A Blockchain-based Greenhouse Gas Emission Tracking System (GETS) for Climate-Related Disclosures

ABSTRACT

Scope 3 greenhouse gas (GHG) emissions are vital components of climate risk metrics, but they are challenging to estimate due to the lack of proper estimation methods and the difficulty in collecting data throughout the entire value chain. To overcome these challenges, we propose a greenhouse gas emission Tracking system, GETS, incorporating the Internet of Things (IoT), blockchain, and Life Cycle Assessment (LCA) to enhance climate-related reporting with a focus on Scope 3 GHG emissions. IoT and blockchain enable reliable data collection from various sources, and LCA contributes to the comprehensive evaluation of a product's environmental impact and the estimation of Scope 3 GHG emissions. The GETS system automatically verifies users' identities, validates input data, reports the firm's overall climate-related performance, including Scope 3 GHG emissions, and validates the metrics disclosed by companies. This study sheds light on utilizing emerging technologies to enable reliable, complete, and accurate climate-related disclosures.

Keywords: climate-related disclosure; Scope 3 greenhouse gas emission; life cycle assessment; blockchain; smart contract; ESG.

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1. Introduction

The growing global momentum to address climate change urges businesses to disclose climate-related information. In December 2022, the European Union (European Parliament & Council of the European Union, 2022) issued rules requiring information on greenhouse gas (GHG) emissions. Increasing emphasis on net-zero targets for companies and demand from stakeholders for decision-useful environmental information also drive more comprehensive climate-related disclosures and the integration of climate risk into business strategies. Failure to provide such information in an accurate and faithful manner may damage companies' reputations, erode investor confidence, and weaken market competitiveness. The low credibility of climate-related disclosures is often due to companies' discretion in reporting, transparency issues in measuring approaches, and inadequate ESG assurance (Boiral & Heras-Saizarbitoria, 2020; Talbot & Boiral, 2018). Consider an automobile manufacturer's claim that its new electronic vehicle (EV) emits fewer GHG emissions annually in the use stage. This does not necessarily indicate environmental progress since the company does not disclose emissions at the manufacturing and disposal stages. Evidence suggests that the GHG emissions saved during the use of EVs are offset by heightened emissions during their production and, to a lesser extent, during disposal compared to traditional vehicles.[1] However, companies may greenwash their ESG reports by emphasizing only emission reduction during their cars' use while omitting the emissions and pollution at the manufacturing and disposal stages. This

[1] Source: https://www.insnet.org/electric-cars-emit-more-co2-than-traditional-cars-at-production/.

example highlights the significance of reporting GHG emissions from all the stages, particulaly Scope 3 emissions, to provide a holistic view of the emissions throughout the entire value chain.

Several emerging technologies have the potential to solve the challenges mentioned above in estimating and reporting Scope 3 emissions. Life Cycle Assessment (LCA) is a method for examining the environmental impact of a product by accounting for all processes throughout its life cycle. LCA can incorporate energy and material data collected from various enterprises along a value chain and evaluate the chain's overall GHG emissions. However, gathering reliable and effective data from various corporations and sites across the value chain is necessary for LCA to yield unbiased, complete, and credible results (De Schryver, Humbert, & Huijbregts, 2013; Zhang, Zhong, Farooque, Kang, & Venkatesh, 2020). Certain input data points may be missing or outdated and must be approximated. Often, site-specific data is needed, but only average data from different sites is available. Blockchain and the Internet of Things (IoT) technologies can mitigate this problem. IoT is an open network of intelligent devices that can auto-organize, share information and resources, and act in response to circumstances and environmental changes (Madakam, Ramaswamy, & Tripathi, 2015). IoT devices can collect real-time energy and material usage data from numerous sites in a value chain, thus solving the data availability issue. Blockchain is a decentralized and distributed computing infrastructure that can verify and store data within an encrypted block structure, protecting the IoT-captured data uploaded to the blockchain against manipulation. Functioning as a shared ledger among participants, it enhances trust and transparency within the system. Furthermore, smart contracts, as self-executing programs that are designed to activate when specific conditions are fulfilled, could automate controls over data when they are uploaded to a blockchain. In turn, the blockchain eliminates the need for a centralized authority to carry out smart contracts, preventing privileged entities from overriding the controls. Collectively, LCA, IoT, blockchain, and smart contracts could promptly generate a comprehensive report on climate-related metrics, including GHG Scope 3 emissions, across the entire value chain with high credibility, authenticity, and completeness.

On this basis, we propose a GHG Emission Tracking System (GETS) to improve the completeness, accuracy, and credibility of climate-related disclosures. By leveraging IoT, the GETS facilitates prompt and comprehensive data collection from diverse sites. To ensure the integrity of this data, the GETS incorporates smart contracts and blockchain to authenticate data sources and validate input values. Finally, the GETS uses LCA to evaluate the overall climate-related performance of an entire value chain and generate a climate report highlighting GHG Scope 3 emissions. The blockchain employed by the GETS is a permissioned blockchain[2], which allows only authorized participants (usually the direct buyer, seller, shipping company, and their internal auditors) to upload and verify detailed energy and material data. External auditors also have access to this data during audits. To protect data privacy, other stakeholders can only access the LCA results in the final report. The GETS can also validate a company's climate-related disclosures by comparing them to its LCA outcomes.

The proposed GETS system is demonstrated using simulation data for EVs. The demonstration provides examples of sensor deployment in different life cycle stages. A smart contract is created on Ethereum, one of the largest blockchain platforms, to validate data inputs for LCA. Next, the validated data is posted on the Ethereum blockchain and securely shared among permissioned participants who verify the information. Using this data, the LCA software assesses the environmental impact of the EV at each stage of its life cycle. Finally, a comprehensive climate-related report, derived from the LCA findings, outlines the EV's total environmental impact of the EV is generated based on the LCA results.

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[2] Unlike public blockchains that power popular cryptocurrencies like Bitcoin, permissioned blockchains operate with predetermined rules about which parties are authorized to record transactions. This approach safeguards privacy to meet corporate governance best practices (AICPA and CPA Canada, 2017; Fortin et al., 2023)

This study presents several contributions to both academia and practice in the field of climate-related disclosure. First, this research advances existing knowledge by addressing current challenges in Scope 3 emission disclosures and proposing innovative solutions using LCA, IoT, blockchain, and smart contracts. This not only enriches the theoretical framework of GHG reporting but also offers practical methods for improving data accuracy and transparency. To our knowledge, this is the first study incorporating emerging technologies to overcome the data-gathering challenges of GHG reporting. Second, we present a novel system that synergizes IoT, blockchain, and LCA to facilitate climate-related reports for an entire value chain, validate information in a company's climate-related report with the system's LCA outcomes, and provide alerts at stages that have high climate-related risks. Moreover, this research demonstrates the feasibility of implementing the GETS system using a simulated EV company and provides a conceptual discussion of the costs and benefits of the system. This simulation provides a roadmap for future studies to evaluate their forward-looking systems in situations where actual implementation would be challenging over the short term. Additionally, we showcase various scenarios for sensor deployment, which can act as guidance for companies to deploy sensors for ESG reporting purposes.

This study also contributes to practice by offering reporting companies a handy tool for tracking and estimating real-time GHG emissions, validating data sources and securing data integrity, alerting firms to take proactive steps to reduce climate change risk, and recognizing Scope 3 emissions through well-defined boundaries. Auditors benefit from easy access to the original and untampered data, enhancing assurance tests. By referring to the blockchain record, regulators and stakeholders can gain a holistic view of a firm's climate-related performance and identify polluting stages in the value chains.

The rest of the paper is structured as follows: Section 2 reviews the literature on climate-related disclosures, LCA, IoT, blockchain, and smart contracts. Section 3 describes the system design. In Section 4, we implement the proposed system using simulation data on EVs. Section 5 discusses the system's strengths, potential hindrances to its adoption, and future research questions. Section 6 offers conclusions.

2. Background and Related Research

2.1. Greenhouse gas emissions

The GHG Protocol classifies a company's GHG emissions into Scope 1 (i.e., direct GHG emissions from owned or controlled sources), Scope 2 (i.e., indirect emissions from purchased energy consumed by the reporting company), and Scope 3 emissions (i.e., all other indirect emissions from upstream and downstream activities in the firm's value chain). Although the GHG Protocol only requires companies to report Scopes 1 and 2 emissions, Scope 3 emissions, referred to as value chain emissions by the United States Environmental Protection Agency (EPA), are a critical component of overall GHG emissions, accounting for more than 70 percent of companies' carbon footprints.[3] According to a report by the Carbon Disclosure Project (CDP, 2023), Scope 3 emissions for an average firm are over 11 times higher than operational emissions for an average firm, highlighting their significant impact on a company's environmental footprint. In recent years, governments and regulators[4] as well as industry and investor initiatives have increasingly emphasized Scope 3 emissions disclosure throughout the value chain. This has led to a noticeable uptick in the number of companies reporting Scope 3

[3] Source: https://www2.deloitte.com/uk/en/focus/climate-change/zero-in-on-scope-1-2-and-3-emissions.

[4] For example, in December 2022, the European Parliament & Council of the European Union (2022) require companies in Europe to report Scope 3 emissions from 2025. In June 2023, the International Sustainability Standards Board (ISSB) released Climate-related Disclosures (IFRS S2) (ISSB, 2023), a mandate for Scope 3 emission disclosures. In October 2023, California formally enacted the Climate Corporate Data Accountability Act (California Legislative Information, 2023), requiring Scope 1 and 2 disclosures from January 2026 and Scope 3 from 2027. Financial organizations require adequate disclosures of GHG emissions, including Scope 3, to track firms' GHG emission reduction commitments and meet their disclosure obligations.

