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EMISSIONS AVOIDANCE QUANTIFICATION AND ALLOCATION FRAMEWORK FOR SECONDARY MATERIALS MARKETPLACES SUPPORTING THE CIRCULAR ECONOMY

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ABSTRACT

Many manufacturers are striving to reduce the negative impacts of their business activities, particularly with respect to greenhouse gas (GHG) emissions, also called "carbon emissions." Estimates of such emissions are ubiquitously used in evaluating overall impacts of manufacturing activities. Additionally, regulations and corporate voluntary goals toward carbon emissions reductions are notably increasing. One area that still lacks methods and consensus on carbon emissions quantification is in the secondary materials marketplaces (SMMs), where more clarity is required on matters such as the allocation of these emissions given that their transactions involve multiple stakeholders. These marketplaces enable material recovery by bringing together organizations with excess and scrap materials with those that can use those materials. The SMMs are integral to implementing a circular economy (CE), as they prolong the longevity of materials in the economy further amortizing their impacts and fulfilling a fundamental premise of CE. In this work, we propose a framework to estimate the "Carbon Avoidance Measurement" (CAM) for transactions in SMMs. Then, we examine why each stakeholder's CAM values may or may not be eligible for GHG reduction credits based on the GHG Protocol. We apply the framework to two different cases of materials transacted in an established SMM. Through this work, we also highlight the importance of such a measurement for broader CE system-level decisions, as well as the major standardization and industry-specific consensus needs for implementing such a framework.

Keywords: Carbon Reductions, Carbon Avoidance Measurement, Allocation, Greenhouse Gases, Secondary Materials Marketplaces, Circular Economy, Sustainable Manufacturing

NOMENCLATURE

CAM	carbon avoidance measurement
CDM	clean development mechanism
CE	circular economy
CER	certified emission reduction
EoU	end-of-use
EPS	expanded polystyrene
ETS	emission trading system
GHG	greenhouse gas
LCA	life cycle assessment
SMM	secondary materials marketplace

1. INTRODUCTION

Manufacturing is one of the major contributors to negative environmental impacts. Due to the increasing global population and consumption levels, manufacturing activities will inevitably expand over the foreseeable future. Therefore, efforts are being made to reduce the environmental impact intensity of manufacturing processes. One such primary effort is to cut down on greenhouse gas (GHG) emissions. GHGs have become the focal point of many climate-related policies at regional and global levels (e.g., *United Nations' Conference of the Parties*[1] discussions). Many firms have begun implementing *net-zero* emissions goals [1]. Since GHG emissions are typically quantified as carbon dioxide equivalent, these practices are also

[1] https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop

called *carbon reduction* practices. In recent years the increased public interest in climate crises and investment considerations such as environmental, social, and corporate governance (ESG) have put carbon reduction practices in the limelight. Additionally, some companies have monetized these practices for significant economic benefits (e.g., the electric car maker Tesla[2] has sold nearly 1.5 billion dollars worth of carbon credits to original equipment manufacturers including internal combustion engine producing auto makers in 2021 [2]).

A secondary materials marketplace (SMM) is an entity that connects businesses that generate excess (or discarded) materials to other businesses that can recover those materials. There is also potential for establishing more sector-specific marketplaces for materials from end-of-use (EoU) products and discards. These SMMs enable interactions that have the potential to significantly reduce the carbon emissions by recovering existing materials to reduce a firm's dependence on virgin feedstocks. Specifically, carbon emission reductions can come by diverting materials away from landfills through recovery activities (e.g., reuse, remanufacture, or recycle) that are typically less carbon intensive than virgin material production [3–5].

For SMMs, the allocation between multiple stakeholders is a critical concern. Although established methods including GHG Protocol [6] provide some guidance on this, they are not developed specifically focusing on SMMs. SMM transactions that avoid or reduce emissions are vital to each stakeholder's carbon reduction goals. Hence, a framework for quantifying the carbon avoidance will allow those reductions through avoidance to be accounted in a more systematic manner and further the adoption of SMMs. Establishing such a framework is also important because SMMs fulfill one of the fundamental premises of circular economy (CE) by prolonging the utilization of materials in an economy through recovery and diverting resources from landfills [7,8].

Within this context of transactions involving multiple stakeholders and the calculation of their voluntary carbon reductions, a framework is necessary to avoid *double counting* of carbon avoidance. Double counting [9] happens when carbon reductions of activities involving multiple stakeholders end up claimed by two (or more) of the stakeholders. That leads to misrepresentation of how much actual reduction happened. Given that SMM interactions always involve multiple stakeholders (at minimum two—a *seller* and a *buyer*), an equitable way to allocate the avoided carbon emissions is necessary.

With such a framework the SMMs can provide the additional *service* of proper accounting of such activities to avoid double counting. This is a compelling value proposition for SMMs to retain the transactions within their platform and provide long term value to the stakeholders.

Generally, environmental analysis, including carbon measurements, also needs to be equitable to incentivize reduction of environmental impacts, rather than only act as tools of accounting [10]. Therefore, a practical framework will also support the overall objectives of CE.

