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Digital Proofs of Origin for Sustainability

Assessing a Digital Identity-Based Approach in the Energy Sector

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Preface

On April 29, 2024, the European Parliament voted in favor of a revised version of the regulation on electronic identification and trust services for electronic transactions in the internal market (*eIDAS Regulation*), paving the way for the introduction of a European Digital Identity. This development aims to empower citizens and organizations to electronically secure digital proof of identity and exchange verifiable documents, facilitating seamless digital authentication across Europe. This revision not only represents a significant step forward in enhancing digital transaction efficiency within the internal market, but also addresses the critical need for secure, universally accepted digital identities.

The eIDAS 2.0 revision is aligned with the Self-Sovereign identity (SSI) principle – both advocate enhanced privacy, security, and user autonomy in managing their digital identities. Instead of a centralized identity with security and privacy issues, personal information is stored directly by a citizen, providing high security and convenience while improving control over the disclosure of personal data. Convenient, secure, and efficient management of cross-provider digital identity credentials is carried out via digital wallets, enabling a wide range of applications, such as password-free log-in to websites or more efficient interactions with corporate and government services. This paradigm also offers new possibilities, such as the selective disclosure of identity attributes or the automatic verifiability of digital proof of identity by service providers. In addition to digital identities for people, SSI also enables proof of identity for machines and organizations, extending existing identity management systems. To further explore the potentials of SSI-based identity management, Germany's government is involved in several SSI projects, such as the four showcases Secure Digital Identities funded by Germany's Federal Ministry of Economics and Climate Protection.

This white paper, which presents parts of the results of the ID-Ideal project, one of the four showcase projects, seeks to advance user-friendly, trustworthy, and economically viable digital identities for individuals, companies, and governments with broad applications across multiple sectors. Within the use case *Energy* (working package 8), our work focuses on the electricity sector, levering the SSI paradigm for organizations, individuals, and machines to enable fine-grained proofs of origin for electricity. The development of a system for such fine-grained proofs of origin for electricity can enable end-consumers and organizations to make CO_2-adaptive decisions and would represent a significant step in the pursuit of data-based decarbonization. The integration of SSI greatly enhances data privacy and sovereignty over users' own data, establishing a robust foundation for widespread acceptance. The proposed architecture can also serve as a blueprint for tracking emissions in sectors other than electricity. Our approach promises transparency and end-to-end traceability, laying the foundation for a data-sovereign Digital Product Passport.

We trust that you will enjoy reading this white paper and warmly invite you to enter into dialogue with us.

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Content

1. Motivation

CO_2-Adaptive Decision-Making

Decarbonization is a critical economic and societal challenge of our time, as illustrated by political efforts across the EU (e.g. the EU Green Deal) and around the world (e.g. the Paris Agreement, the Inflation Reduction Act in the U.S.). One promising approach for decarbonization is to assess and manage industrial processes and economic activities based on their greenhouse gas (GHG) – and especially carbon dioxide (CO_2) – intensity. This requires CO_2-adaptive decision-making for end-consumers and organizations across different stakeholders by for instance shifting CO_2-intensive processes to times and places where they produce the least emissions. Thus, individuals and organizations need a trustworthy data basis to deduce reliable information as the foundation of their economic decisions. Yet existing certification schemes and related information systems (ISs) lack the necessary precision to track GHG emissions in terms of both local and temporal granularity. To enable such local and temporal fine-grained systems, one must more precisely collect GHG emission data. Preferably, these data should be primary, meaning the are obtained directly, for instance through measurement. To address this gap, we have developed a system based on the concept of self-sovereign identities (SSI). By levering SSI for organizations, individuals, and machines, our developed system enables the collection and sharing of primary data from electricity power plants along the electricity supply chain – specifically master data (e.g. the location) and transaction data (e.g. the amount of electricity generated) – as we will outline herein. By doing so, our system accounts for GHG emissions in the energy sector with the required temporal and spatial resolution. Thus, it can among others enable endconsumers to access (near-)real-time information about their electricity consumption's CO_2 intensity, enabling informed decisions so as to minimize their carbon footprints and effectively monitor their emissions.

Context and Use Case

Here, we present the use case Energy in the project ID-Ideal, which is funded by Germany's Federal Ministry for Economic Affairs and Climate Action (BMWK) in the context of the showcase entitled Secure Digital Identities. This initiative seeks to advance user-friendly, trustworthy, and economically viable digital identities for individuals, companies, and governments with broad applications across multiple sectors. The use case Energy focuses on the electricity sector and levers SSI for organizations, individuals, and machines to enable fine-grained proofs of origin for electricity. Our idea is to develop an end-to-end architecture for creating a credential about the CO_2 emissions arising from electricity production and then passing them on, through the various actors in the electricity supply chain, to the end-consumers. Such an end-to-end architecture allows end-consumers to use such proofs of origin for multiple use cases, such as voluntary CO_2 offsetting, individual CO_2 footprint monitoring, or more trustworthy green labels for sustainable products. Our approach can also provide the basis for new business models and sustainability concepts, as we will outline. Our concept has been demonstrated in a prototypical implementation that can determine the CO_2 emissions associated with charging an electric vehicle (EV), showcasing the practical application and potential of the system.

We focus on the electricity supply chain, because electricity generation is a primary source of CO_2 emissions, providing significant potentials for decarbonization. Further, electricity has several unique characteristics, as we will illustrate in Chapter 2. One cornerstone of climate policy that affects the electricity sector is the EU Emissions Trading System (ETS). It obliges electricity suppliers to offset the CO_2 emissions associated with electricity generation by purchasing EU allowances. However, the current system does not allow these allocations to be passed on transparently to users because the latter don't interact with the system. Instead, the main way in which end-consumers notice an ETS's existence is through higher prices, which are passed on to them by the companies concerned. Very high CO_2 prices are currently politically unfeasible owing to social imbalances and expected public resistance. However, a rapid increase in CO_2 prices would be necessary to achieve steering effects. The small increases in CO_2 prices that we are seeing today are overshadowed by general price fluctuations, making it almost impossible to use CO_2 prices as a steering tool. We therefore advocate fine-grained, secure proofs of origin for purchased electricity as a way to make CO_2 emissions visible and traceable, thereby laying the foundation for the desired steering effects. It is crucial that a novel system for such proofs of origin and associated CO_2 emissions be comprehensive and can be integrated with or run in parallel to existing ETSs and other certification schemes (e.g. guarantees of origin / GOs). Thus, the use case Energy seeks to develop an interoperable and flexible technical solution.