GHG emissions, rising from 28 percent in 2017 to 34 percent in 2019 (Task Force on Climate-Related Financial Disclosures [TCFD], 2022).

Despite the progress, measuring and reporting Scope 3 emissions is far more complex than tackling emissions from direct operations (Scope 1 and 2), requiring sophisticated data collection capabilities and collaboration with upstream and downstream partners. Accordingly, most companies only report Scope 1 and 2 emissions. According to TCFD (2022), 71 percent of respondent companies rate Scope 3 emissions as difficult to measure, expressing concerns about the accuracy and completeness of the reported data. First of all, for suppliers that do not calculate their own emissions, defining an appropriate calculation approach for each Scope 3 category presents a methodological challenge. Moreover, establishing clear value chain boundaries when calculating Scope 3 emissions poses another challenge. In principle, GHG emission categories defined by the GHG Protocol Scope 3 Standard (World Resource Institute [WRI] and World Business Council For Sustainable Development [WBCSD], 2011) are designed to be mutually exclusive. However, it is intricate in practice to disentangle responsibilities among organizations involved in multiple life cycle stages, potentially resulting in double counting of Scope 3 emissions and overlapping reporting boundaries. In addition, even though some companies have started to report Scope 3 emissions, they often fail to report all of their Scope 3 emissions. For example, Tesla's 2021 impact report only includes emissions from the use stage as the firm's total Scope 3 emissions.[5] Therefore, a methodology is required for reliably estimating and disclosing the different categories of GHG emissions throughout the value chain.

[5] Source: https://www.tesla.com/ns_videos/2021-tesla-impact-report.pdf.

2.2. *Life Cycle Assessment (LCA)*

LCA is a methodology that estimates the cumulative environmental impact of a product by accounting for all processes throughout the product's life cycle, from raw material extraction through production, distribution, use, and final disposal (Corcelli, Fiorentino, Petit-Boix, Rieradevall, & Gabarrell, 2019; Linkov et al., 2017). Academic research has used LCA to evaluate carbon footprints in solar rooftops (Corcelli et al., 2019), EVs (Wong, Ho, So, Tsang, & Chan, 2021), and buildings (Pierobon, Huang, Simonen, & Ganguly, 2019).

Standard setters also incorporate LCA to assess a product's carbon emissions across its life cycle, such as the ISO standards[6] and the GHG Protocol. Based on ISO standards, the GHG Protocol offers guidance for companies to quantify and report GHG emissions associated with a given product.[7] Specifically, the total product carbon footprint is calculated using the material and energy flow data in the activities associated with the product multiplied by its emission factor and the global warming potential (GWP).[8] The activity data needed is mainly material and energy consumed in a given activity since these values are much easier to capture compared to determining the emissions directly (Brentrup, Küsters, Lammel, & Kuhlmann, 2000). Guided by these standards, some pioneer companies have adopted LCA to evaluate their products' overall environmental impact.[9]

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[6] ISO 14040 describes the principles and framework for LCA, including goal and scope definition, life cycle inventory analysis, life cycle impact assessment, life cycle interpretation, reporting and review, limitations, relationship among the LCA phases, and conditions for using value choices and optional elements. ISO 14044 further specifies requirements and provides guidelines for the LCA phases. ISO14067 provides guidelines for quantifying and reporting a product's carbon footprint. Source: https://www.iso.org/standards.

[7] Source: https://ghgprotocol.org/.

[8] The emission factor is the average emission rate of a given source relative to units of activity or process. It can be used to convert activity data into GHG emissions. GWP values are published by the Intergovernmental Panel on Climate Change (IPCC) for converting GHG emissions data for non-CO_2 gases into units of carbon dioxide equivalent (CO_2e).
Source: https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf.

[9] For example, H&M uses third-party LCA data on materials to assess the impact of its products and to create industry alignment (source: https://hmgroup.com/sustainability/circularity-and-climate/materials/). Apple also conducts a product LCA by collecting data throughout the life cycle of its products and combining it with GHG emission data based on a combination of Apple-specific and industry-average datasets (source: https://www.apple.com/environment/answers/).

Despite its usefulness in assessing environmental impact, LCA's implementation is hindered by the challenge of data collection from various sources across the supply chain, which often involves many businesses that are geographically dispersed (Fauzi, Lavoie, Sorelli, Heidari, & Amor, 2019; Genovese, Acquaye, Figueroa, & Koh, 2017; Mieras, Gaasbeek, and Kan, 2019). The GHG Protocol suggests that the data that firms use to develop Scope 3 inventories should be collected from suppliers and other companies in the value chain, which takes considerable time and effort. Approximately 70–80 percent of the time and costs of performing an LCA are attributed to data gathering (Miah et al., 2018). Missing data must be estimated, which could oversimplify real-world problems and raise doubts about LCA results (van der Meer, 2018). For example, Apple acknowledges the inherent uncertainty in its modeling of carbon emissions, primarily due to data constraints and its frequent reliance on industry averages and assumptions.[10] More recently, Tesla has been criticized for selectively tailoring its Scope 3 figures to produce favorable outcomes (Osmosis, 2021). Specifically, Tesla bases its calculations on the energy mix of China's cleanest province, despite its Gigafactory being situated in the province with the highest carbon intensity. Other automobile companies have also been criticized for estimating key figures, such as lifetime travel distance, in calculating GHG emissions (Osmosis, 2021).

2.3. IoT, blockchain, and smart contracts

The Internet of Things, smart contracts, and blockchain can jointly serve as efficient solutions to obtaining reliable and accurate input data for LCA. IoT is an open network of intelligent devices that can collect data in real time. Using IoT to collect energy and material usage data from various sites in a value chain could solve the data collection issue for LCA. For example, the debate on Tesla's unreliable assumptions in Scope 3 emissions could be

[10] Source: https://www.apple.com/environment/answers/.

largely resolved if IoT sensors are used to record electricity sources and volumes and GPS modules are used to record vehicles' lifetime travel distances, eliminating management's opportunity to manipulate assumptions.

Blockchain, initially introduced by Nakamoto (2008) as the foundation of the cryptocurrency Bitcoin, is a form of decentralized digital record-keeping that establishes trust among distributed nodes through a consensus algorithm instead of a central organization (Iansiti & Lakhani, 2017; Pimentel, Boulianne, Eskandari, & Clark, 2021; Sharif & Ghodoosi, 2022). It is collectively maintained by all participants who can verify transactions. If the majority of participants reach a consensus on the validity of a new transaction, the transaction can then be added to a block. With all parties in the network sharing the same master records, blockchain is highly transparent, and fraudulent results from malicious nodes can be eliminated. By enforcing a sequential and immutable data addition process, it ensures data integrity against tampering and revision (Hughes et al., 2019; Moll & Yigitbasioglu, 2019; Pilkington, 2016).[11] Since each block stores transaction details and timestamps, blockchain offers a comprehensive audit trail for tracking assets within a value chain, increasing data verifiability and traceability (Fanning & Centers, 2016; Hughes et al., 2019; Iansiti & Lakhani, 2017; Yermack, 2017). Thus, blockchains could improve the quality of financial reporting by making accounting information more trustworthy and timely (Brennan, Subramaniam, & Van Staden, 2019; Centobelli, Cerchione, Del Vecchio, Oropallo, & Secundo, 2022; Dai and Vasarhelyi, 2017; Fortin, Pimentel, & Boulianne, 2023). Blockchains have been employed to improve transparency in global supply chains (for example, Walmart [2021], Home Depot [IBM, 2021], and IKEA

[11] It is noteworthy that the fact that blockchain in nature is immutable does not mean records cannot be revised when there are errors, but "every change is documented, is auditable, can be looked at going forward, going backward, going any which way you can," as noted by Fortin et al. (2023).

[Acciona, 2023]) and to enhance corporate sustainability (Brilliantova & Thurner, 2019; Christ & Helliar, 2021; Rogerson & Parry, 2020).

Smart contracts are user-defined computer programs that specify rules agreed upon among participants (Kiviat, 2015; Peters & Panayi, 2016) and are collectively executed by all nodes in the blockchain. Equipping blockchain with smart contracts greatly increases the flexibility and applications of blockchain (Dai & Vasarhelyi, 2017), boosts the accuracy of contract execution, and expedites management and decision-making (Qin, Yuan, & Wang, 2020).

As the saying goes, "garbage in, garbage out", it is important to garuantee the quality of the input data in order to get high-quality the output from the digital systems (Fortin et al., 2023). Initial efforts have been made to investigate the use of blockchain and smart contracts to improve the effectiveness and efficiency of collecting, analyzing, and sharing exclusively validated data to perform LCA (Buyle, Braet, & Audenaert, 2013; Krishna, Manickam, Shah, & Davergave, 2017; Rebitzer et al., 2004). Krishna et al. (2017) integrate blockchain and other advanced technologies into a standard LCA process to boost efficiency and effectiveness. Teh, Khan, Corbitt, and Ong (2020) explore how blockchain can address challenges faced by companies in the materials industry in implementing LCA. Zhang et al. (2020) design a blockchain-based LCA system to manage the environmental performance of a supply chain. However, these frameworks do not tackle issues related to the effective collection of data for LCA, storage scalability, and potential data manipulation or errors before the data is uploaded to a blockchain. Additionally, digital systems act as disclosure devices that can be overridden by managers to selectively choose what to disclose and what to control (Hansen & Flyverbom, 2015; Heembergen, 2016). This study proposes that by deploying IoT sensors at all the stages of the life cycle to collect the data and using smart contracts to validate the data, such shortcomings may be mitigated to a large degree. Moreover, while accounting research has explored the use of blockchain and smart contracts for accounting and auditing (Appelbaum & Nehmer, 2020; Dai, He, & Yu, 2019; Dai & Vasarhelyi, 2017; Gietzmann & Grossetti, 2021; Rozario & Vasarhelyi, 2018; Sheldon, 2021), their potential in climate-related reporting and assurance remains underexplored.

