EXPLORING A BLOCKCHAIN DESIGN FOR THE EUROPEAN EMISSION TRADING SYSTEM

AN INTEROPRABLE, SECURE, AND AUTOMATIZED DATA SHARING ARCHITECTURE

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Exploring a blockchain design for the European emission trading system: *an interoperable, secure, and automatized data sharing architecture*

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ABSTRACT

As the Earth's temperature rises, it is critical that countries address and adapt to climate change. The European Union (EU) is committed to achieving carbon neutrality by 2050 (European Commission, 2018).The cornerstone of the EU's climate policy to combat climate change is the EU Emission Trading System (ETS). It is the world's first major compliance carbon market and remains the biggest one. Currently, the focus of the EU is to strengthen the market of the EU ETS for the next decade and beyond (European Commission, 2022-a). An important development in this phase is the recognition of global carbon markets to reduce global GHG emissions effectively. Three main challenges of ETSs are identified in this research: lack of system compatibility to link with other ETSs, security issues, and (manual) monitoring of transactions. To realize the full potential of ETSs, the added value of a blockchain-based architecture to support the carbon trading market and counteract the current deficiencies is explored. Although the reviewed literature is useful to identify the possibilities of blockchain solutions to address the current challenges in ETSs, it is not clear how the current EU compliance market could allow extension by providing a large, transparent, verifiable, interoperable, and robust carbon system. Research about blockchain-based EU ETSs would contribute so that the development of global carbon markets could happen. This results in the following main research question: *What blockchain-based design can be used by the European Union to improve the technical design of the EU ETS while allowing for the extension to other Emission Trading Systems?*. For this research project, a Design Science Research (DSR) approach is taken to ensure a discipline-oriented creation of a successful design that addresses the challenges in the EU ETS. This research proposes a blockchain-based solution that is able to cover the core functions of the system while actively improving system compatibility, preventing security issues and non-transparency, and enable automatized monitoring of transactions. It is concluded that the proposed design is able to improve the current system by enabling extension to other ETSs, automatizing manual processes, providing data security through encryption, and providing transparency in the narket and trade of emission allowances. Additionally, this research provides a blockchain governance framework to align policy and stakeholder interests with governance and technical blockchain control points in the emission trading sector. Besides contributing to closing a gap in a growing research field, the use of the architecture offers a technological solution in which systems can be integrated with each other without having to throw away the existing principles. This is beneficial because these existing principles have been developed after a great amount of learnings, investments, and experience. Also, the design enables more authorities to join a system that is already running while also able to have a say in the governance. This could lead to convergence of market mechanisms and prices where as a result, a more efficient and unified carbon market will emerge.

Keywords: Blockchain, Emission Trading Systems, Carbon markets, European Union, Interoperability

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ABBREVIATIONS

AAU	Assigned Amount Units
AER	Annual Emission Report
API	Application Programming Interface
CDM	Clean Development Mechanism
CSEUR	Consolidated System of European Registries
DES	Data Exchange Standards
DSR	Design Science Research
EEX	European Energy Exchange
ETS	Emission Trading System
EU	European Union
EUTL	European Transaction Log
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
ICAP	International Carbon Action Partnetship
ITL	International Transaction Log
JI	Joint Implementation
MRV	Monitoring, Reporting, and Verification
MSR	Market Stability Reserve
NGO	Non-governmental Organizations
NSW GHGAS	New South Wales GHG Abatement Scheme
PBFT	Practical Byzantine Fault tolerance
PoA	Proof of Authority
PoR	Programme of Requirements
PoS	Proof of Stake
PoW	Proof of Work
RFD	Research Flow Diagram

RGGI	Regional Greenhouse Gas Initiative
SHA	Secure Hashing Algorithm
TIP	Technical, Institutional, Process
TNAC	Total Number of Allowances in Circulation
UNFCC	United Nations Framework Convention on Climate Change
VAT	Value Addes Tax
WCI	Western Climate Initiative

1. INTRODUCTION

In recent years, public awareness of the issue of climate change has risen dramatically, and an increasing number of corporations, organizations, and individuals are attempting to reduce their impact on the environment. We need comprehensive regulations to minimize greenhouse gas (GHG) emissions at the national and international levels to successfully address the threat of climate change. The EU is committed to achieving carbon neutrality by 2050 (European Commission, 2018).The cornerstone of the EU's climate policy to combat climate change is the EU Emission Trading System (ETS). The EU ETS uses a cap-and-trade principle where a 'cap' limits the total amount of certain GHG that can be emitted by the installations covered by the system and emission allowances are issued accordingly (European Commission, 2021). Within this limit, the participants in the system (installations in the power sector, manufacturing industry, and aircraft operators) can engage in 'trading' these emissions allowances to fulfill their obligation in a cost-effective way. The cap on the total number of allowances creates scarcity in the market and therefore creates value for the allowances (Vlachou, 2014). Currently 38 countries and 29 subnational jurisdictions have an emissions trading scheme in place (World Bank, 2021). The EU ETS is the world's first major compliance carbon market and remains the biggest one, encompassing over 11,500 installations across 30 countries and covering approximately 40% of total EU GHG emissions (European Commission, 2021).

The system was first introduced in 2005 and has undergone several changes since then. The implementation of the system has been divided up into distinct trading periods over time, known as phases. The first phase of the EU ETS ran from 2005 to 2007 and was seen as the pilot phase of the system. This phase was used to test the price formation and to establish the necessary infrastructure for monitoring, reporting, and verification of emissions. The second phase ran from 2008 to 2012, when the countries in the EU ETS had concrete emissions reduction targets to meet. The third phase (20013 to 2020) of the EU ETS was shaped to improve the system based on the lessons learned from the previous phases. The main changes in this phase include a single EU-wide cap instead of national caps, harmonized allocation rules for carbon allowances, and more sectors and gasses included in the system. Currently, in the fourth phase from 2021 and beyond, the focus is to strengthen the market of the EU ETS for the next decade and beyond (European Commission, 2022-b).

An important development in this phase is the recognition of global carbon markets to reduce global GHG emissions effectively, this can be traced back to the approval of Article 6 of the Paris agreement in 2020, which allows countries to voluntarily cooperate with each other to achieve emission reduction targets (European Commission, 2022-c). Linking offers several potential benefits, including reducing the cost of cutting emissions, increasing market liquidity, making the carbon price more stable, levelling the international playing field by harmonizing carbon prices across jurisdictions, and supporting global cooperation on climate change (European Commission, 2022-c). Multiple countries have expressed their positive views on linking, in 2015 the New Zealand Government already expressed strong interest in linking with other domestic carbon markets (New Zealand Government, 2015), in the Republic of Korea an act on Allocation and Trade of GHG emission allowances specifies that the Korean ETS will enable linking with other countries (Climate laws, 2020), and China who unveiled their ETS in 2021 have begun to draft plans to linking China's ETS with the rest of the world (Kleinman Center of Energy Policy, 2022).

However, attempts of the European Commission to link with other ETS have faced several challenges. In 2010, the European Commission proposed opening negotiations on linking the EU ETS with Switzerland's carbon market and was only able to do so 10 years later. Given the small size of the Swiss ETS and Switzerland's close connection to the EU for more than 20 years, a fast and efficient conclusion of any linking negotiations was expected. But the linking aspirations between the EU and Swiss show that technical compatibility must be considered as a necessary condition. Also, an attempt of linking the EU ETS with Australia started in 2012 and failed in 2013 (European Commission, 2022-c). The challenges of successful linking of ETSs are that regulatory changes will need to be developed in close coordination with the other jurisdictions and that the key design features of ETSs need to be harmonized to ensure system compatibility (CMW, 2015)

To realize the full potential of ETSs, this master thesis explores the added value of a blockchain-based architecture to support the linking of ETSs and counteract current deficiencies. Blockchain uses a peer-to-peer (P2P) network in which everyone can participate and all the nodes in the network can create consensus in an efficient, transparent, and auditable way (Valdivia, 2022). Blockchain's distinct features such as security, immutability, transparency, traceability, and trust, make it a robust and reliable solution for the carbon trading market (Al Sadawi, 2021). Researching the implementation of blockchain in the EU ETS will deliver contributions to society, especially in carbon markets, because blockchain has the ability to revolutionize systems like ETSs. This is due to three main attributes: decentralization, trust in the network, and automatization of processes. The use of blockchain in (global) carbon markets provides a mechanism that does not need a central authority coordinating the market because of decentralization (Kostmann & Härdle, 2019), although a governance arrangement still needs to be developed (Olnes et al., 2017). Trust is still ensured by its transparent structure that facilitates irreversible and immutable transactions. Moreover, blockchain technology can automatize processes through smart contracting capabilities. When carbon markets have accelerated their growth trajectory and realized its full potential, it will be able to further support the objective to reduce GHG from power stations to limit global warming. This thesis pursues to provide a blockchain-based EU ETS to enable an interoperable, secure, and efficient data sharing architecture.

The following chapter 2 will discuss the literature review process and investigate the knowledge gap. Chapter 3 will describe the research approach and propose the sub-questions that will lead to answering the main research question. Also, the research methods related to each sub-question will be discussed. In chapters 4 to 8, the sub-questions are answered. At last, the conclusion to answer the main research question and future research is provided in chapter 9.

2. KNOWLEDGE GAP AND MAIN RESEARCH QUESTION

2.1 LITERATURE REVIEW PROCESS

An explorative literature study was conducted to review the existing literature on blockchain for emission trading systems. As a guide, the PRISMA flow diagram is used to report the systematic review. It contains four phases: identification, screening, eligibility, and included (PRISMA, n.d.). The search strategy and selection criteria of down scoping are clarified based on these four phases, see Figure 1. In the identification phase, the search words are put in Scopus to find relevant articles. In the screening phase, articles are screened to analyze the most recent stage of research. In the eligibility phase, articles are screened based on their acknowledgment to applications of blockchain technology in ETS. At last, forward snowballing results in two more articles that are included in this literature review.