Recognizing this gap in measurement methods and opportunities for impacting the adoption of better practices through their introduction, this paper proposes a potential framework titled *Carbon Avoidance Measurement* (CAM) for carbon avoidance allocation in SMMs and some challenges that need to be addressed to implement such a framework. It should be noted that the objective of this work is to discuss a potential direction, rather than prescribing a methodology. The practical implementation must come from building consensus (i.e., standards development) within each industry addressing the unique challenges in their own sectors.

2. BACKGROUND ON CARBON MONETIZATION

Recent interest in carbon accounting and avoidance from industry primarily began with the introduction of GHG regulations and monetization potential related to GHGs [11]. While the framework proposed in this paper does not concentrate primarily on carbon monetization such as *carbon credits*, we summarize some of the concepts and terms associated with the carbon monetization literature in this section to provide the necessary background to this work.

The global warming impact of GHGs are typically considered to be equal irrespective of where they are emitted or reduced. In other words, a unit emission of GHG in one region has the same global effect as another unit emission from another region. That brings forth the possibility to manage GHGs in a region-independent manner, allowing companies to buy/sell carbon credits from/to different regions to offset their carbon emissions [12]. Especially with the 1997 Kyoto Protocol [13] and other policy discussions [11] around regulating carbon emissions for processes and industries, the idea of *carbon offsets* and *credits* arose. Following are some of the terms used when discussing the monetization of carbon.

Carbon Credits (i.e., *Allowance-based*): A permit given to an organization by a carbon regulating authority to emit a certain amount of GHGs during their processes [14]. These are quantified in units of 1 ton of carbon dioxide equivalent (1 tCO_2e) and are used to regulate the total emissions of an organization. If an organization does not use all the carbon credits it is given, it may sell the excess to other organizations for monetary gain.

Carbon Offset (i.e., *Project-based*): If activities of an organization credibly and verifiably demonstrate it reduces GHGs from the atmosphere compared to what would have happened otherwise, they generate carbon offsets [12]. These too are quantified in units of 1 tCO_2e and other entities can purchase those offsets to compensate for their carbon emissions. Carbon offset projects are typically grouped into two categories:

[2] Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.

a. *Avoidance/reduction*: Activities that avoid the emission of GHGs compared to a similar typical activity (e.g., renewable energy projects, protecting forests at risk of logging).
b. *Removal/sequestration*: Activities that remove the GHGs from the atmosphere (e.g., direct carbon capture, reforestation)

In carbon offsets, two common terms used to discuss credibility are *additionality* and *permanence*. Additionality refers to the idea that the activity is not part of a common occurrence (e.g., required by law, market practice, or has other monetary benefits incentivizing) and would not have happened without the incentives of the carbon market [15]. While the GHG Project Protocol does not require demonstration of additionality per se, it is incorporated as an implicit part in estimating baseline emissions [6]. Permanence refers to the idea that the activity needs to sequester carbon for a considerable period of time in order to enable meaningful impact with respect to addressing climate change [15,16].

Carbon Marketplace: A marketplace where carbon credits can be traded between organizations. Since some regions have regulations on carbon credits available to each organization operating from that region, regulatory bodies are setup to issue the carbon credits and account for the emissions (e.g., EU's Emissions Trading System (ETS) platform, California Air Resource Board's Cap-and-Trade Program) [17]. In addition, *voluntary carbon markets* allow entities to buy and sell *carbon offsets*.

2.1 Valuation of Carbon Credits and Offsets

In a recent publication, Michaelowa et al discussed the evolution of international carbon markets as moving through four periods: from the 1997-2004 mechanisms such United Nations' Clean Development Mechanism (CDM), then the 2005-2011 massive expansions including EU ETS, then the 2012-2014 collapse in carbon pricing, and 2015 onwards the gradual stabilization [11].

CDM offered a framework for projects (especially in developing countries) to monetize their GHG reducing activities by allowing corporations globally to buy the carbon offsets made—Certified Emission Reduction (CER) units. Independent organizations such as *Verra* [15] and *Gold Standard* [18] have verification methods built on the CDM framework. However, no single global standard exists to guide price setting of carbon credits and offsets. The value of the carbon credits or offsets is dependent on the organization auditing their credibility and verifiability. The monetary value of carbon credits varies over time and depends on the regional ETS used. For example, in 2021, the value ranged from a few dollars per tCO2eq to over \$100 per 1 tCO_2e across different ETSs [17].

Considerable disparity also exists between the studies as to how much a of a positive impact (i.e., average reduction of emissions) is made due to the carbon pricing [19–21]. Furthermore, to induce emission reduction at speed and scale, the Carbon Pricing Leadership Coalition has recommended a price between \$40 – 80 per tCO_2eq in 2020, increasing to \$50 – 100 per tCO2eq by 2030 [20]. Yet, at a large percentage of the ETSs, the actual value of carbon pricing is acutely lower [17].