3. GHG Emission Tracking System (GETS)

We propose a GHG Emission Tracking System (GETS) for reliable data collection and real-time Scope 3 emission estimation. Unlike the tedious manual data collection approach suggested by the GHG Protocol, the GETS can collect data automatically from various sites in real time utilizing IoT sensors. Data manipulation can be largely avoided by collecting data directly from IoT sensors and uploading the data directly to the blockchain. The GETS also overcomes scalability limitations by combining blockchain with off-chain databases like clouds and ERP systems and by allowing data to be uploaded periodically (e.g., daily or weekly) depending on the risk of manipulation. The GETS focuses on climate-related disclosures and offers several novel applications, including data validation, generation of integrated reports across value chains, and validation of a company's climate-related disclosure with LCA results. Figure 1 shows the proposed system and its applications. The components and applications in the GETS are discussed in the following subsections.

3.1. Life Cycle Component

The life cycle component of the GETS articulates the stages in a product's life cycle, including raw material extraction, manufacturing, delivery, operation, and end-of-life recycling or disposal.[12] It serves as a guide for the system regarding where data collection, analysis, and

[12] This is consistent with the GHG Protocol Corporate Value Chain Accounting Reporting Standard (WRI & WBCSD, 2011), which specifies the life cycle stages as material acquisition and pre-processing (upstream Scope 3 emissions), production stage (Scope 1 and 2 emissions), and distribution and storage, use, and end of life (downstream Scope 3 emissions).

assessment of a product's impact on the environment should be performed. For instance, an EV's life cycle begins with the extraction of raw materials, such as steel and lithium. The materials and electricity are then consumed to manufacture the vehicle. The vehicle is then transported to a customer and put into use. After a certain mileage, the vehicle's batteries, tires, and parts are either disposed of or recycled, consuming resources and generating emissions. Any disposal also generates waste. Based on each stage of the product life cycle, the infrastructure in the system collects material and energy data and estimates emission and waste data for the entire cycle.

3.2. Infrastructure Component

The infrastructure component serves as the technological foundation for the GETS to collect, store, transmit, and process data. In this component, a variety of sensors are deployed at multiple sites to collect data in real-time or in batches. For example, weight sensors and capacitive sensors are employed in the target product's production lines to record the quantities and types of materials consumed; fuel and electricity meters are used to record the fuel and electricity consumption for product delivery; and GPS modules are utilized to track products and corroborate the occurrence of transactions. Many sensors are likely to be in place already as part of the firms' operations and controls, but other sensors would need to be deployed based on the product's life cycle. Note that this study does not propose to use sensors to capture live emission data directly because this approach may be expensive and is not always effective, especially in industries like agriculture and stock farming. Instead, material-balanced methods that trace the flow of energy and materials through the value chain[13] have been shown to estimate emissions more efficiently (Brentrup et al., 2000). Therefore, the proposed system is designed to utilize sensors to collect data on material and energy flows.

[13]Source: https://plasticseurope.org/knowledge-hub/mass-balance-approach-to-accelerate-the-use-of-renewable-feedstocks-in-chemical-processes.

Blockchain functions as a distributed database that decentralizes the system, prevents data tampering, and enhances trust. While a cloud may offer scalability and cost savings, making it a potential substitute for blockchain, it compromises trust and poses data security risks from cyberattacks and data breaches.[14] In contexts that demand high trust, like financial reporting and GHG reporting, blockchain could be a better choice. Although blockchain secures data authenticity, risks of pre-upload tampering persist. Sensor accuracy may be compromised by malfunction or intentional manipulation. For instance, spraying water near air quality sensors decreases pollutant readings, and a recent diesel emissions scandal revealed that several car makers used "defeat devices" in their vehicles to hide true emissions.[15] The GETS addresses these potential problems by incorporating smart contracts to validate data sources. For example, the defeated devices would be unauthorized to upload data to the blockchain. Certain thresholds could also be set to filter out obvious anomalies so that a dysfunctional sensor would trigger an alert that will be posted to the blockchain, and data from that sensor will be blocked. Another solution is for auditors to conduct random spot checks. With our proposed system, climate-related reporting is streamlined, and auditors can focus on infrastructure functionality checks instead of evidence collection.[16]

Smart contracts serve multiple functions in the system, including verifying the identities of users or IoT devices, validating data, and detecting misconduct. Data authentication is a significant concern for climate-related disclosures. Hino Motors, a subsidiary of Toyota, recently falsified emission data by replacing purification equipment during emission tests.[17]

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[14] Source: https://www.sailpoint.com/identity-library/data-security-in-cloud-computing.
[15] Source: https://www.bbc.com/news/business-34324772.
[16] While concerns exist that auditing blockchain companies involves great risks considering auditors's lack of indepth knowledge and the lack of guidance and standards, Pimentel et al. (2021) demonstrate that these issues are surmountable and auditing the blockchain is possible. Audit risk can be reduced through proper vetting of clients and management teams, and collaborating with blockchain experts can enable auditors who are not blockchain experts to provide assurance to this sector. This is also true in our context for auditors to check the infrastructure functionality of the GETS, which involves IoT and blockchain.
[17] Source: https://www.abc.net.au/news/2022-03-08/hino-admits-cheating-emissions-fuel-economy-tests/100890366.

Such greenwashing tactics might be eliminated using smart contracts and IoT sensors. Each IoT sensor would be registered with a unique identification number that would be verified by smart contracts when uploading data to the blockchain. Smart contracts would recognize any unauthorized equipment and prevent it from uploading data to the blockchain. Another responsibility of smart contracts is to validate data and detect abnormal data before uploading it to the blockchain. For example, if an energy value entered by a company or a registered sensor exceeds the normal range, the smart contract would display a warning in the record. In another scenario, if a company's records on the blockchain have many warnings or are frequently delayed or materially misstated, auditors or the firm's managers can be notified to take steps to prevent fraudulent actions and mitigate the potential risks. Despite warnings, information can still be uploaded to the chain if it is validated by the majority of authorized blockchain participants. However, the warnings are useful in that they may indicate potential collusion and fraud and may raise auditors' attention. Furthermore, certain programs could be deployed and implemented using Robotic Process Automation (RPA)[18] or Java scripts to deter the company from greenwashing and incentivize it to improve the quality of its climate-related disclosures. For instance, these programs can send notifications to rating agencies to reduce the company's rating on climate-related performance or pause machines that are producing abnormal amounts of GHG emissions or consuming unusual amounts of electricity.

Thus, the distributed network of sensors and blockchain gathers and integrates data from a variety of procedures and locations in the product's life cycle, overcoming the difficulty with data collection encountered by conventional LCA. Data from the blockchain and supplemental data from ERP systems (such as product types when the data cannot be directly

[18] RPA is a form of business process automation technology based on software robots operating on the user interface of other computer systems in the way a human would (van der Aalst et al., 2018).

collected from sensors) are then fed into LCA software.[19] Then, the LCA software analyzes the input data (materials and energy consumption) together with preset parameters to assess overall environmental impacts across the entire product life cycle.

To mitigate privacy concerns, the GETS uses a permissioned blockchain that allows only authorized users to read and manage data on the blockchain. Competitors and the public would only have access to emissions data reported by LCA without obtaining knowledge of specific suppliers or procedures. In contrast, partners, suppliers, auditors, and regulators can be granted access to detailed information, including energy, materials, and suppliers.

3.3. Applications of the GETS

One essential application of the GETS is to generate a report presenting a given product's collective effect on climate change, especially Scope 3 emissions. Major GHG metrics required by leading climate-related reporting standards like the TCFD and the GHG Protocol[20] are included automatically in results produced by LCA software, including the details of emissions generated at each stage of a product's life cycle.[21] With this detailed information, it is easy to categorize the GHG emissions into Scope 1, 2, and 3 emissions.

Another application is the validation of each company's climate-related reports via tracing and identifying its LCA results. Blockchain enables the tracing of details for each material or energy purchased or consumed back to each company, based on which the LCA-

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[19] As noted by Fortin et al. (2023), unlike Bitcoin, which exists digitally, blockchain itself in a supply chain context "is framed as a record of transactions and does not constitute all the materiality of the transactions themselves." Thus, many companies still maintain parallel systems for record-keeping and store sound business relationships and additional information, as their blockchains still need to completely interface with their ERP system. Therefore, we include ERP systems in the proposed system as well.

[20] Major GHG metrics include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

[21] In more complicated scenarios, if a product (e.g., EV) requires parts (e.g., tires, battery) at its manufacturing stage, its GHG calculation will be the sum of (1) GHG emissions from the direct materials and energy consumption for the EV; and (2) the required parts' Scope 1, Scope 2, and upstream Scope 3 emissions (cumulative GHG emissions until the EV manufacturing stage), which can be obtained directly from the parts' blockchains.

estimated GHG emissions can be apportioned to each company in the value chain.[22] For example, the GETS can calculate a manufacturing company's GHG emissions based on a product's sales volume recorded on-chain or assess emissions from the upstream provider's extraction of the raw materials by tracing transaction volumes on-chain. Thus, based on information on emissions in each stage, the GETS can effectively disentangle the boundaries between Scope 1, 2, and 3 emissions. With this information, auditors can aggregate the Scope 3 emissions of all of a company's products to estimate the company's total Scope 3 emissions. This estimation can be used to validate the company-issued climate-related report.[23] If any inconsistency is noticed, auditors can trace it back to the original transaction details recorded on the blockchain. In this way, auditors can efficiently validate the company's climate-related reports.