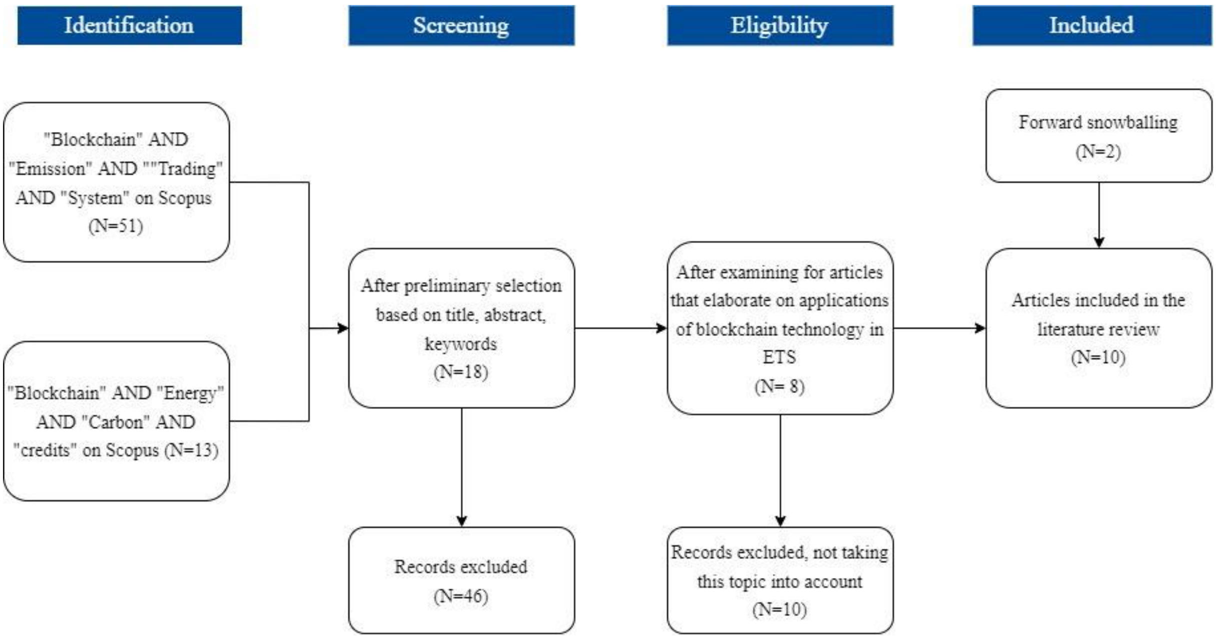

Figure 1 - PRISMA flow diagram

2.2 LITERATURE OVERVIEW

In this literature review, 10 scientific articles that propose blockchain integration for ETSs are reviewed, of which 3 were published in conference papers and 7 in journal articles, see Table 1. Out of these articles, 1 is published in 2018 and the other 9 articles appeared after 2020. This suggests that the efforts to implement blockchain in carbon markets have only just begun. This is in line with the research of Hartmann et al (2020), who demonstrate that the potential use of blockchain in carbon markets has only just begun to be explored.

To get a better understanding of the current research in the academic literature, the research process stages of the articles are analyzed. It becomes clear that 5 out of the 10 articles address a conceptualization stage where the articles generate ideas for the design problem. Some of the articles discuss the current challenges of ETS systems and the relevant properties of blockchain applications to improve current challenges (Alsobhi et al, 2021; Ashley et al. 2021; Kim et al., 2020; Patel et al., 2021). In the research of Bai et al. (2020), an architecture framework of a sovereign blockchain is proposed to construct carbon trading platforms. One article gave an overview of innovative blockchain-based applications and the future directions of it (Alsobhi et al., 2021). Meanwhile, only two articles were found in the analysis that are in the design stage. Al Sadawi et al. (2021) managed to design a comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contracts and Lu et al (2022) designed a blockchain-enabled trading system based on the carbon emissions cap. Furthermore, two articles evaluate possible blockchain applications in the Australian carbon market (Hartmann et al., 2020) and the European market (Mandaroux et al., 2021).

Based on this literature review, a more in-depth analysis will be presented about current carbon markets, challenges, and possible blockchain applications.

Table 1 - Overview of the literature

Authors	Title	Publication type	Research Process Stage
Al Sadawi et al. (2021)	A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract	Journal Article	Design
Alsobhi et al. (2021)	Innovative Blockchain-Based Applications-State of the Art and Future Directions.	Conference Paper	Overview
Ashley et al. (2018)	Establishing a Secure, Transparent, and Autonomous Blockchain of Custody for Renewable Energy Credits and Carbon Credits	Journal Article	Concept
Bai et al. (2020)	Construction of Carbon Trading Platform using Sovereignty Blockchain	Conference Paper	Design
Hartmann et al. (2020)	Applying blockchain to the Australian carbon market	Journal Article	Evaluation
Kim et al. (2020)	Blockchain of Carbon Trading for UN Sustainable Development goals	Journal Article	Concept
Lu et al. (2022)	A Blockchain-enabled Smart Emission Cap restrictive and Carbon Permit Trading System	Journal Article	Design
Mandaroux et al. (2021)	A European Emissions Trading System Powered by Distributed Ledger Technology: An Evaluation Framework	Journal Article	Evaluation
Patel et al. (2021)	Carbon Credits on Blockchain	Conference Paper	Concept
Woo et al. (2022)	Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: A review of the literature	Journal Article	Concept

2.3 CORE CONCEPTS IN CARBON MARKETS

In order to understand the carbon markets, it is important to recognize the difference between two fundamentally different types of carbon commodities: carbon credits and allowances. Carbon credits, which represent one tonne of carbon dioxide equivalent (CO2e), are created by Baseline-and-Credit systems and allowances are created by Cap-and-Trade systems.

A Cap-and-Trade principle is used to achieve emissions reductions by an overall ‘cap’, see figure 4. The ‘cap’ limits the total amount of GHG that can be emitted by the installations covered by the system and emission allowances are issued accordingly (European Commission, 2021). Within this limit, the participants in the system can engage in ‘trading’ these emissions allowances to fulfill their obligation cost-effectively. With a Cap-and-Trade principle, the ‘cap’ is set by regulation and political negotiation, the total number of allowances creates scarcity in the market and therefore creates value for the allowances (Vlachou, 2014). The sources usually covered in systems with a Cap-and-Trade principle are high emitters such as the energy sector and energy-intensive industries. Also, an independent third party plays a role in verifying emissions inventories (Kolmuss et al., 2008).

A Baseline-and-Credit principle on the other hand does not entail a finite supply of allowances. Under this principle, credits are generated with emissions reductions from projects and can be used by buyers to offset an emitting activity, such as an airline flight. The sources that could use Baseline-and-Credit principles are undefined and differ for each project. Here, an independent party plays a fundamental role in verifying the credibility and the authenticity of the claimed emissions reductions (Kolmuss et al., 2008).

Carbon markets exist both under compliance schemes and as voluntary programs. Systems that use the Cap-and-Trade principle exist almost exclusively in the compliance market while systems with the Baseline-and-Credit principle exist both in the compliance and the voluntary market (Kolmuss et al., 2008). Compliance markets are created and regulated by mandatory national, regional or international carbon reduction regimes. Voluntary markets enable governments, NGOs, and individuals to offset their emissions voluntarily through carbon credit trading.

Compliance markets allow emission reductions under the Kyoto Protocol. There are three flexibility mechanisms defined intended to lower the emissions targets: International Emission Trading, the Clean Development Mechanism (CDM), and the Joint Implementation (JI) (UNFCCC, 2007). The participating countries are assigned an emissions target and the corresponding number of allowances, called Assigned Amount Units (AAU).

- Cap-and-trade principle: One of the three flexibility mechanisms is International Emission Trading. The biggest emission trading system is the EU Emission Trading System (ETS). It is the world’s first major compliance carbon market and remains the biggest one. Other emission trading systems in compliance markets are, for instance, the New South Wales GHG Abatement Scheme (NSW GHGAS) from Australia, the Regional Greenhouse Gas Initiative (RGGI) from the Northeast United States, and the Western Climate Initiative (WCI) of 5 western US states and British Columbia. Currently 38 countries and 29 subnational jurisdictions have an emissions trading scheme in place (World Bank, 2021).

- Baseline-and-Credit principle: The other two flexibility mechanisms under the Kyoto Protocol allow financing of carbon emission reduction projects in developing countries (CDM) and non-developing countries (JI).

Voluntary markets function in parallel but outside the compliance markets. They allow participants of the market to offset their emissions by purchasing offsets that were created either through CDM projects or in the voluntary markets. There are no established rules and regulations for the voluntary carbon market yet, but they allow for experimentation and innovation with fewer transaction costs than compliance market projects (Kolmuss et al., 2008).

For an overview of carbon markets, see Figure 2.

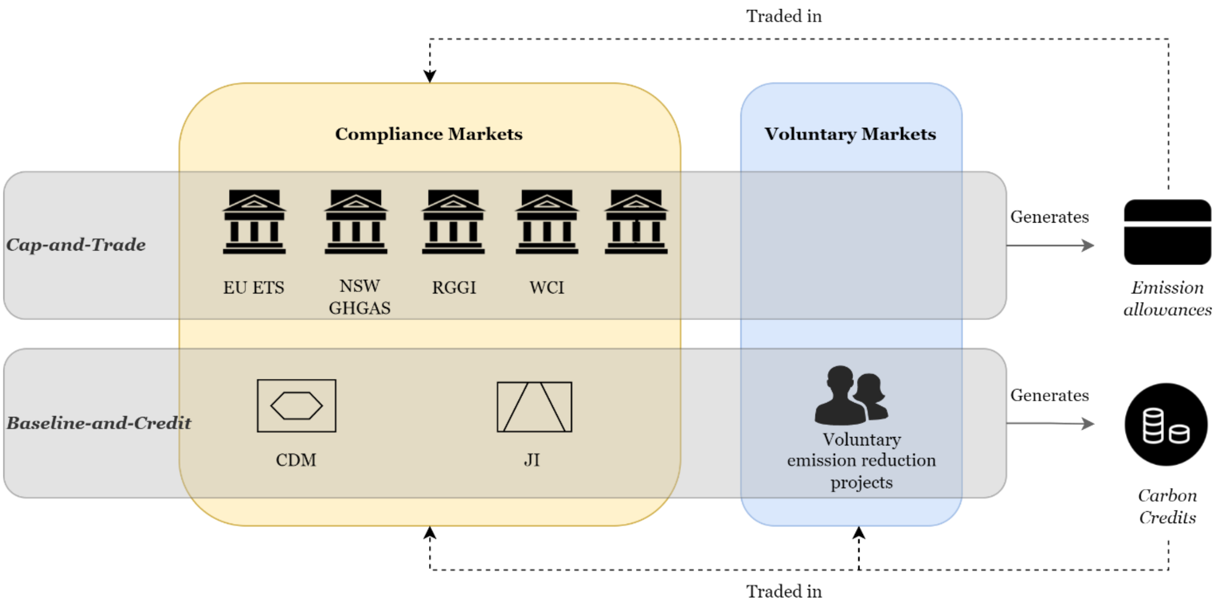

Figure 2 - Overview of carbon markets

2.4 Challenges in the EU ETS and Blockchain as an option

Carbon markets try to mitigate the effects of global warming and climate change. According to a market analysis of Refinitiv in 2022, the compliance market had a market size of €760 billion while the voluntary market size in the same year has been estimated at €1 billion (Refinitiv, 2022). The reason that the compliance market, compared to the voluntary market, is much bigger is that the demand for compliance markets are created by a regulatory instrument (Kolmuss et al., 2008). The EU ETS represents nearly 90% of the global value of compliance markets (Refinitiv, 2021) and mostly focuses on industrial facilities (heavy energy-using installations and airlines).

Despite the effort of the EU to regulate industrial activities to reduce greenhouse gases, the EU ETS still needs to overcome several challenges before it will be able to become scalable and accelerate the market's growth trajectory. Based on the literature review it becomes clear that the two categories of main challenges in current emission trading systems are considered: for extending the EU ETS and for improving the EU ETS. For extending the EU ETS, the challenges include lack of system compatibility which involve technical as well as organizational challenges. For improving the current EU ETS, challenges are security issues, and (manual) monitoring of transactions. This section describes the challenges in current ETSs and explains how blockchain could enhance ETSs as a solution for these challenges.