Product Carbon Footprint and Privacy

Our starting point is the individual allocation or summation of a product's CO_2 emissions, essentially creating a product CO_2 (*carbon*) footprint for electricity. As the allocation relating to individual products and processes requires collecting (partially sensible) data, it is crucial to ensure privacy for all stakeholders (e.g. the electricity producers and the end-consumers). To do so, we adopt the SSI approach. SSI represents a new paradigm that addresses the challenges of current identity management systems and allows users to identify and store information about themselves under their control. In this context, we note that, with an SSI-based approach, it may also be possible to trace the feeding of green electricity into and out of batteries (e.g. for CO_2 balancing in companies).

2. Foundations

The Electricity Sector and Greenhouse Gas Emissions

Most GHG emissions in the EU are associated with our energy supply, accounting for more than 900 megatons of CO_2-equivalents in 2021 (EAA 2024). Thus, the energy sector plays a key role in decarbonization. Owing to sector coupling, which will result in increased electrification (e.g. in the mobility sector), the electricity sector must be swiftly decarbonized. Shifting to more renewable energy sources in electricity generation is the biggest lever for decarbonizing the electricity sector (Papadis and Tsatsaronis 2020).

In a traditional electricity supply chain, electricity flows unidirectionally (i.e., from generation to consumption) and electricity generation, transmission, and distribution are centralized (Bouffard and Kirschen 2008). Owing to technological innovation and the increasing share of renewables in the electricity mix, among others, the traditional supply chain is becoming more decentralized through an increasing amount of distributed generation, which is mainly renewable, small-scale, and close to the points of consumption (Allan et al. 2015)

In the electricity supply chain, a distinction must be made between a physical and a balance sheet path (see Figure 1). The **physical path** is represented by the actual electricity grid. The generator feeds electricity into the local distribution network and consumers withdraw it from there. In this network, it is crucial to balance supply and demand, managed at the local level by balancing group managers (e.g. municipal utilities) and at the supra-regional level by transmission system operators. A key characteristic of the physical path is that it becomes indistinguishable once electricity enters the grid. This makes it impossible to trace where it originated and determine how much CO_2 emissions are associated with this specific amount of electricity.

In contrast, the **balance sheet** is concerned with tracking and tracing electricity as a (tradeable) commodity. In the standard case, an energy supplier contracts with power producers to secure capacity and then buys the electricity. Any overcapacity or undercapacity on the part of producers and suppliers is then usually balanced out in the power exchange. The electricity supplier then passes the electricity on to the demand side. If customers are large enough (e.g. a charging point operator / CPO), they can purchase electricity directly without going through an electricity supplier. By the end of a billing period at the latest, it is always possible to know which electricity producer has delivered how much electricity from which source to the electricity supplier and how the supplier has delivered the electricity to its customers. Based on balance sheet accounting approaches, electricity can be certified independently from the physical electricity flow, count as electricity stemming from renewable energy sources, and contribute to archieving decarbonization goals. We will now explain the two fundamental frameworks in place for certifying electricity and emissions in Europe: GOs and Emissions Trading. The electricity and data flows are illustrated in Figure 1.