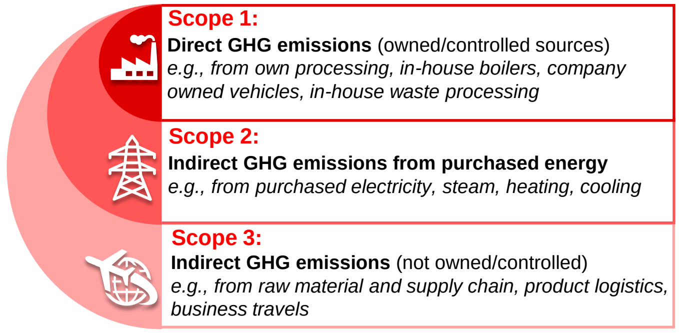

FIGURE 1: SCOPE LEVELS OF CARBON EMISSIONS

The lack of internationally agreed single standard or regulating agency is one reason for the large variability in the carbon pricing.

Within the 48% carbon credit market growth in 2021, the largest growth happened in voluntary markets—managed by independent verifiers such as Verra and Gold Standard and where private entities purchase the credits to comply with their voluntary mitigation commitments [17]. Corporations are interested in voluntarily reducing their emissions, even beyond the regulatory requirements, especially with their net-zero emission commitments [17]. Some corporations implement internal carbon pricing for their own institutions, where the average prices are observed to be between \$5 to 20 per tCO_2e [22].

2.2 Corporate Carbon Accounting and Reporting

Corporate carbon emissions are typically measured across three scope levels (see Figure 1) of the *GHG Protocol* [9]. This includes the *Kyoto gases* (i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3)) converted into *CO_2e* when reporting GHG. Some corporates may also report for additional gases (e.g., CFCs, NO_x).

3. METHODOLOGY

In this work, we propose the idea of CAM as a measure of GHG avoidance due to an activity (i.e., a *transaction*) in an SMM. As detailed below, we developed this framework based on the prior literature on LCA allocation approaches and carbon avoidance estimation standards (such as the GHG Protocol). During this work, we also worked with multiple industry partners (e.g., [23]) to understand the challenges and need for such a framework. Figure 2 below outlines the basic steps involved in the framework.

Step 1: Identify the details of the *transaction* in focus. These details include the specific activities involved in producing and recovering the material.

Step 2: Select the applicable allocation approach to calculate the emissions associated with each stakeholder (i.e., *seller* and *buyer*).

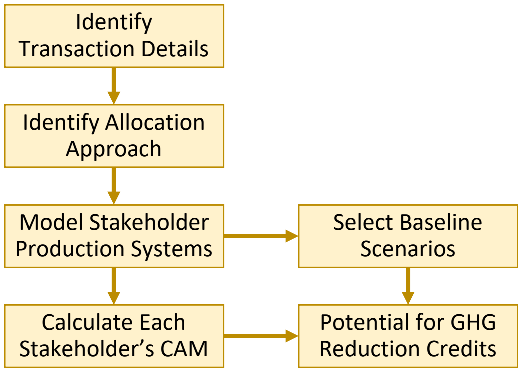

FIGURE 2: OVERVIEW OF THE CALCULATION STEPS OF THE PROPOSED FRAMEWORK

Step 3: Using the allocation selections, model each stakeholder's product system.
Step 4a: Based on the expressions detailed in Section 3.2, compute the CAM value for each stakeholder.
Step 4b: In parallel, using the transaction details and the allocation models, identify *baseline scenarios* appropriate for each stakeholder and estimate their respective GHG emissions.
Step 5: Comparing the CAM calculations of the *transaction* and emissions estimation of the *baseline*, along with guiding additionality tests, examine the potential for each stakeholder's eligibility for recognized GHG reduction *credits* [6].

3.1 Allocation of GHG Emissions

To determine allocation of the CAM between the stakeholders, the allocation approaches offered in past LCA literature can be used [24–27]. These approaches provide several ways to allocate environmental burden between different product systems. With respect to SMMs, the first product system refers to the product life cycle system with respect to the seller and the second product system refers to the one involving the buyer. We have discussed some of the commonly employed allocation approaches below. In addition to assuring allocation calculations avoid double counting of emission burden or benefit, a good allocation approach must also be easy to use, equitable and incentivize the reduction of emissions [10]. The equations below are for the total inventory (E_{Tot})—which includes material extraction, production and EoU recovery, but excludes use and distribution stages—and are comparable to other LCA literature [10,24,27]). Note that although following section uses the term *recycle* (analogous to typical LCA literature which it is based on), the expressions are usable with other recovery pathways such as reuse and remanufacture. Also note that the more general term environmental burden is used in the following sub-sections analogous to LCA literature the expressions are based on. For the purposes of this work, we focus on the burden of GHG emissions.

a. ***Cut-off allocation approach*** (also called *Recycled content* and *100:0*): The environmental burden of material extraction and production, along with EoU collection-related burdens, are allocated to the first product system. Then, the burden of recycling-related (i.e., processing to recover the material to another product) is allocated to the second product system that uses the recycled material. The approach is comparatively simple to apply and takes the view of "polluter pays."

The cut-off allocation motivates the use of the recycled material (rather than the creation of the recycled material). Therefore, this approach is useful for recycled outputs where the demand is low (e.g., by-products that have low value or are the output of pollution control systems) [24]. This is used in modeling of recycling of material such as gypsum, plastics, and glass.