2.4.1 Lack of system compatibility for extending the EU ETS

One of the challenges that EU ETS copes with is the lack of compatible systems to enable linking of systems (Pollitt, 2019 & Kapnick, 2021). The existing schemes in carbon markets cannot straightforwardly be linked up. Linking offers several potential benefits. First of all, linking carbon schemes facilitates cost-effectiveness, linking could lower overall costs by enabling the capture of a wider range of mitigation opportunities and by widening the geographic scope across national borders (CMW, 2015). Linking can enhance price stability as price variations can be absorbed within a larger overall market (CMW, 2015). Moreover, linking could enhance liquidity in the carbon market, which is especially relevant for smaller countries where it might be difficult to establish an own effective ETS. At last, a political advantage is that linking could signal global collaboration, it demonstrates global leadership and a commitment to long-term climate policy (CMW, 2015).

Currently, the carbon trading market has different policies and is characterized by low coordination (Al Sadawi et al., 2021). The current trade of carbon emissions conducted in several markets results in different price levels of emission allowances. As industries under the EU ETS currently are constrained by the system in Europe, concerns are raised about the effects of ETSs on trade and the location of industrial production (Babiker, 2005). One particular effect is referred as carbon leakage, where the associated competitive effects may lead to significant increases of emissions in countries without controls. ETSs cope with the risk that energy-intensive industries relocate from countries with carbon controls to those without, and export their production to these constrained countries (Babiker, 2005).

The International Carbon Action Partnership (ICAP) brings together countries and regions with mandatory cap-and-trade systems (European Commission, 2022-b). Research by Guo et al. (2019) identifies the following top three standards that are necessary to enable compatible systems “industrial accounting and reporting standards”, “verification standards” and “carbon emission metering & monitoring requirements standards”. The lack of compatible systems and standards results in a limited number of industries that get involved in carbon trading markets (Guo et al., 2019).

2.4.2 Security issues and non-transparancy of the EU ETS

Over time, the success of the EU ETS was threatened by several security incidents. Those incidents included reported theft of allowances and phishing attacks to gain access to accounts in the system (European Court of Auditors, 2015).

The biggest incident was the detection of fraud exploiting the Value Added Tax (VAT). Those cases were using the EU ETS to profit from taxes on trading of emission allowances. Europol estimated that the total damage is approximately 5 billion euros (European Court of Auditors, 2015). In some countries, up to 90% of the whole market volume was assumed to be caused by fraudulent trading (Europol, 2009). In Figure 3, an overview of the fraud, also called the Missing Trader Fraud, is provided. Traders first buys non-taxed (without VAT) allowances from another member state. They then sell the allowances on the market in his member state including the VAT in the selling price. The earned treasury is transferred by the fraudulent trader to an offshore bank account and this process is repeated until the trader closes the business and disappears, thus becoming the 'missing trader' (Frunza et al., 2011).

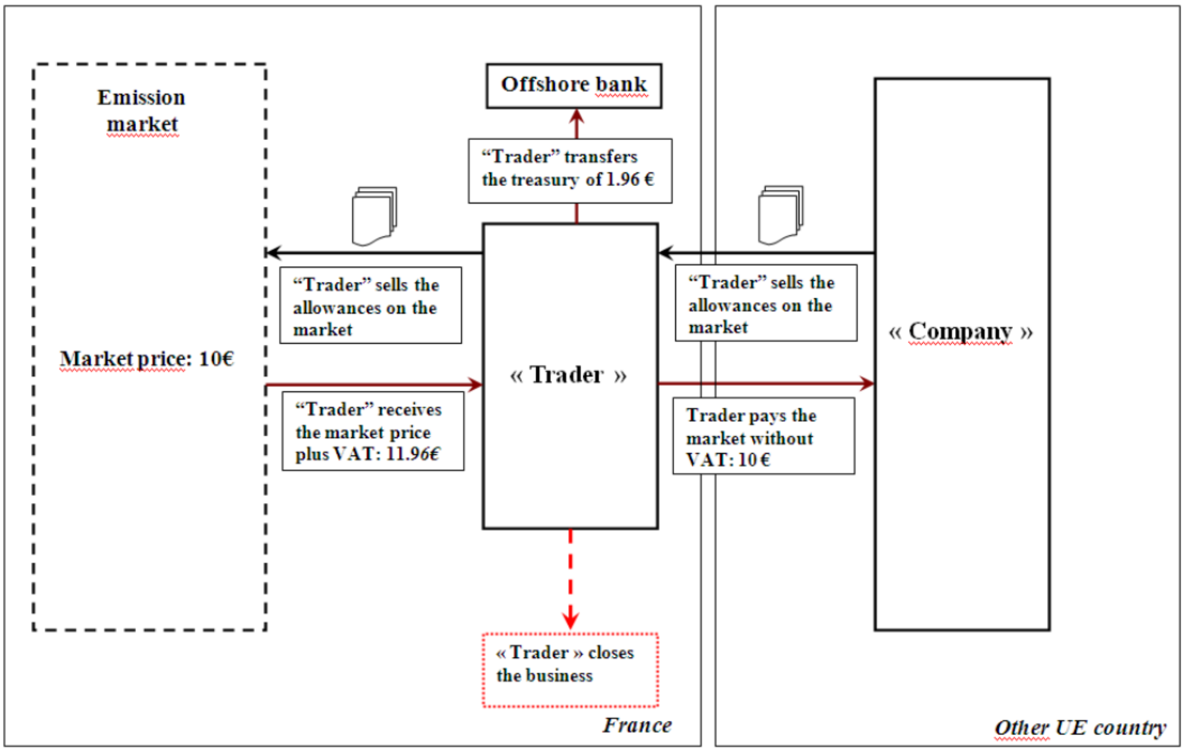

Figure 3 - Overview of Missing Trader Fraud (source: Frunza et al., 2011)

Although the Commission has implemented new security rules to avoid reoccurrence of this specific kind of fraud, research of Al Sadawi (2021) addresses that the EU ETS is still characterized by other fraud due to non-transparency in the trading market. For instance, 30% of the Czech Republic's carbon allowances were issued to the a national energy giant. However, the company misused their carbon allowances to generate profit and this profit was then used to increase coal production which enhances further the country's pollution (Al Sadawi, 2021). It proves that the current EU ETS is still vulnerable for fraud and that the transparency of transactions in the system should be enhanced to detect fraud more easily.

2.4.3 (Manual) monitoring of transactions of the EU ETS

In the research of Ashley et al. (2018), it becomes clear that the current centralized systems use manual credit monitoring in Excel and PDF's. Transactions of allowances between emission enterprises are enabled by exchanges and reported afterwards to the responsible authority. The authorities collect the transaction reports and adjust the emission allowance balances of enterprises in the Union Registry. The Union Registry does not register the price of emission allowances or financial information related to transactions in the system (European Court of Auditors, 2015). Due to the time-consuming manual processes, high transaction costs are involved (Al Sadawi et al., 2021 & Hartmann et al., 2020). Also, regulators have to rely on external market information like the market volume on exchanges. This increases the possibility of fraudulent traders in the market (Liss, 2018).

2.4.4 Blockchain as an alternative

To improve the functioning of ETSs, blockchain applications can be explored.. A blockchain is a digital structure with series of blocks that may contain data records with time stamps and a hash that links to the previous block (Crosby et al., 2016). The data is stored at different nodes in a distributed ledger. Blockchain has the ability to revolutionize systems like ETSs, due to the following attributes (Al Sadawi et al., 2021):

1. Decentralization: There is no central authority that controls the access of files, this attribute could help authorities to come to a global collaboration for emission trading because the power of the system can be designed to be decentralized;
2. Distribution: Multiple participants hold a copy of the records that get updated continuously, this could enable more openness in the system;
3. Security: The blockchain cryptographic structure, based on hash functions, ensures data security and immutability. As transactions are time-stamped on the blockchain and mathematically related to the previous blocks, it is impossible to tamper with it. This prevents fraudulent behavior in the system;
4. Transparency: The data is stored on the blockchain in a decentralized and secure way, it also provides possibilities for transparency. Transactions and information of the EU ETS can be visible to any node within the blockchain;
5. Privacy: Although blockchain is transparent, the system could be designed in such a way that information obtained from each node is kept anonymous using cryptography;
6. Automation: smart contracts could automatize certain actions when certain prespecified conditions are met. This could lower transaction costs in the EU ETS;
7. Traceability: Blockchain holds a historical record of all data from the date it was established. This enables easy investigation of fraudulent behaviors in the system.

These attributes allow for innovative solutions to data sharing or transaction management applications, making it a good first-order match to the requirement for an standardized and interoperable carbon market architecture (Jackson et al,, 2018).

From the overview of the literature, 7 out of the 10 articles proposed either a concept or a design for blockchain as a solution for ETS, see table 2. All these 7 articles propose decentralized carbon emission trading system as a possible blockchain solution. Other solutions that blockchain allows are automating transactions using smart contracts (Al Sadawi, 2021), digital tracking of carbon allowances (Patel et al., 2021) and Monitoring, Reporting, and Verification (MRV) of the ETS (Woo et al., 2022). The proposed blockchain solutions could be used globally in ETSs (Al Sadawi et al., 2021; Bai et al., 2020; Kim et al., 2020; Patel et al., 2021) but it could also enable emission trading in specific markets like between fuel providers (Ashley et al., 2018), vehicle users (Lu et al., 2022) and building owners (Woo et al., 2022). Only one article provides a blockchain solution in the voluntary market (Ashley et al., 2018) while the other articles are all proposed solutions for the compliance market.

Table 2 - Blockchain as a solution for emission trading

Authors	Proposed Blockchain solution	Contribution	Market
Al Sadawi et al. (2021)	• Decentralized carbon emission trading • Automating transactions	Design of a three-level framework using multiple blockchains, sensors and smart contracts.	Compliance
Ashley et al. (2018)	• Decentralized carbon emission trading	Concept of blockchain application for emission trading between fuel providers	Voluntary
Bai et al. (2020)	• Decentralized carbon emission trading	System architecture of a sovereign blockchain model to build a carbon trading system in the application, contract, consensus, network and data layer	Compliance
Kim et al. (2020)	• Decentralized carbon emission trading	Concept of applying blockchain to trade carbon emissions	Compliance
Lu et al. (2022)	• Decentralized carbon emission trading	Concept of a blockchain-enabled motor vehicle restrictive and trading system based on the carbon emissions cap	Compliance
Patel et al. (2021)	• Decentralized carbon emission trading • Digital tracking of carbon allowances	Concept of token-based economy for carbon trading and digital tracking of carbon emission permits	Compliance
Woo et al. (2022)	• Decentralized carbon emission trading • Monitoring, reporting and verification (MRV)	Concept of blockchain technology to add buildings in ETSs	Compliance

2.5 KNOWLEDGE GAP AND MAIN RESEARCH QUESTION

Based on this literature review, we see that the potential use of blockchain in carbon markets has only just begun to be explored. The majority of articles are focused on developing conceptual frameworks and there is a lack of empirical evidence as the proposed designs have not been implemented yet. The analysis shows that academic research in this field is still very scarce and that it will take time to analyze empirical evidence, which will lead to benefits and strengths of blockchain technology in ETSs.