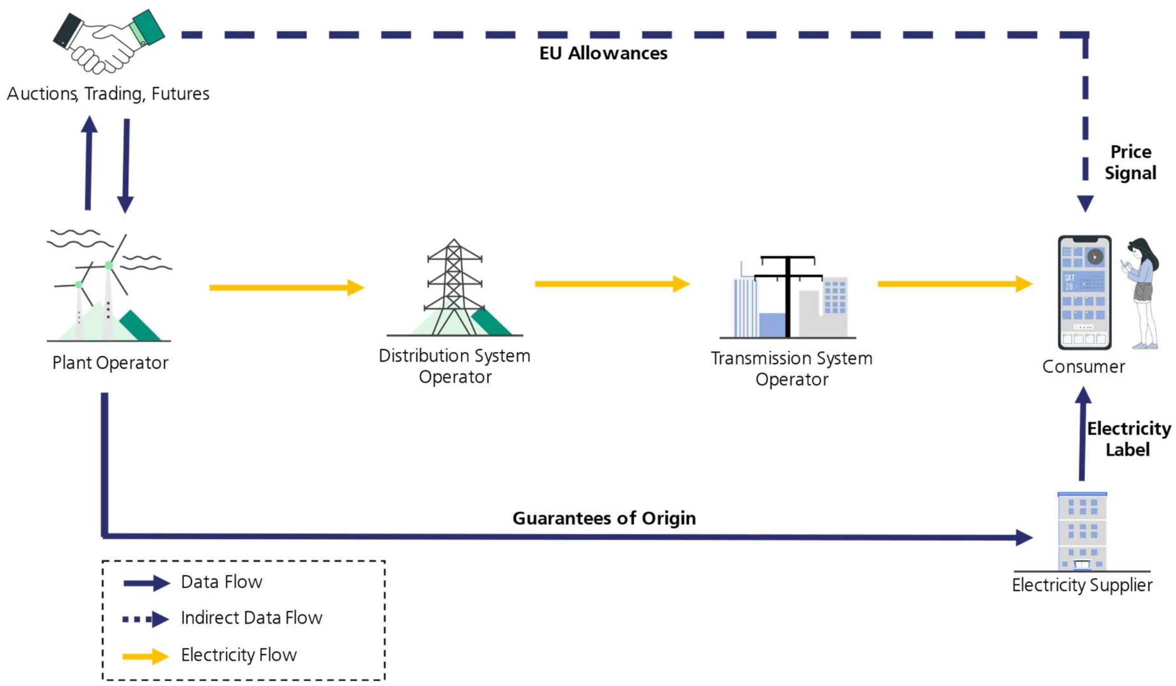

Figure 1: Physical flow and balance sheet flow of electricity and emissions

Guarantees of Origin

In the EU, GOs provide a way to voluntarily certify electricity. Established by the Renewable Energy Directive 2018 (2018/2001/EC), each GO certifies for end-consumers that 1 Megawatt is generated from renewable energy sources[1] and is spent only once. GOs are valid for a year, so there is no **temporal match** between production and consumption. Thus, a company could for instance use GOs from electricity produced in January to cheaply certify all the electricity it consumed during a year. This is possible owing to the surplus of renewable energy during specific times. However, the companies' physical electricity would still be produced from sources such as coal in times of low renewable electricity generation.

Further, GOs can be purchased from any producer participating in the respective European market, i.e. there is not necessarily a **local match** between production and consumption in this large geographical area. This reinforces the abovementioned problem concerning cheap GOs. A German company could for instance use GOs from electricity produced in Norway to certify its electricity even if there is little or no physical flow of electricity between the two countries. The physical electricity would, again, be produced from non-renewable sources.

Emissions Trading

Emissions trading was first established on an international level in the Kyoto Protocol as one of the voluntary and flexible economic mechanisms proposed to the signatory states for achieving their individual GHG emission reduction targets (UNFCCC 1997). Most ETSs operate on the **Cap-and-Trade** principle. The general idea is to set a cap on CO_2 emissions and distribute emission permits to companies, giving them the right to emit GHGs (Hepburn 2007). These permits can be traded on a market so that a company can buy more credits if necessary or sell them if it does not need them (Sonneborn 1999). The approach of allocating emissions to polluters is called **upstream**, while in **downstream** approaches authorities distribute allowances to consumers (Kothe et al. 2021). The EU ETS represents a mandatory downstream approach following the Cap-and-Trade principle where, among others, electricity suppliers must offset the CO_2 emissions embodied in their generated electricity by purchasing EU Allowances. Besides mandatory emissions trading, voluntary carbon markets also enable the voluntary offsetting of CO_2 via a similar approach. Established ETSs – similarly to GOs – do not provide a temporal and local matching for certification.

[1] In some EU member states, certification for nonrenewable energy sources is also possible.

Digital Identities and Self-Sovereign Identity

Digital identities are becoming increasingly important in an interconnected world, where virtual interactions and transactions are omnipresent. Typically, a digital identity refers to a subject, such as a person (Alamillo-Domingo 2020), and is used for digital identification, authentication, or authorization in different services. These identities are relevant in various application areas – such as e-commerce, e-government, or digital banking – and can provide the necessary trust for secure online interactions. Current trends include extending digital identities beyond individuals to machines and organizations, thereby opening various use cases.

The ID-Ideal project seeks to explore different application areas of digital identities, particularly SSI. Unlike traditional models, where identity information is centralized and managed by third parties, SSI empowers individuals to maintain complete control and ownership of their identity data. This paradigm grants users the autonomy to manage and share their personal information as they choose (Sedlmeir et al. 2021). It resonates strongly in today's digital landscape, as it addresses critical concerns around privacy, security, and user consent, promoting a privacy-centric and user-controlled approach to digital identity management. A distinct feature of SSI is the bilateral flow of information with the user at the center and the interoperability between different application cases, enabling the creation a digital ecosystem.

SSI architectures are generally built on several foundational elements. Central to these are Verifiable Credentials (VCs), which function as an envelope in which various information types can be stored. These VCs can represent physical credentials, such as passports and driver's licenses, or more abstract ones, such as CO_2 certificates or prescriptions. VCs are typically cryptographically secured, making them tamper-proof and verifiable (Sedlmeir et al. 2021). Verifiable Presentations (VPs) are another crucial component, as they allow the presentation of one or more VCs in a verifiable form, tailored to the requirements of a specific transaction (e.g. a person's address and date of birth). Various cryptographic methods, such as Zero Knowledge Proofs (ZKPs), can enable selective disclosure, allowing users to provide only the attribute relevant to the presentation (e.g. a person's age) without compromising the displayed credentials' verifiability. Similar to a physical wallet, digital wallets act as secure storage for VCs from multiple sources, facilitating their management and use in different applications (Preukschat 2021), thereby becoming a critical interface for users in the digital identity system (Jørgensen and Beck 2022). To introduce the different actors in an SSI ecosystem, Figure 2 provides an overview over their typical interactions therein (Preukschat 2021):

- Each VC is created by an *issuer*, who can be uniquely identified with a Digital Identifier (DID) stored in a verifiable data registry. This VC contains claims and corresponding metadata, which are digitally signed so that they cannot be altered. The VC is then transmitted to the holder.
- The *holder* can store the VC in their digital wallet after receiving it. When creating a VP, the holder can, among other things, combine several credentials or can selectively disclose specific claims without affecting the credentials' validity. The holder does not necessarily have to be the subject of the credential.
- The *verifier* requests a VP from the holder. The VP proves to the verifier that the presented information is valid and has not been modified or revoked by the issuer.