The total environmental burden (E_{Tot}) of each product system is expressed as [10]:

$$E_{Tot} = (1 - R_1)E_V + R_1 E_R + (1 - R_2)E_D \qquad (1)$$

where,

R_1 is recycled content ratio (i.e., share of secondary material compared to total material [24]) of the product,

R_2 is the end-of-life recycling rate of material, which is the ratio of recycled amount of material out of the total material available at the end of product use (also called collection rate) [24],

E_V is the environmental burden of producing the virgin (i.e., primary) material for the product,

E_R is the environmental burden of recycling activities of the input secondary material to the product, and

E_D is the environmental burden of waste disposal.

b. ***End-of-life recycling approach*** (also called *Closed-loop approximation* and *0:100*): All recycling benefits and burdens are allocated to the first product system which produced the recyclable virgin material. The benefits are attributed as a credit for avoiding the (future) production of virgin material. The second product system that repurposes the recovered material is not allocated any benefit of recycling and it incurs environmental burden as if using virgin material.

The approach is especially applicable when the recycled material's demand is typically higher than the supply; then, when one entity uses recycled material, more virgin material must be produced to fulfill the demand elsewhere. This is typically used for modeling the recycling of metals [28].

The total product system's environmental burden (E_{Tot}) can be expressed as:

$$E_{Tot} = E_V + R_2 E_R - R_2 E_V^* Q_2 + (1 - R_2)E_D \qquad (2)$$

where,

E_V* is the environmental burden of virgin material that was avoided by the recycled material in the next product cycle. When the substituted material is not the same as the original material, $E_V* \neq E_V$.

A quality correction factor is added to account for any change in the amount of primary materials used [24]. For example, if 10 kg of EoU recycled material only substitutes 7 kg of virgin material (E_V*) in the second product system, the quality correction factor (Q_2) is 0.7.

c. ***50/50 Hybrid approach***: This approach allocates the credits and burden of virgin material avoidance and production and

EoU recovery to first and second product systems equally. It is a compromise between the two above approaches and may be used when it is unknown if the recycled material's consumption or its production should be promoted [24,28].

The total environmental burden (E_{Tot}) of each product system can be expressed as:

$$E_{Tot} = E_V(1 - R_1) + 0.5R_1(E_{R1} + E_V - E_D^*) + 0.5R_2(E_{R2} - QE_V^* + E_D) + (1 - R_2)E_D \tag{3}$$

d. ***Market price-based substitution approach***: While the 50/50 approach is mandatory in instances such as the PEF Guide of the European Commission [29], the allocation factor of 50:50 may seem arbitrary (and different applications have considered other ratios) [24]. As an alternative, materials' market price-based approach is available [24], using the ratio A between the price of recycled material and the price of substituted primary material.

Higher value of A indicates the recycled material has higher demand and/or is of sufficient quality. Low A indicates that the recycled material is not a good substitute, or it is in excess, and additional production may lead to disposal of that material elsewhere. Therefore, economic allocation can be done using A as the factor for crediting the production of recycled material (i.e., first product system) and (1-A) as the factor for crediting consumption of recycled material (i.e., second product system) [24].

The total environmental burden (E_{Tot}) of each product system can be expressed as:

$$E_{Tot} = E_V(1 - R_1(1 - Q_1)) + E_D - (1 - A_1)R_1(E_VQ_1 + E_D^* - E_{R1}) - A_2R_2(E_V^*Q_2 + E_D - E_{R2}) \tag{4}$$

where,

A_1 is the market price ratio between incoming recycled material to the first product system (i.e., the recycled material consumed by product system in focus) and the avoided primary material in the current life cycle,

A_2 is the market price ratio for incoming recycled material to the second product system (i.e., the recycled material produced by product system in focus, for the use in next system) and the avoided primary material in the subsequent life cycle, and

E^*_D is the environmental inventory of avoided disposal of waste in previous life cycle.

If a single EoU allocation approach for all SMM transactions can be found, it would be convenient. But general SMMs involve a large variety of materials which have different market demand and supply characteristics. Since the allocation method serves to promote a balance of supply and demand to foster more optimal recovery methods, the estimator must deliberately choose the most appropriate allocation method considering each transaction's details when calculating the CAM. However, in a specialized SMM with limited types of material involved, a single approach may be prescribed. Defining the allocation method has the benefits of more uniform, consistent, and transparent outcomes and agreed to through an open deliberative process, rather than varying on case-by-case manner.

3.2 Calculation of CAM in the SMM Applications

Instances of SMMs have two main stakeholder types (other than the marketplace itself—which typically limits its role to facilitate the transaction). First is the "seller" of the product/material (i.e., *first product system* in terms of allocation equations stated). Second is the "buyer" who recovers the transacted material through reuse, remanufacture, recycle, etc. (i.e., *second product system*).