It is substantiated by the literature that Blockchain could be a solution for the current challenges in ETSs, especially in the mandatory market, see table 2. Although the reviewed literature is useful to identify the possibilities of blockchain solutions to address the current challenges in ETSs, it is not clear how the current EU compliance market could allow extension by providing a large, transparent, verifiable, interoperable and robust carbon system. This involves two categories of challenges: 1) challenges about linking with other emission trading systems, which include technical system compatibility as well as organizational and political challenges, and 2) challenges about the technical design of the current EU ETS such as security issues and non-transparency, and (manual) monitoring of transactions. While research shows that blockchain attributes allow innovative solutions for emission trading, especially in the mandatory market (Al Sadawi et al., 2021; Bai et al., 2020; Kim et al., 2020; Lu et al., 2022; Patel et al., 2021, Woo et al., 2021) it is mostly only conceptual and it does not focus on the extension of existing ETSs. Possibilities to link ETSs within mandatory markets could enable future developments of the EU ETS so that collaboration between many independent entities and systems will become possible. Considering that the EU ETS is the first (since 2005) and most established ETS (representing nearly 90% of the global value of compliance markets), it will be interesting to research what blockchain-based EU ETS would contribute so that the development of global markets could happen. Taking the EU ETS as a starting point for a global market allows for an innovative design without having to throw away the existing principles, which are developed after experience and knowledge. This results in the following main research question:

What blockchain-based design can be used by the European Union to improve the technical design of the EU ETS while allowing for the extension to other Emission Trading Systems ?

This research focuses on designing a blockchain design to improve the current technical design of the EU ETS while also providing an architecture that allows technical system compatibility for extending to other ETSs. In this research, the organizational and political challenges will not be part of the design but rather evaluated on at the end.

3. RESEARCH APPROACH AND RESEARCH METHODS

3.1 RESEARCH APPROACH

For this research project, a Design Science Research (DSR) approach is taken, see Figure 4. Advantages of this approach are that this ensures a discipline oriented creation of a future-proof design that addresses current challenges of the EU ETS. The DSR methodology of Peffers et al. (2007) is used to incorporate required principles, practices, and procedures to carry out such research, see figure 5. The six phases are: Explicate problem, Define requirements, Design and Development, Demonstration, Evaluation and Communication (Ramraika, 2015). Due to time constraints of the Master Thesis Project, the last phase (Communication phase) will not be taken into account. A possible limitation of this approach is that cognitive limitations, information imperfection and time constraints result in bounded rationality (Simon, 1990). This might result in a design with suboptimal decisions. This is a limitation that is evaluated on in the fifth phase (Evaluation) of the research approach, see chapter 8.2.1.

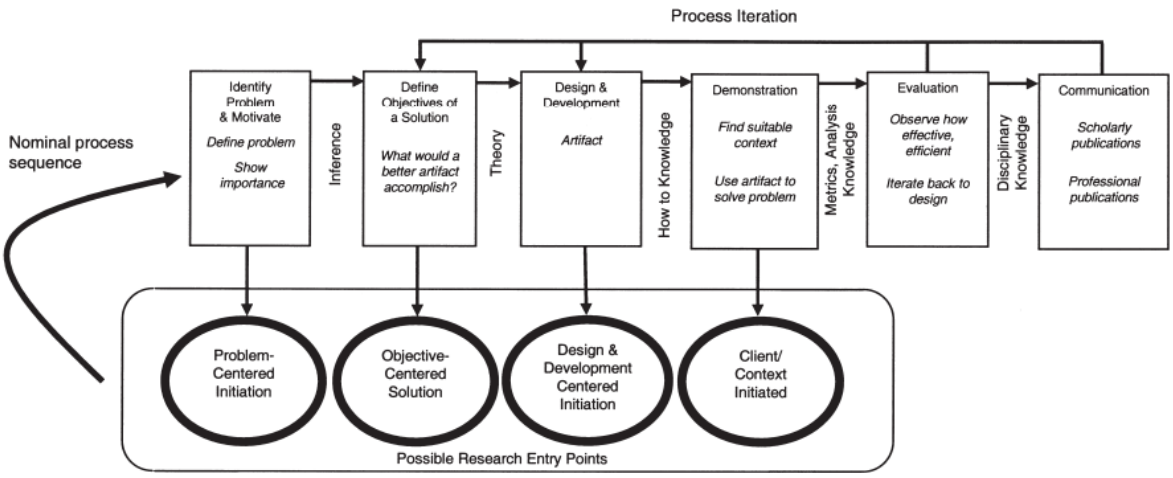

Figure 4 - DSR methodology (Peffers et al., 2007)

3.2 SUB QUESTIONS AND RESEARCH METHODS

This section describes the research methods for each sub-question. It also elaborates on the data requirements, how the data is gathered and the data analysis tools that are used in this research.

1. What is the current socio-technical composition of the EU ETS?
   a. Who are the relevant stakeholders in the EU ETS and what is their role?
   b. In what institutional environment does the EU ETS take place and how is it linked with other ETSs?
   c. What is the current technical composition of the system?

The first sub-question I is proposed to address the first phase of DSR: Explicate problem. To do this, a system description is needed with a Technical, Institutional, and Process (TIP) approach. This TIP design means that technical and institutional components are studied to produce functional processes. In this regard, a system description is presented by conducting a desk study, here the focus lies on existing scientific articles that explore the technical, institutional and stakeholder aspects. Additionally, the documentation of the European Commission and carbon reports provided great insights. For the stakeholder analysis, the EU ETS Handbook (European Commission, 2015) and carbon market reports that are published by the European Commission annually are used to collect information about the roles and interests of relevant stakeholders. To explore the institutional environment of the EU ETS, a dive into the main EU ETS legislations (2003-2018) has been done. These legislations consist of directives, which are legislative acts that sets out a goal that all EU countries must achieve (European Union, n.d.) and EU decisions, direct applicable and binding (European Union, n.d.), considering the linking of the EU ETS with other greenhouse gas ETSs. The data collected from these sources were useful to understand the institutional environment of the EU ETS and what the institutional possibilities are to link the current EU ETS with other ETSs. At last, to explore the technical composition of the system, several sources are used to gather data. Relevant ones are the EU ETS Handbook (European Commission, 2015) and technical schemes provided by the EU ETS from past phases. This latter one consists of XML schemes, tree view representations and entity-relationship diagrams of Request and Report functions in the system (European Commission, 2022-c). The important functions in the technical system of the ETS are summarized. The data collected from the literature areexplored and combined into a system analysis. The data from the desk research is be combined in the data analysis tool Microsoft Excel, to cluster the literature based on the content. The output of this chapter is an overview of system as an input for the design principles and requirements (next chapter).

2. What are the design principles and requirements needed blockchain-based design to allow extension of the current EU ETS?

The goal of question *II* is to address the second phase of DSR: Define design principles and requirements. In this phase, the identified subsystems from sub-question *I* are be aligned by a structured method for writing requirements of subsystems (Ruijgh, 2020). Because the research methods of question *I* are limited to desk research, the requirements are complemented and validated through semi-structured interviews to verify the wishes and needs of real-life stakeholders. Interviews are a method for exploration of non-documented information. These interviews are held with current market parties like oil refineries, chemical manufacturing companies and EU ETS authorities to validate the current challenges in the system and propose requirements for it. Also, interviewees are from (Blockchain-based) carbon platforms to gather requirements for technical mechanisms, these platforms could be from the mandatory as well as the voluntary market. A possible limitation could be that the data gained from these interviews might be biased, because stakeholders have their own interest and they might want to influence the governance process design. However, interviews are held with different market parties so that different perspectives can be considered. This also improved the insight into the complexity of the problem. Another drawback is that the interviews are time-consuming. To make this manageable, the preparation of interviews were done in an early stage of the research. The tool used to record the semi-structured interviews is called Otter, this tool allows recordings to be transcribed automatically. From this, the semi-structured interviews are translated into relevant requirements. The output is a set of requirements that is used in the next phase of the research for the designing an artefact.

3. How would blockchain design components be implemented in the EU ETS?
    a. What are the components for a blockchain design?
    b. What are the design choices of the blockchain design for the EU ETS?

The third sub-question refers to the phase of Design, Development and Demonstration in the DSR approach. To design alternatives, a literature review about multi-criteria decision frameworks and ontologies for blockchain technologies will be done to compare different frameworks. In these frameworks/matrices, the relevant design properties of Blockchain architectures are given. Due to time constraints, only the most relevant design components are selected for this design based on the requirements from chapter 2 (e.g. Consensus). This resulted in a blockchain architecture including all relevant design properties for this research but also a less detailed design architecture. This is evaluated on in the evaluation phase. The components are all analyzed and design choices are made using the requirements as a multi-criteria decision framework. After this, the design choices are demonstrated. The tool used to complete the design is draw.io.

4. How can the blockchain-based EU ETS design be demonstrated and evaluated?

The purpose of the demonstration phase of the research is to demonstrate the proposed artefact in this research. The demonstration is done through illustrations of the institutional and stakeholder environment of the system. Furthermore, cross-functional process diagrams (also: swim-lane diagrams) are used to present the processes of the EU ETS in the blockchain architecture. The cross-functional process diagrams are a series of interrelated work activities and resources that follow a distinct path to transform it into outputs with value (Damelio, 2011). A limitation of the diagrams is that they do not show the connection between the processes. However, the processes and their connections are described thoroughly in the system analysis and the diagrams are presented in a sequential way to provide a logical overview.

At last, in the evaluation phase of the DSR approach, the demonstration is used for the evaluation of the design and has two objectives: 1) to assess whether the proposed artefact complies with the requirements generated in the second phase of DSR: Define design principles and requirements, and 2) to assess the relevance and feasibility of the proposed artefact with experts. The first objective is reached by analyzing the artefact and the requirements. The second objective is completed through semi-structured interviews with a group of experts. This is a way to quickly collect input data to evaluate the design. Experts in this domain include academics and experts in the working field that could evaluate the blockchain-based EU ETS design and the content of the design. The data retrieved from the evaluation interviews are qualitative evaluations. The evaluations are used to provide an overview of limitations and improvements of the design.

3.3 Research flow diagram

The research methods for each sub-question are summarized in a Research Flow Diagram (RFD), see Figure 5.