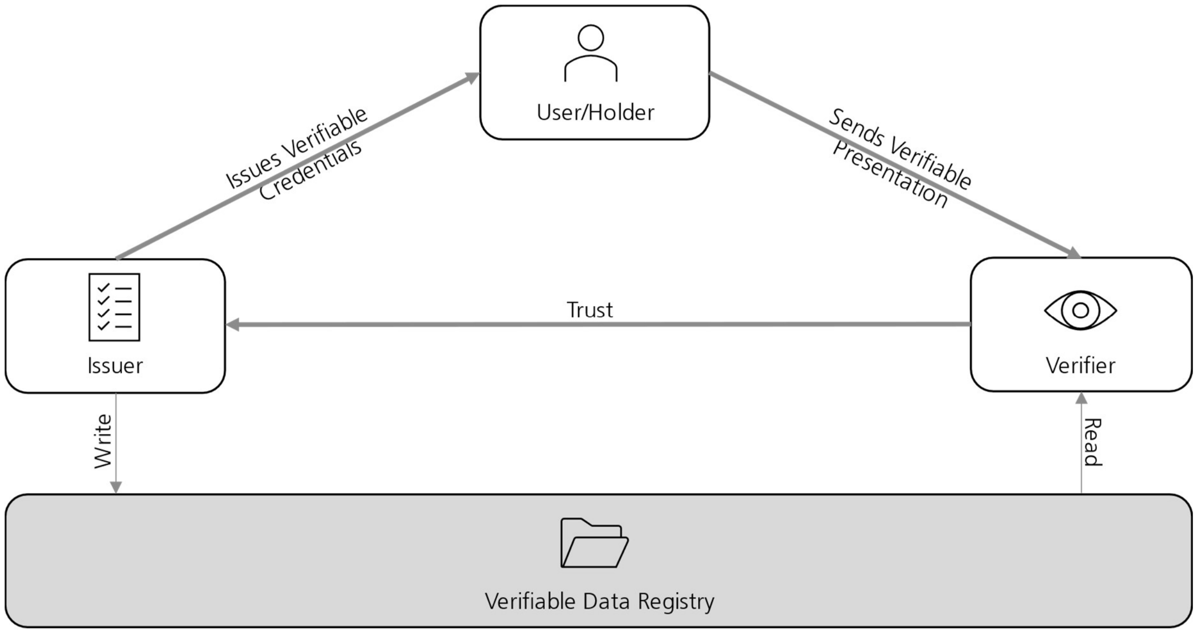

Figure 2: Roles in the SSI Paradigm

The concept of SSI is explained more in detail in the white paper [Self-Sovereign Identity – Foundations, Applications, and Potentials of Portable Digital Identities.]()

3. The Use Case

Requirements for a System Architecture

In response to the evolving landscape of an electricity system characterized by increasing decentralization and the need for a precise, reliable way of accounting for GHG emissions (cf. Chapters 1 and 2), the ID-Ideal use case Energy seeks to develop a system architecture that enables accurate CO_2 accounting for specific electricity consumption volumes. In this chapter, we describe the requirements for such an architecture as part of our results.

To accurately account for the carbon emissions embodied in electricity, it is first necessary to have a fine-grained data collection of electricity generation and consumption (e.g. at 15-minute intervals, which is the standard in the energy industry). Equally important is the ability to unambiguously identify the master data of the generation assets and link them to the transaction data to verify the origin of CO_2 and, for instance, the validity of a CO_2 certificate. Master data are static data that change little or not at all over time. In our use case, for instance, these data refer to the location and the power plant type. On the other hand, transactional data are dynamic and change constantly. In our use case, this includes for instance the amount of electricity produced and the resulting carbon emissions in a specific time interval. Owing to the high potential for damage from the misuse of fine-grained CO_2 data, fraud protection and regulatory compliance are critical aspects in the overall system. This requires robust measures to safeguard the integrity of the exchanged data by preventing manipulation, ensuring their authenticity and avoiding double-spending of certificates. It is also crucial to protect personal and consumption-related data. Further, a clear definition of interoperability with other ISs is required so that the obtained data can be processed and used in further steps along the electricity supply chain. In this context, one must pay attention to the data structure: it must be designed for scalability and performance in light of large datasets. The data must be easily accessible by end-users for decision-making and re-use in other use cases so as to ensure widespread adoption. Distinct and immutable identities of assets are critical to ensure the exchanged certificates' validity (Babel et al. 2023). This requires integrating the plant's master data – such as the type and specification – into its digital identity. Trusted institutions can verify the master data's accuracy and can issue the digital identity for each plant by signing it with their public key. To protect this master data from loss, manipulation, and unauthorized access, the digital identity should be stored on tamper-resistant hardware that ensures the data's integrity and confidentiality (e.g., a Secure Element). Smart meters that are certified and calibrated by a trusted entity facilitate automated, fine-grained data collection and transmission throughout the supply chain, enabling detailed data collection at short intervals.

The developed system seeks to enable CO_2-adaptive decision-making for end-consumers as well as in organizations. To ensure easy, innovative use by both stakeholders, the system must fulfill additional requirements:

Requirements for easy, innovative use by organizations

High interoperability is a fundamental requirement for a system designed to enable fine-grained data exchange across the energy supply chain. This is necessary to seamlessly integrate existing ISs and workflows, ensuring uninterrupted data flow and operational efficiency. Interoperability is achieved primarily through Application Programming Interfaces (APIs) and standardized data formats. APIs serve as connectors that allow enterprises to communicate with one another independently of their existing systems, enabling efficient and seamless data communication. Standardized data formats are crucial for maintaining a consistent data structure in this decentralized environment, ensuring data quality and compliance.

In addition to the requirements for the system itself, it should be compatible with existing transparency and certification systems in the energy industry. Our approach aims to complement the EU ETS and can therefore operate in parallel. However, the proposed solution functions similarly to GOs. Thus, the certificates should at least meet the standard requirements of GOs in order to be useful for companies that want to certify their electricity.

Requirements for easy, innovative use by end-consumers

In addition to ensuring security and interoperability, such a system requires a strong focus on end-consumers. The data must be comprehensive but also accessible and actionable for end-consumers. Standardized data formats enhance data sovereignty by enabling the free choice of digital wallets and facilitating the reuse of personal data across applications. It should also be easy and clear for end-consumers to use the system and to have interactive access to their own data. In this context, a user-friendly design can enable CO_2-adaptive decision-making and a conscious choice about using end-consumers' data while protecting their privacy and sensitive information.