Auditors can also cross-validate transacting companies' inputs and collect evidence on erroneous data or fraudulent activities by matching values uploaded from two parties for the same types of transactions. If Company A provides electricity for Company B, the electricity meter readings for both companies can be uploaded to the blockchain at the end of each day, reflecting the amount of electricity sent by A or received by B. A discrepancy between the two electricity readings would indicate erroneous or fraudulent data input, and the smart contract would trigger a warning for both companies and their auditors. This suggests that the GETS application can mitigate the "first-mile" problem, which captures the distinction between records on the blockchain and actual physical events (Alles & Gray, 2020). Moreover, firms

[22] The apportioning to companies is possible as explained by Fortin et al. (2023) "the relationships encoded into a permissioned blockchain are different from the anonymous relationships that characterize public blockchains like Bitcoin. In a permissioned blockchain, each network participant may know the others." To apportion the emissions among companies in the value chain, companies can follow the GHG Protocol Corporate Standard Section 5.2 to determine the organizational boundary by choosing one of three options: 1) accounting for GHG emissions from operations according to its share of equity in the operation, 2) accounting for 100% of the GHG emissions over which it has financial control, or 3) accounting for 100% of the GHG emissions over which it has operational control.

[23] If a company manufactures several products, the LCA-estimated GHG emissions of all of its products should be aggregated and the total can then be compared with the value reported by the company.

with many mismatches could be identified, suggesting that further investigations should be performed to detect potential errors or fraud.

The applications of GETS will be useful for various stakeholders. For example, corporate managers can report the GHG Scope 3 emissions in their climate-related reports. Customers can evaluate a product's climate impact to decide whether to purchase it. Investors can assess a firm's climate performance to evaluate whether it has sustainable investment prospects. Potential partners can assess whether a firm's supply chains and production processes meet environmental requirements before making business deals. Auditors can use the untampered data recorded in the blockchain to perform assurance tests. Non-profit and government agencies that are concerned about climate change can obtain a reliable summary of GHG emissions for the entire value chain, monitor major emission sources promptly, and take proactive steps to reduce climate change or develop better environmental protection policies.

In summary, the life cycle component of the GETS serves as a guide for collecting climate-related data and sets up boundaries for the three scopes of GHG emissions. The infrastructure component consists of sensors that collect data from each life cycle stage, a blockchain that stores the data, and LCA software that assesses a product's overall environmental impact throughout its life cycle. The GETS offers two major applications based on the data obtained: a report on climate-related metrics, including Scope 3 emissions, and validation of companies' climate-related disclosures.

4. System Implementation

This section demonstrates the implementation of the GETS to facilitate climate-related disclosures for EVs across the entire value chain. Figure 2 shows the five steps of system implementation. Motivated by the recent critiques of automobile companies' inappropriate approach to estimating GHG emissions (Osmosis, 2021), we adapt public data and use an assumed EV manufacturing company to implement the GETS.

4.1. IoT sensor deployment

The first step is deploying IoT sensors at multiple phases of a product's life cycle to collect material and energy data. While some sensors may already be integrated into a company's operational and control systems, others will be deployed in alignment with the product's life cycle. Due to the difficulty in real implementation of IoT sensors, we provide examples and guidelines for deploying the sensors throughout the life cycle.

Table 1 shows examples of sensor deployment in different life cycle stages. For example, in raw material extraction, spectrometers could be used at mining sites to identify the mineral composition of the soil, ensuring that the extraction process targets the most valuable resources efficiently; GPS could help in mapping and planning extraction operations, enhancing safety and productivity. During manufacturing, weight and capacitive sensors could be employed at production lines of the target product to record the types and quantities of materials used, while meters could be used to monitor electricity consumption. At the delivery stage, meters could be used to record the fuel and electricity consumption of the EV, and GPS modules could be utilized to track products and corroborate the occurrence of each transaction. During the vehicle's operational life, power meters can monitor electricity consumption, and odometers can record vehicle mileage, enabling reliable calculation of emissions at this stage. Finally, spectrometers could play a role in identifying materials for recycling, ensuring that valuable components are recovered and reused. Load cells could measure the weight of recycled materials, optimizing the recycling process.

Once sensors are deployed at various sites in the product's life cycle, they can collect data needed to calculate Scope 3 emissions automatically in real-time, eliminating tedious manual data collection work. Additionally, choosing a uniform data transmission protocol for sensors before deployment would also ensure seamless integration and interoperability. Governmental agencies could establish technical specifications for sensors' design from the outset to minimize problems with data integration and comparability.[24]

4.2. Smart contracts and blockchain

The second step is verifying sensor data with smart contracts before uploading them to the blockchain. Collecting data for GHG emission estimation directly from IoT sensors and uploading the information to the blockchain can largely avoid data manipulation. We create a smart contract to automate several key functions during the posting of data collected from IoT sensors on a blockchain: 1) verifying data sources and 2) validating the data by comparing it to pre-determined thresholds and reporting any anomalies. We use Ethereum[25] as the blockchain infrastructure and Remix[26] as the integrated development environment to create the smart contract.

We program two rules into the smart contract. The first rule is to verify the data source to ensure that only permissioned participants (e.g., companies in the value chain and their registered sensors) can upload data to the blockchain. Specifically, we create one blockchain account with permission to post information on the blockchain and another account without permission.[27] Data from the permissioned account can be uploaded to the blockchain, whereas data from the unauthorized account will be rejected and trigger a warning about the unauthorized account. For example, had Hino Motors' purification equipment been registered as an authorized blockchain account, any attempts to replace it with alternate equipment that

[24] One example is ISO/IEC 30141:2018, a standard which includes considerations for IoT sensor integration and data comparability. Source: https://www.iso.org/standard/65695.html.
[25] Source: https://ethereum.org/en/.
[26] Source: https://explorer.testnet.rsk.co/.
[27] In this simulation, the account ID with permission is 0xb643d8DC8a77b18083C897095BE1e53E7C929250 and the one without permission is 0xb333d8DC8a77b18083C897095BE1e53E7C929222.

would allow the firm to pass emission evaluation tests would have been detected by the smart contracts, and the data would have been prevented from being uploaded to the blockchain.

The second rule is to monitor data and report anomalies. For example, if Energy Company A can only provide 95 kJ of electricity to manufacture the product each day, then 95 kJ can be set as the threshold in a smart contract, and any electricity consumption data above the threshold will trigger the smart contract to send a warning. This comparison function is also essential for cross-validation between pertinent data reported by two transacting companies regarding the same materials or products since nonconformity may indicate suspicious disclosures. To illustrate, if Company B records purchasing 95 kJ of electricity from Company A, but Company A records selling 150 kJ to B, the discrepancy will indicate a potential error or fraud associated with this transaction, which should be prohibited from being recorded on-chain.

The smart contract is created based on these two rules and deployed on Ethereum. Figure 3 shows the user interface of the deployed smart contract and its functionality. System users can see a data input form (Panel A, Figure 3) that sends climate-related information to the smart contract. Users first enter their addresses to verify that they are authorized to upload data to the blockchain. Panel B shows a warning raised when an unauthorized user tries to upload data. By contrast, authorized users can enter their addresses and electricity values into the form that posts the information on the blockchain. At this point, the smart contract compares the entered value with the pre-set threshold and shows a warning if the value exceeds the threshold, as shown in Panel C. Panel D shows the result when the entered value is valid and below the threshold. Note that while electricity values are manually entered into the smart contract in this implementation, the system could link with IoT devices that automatically capture the data throughout the product life cycle and upload data directly to the blockchain.

Figure 4 shows a specific transaction record on the blockchain, featuring a block number, addresses of transaction parties, transaction value, time of posting, and input. In this example, the electricity value of 65 is highlighted in a red rectangle. Thus, every interested party using this system can access climate-related data collected promptly and trust in the data integrity secured by the smart contract and blockchain.

4.3. LCA and GHG emission reports

The third step is feeding data from the blockchain and ERP systems into LCA software, and the fourth step is analyzing the input data with LCA software to generate overall climate impacts from the entire product life cycle. With material and energy data collected from sensors, validated by the smart contract, and secured by the blockchain, we feed the data from the blockchain into LCA software to assess the product's overall climate impact. In this simulation, we use GREET,[28] the free LCA software known for its ability to simulate energy use, pollutant discharge, emission output, and water consumption by various vehicles. Appendix A explains how GREET works to conduct LCA.

The fifth stthep is extracting the climate-related information from GETS applications based on users' needs. The first application of the GETS is the generation of an LCA report for the product's overall climate impact throughout its life cycle. We achieve this goal by feeding EV data into GREET, which automatically generates the report. We adapt the public GREET Database to simulate LCA and summarize the input data and parameters in Appendix B.[29] Following common LCA procedures, GREET first calculates all energy use and emissions output in the life cycle stages before the vehicle operation phase. Next, it estimates electricity consumption from the raw materials for electricity to its delivery at EV charging stations.[30]

[28] Source: https://greet.es.anl.gov.

[29] We use most of the default parameters of the "EV-Conventional material" vehicle model in GREET which resembles the parameters for most electric vehicles on the market.

[30] We calculate electricity generation by referring to the contribution of various power sources (e.g., natural gas,

Finally, GREET calculates electricity consumption and emissions output during the vehicle operation and end-of-life phases.