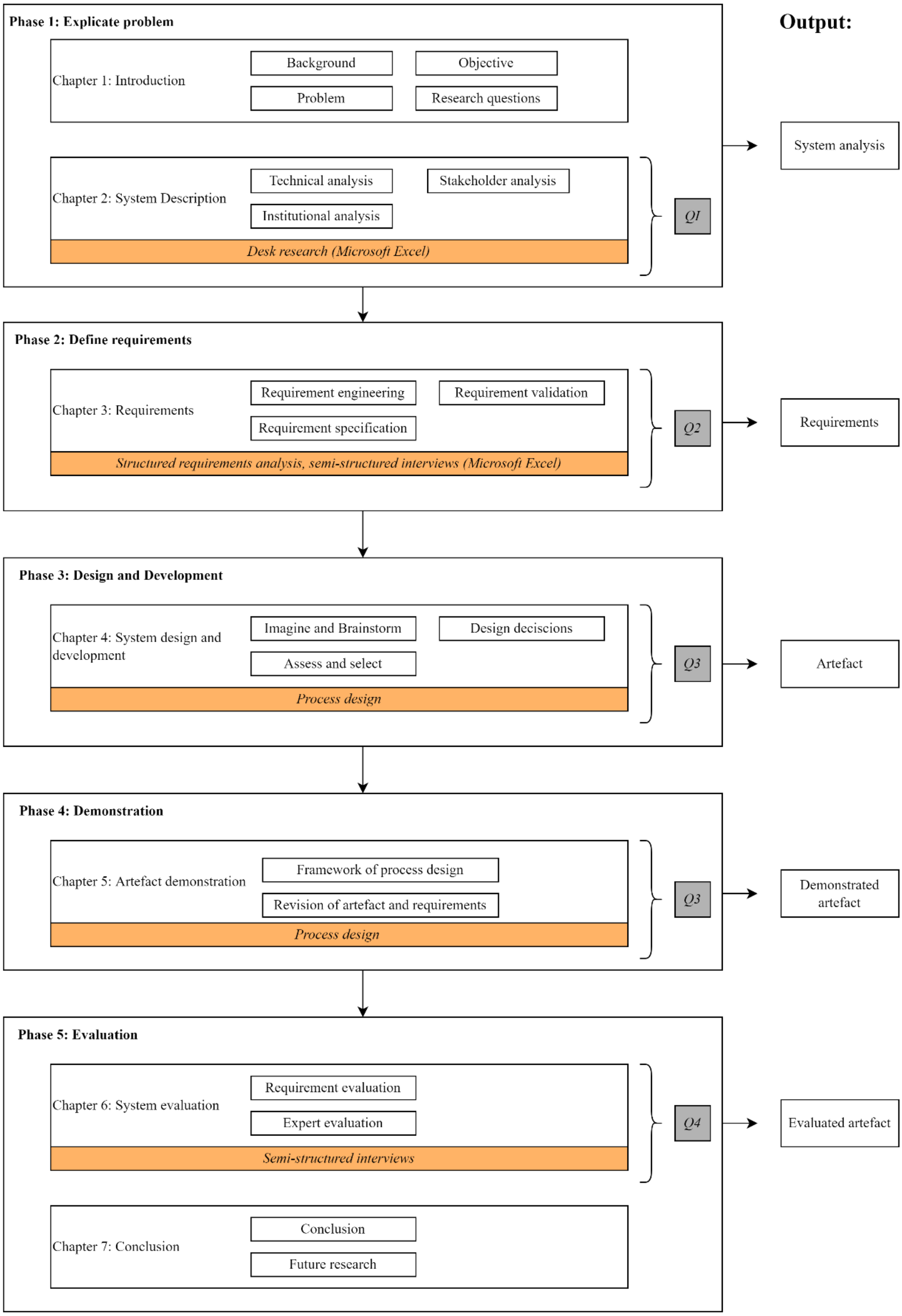

Figure 5 - Research Flow Diagram

4. THE EU EMISSION TRADING SYSTEM

This chapter provides a system description of the EU ETS to answer the first sub-question: *What is the current socio-technical composition of the EU ETS?* This is done by desk research in which the system is divided into three sub-systems: technical, institutional, and stakeholders. The analysis delivers socio-technical insights about the design choices and assumptions to be made in a blockchain-based design, which will be elaborated on in further chapters. The results of this analysis will guide the making of an integrated Programme of Requirements (PoR), see chapter 4. First, in section 4.1, the system boundaries of the EU ETS in this research will be defined. A representation of the stakeholders in the EU ETS will be covered in section 4.2. The institutional overview is covered in section 4.3. At last, an analysis on the Union registry and the EUTL will be provided in section 4.4.

4.1 SYSTEM BOUNDARIES

In this research, we focus on the EU ETS which is categorized as a system in the compliance market with a cap-and-trade principle. A 'cap' limits the total amount of certain GHG that can be emitted by the installations covered by the system and emission allowances are issued accordingly (European Commission, 2021). Within this limit, the participants in the system can engage in 'trading' these emissions allowances to fulfill their obligation in a cost-effective way. The cap on the total number of allowances creates scarcity in the market and therefore creates value for the allowances (Vlachou, 2014). The Cap-and-Trade allows for a cost-effective way to reduce GHG.

The EU ETS represents nearly 90% of the global value of compliance markets (Refinitiv, 2021) and mostly focuses on industrial facilities (heavy energy-using installations and airlines). The EU ETS includes the entire European Economic Area (EEA) of 28 countries containing all EU countries plus Iceland, Liechtenstein, and Norway. Currently, more than 11.000 heavy energy-using installations are covered, such as power stations and combustion plants, and aircraft operators (European Commission, 2021). In the EU ETS, allowances are created and issued for the following GHGs: CO2 emissions, N2O emissions from all nitric, adipic, and glyoxylic acid production, and PFC emissions from aluminum production (European Commission, 2015). In this research, we focus on the following three core functions of the EU ETS:

1. Creation and issuance of emission allowances
2. Monitoring, Reporting, and Verification (MRV) of emissions
3. Market and trading of emission allowances

See Figure 6 for an overview of the EU ETS system boundaries and core functions.

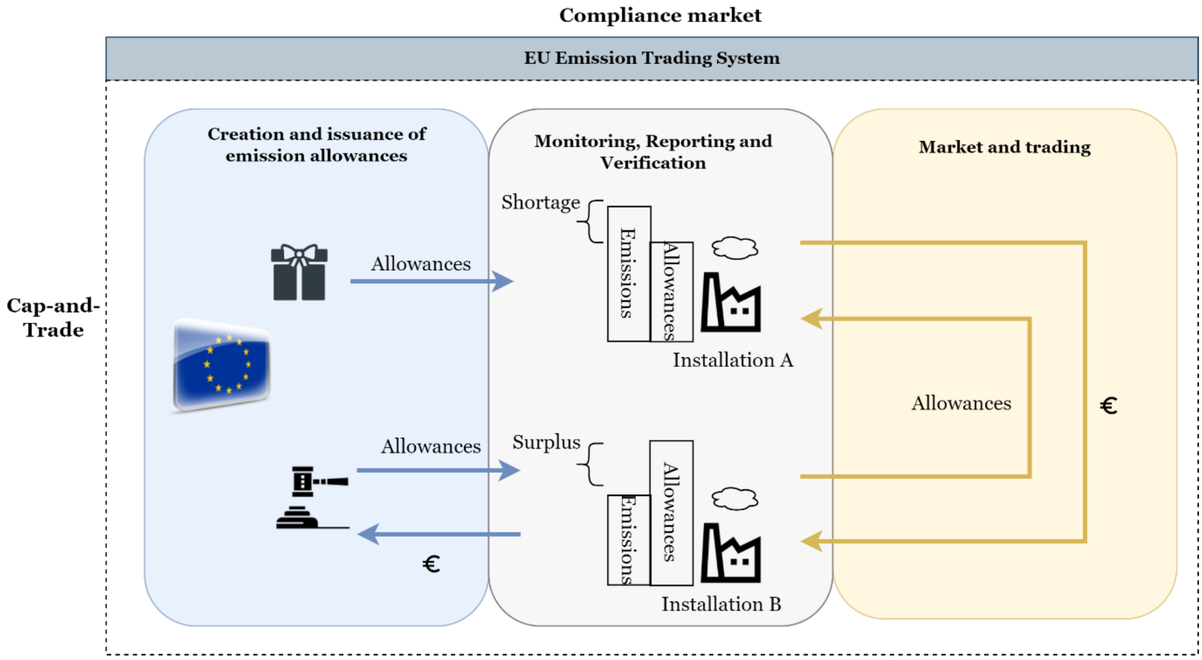

Figure 6 - Overview of the system boundaries and core functions

The first function, the creation, and issuance of emission allowances, is executed under the provision of the European Commission. The creation of emission allowances is dependent on the objective of achieving climate neutrality in the EU by 2050 and an intermediate target of at least an 55% net reduction of emissions (European Commission, 2022-a). Based on these targets, the EU decreases the cap on emissions with an annual increase of a linear reduction factor of 2,2% until 2030 (European Commission, 2022-a). Additionally, the EU ETS uses the Market Stability Reserve (MSR), a fully rules-based mechanism that aims to providing price stability for installations covered under the system. Starting in 2019, the MSR absorbs a part of the emission allowances in circulation because a surplus of allowances has been built up in the EU ETS resulting in volatile prices in the market. The total number of allowances in circulation (TNAC) is a measure of allowances in a year (*y)* and defined as the difference between all allowances issued and international credits used since 1 January 2008 (European Commission, 2017):

$$TNAC = \sum_{y*=2008}^{y} \left(Supply_{y*} - (Demand + voluntary\ cancellation)_{y*} \right) - Allowances\ in\ the\ MSR$$

The threshold for the TNAC is set to be 833 million allowances. So when the TNAC exceeds this threshold, the MSR will absorb these allowances from the to be auctioned supply of that year. There is no expiration date for the allocated emission allowances in the EU ETS but as from 2023, allowances held in the MSR above the previous year’s auction volume will no longer be valid (European Commission, 2017).

There are two methods for the issuance of emission allowances: auctioning and free allocation. Since the third trading period of the EU ETS (2013-2020), auctioning has been the default allocation method. All Member States in the EU ETS are responsible for auctioning their allowances on the common auction platform. Currently, the European Energy Exchange (EEX) in Leipzig is the common auction platform. The common auction platform is nominated for up to five years by a joint procurement between the Commission and the participating countries.

The ETS Directive provides that the countries should at least use 50% of the auction revenues for climate and energy-related purposes (European Commission, 2022-a). On the other hand, free allowances are allocated to installations that are at the highest risk of carbon leakage. This refers to the situation that may occur if businesses transfer their production to other countries with laxer emission constraints to avoid the costs of climate policies. A benchmarking method is used for the allocation of free allowances in the EU ETS. The European Commission draws up a list with installations that qualify for free allocation in agreement with the Member States and the European Parliament, following an impact assessment and extensive consultation with stakeholders (European Commission, 2015).

On the other hand, the annual emissions of enterprises need to be verified. This is the result of the second function, MRV of emissions. The MRV process is essential in the ETS to assure that one tonne CO2 equivalent emitted is equivalent to one tonne reported. The EU Monitoring and Reporting Regulation (Commission Regulation (EU) No 601/2012) and the EU accreditation and verification Regulation (Commission Regulation (EU) No 600/2012) must be followed when monitoring, reporting and verifying GHG emissions. Operators of installations and aircraft must submit an annual emission report (AER) to the Competent Authority in accordance with the regulations every year. The AER is the essential document that shows how much greenhouse gas the operator emits in a particular year following the compliance cycle. Each compliance cycle has a duration of a year and by 30 April of each year, ETS operators are required to surrender their emission allowances, equal to the verified GHG emissions of the previous year, see the compliance cycle in Figure 7. The installation must be compliant with the regulations and surrender enough allowances to cover fully its emissions, otherwise heavy fines are imposed. Surrendered allowances are removed from the system. The allowances that the emission enterprise purchased this same year and did not surrender can be used to cover emissions in a future year. Emission allowances do not expire and only evaporate when tokens are surrendered.