System Architecture

Based on the abovementioned requirements, we propose a system architecture that, in contrast to existing approaches, allows for the determination of the origin of electricity with precise time and location granularity. To illustrate the concept, we use the charging of an EV as an exemplary use case. We will now simplify the supply chain by considering only a subset of stakeholders, assuming direct marketing of electricity by an electricity producer to a supplier to exemplify the concept. This electricity supplier also represents the Charging Point Operator (CPO) that supplies electricity to an EV (see Figure 3):

Electricity is generated by a power plant and is accurately measured by smart meters. A labeling certificate and an associated shielded nonfungible token (NFT) are then created. This token is stored on a verifiable data registry. The certificate contains information about the origin of the electricity and the CO_2 emissions and the token functions as proof of validity for the certificate. As the electricity moves through the supply chain to the retailer, the associated certificate is also transmitted, and the NFT is fractionalized to accurately represent the emissions relating to the received electricity at each stage. The CPO delivers electricity to the EV and generates a charging receipt containing multiple certificates that equal the amount of electricity received.

The certificates are passed down along the electricity supply chain and contain all necessary information about the specific power plant; they may consist of a combination of master data and transaction data of the plant. Each participant in the electricity supply chain has at least one organization, machine, or human identity, depending on their role. Using the SSI paradigm, this implementation provides decentralized master data management, bilateral communication channels, and dedicated rights and access management.

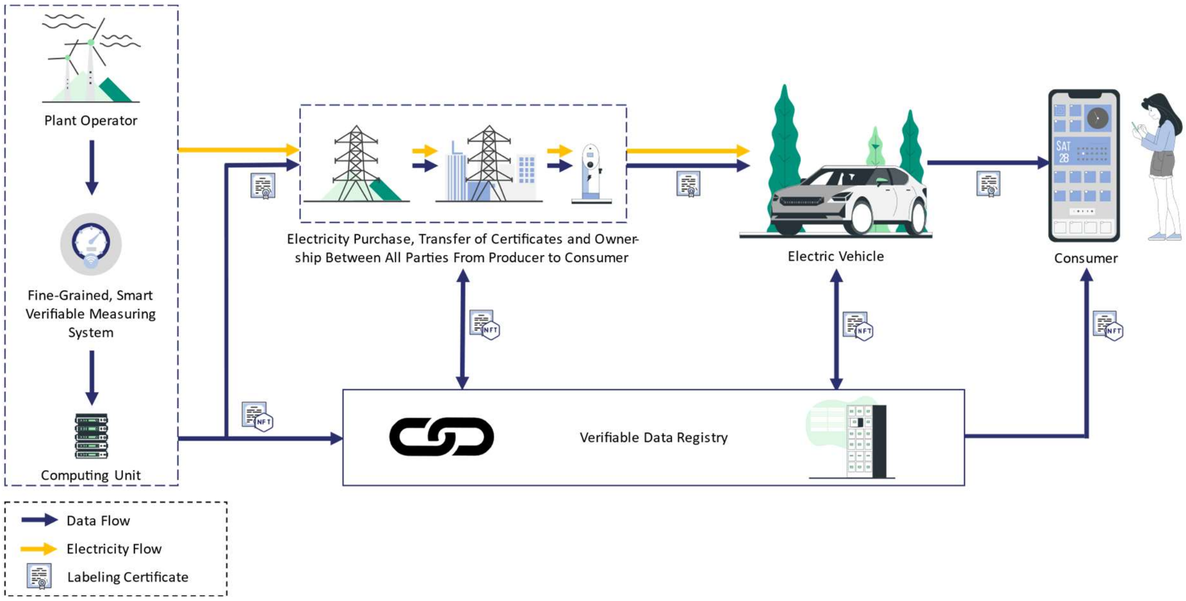

Figure 3: Representation of fine-grained verification of emissions data using SSI

Technical Implementation

Our implementation has two cornerstones:

Cornerstone 1: Labeling certificates to transport data

We present a certificate-based approach to transporting data. The process illustrated in Figure 3 starts with the power plant issuing labeling certificates. These certificates, which combine the power plant's master data with the electricity production data measured by the smart meter, are signed by the power plant's public key to ensure the data's integrity. The smart meter collects data at fixed intervals, such as every 15 minutes. By using calibrated and certified smart meters, this method ensures the data's trustworthiness and addresses the Oracle problem (i.e. the issue of relying on external data sources that cannot inherently ensure accuracy or reliability), as discussed by Babel et al. (2023). While our approach is designed to be versatile and technologically agnostic, it strongly benefits from incorporating the SSI principle. The use of VCs underpins the data's integrity and authenticity. The labeling certificates are then bilaterally transferred as a VC to every actor in the supply chain. This eliminates the need for centralized data storage and allows end-consumers to store their certificates in their personal digital wallets, giving them control over their own data. Further, an SSI implementation based on established standards can offer multiple advantages, such as integration into an existing SSI ecosystem, the use of selective disclosure, or the option for users to choose between different wallets with different functionalities.

Cornerstone 2: Shielded NFT as a tool for preventing double-spending

In our developed concept, these label certificates are paired with NFTs to prevent double-spending. This safeguard is crucial owing to the bilateral data exchange between the actors, preventing centralized storage of credentials. By linking each certificate to a distinct NFT, we ensure that each credential is only accounted for once, effectively preventing double-spending. The NFTs may be stored in a verifiable data registry that is publicly available to anyone. While the information can be stored in any format, we designed our NFTs based on the ERC-1155 standard, which allows for the creation of a token that can represent a unique certificate but can also be fractionalized into smaller tokens that correspond to a specific amount of electricity consumed by an end-consumer. Further, we enhanced privacy by shielding the information within the NFTs using ZKPs. This ensures that no personal information is stored in the NFTs, preserving privacy while allowing NFTs to be fractionalized along the supply chain. Through this approach, NFTs not only serve to verify each certificate's authenticity by avoiding double-spending, but also do so without revealing the underlying data (Babel et al. 2022).