Allocation approaches in the above section provide the basis to allocate the total GHG emissions related to the transaction to each stakeholder's (i.e., the seller's and buyer's) product system. To calculate the change in emissions due to a transaction in the SMM, total emissions are compared to the *prior* practice (i.e., course of action in lieu of the SMM transaction). Total emissions inventory for a stakeholder's product system ($G_{Tot\_Stakeholder}$) is calculated similarly to total environmental burden E_{Tot} in the above allocations, but only considering the GHG emissions inventory (since the interest is to quantify "carbon" impacts). An element that needs to be added to ($G_{Tot\_Stakeholder}$) that was not included in E_{Tot} of the prior literature (for brevity) is the logistics-related impact. Since the logistics can be different prior to and after the SMM transaction, it is important to include that in $G_{Tot\_Stakeholder}$. Furthermore, it is important to use appropriate emission factors when calculating the GHG emission of each activity. Part of the sector-specific standardization efforts (as discussed in Section 4.3) is to provide guidelines on selecting emission factors that best represent the activities involved and make the results comparable across an industry sector.

The CAM values for each stakeholder is calculated as,

$$CAM_{Seller} = G'_{Tot\_Seller} - G_{Tot\_Seller} \tag{5}$$

$$CAM_{Buyer} = G'_{Tot\_Buyer} - G_{Tot\_Buyer} \tag{6}$$

where,

CAM_{Seller} and CAM_{Buyer} are seller's and buyer's CAM respectively,

G_{Tot_Seller} is the total environmental burden allocated for seller after the transaction,

G'_{Tot_Seller} is the total environmental burden allocated for seller prior to the transaction,

G_{Tot_Buyer} is the total environmental burden allocated for buyer after the transaction, and

G'_{Tot_Buyer} is the total environmental burden allocated for buyer prior to the transaction.

Therefore, the SMM transactions that lead to a reduction of overall GHG emissions for a stakeholder will be calculated as positive CAM values.

3.3 GHG Reduction Credits and SMM Transactions

Given the interest from the industry, in the second part of this work, we examined the potential of the transactions in SMMs to be considered for officially recognized GHG reduction *credits* [6]. The allocation and the $G_{Tot\_Stakeholder}$ calculations done in the above section provide an estimation of burden and benefit allocations for each of the two stakeholders in the transaction. Those values are useful in calculating their emissions, both at the product level and overall business levels. Beyond that, in order to be recognized as GHG reduction *credits*, the GHG Protocol provides guidelines on accounting the credits [6].

GHG Protocol

The *GHG Protocol* provides principles and guidelines for both corporate-level [9] and project-level [6] emissions accounting. A GHG project is defined as a specific activity or set of activities intended to reduce GHG emissions, increase the carbon storage, or enhance atmospheric GHG removals [6]. The GHG Project Protocol also facilitates the application of ISO requirements in standards such as ISO 14064 [6]. Thus, this section's discussion is based on this protocol.

The *ownership* of GHG reductions in activities are intentionally not discussed in the GHG Protocol's Project accounting guideline (as it is considered out of scope for the document) [6]. Therefore, the above allocation approaches are applied here to discern where the reductions must be allocated. Then, the GHG Protocol is used to check if those allocated reductions have the potential to be claimed as GHG reduction credits.

Following are a few directly relevant concepts from GHG Protocol this work uses, and how they are applied when quantifying the GHG emissions here. For more detailed information on these concepts, calculations and best practices, readers are invited to refer to the GHG Protocol [6,9,30].

GHG Accounting Principles

GHG Protocol identifies six principles in accounting emissions: *Relevance* (use of data, methods, assumptions relevant to the reported information), *Completeness* (consideration of all relevant information that could affect estimations), *Consistency* (Use of data, methods and assumptions to allow valid comparisons), *Transparency* (providing sufficient information to verify the credibility and reliability of GHG reductions), *Accuracy* (reduction of uncertainty), and *Conservativeness* (use of conservative assumptions and procedures when uncertain). These principles are derived from common financial accounting and financial principles [6].

Assessment Boundary Definition and Primary vs Secondary GHG effects

Primary GHG effect is the intended change due to the marketplace transaction in focus. In addition to that, other unintended secondary effects could happen downstream or upstream of the main transaction and include market responses stemming from the transaction. For example, it is useful to consider whether selling a material at an SMM can reduce the pricing of virgin material for the second product system due to a corresponding reduced demand. Such a decrease in price can increase the consumption rate of virgin material in other applications increasing the GHG emission beyond the supply chain in focus. While these secondary effects are generally not significant unless a transaction activity can considerably impact the overall market, GHG Protocol provides guidelines on verifying them. If any significant secondary effects are found, those must be accounted for when estimating the GHG emissions and CAM. However, given the amount of time and effort required, GHG Protocol does not require performing a complete LCA when considering the secondary effects.

Selecting a Baseline Candidate and Estimating Potential Credits

Baseline scenario is defined to identify a reference case for project activities in the GHG Protocol [6]. Here, it describes the most likely outcome (separately for each stakeholder, i.e., the seller and buyer) in absence of the SMM transaction, or the common market EoU practice for the transacted material. By comparing the transaction's GHG emissions ($G_{Tot\_Stakeholder}$) with the baseline scenario's emissions ($G_{Tot\_Stakeholder\_Baseline}$), avoidance is calculated.