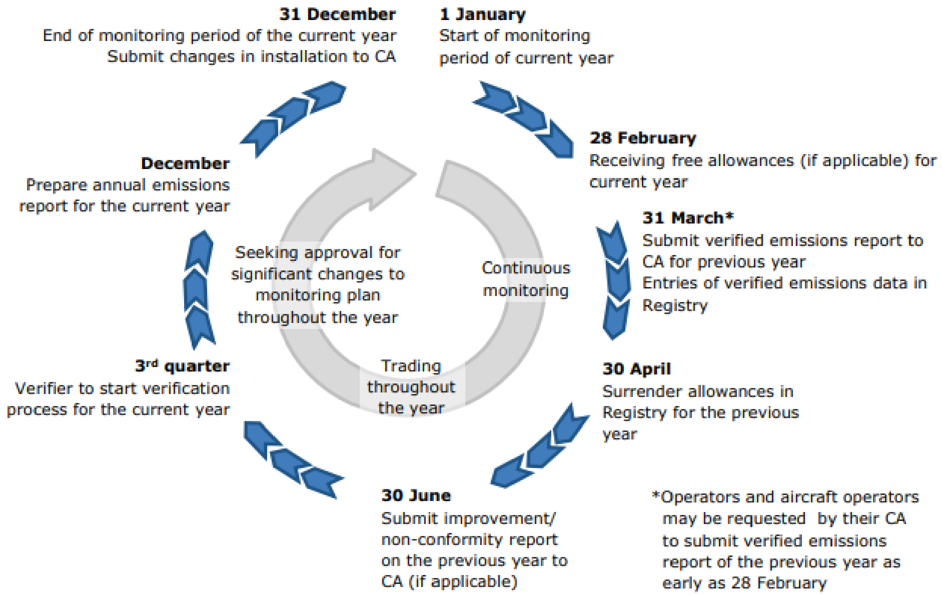

Figure 7 - EU ETS compliance cycle (source: European Commission, 2015)

At last, the emission allowances are traded throughout the year. Anyone with an account in the EU registry can engage in the trading of allowances. Trading is possible directly between buyers and sellers through organized exchanges. An emission allowance is traded in the same way as commodities and financial instruments. Trading of allowances are subject to the same EU financial market regulation as other financial instruments and trades. Market supply and demand determines the value of the units. Emissions could potentially be lower than anticipated and lower than the number of available allowances, for example because of measures made by the company in emission-reduction strategies. The remaining allowances, which enterprises can utilize to trade, will then be available. Companies must buy additional units through trade or auction if their emissions exceed their allowances. Therefore, these enterprises can choose for themselves whether it is more cost-effective to buy more units or invest in clean technologies.

4.2 Stakeholders in the EU ETS

A stakeholder analysis is a method or a process which evaluates the economic interests and preferences of actors – individuals and organizations, to understand their behavior, intentions, interrelations, and interests (Varvasovszky, 2000). This enables policy-makers to assess the influence and resources that stakeholders bring to bear on decision-making or implementation processes. In this case, the stakeholder analysis provides a better understanding of the power and interests of the stakeholders in the EU ETS for a the possible implementation of a blockchain-based system.

4.2.1 Stakeholder overview

The stakeholder chart is used to describe the relations between the relevant actors, see Figure 8. The chart gives insight in the way (in)formal relationships shape hierarchy and helps to define the power of each actor in comparison to each other.

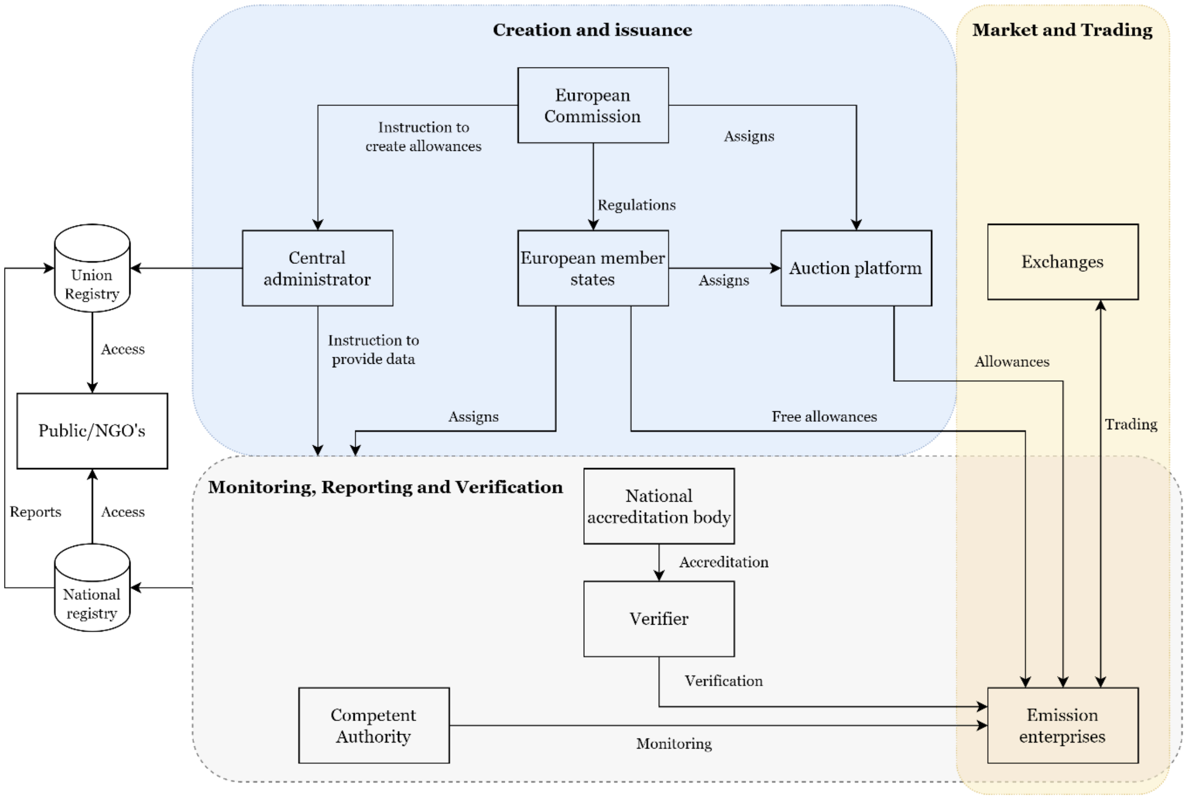

Figure 8 - Stakeholder chart EU ETS

Stakeholders: Creation and Issuance

European Commission

The European Commission is the executive arm of the EU and responsible for ensuring that EU legislation is correctly implemented. The European Commission is the only institution with the power to initiate a legislative proposal such as new regulations in the EU ETS. The Commission has powers of implementation e.g. in determining the allocation of free allowances and MRV of emissions. The commission can take action and impose sanctions against a Member state if government legislation is not properly implemented.

European Member States

The European Member States are responsible for allocating the free allowances by following the list of the European Commission for the installations in their country. Together with the European Commission, the European Member States nominate a common auction platform for up to five years. At last, the European Member States are responsible for a assigning a national administrator/accreditation body for the EU ETS.

Auction platform

The auction platform facilitates auctions of emission allowances. Currently, the EEX in Leipzig is the common auction platform. Bidders may apply for admission to bid on auction platforms. Each application must be checked by the auction platform to ensure that bidders are eligible to participate under the Auctioning Regulations and to prevent auctions from being exploited for illegal conduct.

Central administrator

The Central Administrator issues all allowances by creating them in the Union Registry. The Union Registry is the where all allowances are recorded. The Central Administrator is responsible for transferring allowances for auctioning and free allocation to the appropriate accounts. Member States are responsible for allocating the free allowances.

Stakeholders: Monitoring, Reporting and verification (MRV)

Every year, operators of installations need to hand in an AER that is in line with the monitoring and reporting regulations of the competent authority. The relevant stakeholders in this process are the Emission enterprises (aircraft/installation operators), the competent authority, the verifier and the national accreditation body, see Figure 9.

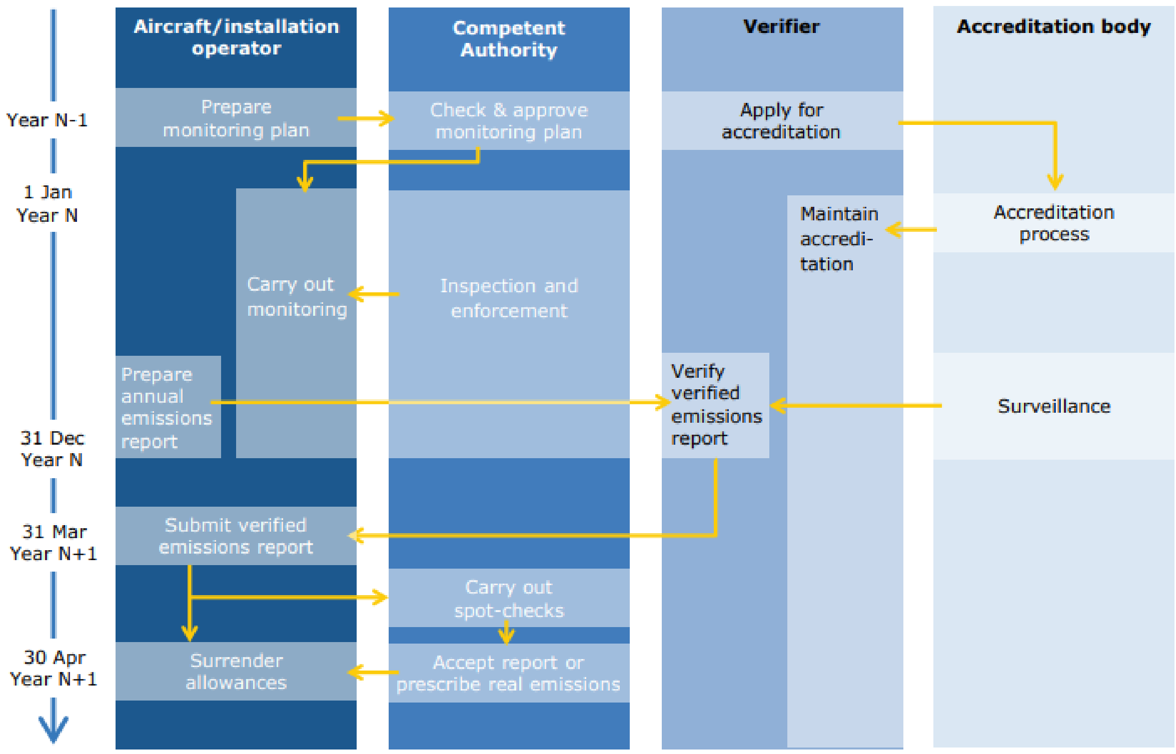

Figure 9 - Stakeholders in the MRV process (Source: European Commission, 2015)

Emission enterprises (aircraft/installation operators)

The emissions of obligated enterprises are bounded by the cap set by the European Commission. The emission enterprises obtain emission allowances and go through the MRV process in the compliance cycles, which have a duration of one year. They have to open a registry account in the Union Registry, prepare a monitoring plan, obtain allowances and submit annual emissions reports. When the annual emission reports are verified and submitted, they need to surrender their allowances. Dependent on the amount of allocated allowances owned by the emission enterprise, the choice to buy or sell the allowances on an exchange could be made. When emission enterprises transacted emission allowances, both need to report this transaction to the competent authority. After verification by the competent authority, the transaction will be registered in the national registry and passed to the union registry.