4. Evaluation of Technical, Regulatory, and Economic Feasibility

To determine the suitability and effectiveness of our proposed architecture, we conduct an evaluation focusing on its technical, regulatory, and economic dimensions, to ensure that our findings are both validated and relevant. While our primary focus is on technical aspects owing to our project's scope, it is crucial to understand the regulatory and economic implications in order to assess real-world viability. However, notably, our evaluation of the regulatory and economic aspects is preliminary and not exhaustive – it seeks to determine whether our proposed approach is theoretically feasible across technical, regulatory, and economic dimensions, or whether there are significant barriers to implementation and deployment. Our initial assessments may necessitate further exploration, potentially examining the broader economic impacts on specific industries or the detailed effects of sector-specific regulations beyond our immediate scope. Our evaluation's results are summarized in Figure 5.

During the project, we developed a web application with a prototype user interface. For designing this user interface, we followed an iterative approach, including interviews with experts and a workshop with 30 potential users. Figure 4 illustrates exemplary screenshots of our final user interface.

Our application includes several functionalities that were made available for user testing to gauge the acceptance of each functionality. However, notably, our implementation only mimics these features and does not incorporate actual asset data or connect to external services, such as CO_2 offsetting websites. These features include:

1) Simulating an EV's charging process at a charging station.
2) Issuing certificates with fine-grained and verifiable information on the amount of electricity purchased and the associated CO_2 emissions.
3) Offering the option to sell CO_2 savings and offset residual emissions through external certificates.

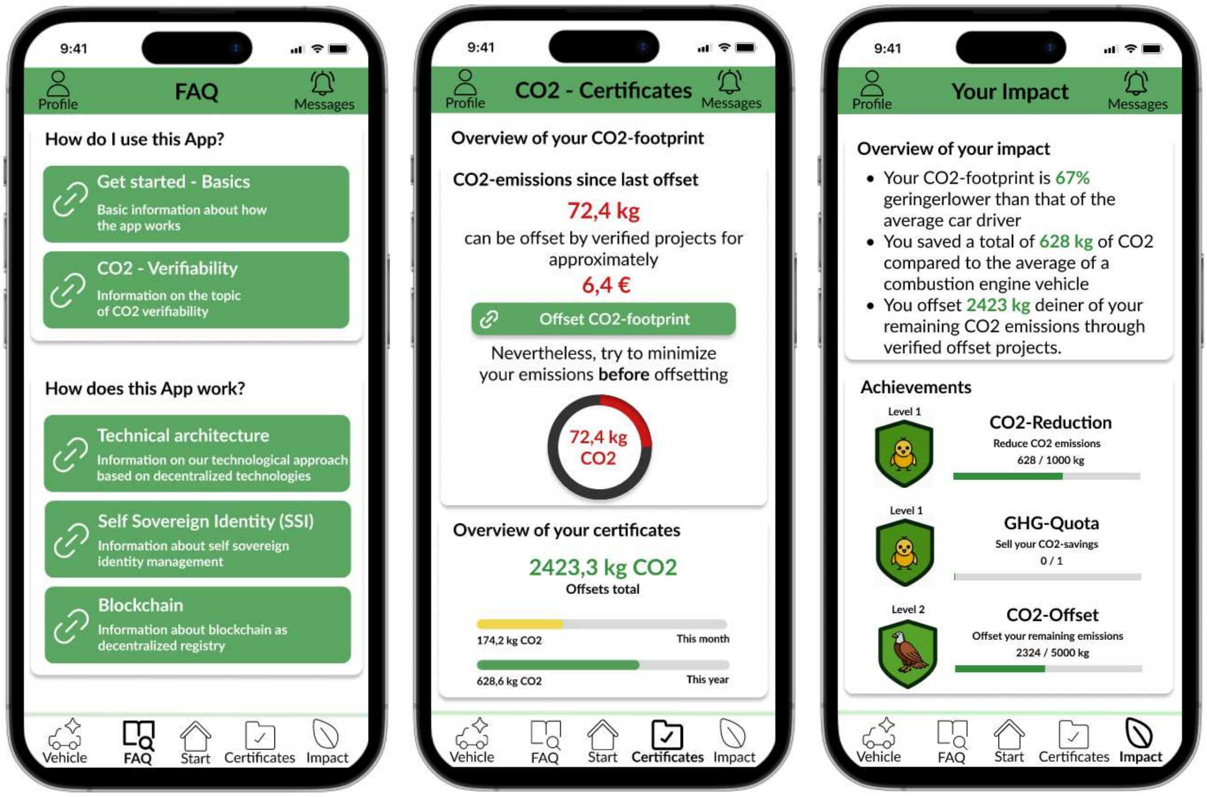

Figure 4: Exemplary screenshots of our user interface

Technical Feasibility

We qualitatively assessed six key technical requirements essential for the proposed system's operation, with the findings detailed below and summarized in Figure 5.

1) *Fine-grained data collection*

   The ability to collect metering data at a fine-grained level is achievable with the provision of the necessary smart meters, ensuring detailed and accurate recording of energy-related data.

2) *Data verifiability*

   Our architecture employs digital identities stored on tamper-resistant hardware to securely link master and transactional data, ensuring the integrity and the reliability of data provided by the asset.

3) *Performance*

   The system's performance depends on the design and selection of both the registry and the communication protocol. Given the agnostic architecture, scalability considerations become critical when deciding between different registries and protocols, especially for broader deployment on a national or an international scale.

4) *Data sovereignty of users*

   The system design strongly emphasizes data sovereignty, ensuring that users retain full control over their personal data. The exchange of personal data as VCs is consistent with the principles of privacy and user autonomy.

5) *Interoperability*

   While partially achieved, interoperability remains a challenge. While SSI standards provide a path to interoperability, there is still a lack of universally accepted standards, particularly in the energy sector. According to the ERC-1155 standard, the token's structure allows for the flexible representation of linked credentials, enabling both unique and batch processing. This enhances the system's interoperability by enabling uniform token management across different platforms and systems.