The recognizable GHG reduction credit amount becomes,

$$G_{Stakeholder\_Credits} = G_{Tot\_Stakeholder} - G_{Tot\_Stakeholder\_Baseline}. \quad (7)$$

GHG Protocol provides important guidelines on selecting the baseline scenarios that are geographically and temporally valid, and accounting for their emissions. Correct identification of a baseline will help recognize activities that would have anyway happened (e.g., common practices, regulatory requirements) and avoid giving GHG reduction credits to such activities. Therefore, it helps in determining the *additionality* of the transaction.

The key difference of $G_{Tot\_Stakeholder\_Baseline}$ from $G'_{Tot\_Stakeholder}$ used in the previous section is that $G_{Tot\_Stakeholder\_Baseline}$ also considers common market practices for EoU material streams along with secondary GHG implications, in addition to considering the likely alternative in lieu of SMM transaction. $G_{Tot\_Stakeholder\_Baseline}$ may also include multiple baseline scenarios, which require the calculation of $G_{Stakeholder\_Credits}$ multiple times and identify the most conservative value for the credits.

Additionality Tests

Table 3.1 of the GHG Project Protocol [6] lists possible tests to identify whether the GHG reduction was a *decisive* reason for implementing a change. The tests are adapted below for this application to check whether GHG reduction was a decisive factor (even when it was one among many factors) in the decision to use the transacted material from SMM. The tests include:

a. Legal, regulatory, or institutional test: the transaction reduces the GHG emissions below the level required by regulations. If it is not below required levels, the assumption is that the reason for taking this option was to comply with regulations, and therefore GHG reductions are not additional.

b. Technology test: transaction involves the use of a technology (e.g., a special recycling process) that is unlikely to be employed for reasons other than reducing GHG emissions.

The assumption here is that a decisive factor in implementing such a technology is GHG reductions.

c. Investment test: the transaction is of low rate of return compared to alternatives. Assumption is that finances are not necessarily a motivator.

d. Common practice test: the transaction reduces GHG emissions below the level produced by common practice alternatives. The assumption is that if it does not reduce the emissions below common practices, the decisive reason may be to conform to market practice.

e. Timing test: the transaction must have initiated after a certain date. The assumption is that if it was initiated before a certain date (e.g., start of a GHG program), it may not have motivated by GHG reductions.

While these are not end-all be-all tests that give a verdict as to whether an activity was *additional*, and therefore worthy of credits, it is useful guidance to examine when a specific transaction has the potential to be creditable. A particular GHG crediting program may also decide whether and which additionality test are required. The GHG Protocol further allows for circumstances (e.g., at the initial stages of a GHG program to maximize participation and therefore GHG reductions) where GHG programs may choose to moderate the stringency of additionality tests to reduce the potential to reject activities which should be included [6].

4. APPLICATIONS

Two example cases involving materials that were listed in the established SMM called the *Materials Marketplace* are examined below to illustrate application of the proposed framework. We chose these two specific cases due to the different types of materials involved which have different EoU value recovery potentials, and therefore, different allocation requirements. Intention of this section is to highlight some of the practical considerations and challenges of implementing such a framework, rather than providing numerical examples. The equations below are based upon the equations described in Section 3.1, but are specifically computing the GHG emissions.

4.1 An Example Case of Recovered Nickel Oxide Transaction

In our communications with a specific SMM, we examined a transaction involving transfer of 2696.1 kg of Nickel Oxide to extract Nickel metal. Nickel Oxide is typically used as a glass colorant and the composition of this particular batch was NiO > 95% and $Ni(OH)_2$ < 5%.

The recycled (secondary) material (i.e., *Ni*) of the transaction is a metal and it has market demand (i.e., motivation is unnecessary for consumption of the recycled material). Therefore, the *End-of-life recycling* allocation approach is most suitable. According to the Eq 2,

$$G_{TotSeller} = G_V + R_2 G_R - R_2 G_V^* Q_2 + (1 - R_2) G_D. \quad (8)$$

Similarly, for the alternative case (G'_{Tot_Seller}) in lieu of the SMM transaction, since the material is typically recycled to get *Ni* metal anyway, (i.e., $R_2 = R'_2$), emissions can be calculated as,

$$G'_{TotSeller} = G_V + R'_2 G_R - R'_2 G_V^* Q_2 + (1 - R'_2) G_D. \quad (9)$$

According to Eq 5,

$$CAM_{Seller} = (R'_2 - R_2) G_R - (R'_2 - R_2) G_V^* Q_2 - (R'_2 - R_2) G_D. \quad (10)$$

Here, G_V^* is the substituted virgin material (i.e., *Ni* metal) production's typical emissions, and Q_2 is the quality correction for substituted *Ni* production. Based on reduction chemical equations, the transacted 2691.1 kg of material can provide 2118.6 kg of *Ni* metal. Assuming a 95% efficiency [31] in *Ni* yield accounting for impurities and processing waste, 1 kg of transacted material can be expected to substitute approximately 0.75 kg of *Ni* metal (i.e., $Q_2 = 0.75$). R_2 and R'_2 are the end-of-life recycling rates for *NiO* in the SMM and the alternative scenarios respectively, Therefore, CAM_{Seller} value will depend on the difference between recycling rate of two scenarios. If both scenarios have similar recycling rates, CAM_{Seller} will become zero.

