without as much incentive in return (Rice et al. 2006 & Garcia et al. 2015) Effective at reducing antimicrobial resistance and pathogens in manure (Agga et al. 2022) Produces biogas that can be used for energy, and biofertilizers that are more predictable and soluble than manure (Wilkie 2005)
Deep Bedding, No Mixing	+43.3%	-14.7%	
Deep Bedding, Active Mixing	+43.3%	+394.9%	
Composting in Vessel	-3.4%	-18.1%	
Composting, Static Pile	-2.3%	+15.7%	
Composting, Frequently Mixed (Intensive Windrow)	-3.4%	-18.4%	
Composting, Passive Windrow	-2.3%	-22.9%	Common in North America (IPCC 2019)
Aerobic Treatment, Natural Aeration	-4.6%	Unknown	

Aerobic Treatment, Forced Aeration	-4.6%	-7.8%	Effective at reducing antimicrobial resistance and pathogens in manure (Agga et al. 2022)
Biological treatment processes	-55% (Loyon et al. 2007)	-50% to -99% depending on setup (Ndwega et al. 2008) -55% (Loyon et al. 2007)	Expensive to install and operate; requires carbon source to complete the denitrification process (Ndwega et al. 2008, Carew 2010)

The only alternative not directly accounted for in IPCC 2019 methodology is the last method listed in Table 6, use of biological treatment processes. Other manure management methods have been suggested, but conclusions are unclear; these include mechanically aerated lagoons, autothermal thermophilic aerobic digestion, biofilm reactors, sequencing batch reactors, combinations of anoxic and aerobic treatments, wetland treatment, and even insect digestion (Rice et al. 2006).

It should be noted that the above methods do not account for the eventual use of manure as fertilizer. Fertilization using direct injection methods can reduce nitrogen emissions almost entirely (Kirchmann & Lundvall 1998), but more common fertilization methods would likely continue to result in nitrogen emissions during application. It has been noted that extensive management and cooperation between cattle and other farmers, treating manure as a resource instead of a waste product, can reduce nitrogen pollution to nearly zero (Menzi et al. 2013), but an extended SGA accounting for these relationships would be necessary for a clearer picture on how this could be achieved.

Other Costs Not Included

Another important cost involved with manure management is the production of ammonia emissions. Some effects are listed in the considerations in the table, but Tier 2 IPCC recommendations do not directly predict ammonia and ammonium emissions, so they are not accounted for in the above models. The only cattle life cycle proposal that included estimates for ammonia was the Lowered Crude Protein model, which has been shown to reduce ammonia output overall (Carew 2010).

Methods of reducing ammonia emissions include manure injection into the soil, nitrification inhibitors, segregation of urea and feces, slurry acidification, and biological treatment processes, with impacts varying from 0 to 100% ammonia reduction (Ndegwa et al. 2008, Carew 2010). Some of these methods, like nitrification inhibitors (Lam et al. 2016) and manure injection (Webb et al. 2010) can increase nitrous oxide emissions, while others like slurry acidification can reduce methane emissions (Petersen et al. 2012).

This is one area this particular SGA analysis could be directly expanded. Some cattle LCA studies also include phosphorus and sulfur emissions from manure (Lupos et al. 2013), which could be accounted for with an extended model.

Summary

The SGA of manure management presents a complex picture. Although there are plenty of ways to reduce nitrogen emitted from manure, many of these methods directly increase emitted methane, and others have little to no impact. Since manure accounts for only a fraction of total methane released in the cattle life cycle (Lupos et al. 2013), nitrogen management is much more important, but the trade-off in costs is still worth noting when considering mitigation for the industry as a whole.

Cattle SGA Discussion

This case study highlights the difficulties and nuances present in mitigating emissions from beef cattle farming. Management practices can reduce emissions and costs in promising ways, but not in large enough amounts to bring cattle farming to anywhere near zero environmental cost, especially when the trade-offs from such strategies are considered.

One clear lesson from this case study is that cattle farmers are too often considered last when mitigation techniques are studied. Many of the proposed solutions show no benefit to the cattle farmer, and some even present economic costs or difficulties in implementation that would currently be placed directly on the cattle farmer. Some techniques, such as defaunation, do have promising results for production or health benefits for cattle, but more research is needed to determine whether these results provide enough of an incentive to become widespread.

A resulting implication is the importance of outside help to mitigate costs associated with cattle farming. Power grids and vehicles need to be developed with environmental considerations in mind, because cattle farmers and others are (at least currently) unlikely to take the expensive initiative in producing their own power and fuel. Governments could help facilitate these developments, and could also require careful management practices on farms, provide incentives for farmers to reduce emissions, or even directly provide the additives and other technologies that can help mitigate environmental costs. Some of these options could also be provided by non-governmental organizations and foundations.

Lastly, while it is hypothetically possible to reduce methane and nitrogen emissions from cattle to zero — or net zero, if offsets are considered viable solutions — it is not possible to reduce land and water use beyond a certain limit even if incentives are perfectly aligned. Water use, in particular, is bound to create friction if demand for cattle continues to increase unchecked.

Conclusions: SGA vs. LCA

Source-Gap Analysis provides a framework for valuable insights into an environmental problem and allows considering relative impacts of alternatives alongside their practicality to the producer. Since it does not inherently consider the entire life cycle as a whole, its results are only complete if viewed alongside existing life cycle assessments, but such a comparison does give a clear picture of the overall situation — even if the situation does not itself lead to clear conclusions.

The trade-offs between SGA and LCA highlight the difficulty inherent in making models of a system as complex as "the environment". Given the interconnectedness of everything that exists in a globalized economy and a closed atmosphere, it may be impossible to accurately determine all of the pros and cons of any proposed environmental mitigation technique. However, both simplifications, while subject to their own errors, provide important perspectives that should be considered by those working in environmental policy, businesses, or even journalists reporting on environmental concerns.

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