Table 2 shows a portion of the final report, which provides a detailed breakdown of GHG emissions generated at each stage of an EV's life cycle.[31] While the GREET report includes many details, Table 2 only displays a subset of key metrics for simplicity. For example, in the raw material extraction and delivery phases, we report the two representative materials, steel and LiPF6.[32] While the original GREET report does not show whether emissions belong to Scope 1, 2, or 3, it specifies emissions at each life cycle stage, enabling us to separate Scope 3 emissions from Scope 1 and 2 emissions according to GHG Protocol Standards. We observe that an EV produces approximately 35,569 kg of GHG emissions throughout its life cycle, with Scope 3 emissions contributing 98.1 percent. In addition, the emissions in the EV's use stage account for only 73.3 percent of the total Scope 3 emissions, suggesting 26.7 percent of Scope 3 emissions should also be reported for companies that only report emissions for the EV operation phase.[33] The table also details the substantial environmental impact of certain materials (e.g., steel and lithium) used in EV production and a breakdown of GHG emissions at different stages, making it useful for various stakeholders. For a company that manufactures several products, the estimated GHG emissions must be aggregated across all its products, and the aggregated results can then be compared to the value reported by the company.

coal, oil, nuclear) to the total electricity production in the U.S., as shown in the GREET database.

[31] GREET also reports other pollutants generated at each life cycle stage in addition to GHG emissions.

[32] In the GREET database, steel is the most used material by weight. According to the International Energy Agency, about 60 percent of lithium, 30 percent of cobalt, and 10 percent of nickel demand was for EV batteries in 2022 (Source: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries). Therefore, we report lithium hexafluorophosphate (LiPF6), which is used in most commercial lithium-ion batteries.

[33] Emissions from the EV operation stage contribute to upstream electricity production, so they also belong to Scope 3 emissions. The operation stage GHG emissions are in total 25,579 kg, and the Scope 3 emissions are the sum of Scope 3 Upstream GHG emissions (9,137 kg) and Scope 3 Downstream GHG emissions (25,760 kg). Thus, the use stage emissions account for 73.3% of Scope 3 emissions (34,897 kg).

We further analyze the credibility and usefulness of reports on GHG emissions by comparing GETS-generated reports to reports that are commonly issued by EV companies. Table 3 shows a typical report on Scopes 1, 2, and 3 GHG emissions created for the EV company from the simulation, following common practices that specialize in one type of EV product. While the Scope 1 and 2 emissions in sum are consistent with the LCA report shown in Table 2, it is evident that the company explicitly reports its Scope 3 emissions only for the use stage while omitting other sources, such as emissions from purchased parts and emissions related to upstream and downstream transportation and distribution. As a result, the reported Scope 3 emissions totals about 25,579 kg, much lower than the 34,897 kg calculated by adding all the Scope 3 emissions based on Table 2. This type of omission is not rare in practice. For example, Tesla was criticized for reporting only the emissions from its vehicles' use stage as the Scope 3 emissions in its 2021 report and not reporting comprehensive Scope 3 emissions from all stages of its vehicles' life cycle in its 2022 report (Osmosis 2021). The GETS could tackle this challenge by directly using emission details reported in Table 2. For example, the company should also report 8,680 kgCO2e from raw material extraction, 457 kgCO2e from the delivery, and 181 kgCO2e from the recycling or disposal of the EV in its Scope 3 emissions. In addition, the number of vehicles sold and their mileages can be collected by IoT sensors and recorded on the blockchain without requiring managers to estimate these values. Thus, the number of vehicles presented in the report can easily be checked, reducing the potential for managers to manipulate total GHG emissions through assumptions about vehicle usage. Moreover, auditors could readily find details by tracing back to the blockchain's original transaction records.

5. Discussion

The GETS provides prospective solutions for addressing challenges in GHG emission reporting, but its practical application would depend on whether its benefits outweigh the associated costs. Given the difficulty in actually implementing the GETS, we offer a conceptual discussion of the costs and benefits. The primary costs stem from the deployment of sensors and blockchain. The expenses associated with sensor deployment could potentially be reduced because many sensors may already be integrated into existing business operations. According to Statista, nearly two-thirds of devices now use IoT, with a global count of 15.1 billion IoT devices, projected to double by 2030.[34] Additionally, the newly deployed sensors can serve other purposes in business operations and control beyond GHG reporting. Most sensors are relatively inexpensive, with prices ranging from \$6.9 to \$169 (de Camargo et al., 2023). As for blockchain, although its initial adoption can incur substantial expenses, ranging between \$15,000 and \$130,000, depending on the project complexity and resources involved[35], participating companies will benefit in the long run. Benefits include lower transaction costs, savings in data collection efforts, and enhanced reliability and transparency of GHG data. Iansiti and Lakhani (2017) view blockchain as a foundational technology with a slow but steady uptake. They believe that blockchain will significantly reduce transaction costs and enhance transparency, and its economic impact will rival that of standardized internet protocols. According to Ripple (2023), blockchain has the potential to save approximately \$10 billion in cross-border payment costs for financial institutions by 2030. In addition, costs related to deploying and running the IoT and blockchain are expected to drop as the technology advances. Other costs may arise from the learning curve associated with LCA software and the

[34] Source: https://explodingtopics.com/blog/number-of-iot-devices.
[35] Souce: https://www.pixelcrayons.com/blog/digital-transformation/blockchain-development-cost/.

environmental impact of blockchain. These concerns can be mitigated with user-friendly LCA software like GREET and nearly carbon-neutral blockchain platforms like Ethereum.[36]

Despite the potential costs, the GETS offers several benefits. It can enhance the completeness, accuracy, credibility, and timeliness of climate-related disclosures, benefiting reporting companies, auditors, regulators, and stakeholders. Compared to the recognized GHG Protocol approach, which collects data for LCA on a yearly basis, the GETS collects data via IoT, blockchain, and smart contracts, speeding up the data gathering and reducing human errors. This saves companies significant effort since 70 to 80 percent of the time and costs of performing an LCA are attributed to data gathering (Miah et al., 2018). In addition, the GETS can identify abnormal emissions and energy consumption and send warnings to management, enabling companies to identify inefficiencies in their processes, optimize the use of resources, improve operational efficiency, and minimize the firm's carbon footprint.[37,38] Accurate data and real-time tracking support better decision-making, such as switching to cleaner energy sources or more sustainable materials. Moreover, by reducing GHG emissions, companies can lower costs by avoiding carbon taxes or reducing the use of carbon credits. The GETS also benefits firms' compliance and reputation by helping them to meet regulatory requirements more effectively and enhancing their sustainability image, which could convert into revenue. The integration of blockchain and smart contracts in the GETS not only ensures data integrity but also facilitates data sharing across value chains, leading to better coordination among suppliers and manufacturers in efficient resource allocation. For the environment, the GETS

[36] Ethereum has been transitioning from a Proof of Work (PoW) to a Proof of Stake (PoS) consensus mechanism through its Ethereum 2.0 upgrade, turning much more energy-efficient because it removes the computationally intensive process of mining. This transition is expected to reduce Ethereum's energy consumption by over 99%, moving it closer to carbon neutrality.

[37] According to Fortin et al. (2023), organizations benefit from permissioned blockchains by rethinking and reshaping the their work practices and information flows, and thus streamlining their business and accounting processes. Companies are also using the GPS location, the temperature data on the truck, the whereabouts to track their goods in real-time.

[38] Brilliantova and Thurner (2019) find that electricity sector is using blockchains support the decentralisation of energy production and the oil and gas sector is using the blockchain for business process optimisation.

can not only aid in direct reductions of GHG emissions through more efficient operations and material use but also promote a systemic shift toward sustainability by enhancing transparency and improving resource allocation. The environmental and social impact of making activities visible can encourage businesses to innovate and adopt greener technologies and practices, contributing to sustainable development goals. Collectively, these advancements contribute to more sustainable industry practices and help to tackle the broader challenges of climate change.

The effectiveness of the GETS relies on the active participation of companies in the value chain. Limited engagement may hinder system performance due to a lack of verification for the blocks, insufficient data input for the LCA model, and lack of evidence to perform cross-verification among companies' GHG emission disclosures. Future research can investigate appropriate incentive mechanisms to encourage companies to participate in the system. Regulators and industry associations could support the adoption of the system and use it as the primary channel to record and disclose companies' climate-related activities and transactions. Auditors may need to assess collusion risks and consider the participation of companies throughout the value chain when utilizing information from the chain.

6. Conclusion

Scope 3 emissions are a key component of climate-related disclosures, but their measurement and reporting remain challenging due to complexities in data collection and emission allocation throughout the entire value chain. LCA addresses this problem by examining the environmental impacts of a product throughout its entire life cycle. A well-known challenge for LCA is finding a way to collect data reliably and effectively. This study introduces blockchain and IoT to alleviate this concern by leveraging blockchain's advantages of decentralization, transparency, trustworthiness, and programmability.

This paper proposes GETS, a system that leverages LCA, blockchain, and IoT to collect and distribute climate-related data effectively, providing a comprehensive overview of environmental impact across an entire value chain. We implement the system and demonstrate that it can be used to generate a comprehensive climate-related report for an entire value chain and validate climate-related information reported by participating companies.

This paper contributes to climate-related disclosure by creating synergy through the innovative integration of LCA and technologies within the GETS. The IoT enables automatic data collection from various sites, and smart contracts and blockchain ensure data authenticity. The proposed system provides integrated climate-related reports for an entire value chain and enables the validation of company climate-related reporting via LCA outcomes. Reporting companies can benefit from the system for estimating Scope 3 emissions, offering a trustworthy summary of emissions across the value chain, identifying major emission sources promptly, and enabling more proactive measures to be taken to reduce climate risks. Additionally, the system aids auditors in assurance tests by providing traceable records and original, untampered data. By adopting our proposed system, policymakers can also gain insights into the most polluting segments and stages of value chains, facilitating the promotion of digitalized climate disclosures. Overall, our results highlight the potential for emerging technologies to enable reliable, complete, and accurate climate-related disclosures.