6) *Protection against fraud*

   The system's design ensures data verifiability throughout the entire supply chain, a critical feature for maintaining integrity. However, vulnerabilities such as the Oracle problem can persist if additional strategies are not implemented to mitigate the risk of exchanging incorrect data (Babel et al. 2023).

Regulatory Feasibility

In evaluating our proposed approach from a regulatory perspective, we examined two critical dimensions: data privacy and compatibility with existing transparency and certification schemes.

1) *Data privacy*

   Our architecture is designed to comply with regulatory requirements, including the EU's GDPR, albeit with certain limitations. We effectively address major privacy concerns by employing a *privacy by design* approach, which includes not storing personal data on the verifiable data registry and by shielding information with privacy-enhancing technologies (e.g. ZKPs) and VCs. Despite these achievements, challenges may remain in meeting energy sector-specific regulations. Since these regulations are subject to change, particularly with the implementation of new systems or industry standards, addressing these regulatory issues exceeds this study's scope.

2) *Compatibility with existing systems*

Our concept partially meets the requirement for compatibility with existing transparency and certification systems. By being able to run in parallel with the ETS, it meets our minimum compatibility criterion. While the system's ability to function as a GO and to provide more fine-grained data is promising, achieving full compatibility will require efforts to ensure that data presentation is seamlessly aligned with GO requirements. The directive on GOs[2] does not consider more detailed information within a certificate. Thus, as an extension of GOs, our concept would either run in parallel on a voluntary basis – which makes market penetration questionable – or regulations must be adapted to allow or require additional information (e.g. on the place and time of GO generation). However, establishing different initiatives and approaches – such as the Granular Certificates of the nonprofit organization EnergyTag (2021) – illustrate the need, the drive, and the market demand for more fine-grained renewable energy certificates.

Economic Feasibility

Our economic assessment focuses on the system's ability to enable multiple use cases (and corresponding business models) and supports economic decision-making based on the exchange data.

1) *Enabling multiple use cases for businesses*

Our approach allows for the detailed traceability of emissions, which allows among others for more fine-grained emission certificates. These can be useful for different stakeholders in different use cases. For instance, companies with their own renewable energy sources can utilize these certificates, which can be sold when their production exceeds their electricity consumption, allowing additional economic returns. Further, a company with steady electricity consumption would only need to purchase certificates during times when it consumes electricity from the grid and when this grid electricity is associated with high emissions. Other private sector use cases that exceed sole certification may for instance include integrating fine-grained emissions data into companies' monitoring, reporting, and verification (MRV) processes. This provides a foundation for more precise and efficient digital MRV through automated data collection and management. Companies are therefore better prepared for existing and upcoming emissions reporting laws and regulations, such as the Corporate Sustainability Reporting Directive. Further, companies can provide sustainability information about their products, which can strengthen their market position by differentiating themselves and their products from their competitors. This is also relevant since investors increasingly consider sustainability aspects in their investing decisions (e.g. through ESG ratings).

2) *Enabling economic decision-making*

Fine-grained data enable stakeholders – such as companies and individuals – to take CO_2-adaptive decisions. These data are transferred as VCs, increasing transparency and building trust without necessitating full disclosure. As these data's effectiveness in facilitating decision-making depends on how they are presented, the way they are presented must be tailored to specific situations to ensure that the displayed data are understandable, relevant, and actionable.

[2] Directive 2009/28/EC on the promotion of the use of energy from renewable sources. *Article 15: Guarantees of origin of electricity, heating and cooling produced from renewable energy sources.*

Dimension	Requirement	Assessment	Explanation
Technical	Fine-grained data collection	Feasible	Metering data can be as fine-grained as necessary if the required smart meters are provided.
Technical	Data verifiability	Feasible	Digital identities, stored on tamper-resistant hardware, allow for a secure linking to the asset and its transactional data.
Technical	Performance	Feasible but dependent on the design of the registry and communication protocols	The architecture is registry-agnostic. Performance must be considered when selecting the registry and the communication channels of the VC, as such a system will have a large number of transactions when scaled to a national or an international level.
Technical	Data sovereignty of users	Feasible	Exchanging personal data as VCs gives stakeholders control over their own data.
Technical	Interoperability	Feasible with limitations	Our architecture supports interoperability, although no industry-wide standard for SSI implementations exists as yet.
Technical	Fraud protection	Feasible with limitations	While verifiability along the supply chain is ensured, vulnerabilities such as the Oracle problem present risks when malicious actors introduce false data.
Regulatory	Data privacy	Feasible	GDPR concerns are addressed by not storing personal data on an open registry and employing privacy-enhancing technologies and VCs.
Regulatory	Compatibility with existing transparency and certification systems	Feasible with limitations	The system can run in parallel to an ETS and fulfills the minimum requirement of a GO, since it can provide the same data but even more fine-grained. Current regulations do not allow for more detailed information than 1 kWh of (renewable) energy.
Economic	Enabling multiple use cases for businesses	Feasible	Fine-grained primary data serve as a foundation for multiple use cases.
Economic	Enabling economic decision-making	Feasible	Stakeholders (e.g. end-consumers) can base their decisions on fine-grained carbon data.

Figure 5: Our evaluation's results

5. Implications and Recommendations

Societal and Policy Implications

As outlined in our foundation section, a promising approach for decarbonization involves assessing and managing electricity-consuming processes and economic activities based on their GHG intensity, particularly CO_2. This approach necessitates a shift to CO_2-adaptive decision-making for organizations and end-consumers. As we conceptualize and demonstrate in the ID-Ideal project's use case Energy, the implementation of fine-grained CO_2 tracking has potentially far-reaching societal implications. It offers end-consumers and organizations greater transparency regarding the their electricity consumption's CO_2 intensity, enabling them to make more environmentally aware choices (Körner et al. 2023). Over time, this transparency can contribute to the gradual shift in societal attitudes, with sustainability and environmental concerns becoming more prominent in daily decision-making.