Competent authority

The competent authority functions as the main contact point for operators, verifiers and National accreditation bodies. The main responsibilities are checking, approving the monitoring plan of the emission enterprises and allocating issues in the process. Also, the competent authority manages the accounts of a Member State and the accounts under the jurisdiction of that Member State in the national registry. They connect with the central administrator for the data to put into the union registry, e.g. for opening an account in the union registry, the national administrator has to check specific evidence of an account holder and provide it to the central administrator before the account can be activated.

Verifier

The verifier in the MRV process must verify the verified emissions report of emission enterprises, apply for initial accreditation and maintaining it. The National Accreditation Body monitors the verifiers. The main objective is to conclude with a high degree of certainty that the operator reported data that are free from inconsistencies and collected according to the monitoring methodology approved by the competent authority and the requirements.

National Accreditation body

The national accreditation body is responsible for the accreditation of verifiers. Its personnel, accreditation assessors and technical experts must be competent, independent, and impartial. Furthermore, it surveilles the verification process of the verifier to ensure evaluation of the independent verifier.

Stakeholders: Market and Trading and others

Exchanges

Exchanges are marketplaces in the ETS where the emission allowances are traded. The core function of an exchange is to ensure fair trading between buyers and sellers.

Public/NGOS's

The public and non-governmental organizations (NGOs) are not directly active in the EU ETS but are concerned with the environmental impact that the ETS has. The public and NGOs are able to retrieve public data from the national and Union registry.

4.2.2 Stakeholder analysis

The stakeholder analysis assesses the abovementioned stakeholders by taking into account their power and interest in the EU ETS. This technique is based on Eden and Ackermann's method (1998), taking into account low and high power and interest results in four quadrants and stakeholder roles: players, subjects, context setters, and crowd.

Stakeholders with high interest and power are the key players, these are important partners where close collaboration is essential. The European Commission is the biggest key player as the executive arm of the system. Together with the Member States, they fill in the context of the ETS.

Context setters are stakeholders with high power and less interest. The auction platforms and exchanges are parties that are needed to ensure the possibility of allocation of allowances and emission trading. These stakeholders are important and therefore need to be kept satisfied.

Stakeholders with low power but high interest are subjects. The emission enterprises are subjects in the context of the EU ETS as they are obligated to comply with the regulations. The other authorities (the central administrator, national accreditation body, verifier and competent authority) play a crucial role to ensure that the processes are done correctly, also following the regulations from the key players in the EU ETS.

At last, the crowd are stakeholders with low interest and low power. The public and NGOs are not directly involved in the EU ETS but are concerned with the environmental impact that the ETS has. Therefore, these stakeholder have the lowest priority but could be monitored.

4.3 Legal framework EU ETS registries

The institutional analysis provides an overview of the regulatory environment of the EU ETS and elaborates on the existing coordination mechanisms that allow linking to other ETSs. It aims to answer the subquestion 1a: *In what institutional environment does the EU ETS take place and how is it linked with other ETSs?* This question needs to be answered to define the institutional requirements of the EU ETS. In Europe, greenhouse gas registries are established to conform to provisions of international, European, and national rules, see Figure 10 for a legal framework.

International rules

The Kyoto Protocol (1997) is implemented with the objective to reduce the onset of global swarming by reducing GHGs and it operationalizes the United Nations Framework Convention on Climate Change (UNFCC) which was introduced in 1992 (UNFCC, 2022). The international rules laid down under the UNFCC have been translated into technical specifications in the Data Exchange Standards (DES), which set the basic rules and conditions on which national registries have been developed.

European rules

European legislation supports the rules set in the UNFCC and the Kyoto Protocol and forms the basis for the EU ETS. Regulations and decisions become binding automatically throughout the EU on the date they enter into force and directives must be incorporated by EU countries into their national legislation. The base legislation for the EU ETS is the European emission trading directive, Directive 2003/87/EG of 13 October 2003. It establishes the basis for a common system of tradeable emission rights between European Member States conform to detailed specifications. Amongst others, it establishes compliance obligations for fixed installations and aircraft operators, it determines the responsibilities of the stakeholders in the system, and it sets accounting rules under the EU ETS (European Commission, 2015).

National rules

On a national level, regulations in the form of laws ensure the compliance of the EU Directives. For instance, the Netherlands implemented the wet Milieubeheer BWBR0003245, which is the most important Dutch environmental act to determine which legal tools can be used to protect the environment. The main instruments are environmental programs, environmental quality requirements, permits, general rules, and enforcement (Rijkswaterstaat, 2022)

Emission trading registries

An emissions trading registry is an online database that issues, records, and tracks the carbon units that are exchanged within market mechanisms. The following registries are related to the EU ETS:

- Consolidated System of European Registries (CSEUR): provides an EU-wide standardized and centralized registry system for all EU Member States, Iceland, Norway and Liechtenstein. The European Commission is responsible for the technical management of the CSEUR and the EU Member States are in control of the user and account management.
- International Transaction Log (ITL): is operated by the UNFCC based on the DES under the Kyoto Protocol like national emission reduction objectives. International credits are verified by the ITL. In case of transactions towards a European registry, ITL will forward the transaction to the European Transaction Log (EUTL) for European verification.
- European Transaction Log (EUTL): The EUTL is the central reporting and monitoring tool of the EU ETS. Compliance with the rules of the EU ETS is checked by the EUTL and stored in the Union Registry.
- Union Registry: serves to guarantee accurate accounting for allowances in the EU ETS. It records national implementation measures, allowances of installations and aircraft operators, transfers of allowances, annual verified emissions and annual reconciliation of allowances.
- National EU registries: each national register has its own access point to the CSEUR. National registries consists of two parts: under the EU ETS and under the Kyoto Protocol (KP). The EU part ensures that all installations and aircraft operators within the EU-ETS effectively fulfill their obligations under the EU-ETS. The KP part of the registry monitors that the Parties of the KP are achieving their emission reduction objectives.
- Clean Development Mechanism (CDM) registries: The CDM registry is part of the UNFCC and is used to issue certified emission reduction credits for CDM projects.
- Other registries: other national registries (non-EU, under KP) are transacting with the ITL to ensure compliance with the emission reduction objectives of the KP.

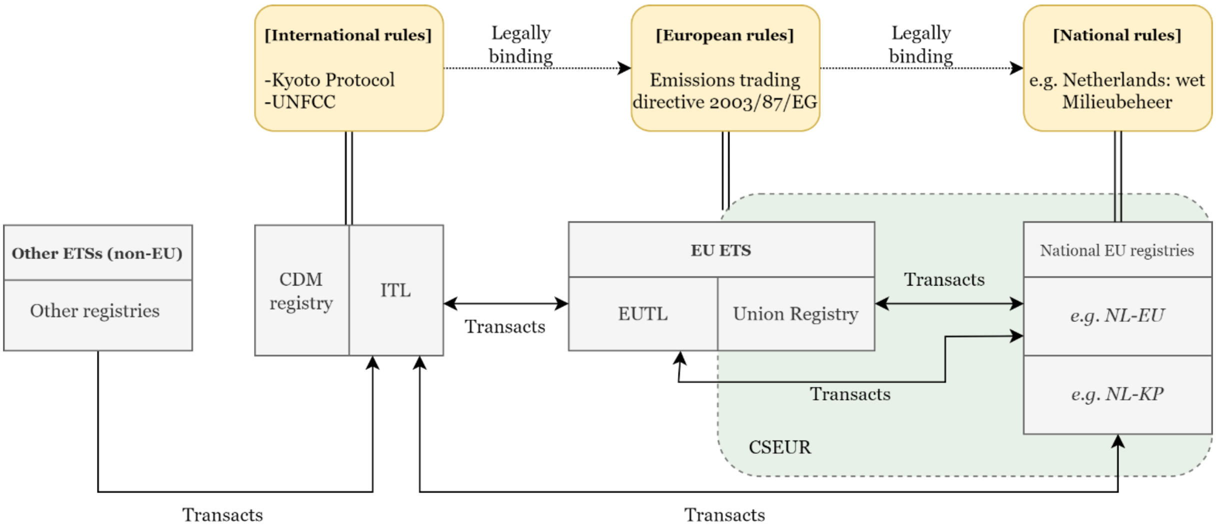

Figure 10 - Legal framework of international, european and national trading schemes/registries

In the current institutional environment of the EU ETS, we find that the EU ETS is fully connected with the EU national registries and partly connected with the ITL (only for verification of European transactions on international level). Although non-EU ETSs under the Kyoto Protocol also are partially connected with the ITL, there is no direct institutional connection between the EU ETS and non-EU ETSs. The EU ETS also does not have any connection with a scheme using the baseline-and-credit principle, such as the international CDM registry.

4.4 THE UNION REGISTRY AND THE EUTL

The objective of the technical analysis is to define the boundaries of the technical system used by the EU ETS, which is the Union Registry and the EUTL. The objective of the technical analysis is to specify the functions of the system within the boundaries of this research and analyze where the touchpoints are for a blockchain-based system. We answer sub-question 1b: *What is the current technical composition of the system?* The specification of the functions will be used in chapter 4 to identify the technical requirements for a design of the EU ETS.

4.4.1 Union registry

The Union Registry is an online database that holds accounts for accurate accounting for all allowances issued under the EU ETS. The Union Registry is connected to all the countries participating in the EU ETS, each country has their own section in the database. The registry records:

- All countries participating in the EU ETS
- A list of installations covered by the ETS directive (in each country)
- Accounts of companies or individuals holding allowances
- Transfers of allowances performed by account holders
- Annual verified CO2 emissions from installations and aircraft operators
- Annual reconciliation of allowances and verified emissions, where each company must have surrendered enough allowances to cover all its verified emissions

Requirements Transactions of allowances in the EU ETS take place between accounts in the Union registry. Actors in the EU ETS first need to open an account with the Union registry to be able to perform any transaction. The Union Registry has two main types of accounts: management accounts and user accounts. Management accounts include accounts for administrative functions of the EU ETS. User accounts are operator/person holding accounts, trading platform accounts and verifier accounts.

4.4.2 European Transaction Log (EUTL)

All transactions between accounts in the Union Registry are automatically checked, recorded, and authorized by the EUTL. The data in the Union Registry and the EUTL is a valuable source of information for different sorts of ETS reporting, including the calculation of the MSR surplus indicator and the European Environment Agency's reporting. The EUTL further promotes transparency in the EU ETS by publishing data on the compliance of stationary installations and aircraft operators' with ETS requirements. Data published in the Union Registry are consistent with the data provided by the EUTL. To operationalize the link between the EU ETS and other ETSs, a direct link between the EUTL of the union registry and the other ETS shall be established, because this enables registry-to-registry transfer of emission allowances.