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Figures

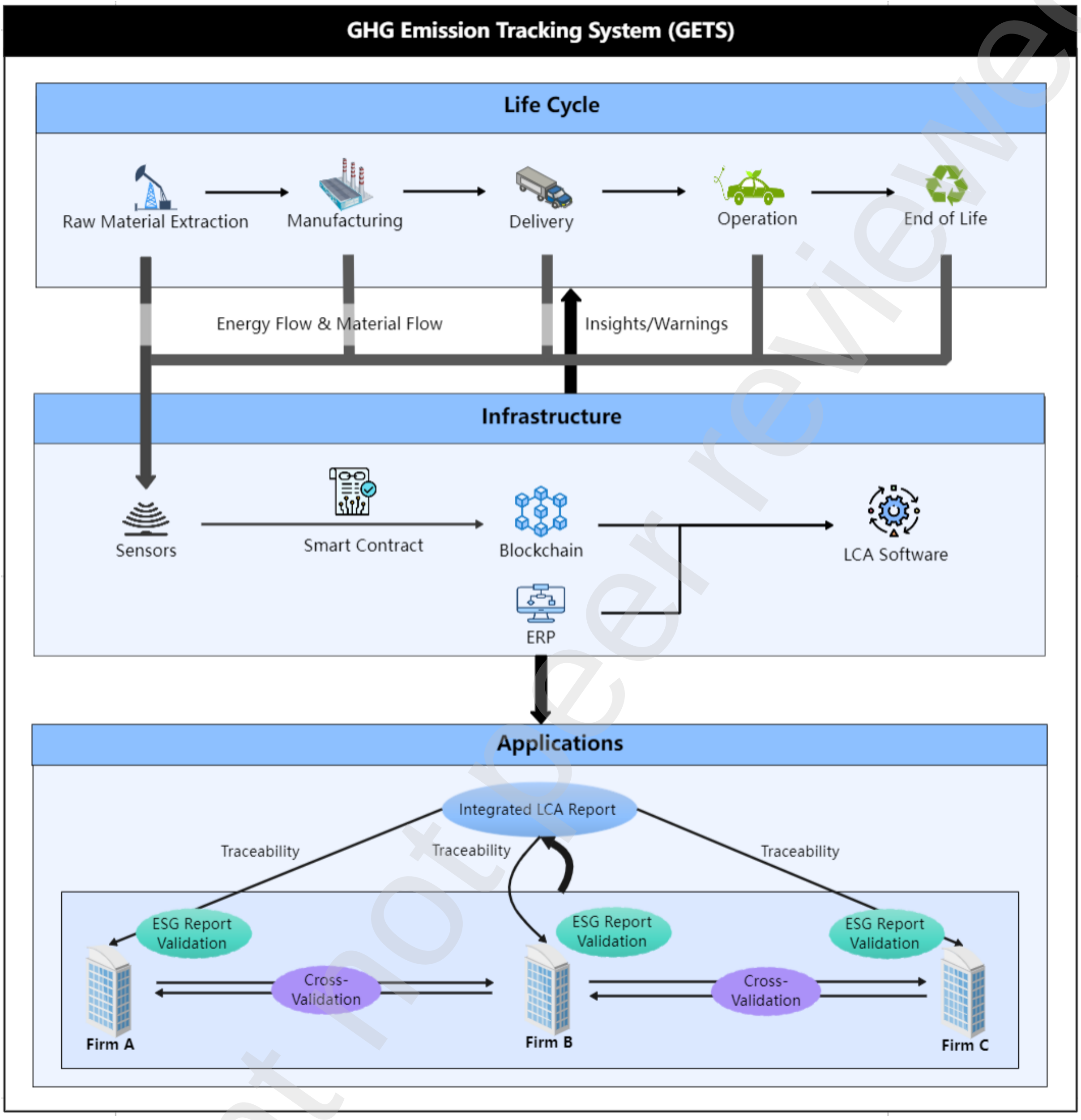


Fig. 1. Proposed GHG Emission Tracking System (GETS) and Its Applications

Fig. 1 shows the components of proposed GHG Emission Tracking System (GETS) and its applications.

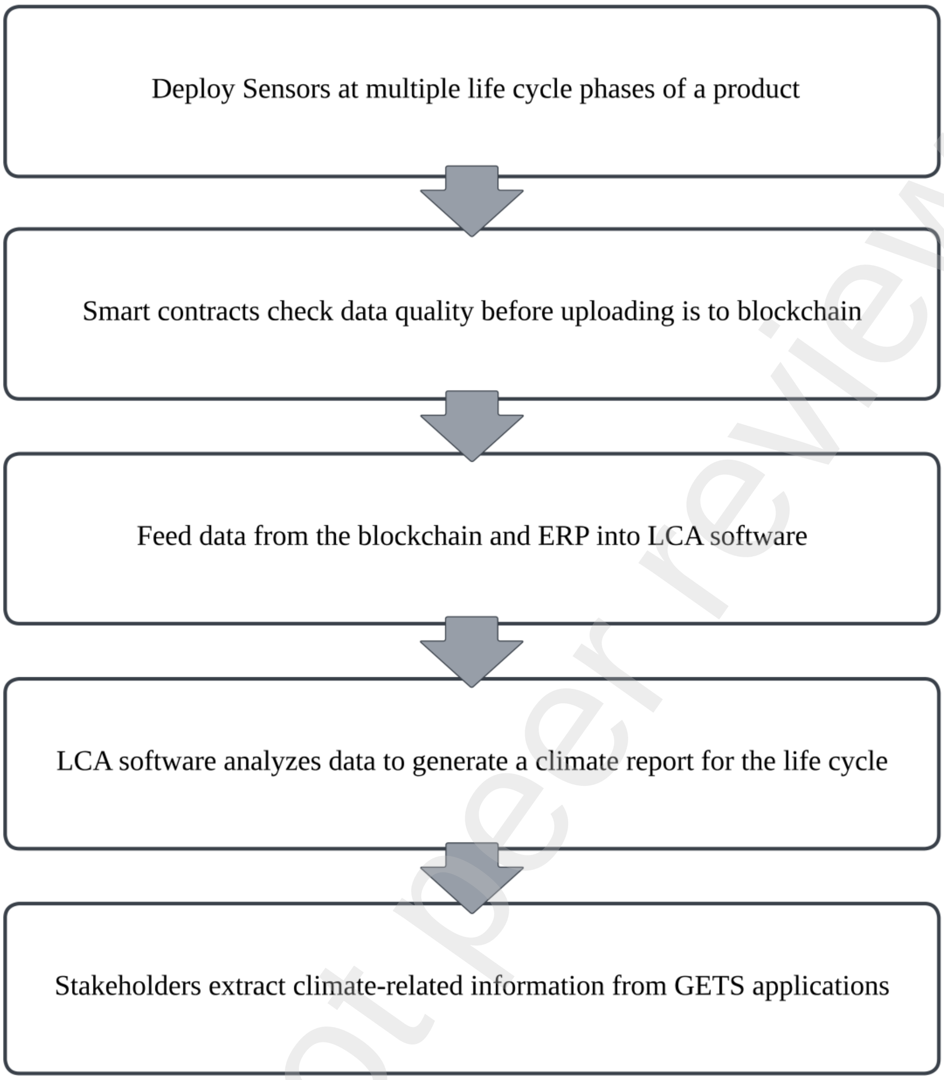
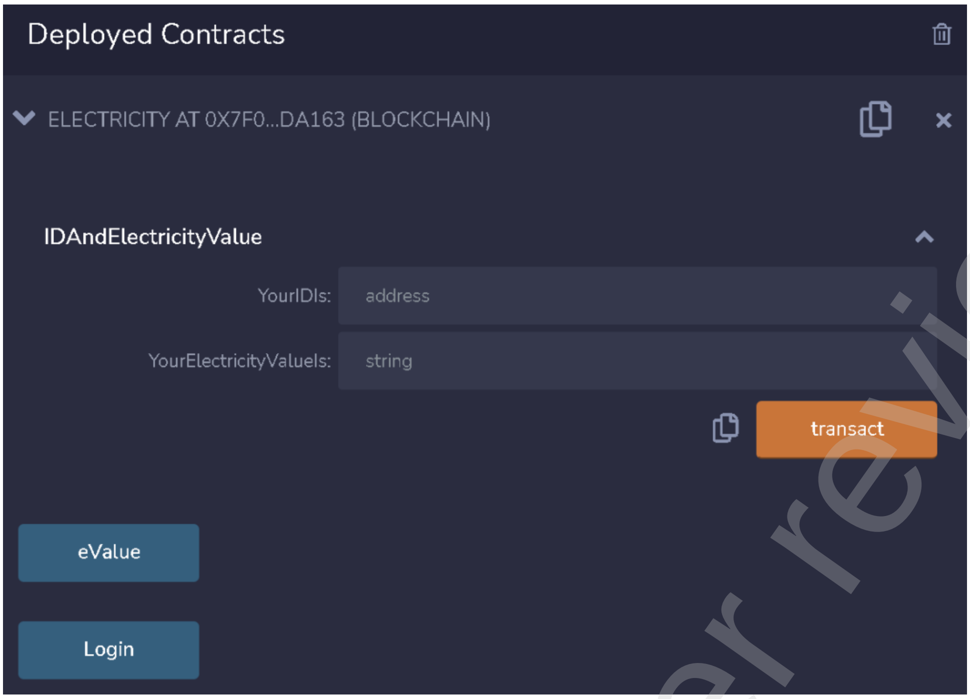
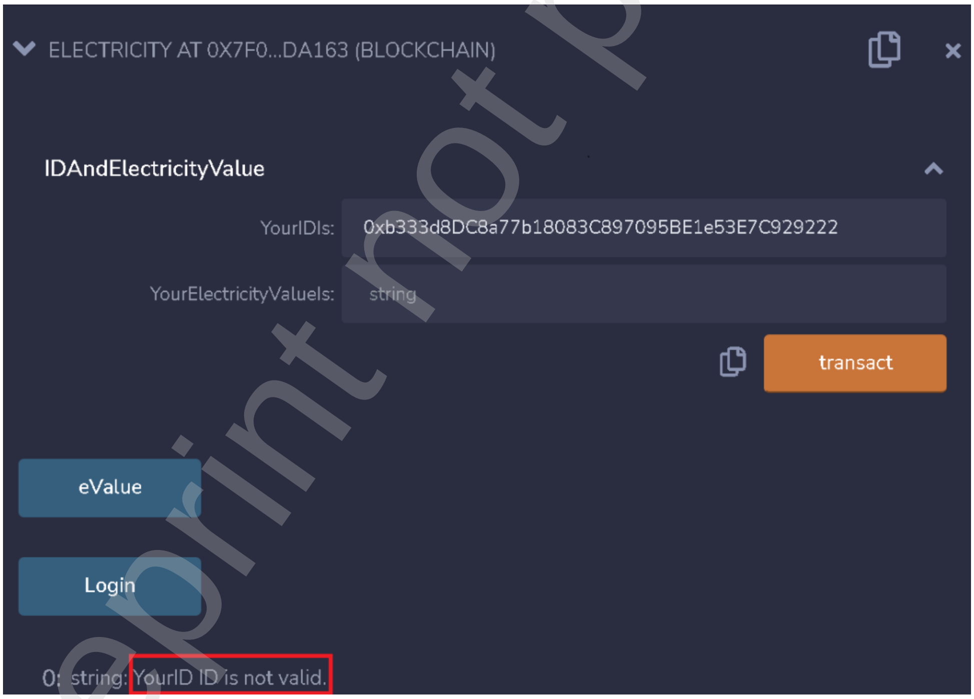