The implementation of our proposed system demands a careful approach so as to ensure widespread support. Against this background, we suggest focusing initially on data collection, with a gradual transition to incentive mechanisms – such as certificates – to support individuals to adapt to the new system. Accordingly, positive incentives that encourage behavioral changes may be created. To illustrate this strategy, we employ a nudging approach in our prototypical implementation (see Figure 5), including an intuitive display of historical CO_2 emission data and awards for sustainable behaviors such as reducing CO_2 emissions.

Ensuring transparency and clarity regarding data sovereignty and privacy issues is as important as providing positive, transparent incentive mechanisms. Without proper safeguards, the fine-grained collection and sharing of electricity data – as we propose – could reveal sensitive information, such as the societal status of households and individual behaviors. It is therefore crucial to adopt a privacy-preserving approach to handle these highly sensitive data and communicating these measures to the public so as to build trust. While our approach addresses these issues from a *technical* perspective, it is crucial to ensure that members of the public have a general *understanding* of these concepts. We exemplify this in our prototype through an FAQ page in the user interface (see Figure 4).

Recommendations for Policymakers, Researchers, and Practitioners

To contribute to the successful deployment, integration, and further development of our proposed architecture, we formulate recommendations for policymakers, researchers, and practitioners.

Policymakers may create a comprehensive legal framework to enable and foster the fine-grained collection of CO_2 data. Such a framework must define clear guidelines and responsibilities for data collection, sharing, and privacy protection. This initiative should promote transparency and accountability. Also, policymakers may introduce incentives for organizations to *enable* active participation in a CO_2-adaptive decision-making system. Policymakers could *enforce* such fine-grained data collection, for instance by expanding and specifying current legislation regarding GOs in a way that increases the amount of information in a GO (e.g. precise CO_2 values instead of only distinguishing between renewable and conventional electricity), requirements for temporal and spatial granularity (e.g., include the location of the electricity power plant and a time stamp for the produced electricity), as well as verifiability (e.g. require technical verifiability). As noted, such a policy framework could create positive incentives for sustainable practices and can, among others, include tax benefits, regulatory advantages, or recognition for environmentally responsible practices. Such incentives could encourage both more widespread adoption of the architecture and cooperation around decarbonization interventions.

Researchers are encouraged to intensify their efforts to explore the technical building blocks, such as ZKPs. These privacy-preserving technologies have the potential to enable new use cases that require the collection and exchange of sensitive information. However, the practical, scalable application of ZKPs in real-world contexts has been largely underexplored and requires further investigation. There is also a need for scholars to investigate strategies for navigating the political landscape essential to the implementation systems that enable CO_2-adaptive decision-making. As outlined by Fuso Nerini et al. (2021) and illustrated with our system architecture, current advances in digital technologies – such as artificial intelligence or privacy-preserving technologies – offer new opportunities for personal carbon trading approaches, which researchers may further explore. Engaging with policymakers, addressing pertinent concerns, and securing support require a nuanced approach that goes beyond technical solutions. Given these challenges' multifacetedness, encompassing technical, political, and legal dimensions, it is crucial for researchers from different fields such as IS, economics, and law to collaborate. Such interdisciplinary teamwork is vital to advancing the practical application of CO_2-adaptive decision-making.

Practitioners should encourage active involvement in the implementation of CO_2-adaptive decision-making systems. Industries may proactively adopt and contribute to the development of industry standards. By engaging with and influencing sector-specific regulatory frameworks, especially considering climate concerns, they can help shape a more responsive and effective regulatory environment for GHG emissions management. Further, practitioners should promote collaboration among various industries to develop common standards for CO_2 data collection and reporting. Establishing industry-wide best practices will not only streamline the implementation of the system but can also foster a collective commitment to environmental responsibility.

6. Conclusion and Outlook

The development of a system for fine-grained proofs of origin for electricity that enables end-consumers and organizations to take CO_2-adaptive decisions – as we conceptualize, prototypically implement, and present here – represents a significant step in the pursuit of decarbonization. Such a system also aligns industrial processes and economic activities to their environmental impacts by providing precise CO_2 data for them, strongly enhancing transparency and promoting sustainable practices. As we illustrate, incorporating the SSI paradigm for people, organizations, and machines can ensure data privacy and self-sovereignty, establishing a robust foundation for a widespread acceptance.

Beyond its application in the electricity sector, our proposed system architecture can serve as a blueprint for tracking emissions across multiple domains, for instance to comply with requirements in supply chains of sustainable hydrogen. The prototype may also be further developed to serve as a foundational model for monitoring and tracking other types of sustainability data, such as the exclusion of child labor. This system can also serve as the foundation for holistic product traceability, providing transparency and comprehensive traceability of production processes, from upstream products and raw materials to the environmental footprint of the final product, essentially creating a Digital Product Passport that combines data verifiability and traceability with data control and privacy at scale.

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Abbreviations and Initializations

API(s)	Application Programming Interface(s)
CO_2	Carbon Dioxide, ‘carbon’
CPO(s)	Charging Point Operator(s)
DID(s)	Digital Identifier(s)
eIDAS Regulation	Regulation (EU) No 910/2014 on Electronic Identification and Trust Services for Electronic Transactions in the Internal Market
EU	European Union
EU ETS	The EU’s Emissions Trading System
EV(s)	Electric Vehicle(s)
ETS(s)	Emissions Trading System(s)
GDPR	The EU’s General Data Protection Regulation
GHG(s)	Greenhouse Gas(es)
GO(s)	Guarantee(s) of Origin
IS(s)	Information System(s)
kWh	Kilowatt Hour
NFT(s)	Non-Fungible Token(s)
MRV	Monitoring, Reporting, and Verification
SSI	Self-Sovereign Identity
U.S.	United States of America
VC(s)	Verifiable Credential(s)
VP(s)	Verifiable Presentation(s)
ZKP(s)	Zero-Knowledge Proof(s)