For the buyer, due to the use of *End-of-life recycling* allocation approach, no benefit of recycling is allocated (i.e., emissions are assumed to be the same as using primary material inputs for their production). Therefore, G_{Tot_Buyer} is the same as G'_{Tot_Buyer}, leading to CAM_{Buyer} being zero.

4.1.1 Potential for GHG Reduction Credits

Due to the higher economic value of the secondary material, it is possible that the recycling rates of both scenarios are higher, and therefore, similar to each other (i.e., $R_2 \approx R'_2$). So, it is likely that the CAM_{Seller} is zero. Even when considering this type of transaction's potential to be eligible for credible GHG reductions, following additionality tests, among others, can be expected to fail: Technology test (reduction of *NiO* to *Ni* is not a *special* technology), and Investment test (given the usefulness of recycled *Ni*, the transaction can be expected to be much more financially motivating than an option such as disposal of material). Furthermore, given that reduction of *NiO* to recover *Ni* metal is a common practice in the industry, even if $G_{Seller\_Credits}$ is calculated, it is expected to be zero as $G_{Tot\_Seller\_Baseline}$ will be the same as G_{Tot_Seller}.

In this example, since the buyer is not being allocated GHG reductions (i.e., CAM_{Buyer} is zero), the buyer will not be considered for credits either.

4.1.2 Additional Practical Considerations

Examination of this SMM transaction also brought forward the following practical considerations and questions that need to be addressed when developing industry-specific guidelines and standards for such a framework.

a. The buyer of the Nickel Oxide in this specific example was found to be an intermediatory who then resold it to a refinery. In such cases, a clear identification must be made if the allocation is attributed to the end user. i.e., refinery in this case.

b. The specific buyer of this transaction had used a "backhauling" (i.e., use of a return trip truck) for the transportation. It raises the question of whether it is equitable to only account the additional miles incurred due to the detour specific to this transportation rather than taking the total distance traveled.
c. For G_R, and G_D, the application-specific GHG emissions must be estimated. If the buyer has detailed information on their processes and materials used, the emissions can be calculated accurately. However, in many cases the detailed specifications necessary may not be available due to time and resource limitations, buyer not being the final user of the material (which also was the case here), as well as confidentiality concerns of the stakeholders. Even in our communications with the industry experts, GHG emissions factors such as G_R for *NiO* was found to be very difficult to obtain due to the sensitive nature of the data points.
d. If $G_{Tot\_Buyer\_Baseline}$ was to be calculated, the GHG emissions related to typical production of *Ni* metal (geographically and temporally valid for this application) must be estimated. If the buyer already has process information (e.g., buyer typically used Nickel ore for extracting *Ni* metal and the information on the baseline scenario is already available), data can be easier to find. Otherwise, the baseline scenario details may not be available to the buyer. While the GHG Protocol does guide on how to estimate in such cases based on average values for similar processes [6]), it can require considerable process knowledge and effort.

4.2 An Example Case of Automotive Insulation Material Transaction

Another material listed on the SMM was automotive insulation scrap material. Following is a hypothetical example illustrating the application of the proposed framework in such a transaction. The transaction involves 2500 kg of scrap material made with jute fibers, and the buyer is using the obtained material to substitute purpose-made expanded polystyrene (EPS) filler material. Life cycle data for the example was estimated using the ecoinvent database [32] and using Traci 2.1 method [33]. The numbers are provided only for the representative purposes of the example; they should not be taken as absolute values for the specific materials involved.

The recovered material typically does not have a high market demand. In this case it is more appropriate to motivate the consumption of the recovered material. Therefore, the *Cut-off* allocation approach is suitable for this case. According to Eq 1, for seller,

$$G_{TotSeller} = (1 - R_1)G_V + R_1 G_R + (1 - R_2)G_D \quad (12)$$

Without the transaction, assuming the scrap material would have been disposed by seller, the R_2 becomes zero. Therefore,

$$G'_{TotSeller} = (1 - R_1)G_V + R_1 G_R + G_D. \quad (13)$$

According to Eq 5,

$$CAM_{Seller} = R_2 G_D. \quad (14)$$

Therefore, the seller's CAM is equal to avoided emissions of the material disposal avoided through the transaction. Assuming that 2400 kg of the 2500 kg was recycled after quality check, R_2 here is the 2400/2500 = 0.96. Life cycle inventory data for disposal of waste yarn and textiles including jute fibers approximates 0.81 $kgCO_2e$ for 1 kg of disposal in landfill. Therefore,

$$CAM_{Seller} = 0.96 * 0.81 * 2500 = 1944\ kgCO_2e.$$

For the buyer's allocation, the virgin material GHG emissions (G_{VS}) is calculated for the emissions of producing the substituted material (i.e., the purpose-made filler material).