Fig. 2. System Implementation Procedures
Fig. 2 shows the five steps of the GETS system implementation.

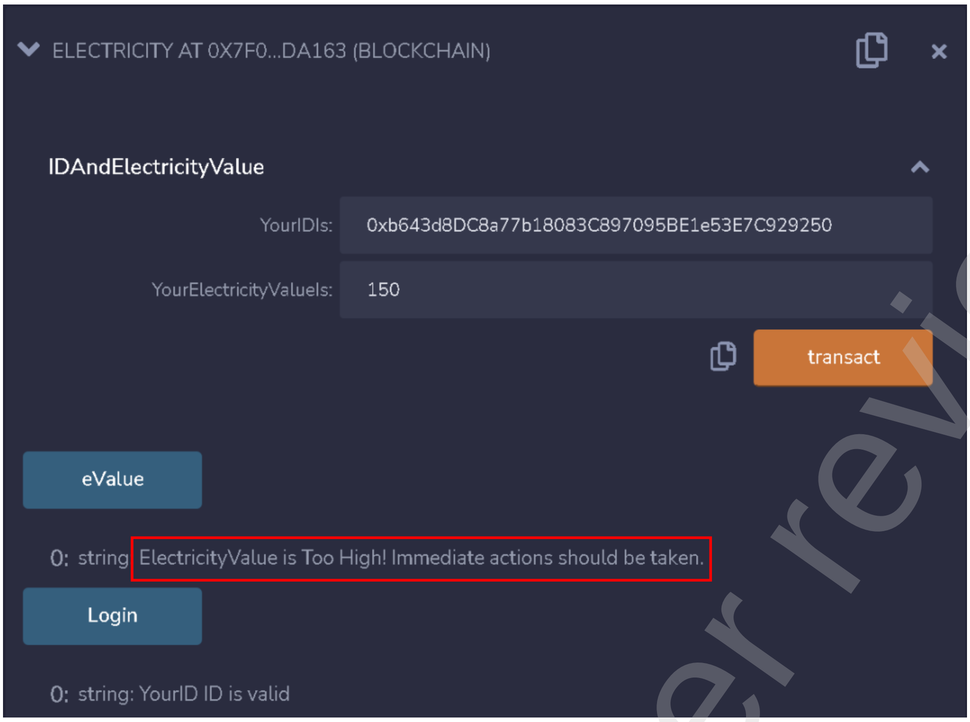
Panel A: Data Input Window for Data Source Verification and Data Monitoring



Panel B: An Unauthorized Attempt Identified by Data Source Verification



Panel C: Data Monitoring and Anomaly Reporting



Panel D: Data Monitoring in a Normal Case

Fig. 3. Smart Contract Examples

Fig. 3 shows a smart contract and its functions. Panel A shows the user interface. Panel B alerts an unauthorized user. Panel C wanrs an authorized user of input surpassing the threshold. Panel

D shows the scenario when the input value is valid.

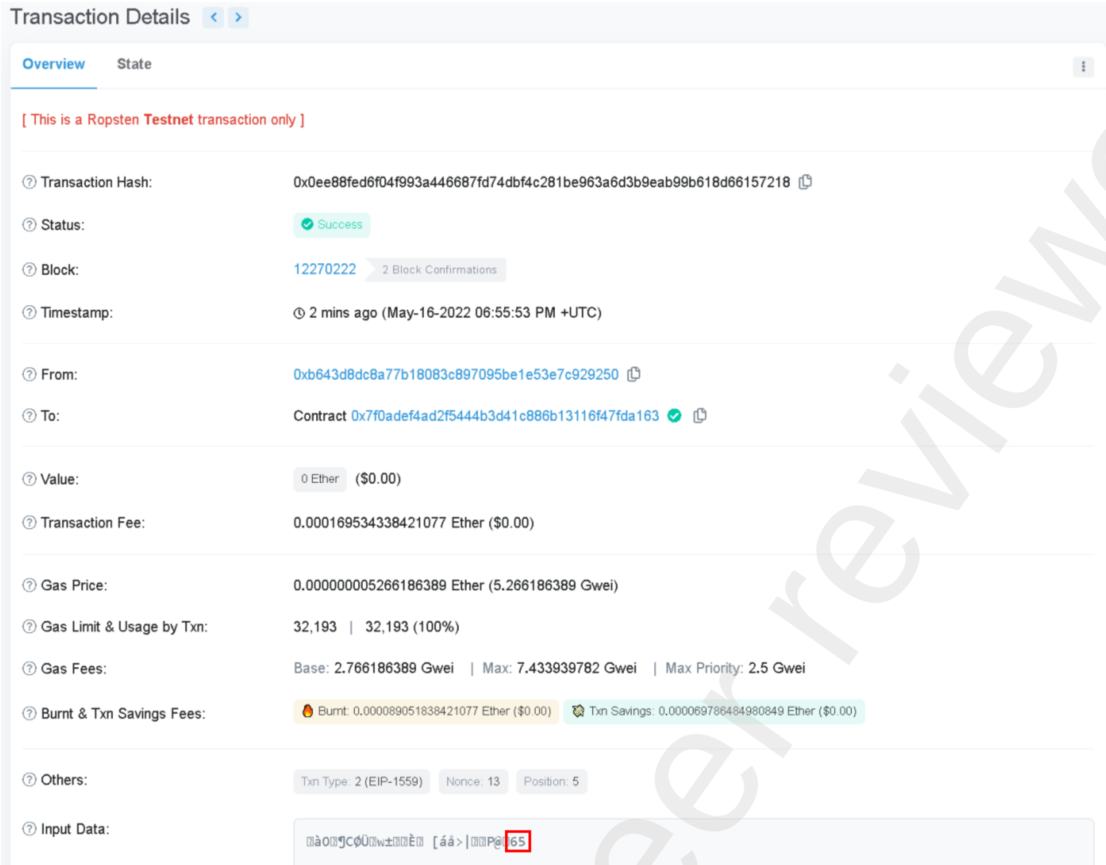


Fig. 4. Detailed Information of a Record

Fig. 4 shows a specific transaction record on the blockchain with details including a block number, addresses of transaction parties, transaction value, time of posting, and input data.

Tables

Table 1
Sensors and Their Usage at Various Sites

Sensor	Usage	Data Captured	Location
Raw Material Extraction Stage			
Spectrometer	Identifying mineral composition of ores	Mineral content, ore grades	Mining sites, ore processing facilities
GPS	Tracking mining vehicles and equipment	Location data	Mining sites, transportation vehicles
Flow Meters	Monitoring water usage during extraction	Water consumption	Water supply pipelines
Manufacturing Stage			
RFID Tags	Tracking materials and components throughout production	Material identification	Production lines and assembly stations
Load Cells	Weighing raw materials and components	Weight of materials	Conveyors, production lines
Capacitive Sensors	Recognizing types of materials used	Types of materials	Inspection points in the production lines
Ultrasonic Sensors	Measuring thickness and quality of coatings or materials	Coating thickness, material integrity	Inspection points in the production lines
Temperature Sensors	Monitoring energy consumption and process efficiency	Temperature, energy usage	Machinery and process equipment
Delivery Stage			
Fuel Flow Meters	Measuring fuel consumption during transportation	Fuel usage	Delivery vehicles
GPS	Tracking vehicle routes and locations	Location data	Delivery vehicles
Use Stage			
Power Meter	Monitoring electricity consumption during vehicle use	Energy usage	Charging stations, electric vehicle energy meters
Battery Management System	Tracking battery performance and efficiency	Battery status, charging/discharging data	Electric vehicle battery pack
Odometer	Recording vehicle mileage	Distance traveled	Electric vehicle dashboard
Recycling/Disposal Stage			
Near-Infrared Sensors	Identifying and sorting recyclable materials	Material identification, sorting data	Recycling facilities
Weight Sensors	Weighing recyclable materials	Weight of materials	Conveyor belts at

			recycling facilities
Barcode/RFID Scanners	Tracking recycled materials and components	Material identification, quantity	Recycling and disposal facilities

Note: This table shows examples of sensor deployment in different life cycle stages of an electric vehicle, from raw material extraction through to recycling/disposal. It categorizes sensors such as spectrometers, GPS, flow meters, RFID Tags, and load cells by their usage, data captured, and location.

Table 2
Life Cycle GHG Emission Report of an Electric Vehicle

Electric Vehicle Life Cycle GHG Emission Report										
Stages	Raw Material Extraction			Delivery			Manufacturing	Operation	End of life	Total
	Steel	LiPF6	Total	Steel	LiPF6	Total				
GHG Emission (kg)	Scope 3						Scope 1&2	Scope 3		
CO_2	1,787.848	47.220	8,646.960	94.097	2.485	455.103	670.569	25,525.351	180.446	35,478.429
CH_4	3.081	0.098	32.600	0.162	0.005	1.716	1.783	53.612	0.379	90.090
N_2O	0.017	0.000	0.308	0.000	0.000	0.016	0.018	0.509	0.004	0.854
Total	1,790.946	47.319	8,679.868	94.260	2.491	456.835	672.370	25,579.471	180.829	35,569.373

Note: This table shows GHG emissions generated at each life cycle stage as estimated by GREET. For simplicity, we only report a subset of key metrics among many available in GREET. In the raw material extraction and delivery phases, we use the two most representative materials, steel and LiPF6, as examples. We separate Scope 3 emissions from Scope 1 and 2 emissions based on the life cycle stages according to GHG Protocol Standards. Note that the emissions associated with vehicle operation all contribute to upstream electricity production, so they belong to Scope 3 emissions.

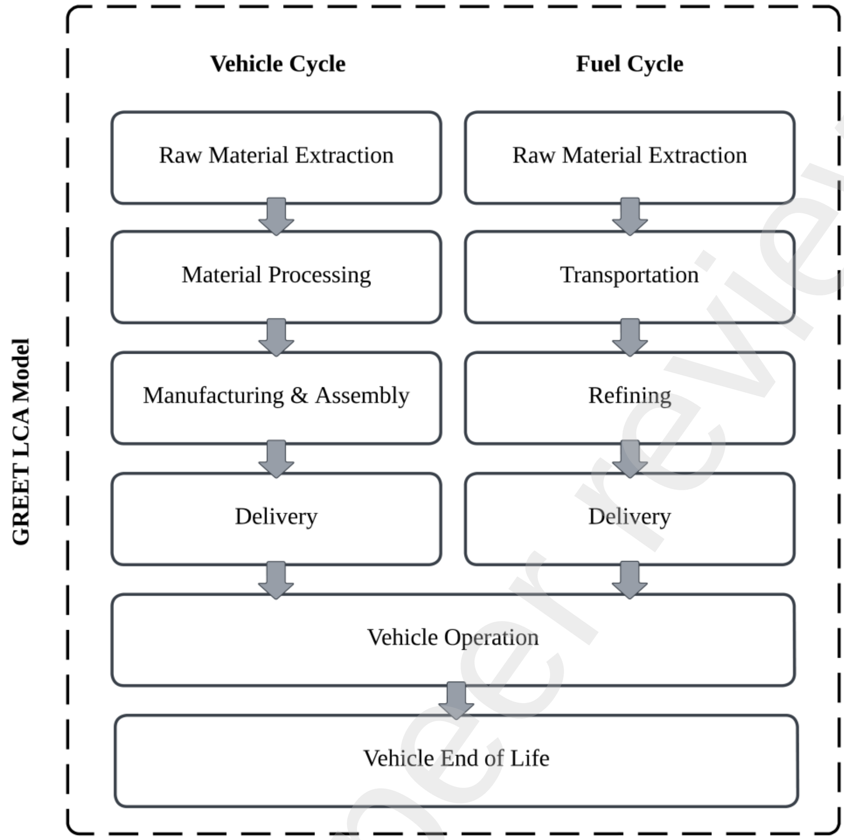
Table 3
The Electric Vehicle Company's GHG Emission Report

2023 Electric Vehicle GHG Emission Report	
Scope 1 & 2 Emissions (kgCO2e)	
Manufacturing	504.28
SSD	100.86
Other	67.24
Total	672.37
Scope 3 Emissions (kgCO2e)	
Use of sold EV products	25,579.47
Estimated sales volume of EV products	1,110.00
Total	283,932,12.81

Note: This table shows the GHG emissions of Scope 1, 2, and 3 reported by the EV's company itself. The company report only the use stage of the EV product as Scope 3 emissions, while omitting other important components of Scope 3 emissions, including emissions from purchased goods, as well as emissions related to upstream and downstream transportation and distribution.

APPENDIX

Appendix A. LCA Software: GREET Model



As shown in the figure above, GREET has two life cycle streams. The *Fuel Cycle* model calculates energy use and emission output in the raw material extraction, transportation, refining, and delivery phases. For EVs, electricity is the main focus of the *Fuel Cycle*. Accordingly, the raw material extraction stage refers to the extraction of initial energy resources (e.g., oil, coal, or biomass) to generate electricity. The transportation stage refers to transporting energy resources to power stations. The refining stage refers to the generation of electricity. The delivery stage covers the transportation of electricity from power stations to charging facilities.

The *Vehicle Cycle* model explores the life cycle stream of energy and material use, and the emission output associated with the life cycle stages of EVs. Together, the *Fuel Cycle* and the *Vehicle Cycle* constitute GREET's LCA model for EVs.

Following common LCA procedures, GREET first calculates all energy use and emissions output in the *Vehicle Cycle* before the vehicle operation phase. Next, it estimates electricity consumption during the *Fuel Cycle* from the raw material for electricity to delivery at EV charging stations. Finally, the *Vehicle Cycle* model calculates electricity consumption and emissions output during the vehicle operation and end-of-life phases.

Appendix B. LCA Data Input

Input Data	Value	Unit
Raw Material Extraction Stage		
Steel	1,772.99	lb
Cast Aluminum	310.66	lb
Glass	64.93	lb
Extraction Use of Electricity	24,857.25	KWh
Manufacturing Stage		
Battery - Lead-Acid (Vehicle Battery Assembly)	22.1	lb
Battery - Lithium-ion Battery Bill-of material	1,373.24	lb
Lithium Ion (Vehicle Battery Assembling Part)	47.16	lb
Components Power train System	105.81	lb
Components - Transmission System/Gear box	130.09	lb
Components - Chassis (w/o battery)	563.75	lb
Components - Traction Motor (HEV, PHEV, EV, FCV)*	216.81	lb
Components - Electronic Controller (HEV, PHEV, EV, FCV)	137.31	lb
Components - Vehicle Body	1,173.74	lb
Components - Vehicle Tire Replacement*	20.00	lb
Fluids - Brake Fluid*	2.00	lb
Fluids - Transmission Fluid*	1.85	lb
Fluids - Engine/Powertra: Coolant*	15.77	lb
Fluids - Windshield Fluid*	6.00	lb
Fluids – Adhesives*	30.00	lb
Manufacturing Use of Electricity	16,539.15	KWh
Delivery Stage		
Fuel Consumption of Transportation	15.83	L
Delivery Use of Electricity	502.12	KWh
Vehicle Operation Stage		
Lifetime VMT (Vehicle-miles Travelled)	200,000	km
Operation Use of Electricity	31,247.53	KWh
End-of-life Stage		
Vehicle Disposal and Recycling	1897	kg
Battery - Lithium-ion Battery Bill-of material	1,373.24	lb
End-of-life Use of Electricity	2,637.64	KWh

Note: This table summarizes data input to the LCA software. The data is publicly available in the GREET database. In the manufacturing phase, some materials are products produced by a supplier rather than by the electric vehicle company itself. For those products, the LCA uses Scope 1, Scope 2, and upstream Scope 3 GHG emissions reported from their blockchains. We use * to indicate the products produced by a supplier rather than the company itself. We calculate electricity generation by referring to the contribution of various power sources (e.g., natural gas, coal, oil, nuclear, wind) to the total electricity production in the U.S., as shown in the GREET database.

A Blockchain-based Greenhouse Gas Emission Tracking System (GETS) for Climate-Related Disclosures

Lanxin Jiang*[a], Yu Gu[b], Wenjun Yu[c], Jun Dai[d]

[a]Rutgers, The State University of New Jersey, Rutgers Business School, One Washington Park, Newark NJ 07102, USA, email: lj334@scarletmail.rutgers.edu

[b]Rutgers, The State University of New Jersey, Rutgers Business School, One Washington Park, Newark NJ 07102, USA, email: yg431@scarletmail.rutgers.edu

[c]PricewaterhouseCoopers Digital & Data Center (Chengdu) Co. Ltd., 1268 Tianfu Avenue Middle, Chengdu 610041, China, email: jevin.w.yu@cn.pwc.com

[d]Michigan Technological University, College of Business, 1400 Townsend Drive, Houghton, Michigan 49931, USA, email: judai@mtu.edu

*Corresponding author

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JEL classifications: M40; M11; M15; Q54; Q55.