$$G_{TotBuyer} = (1 - R_1)G_{VS} + R_1 G_R + (1 - R_2)G_D \quad (15)$$

Without the transaction, assuming the buyer would entirely use the purpose-made filler material, the R_1 for buyer becomes zero. Therefore,

$$G'_{TotBuyer} = G_{VS} + (1 - R_2)G_D \quad (16)$$

According to Eq 6,

$$CAM_{Buyer} = R_1 G_{VS} - R_1 G_R. \quad (17)$$

Therefore, the buyer will have a positive CAM when the emissions intensity of producing substituted virgin material (G_{VS}) is higher than the emission intensity of the recovery processes for the transacted material (G_R). In this case, since the recovery process is *reuse*, which requires minimal preprocessing (e.g., separation or cleaning), G_R is negligible and CAM_{Buyer} will be a positive value. However, in calculating the CAM_{Buyer}, it was assumed the downstream EoU processing for second product system (i.e., buyer's) will remain unchanged in both with transaction ($G_{TotBuyer}$) and without transaction ($G'_{TotBuyer}$) alternatives above. This is reasonable, especially in low-value applications where EoU material is typically disposed as waste. We can assume G_R= 0 (due to negligible processing needs), and R_1=1 (since we are only looking at recycled material in this example). Since the buyer's application reuses the material as a filler material, the utilization factor of the material is based on the volume. Therefore, by comparing the density of jute fiber-based insulation pad material (24 kg/m^3) to the EPS filler material (16 kg/m^3), the substitution factor for material can be calculated as 16/24 = 0.67. Life cycle inventory data for general purpose EPS material production is 3.51 kgCO2e for 1 kg.

An approximate value can be calculated as,

$$CAM_{Buyer} = 3.51 * 0.67 * 2400 = 5644\ kgCO_2e.$$

While these values may not seem especially large compared to the immense amount of emission in industrial processes, it should be noted that these represent the carbon avoidances of a single SMM transaction.

To avoid the effect of the location-specific transportation differences, we assumed transportation requirements are similar across scenarios. Even if the transportation requirements were to be different, given the magnitude of processing emissions, results are not expected to be widely divergent (e.g., transporting this material 500 miles in a medium-duty truck would add approximately 448 kgCO2e).

Potential for GHG Reduction Credits

When considering the potential for this type of transaction to be eligible for credible GHG reductions, for both seller and buyer, the following additionality tests, are at risk to fail: 1) Technology test since repurposing of the EoU material is not necessarily a *special technology* used specifically to reduce GHG, and 2) Investment test since given the possible monetary income to the seller and the reduced cost of acquisition to the buyer, the transaction can be expected to be financially motivating for both parties.

4.3 Carbon Avoidance and the System-level of Circular Economy (CE)

The two sub-sections above considered CAM in two different applications that align with material recovery within a CE. Taking a wider *system-level* perspective is an important element in establishing effective CE [34]. This is especially important when a variety of open-loop pathways for a secondary material are available. Say, a certain secondary material can be recovered by several stakeholders for different applications. By estimating the CAM for those applications, the stakeholders can recognize the most beneficial pathway the material could take (e.g., due to minimal processing or logistics needs at a specific stakeholder's application). This expands beyond the economic information typically available for manufacturers when making such decisions and informs the consequences of their decisions in terms of the broader sustainability concerns.

Towards the goal of a wider system-level perspective, the SMMs can provide the service of a third-party estimator of the CAM keeping an account of the allocations of CAM to avoid double counting—i.e., a new value proposition for SMMs. Further down the road, SMMs may be poised to support future opportunities for system-level optimizing of flows—i.e., optimizing for the benefits of the larger CE system rather than for individual stakeholders.

To implement system-level perspective and adopt CAM, more consensus and standards will be necessary to enable these estimations. The following are some of the major standards and industry-specific consensus needs for implementation of a system-level framework.

- Guidelines on industry-specific common practices.
- Standardization or consensus on industry and materials specific allocation methods.
- Guidelines on GHG reduction allocation when material ownership transfers between multiple stakeholders—e.g., intermediaries between the producer and consumer of recovered material.
- Guidelines on estimating and accounting of GHG emissions and CAM for special industry practices–e.g., backhauling.
- Guidelines on selecting appropriate and comparable emission factors.

5. CONCLUSION

In this work, we propose the CAM framework to quantify and allocate the GHG emissions avoidance of SMM transactions. Following are the major highlights and contributions of this work towards overcoming the gaps identified in the current literature.

- We present a carbon avoidance framework specifically for SMM applications and focus on the equitable allocation between the stakeholders involved.
- We identify how SMMs, being a neutral third party, can systematically allocate carbon avoidance between stakeholders to prevent any double counting errors.
- The systematic allocation presented here has the potential to abate environmental impacts by incentivizing the correct stakeholder.
- We demonstrate the CAM estimation for two example SMM transactions and further examine them with the GHG Protocol to identify the challenges to their eligibility for GHG reduction credits.
- We establish the significance of such a measurement for broader CE system-level decisions.
- We summarize the standardization and industry-specific consensus needs to implement this framework.

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