4.4.3 Relational database model

Figure 11 shows the relations in the database among the core tables of the EUTL. The header of each box state the table names and the connections represent the relations between the tables. Each installation (see table: installation) relates to a number N different entries for compliance and surrendering because an installation could surrender and comply each year for their emissions in the ETS. At each instance of time, an installation is associated with exactly one active account, but over time due to changes of account settings, an installation might relate to more user accounts (former and current accounts). Furthermore, each account, representing one installation in the EUTL, relates to only one account holder. However, an account holder could have more accounts (installations), e.g. a large power company with several power plants. At last, a transaction relates to two accounts: a transferring account and an acquiring account.

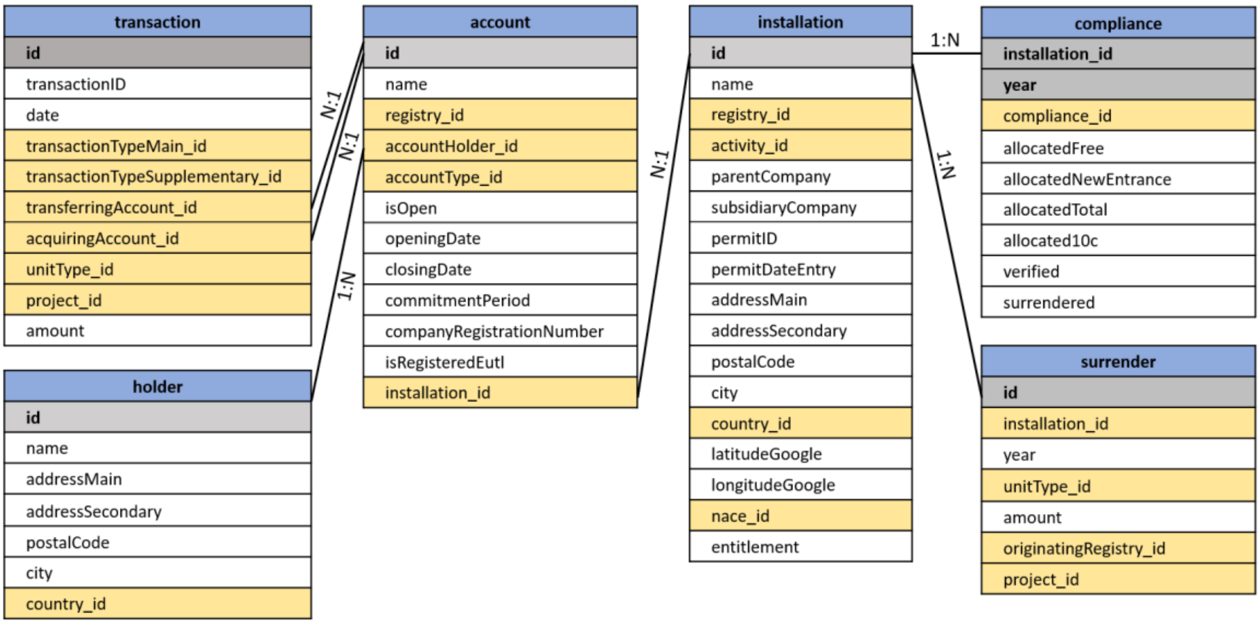

Figure 11 - Relational database model (source: Abrel, 2022)

The relational database model constructs the different elements stored in the EUTL facilitating the analysis of compliance by installations and transaction behavior. From this analysis, we conclude that the EUTL is able to store emission data and the transaction data of emission allowances efficiently to check the compliance of installations. However, the relational database model demonstrated that the price of emission allowances or financial information related to transactions is not stored in the in the database. So when regulators need information about this, they have to rely on external market information like the market volume on exchanges. Also, in the current construction of the database, there is no clear entry for linking with other systems.

4.5 Conclusions

To answer the first sub-question *What is the current socio-technical composition of the EU ETS?*, an socio-technical approach is taken to analyze the EU ETS. In the stakeholder subsystem, insight is provided on stakeholders about the way (in)formal relationships shape hierarchy and the definition of stakeholders' power comparison to each other. In the EU ETS, the European Commission is the biggest key player as the executive arm of the system. Together with the Member states, they fill in the context of the ETS. The other authorities (the central administrator, national accreditation body, verifier and competent authority) play a crucial role to ensure that the processes are done correctly, also following the regulations from the European Commission and the Member States in the EU ETS. The emission enterprises are subjects in the context of the EU ETS as they are obligated to comply with the regulations. The auction platforms and exchanges are parties that are needed to ensure the possibility of allocation of allowances and emission trading.

The EU ETS registries are dependent on institutional environment of the EU ETS. In Europe, greenhouse gas registries are established to conform to provisions of international, European, and national rules. The Union Registry and the EUTL operate under the European emission trading directive, Directive 2003/87/EG of 13 October 2003. These registries need to transact with EU national registries under national regulations and the ITL under international regulations. This is enabled by the hierarchical structure and legal bond of regulations, from international agreements translated into European directives, and converted into national laws. While the EU ETS is well organized under European supervision and compliant with international agreements, a legal connection between the EU ETS and nations outside the EU currently does not exist.

At last, the technical composition of the EU ETS consists of the European registries which are the Union Registry and the EUTL. The Union registry functions as the database of the EU ETS where all relevant data is stored, such as the countries participating in the EU ETS, the installations covered (in each country), accounts of companies or individuals holding allowances, transfers of allowances performed by account holders, the annual verified CO_2 emissions from installations and aircraft operators, and annual reconciliation of allowances and verified emissions. On the other hand, all transactions between accounts in the Union Registry are automatically checked, recorded, and authorized by the EUTL. Data published in the Union Registry are consistent with the data provided by the EUTL.

This system analysis will serve as an input for the generation and elicitation of the design principles and requirements in the next chapter, see chapter 5.

5. DESIGN PRINCIPLES AND REQUIREMENTS

This chapter answers subquestion II: *What are the design principles and requirements needed blockchain-based design to allow extension of the current EU ETS?* This is achieved by eliciting, categorizing and prioritizing the requirements based on the system analysis, see Chapter 4 and semi-structured interviews, see Appendix A. Section 5.1 describes the Design principles and section 5.2 Finally, an overview of the design requirements is provided in section 5.3.

5.1 DESIGN PRINCIPLES

In this research, the term design principle is used to refer to an inductive principle that will be applied in the design. The design principles form the general guideline for the design and will be developed into specific design requirements. Based on the literature review, see Chapter 4, it becomes clear that the following main challenges in current emission trading systems are considered: lack of system compatibility, security issues, and (manual) monitoring of transactions. The goal of this research is to design an artefact that is able to allow extension by assessing these challenges. Therefore, the design principles that drive the utility of the artefact are:

1. **Architecture interoperability.** The design provides features that support the compatibility of data exchanges between Emission trading systems and different blockchain platforms

To address the challenge of system compatibility, one of the design principles is that the architecture should enable interoperability with other systems. The artefact should have the ability to connect and communicate in a coordinated way with other systems without effort from the end user. Interoperability describes the extent to which systems and devices can exchange data, and interpret that shared data (Gurcan et al., 2017).

2. **Emission trading system security.** The design provides features that allow secure transactions across the emission trading domain

From the literature review, we learned that the EU ETS is vulnerable for fraud and should therefore be solved in the design of a new artefact. ETS security is important as is keeps information protected. Addressing this design principle in the artefact could lower the risk of fraudulent behavior in the system end therefore strengthen the ETS.

3. **Emission monitoring automatization.** The design provides features that ensure the automatization in the monitoring of the data used for emission trading.

By keeping automatization of emission monitoring in mind as a design principle for the artefact, the system could achieve higher efficiency. This means that the level of performance (outcome), relative to the inputs (resources, time, money) consumed. This is important for the EU ETS as it will allow to achieve more with less while delivering more value to the stakeholders of the system.

Limiting the design principles to these three factors does not imply that other artefact properties will be overlooked, these three factors form the general guideline of the artefact.

5.2 Design requirements

Requirements can be divided into two main categories: functional and non-functional (Johannesson et al., 2014). Functional requirements cover the tasks to be executed and drive **the application architecture**. The non-functional requirements provide criteria to assess the operation of the artefact and define **the performance of the architecture.** The functional requirements are divided in stakeholder, institutional, and technical requirements, see section 5.2.1. The non-functional requirements are elaborated on in section 5.2.2. Using the existing principles of the EU ETS as a starting points for the requirements of this new artefact enables the incorporation of the experience, knowledge and lessons learned from the existing system into the new design. The system analysis see Chapter 4.The EU Emission Trading System and semi-structured interviews are used to engineer the requirements. The semi-structured interviews are conducted with installations and authorities of the EU ETS, blockchain experts and global trading experts, see Appendix A for the list of interviewees and the semi-structured interview protocol. For future referral of the requirements, the functional requirements are coded with F and non-functional requirements are coded with NF.

5.2.1 Functional requirements

While generating the functional requirements, the standardized system architecture and the core processes of the existing EU ETS are modeled after.

Stakeholder requirements	F1, F2, F3, F4, F5

F1 The artefact allows the European Commission to verify the supply of emission allowances.

F2 The artefact enables the implementation of an auction house mechanism where allowances can be allocated.

F3 The artefact is able to receive and process data from stakeholders securely.

F4 The artefact allows emission enterprises to trade their allowances with each other.

F5 The artefact enables the verification of reports by the National verification bodies.

First, the stakeholder requirements are derived from the stakeholder analysis and interviews. The stakeholder requirements involve the functional requirements needed to cover the tasks of all relevant stakeholders of the system. In the EU ETS, the cap-and-trade principle is the core concept for the functionality of the system (European Commission, 2021). Therefore, F1 is required for the setting of a cap by the authority, which is the European Commission. For the issuance of emission allowances, the system use auctioning and free allocation as methods (European Commission, 2022-a). Therefore, F2 is essential for the allocation of allowances. For F3, interviewee I1 mentioned the importance of safe data processing: *"“We (as an authority in the ETS) are increasingly becoming a data-driven organization…All kinds of mechanisms are in place in the EU ETS to enable safe and secure transactions and processing of data from stakeholders”.* Also, this interviewee I4 said that *"In the EU ETS, trade must be made possible between emission enterprises for economic efficiency"*. Therefore the functional stakeholder requirement F4. At last, interviewee I1 also emphasized the importance of independent verification bodies (F5): *"Private independent verifiers must sign that the emission reports of enterprises are reliable, they are not under the authority of an instance but are accredited by the accreditation body."*.

Institutional requirements	F6, F7, F8, F9
F6 The artefact fits in the regulatory environment of the EU ETS.	
F7 The artefact is able to check the annual compliance of emission enterprises.	
F8 The artefact is able to represent the emission allowances on the blockchain.	
F9 The artefact is able to charge emission enterprises when they do not comply with the regulations.	

Additional, institutional requirements are derived to fulfill the application architecture on the regulated aspects of the system. Following the institutional analysis, see Chapter 4.3, it is concluded that the to-be-designed artefact needs to fit in the regulatory environment of the EU ETS, see requirement F6. The requirements F7 & F0 requires the system to enforce the compliance of the system regulations by the ability to check the compliance and charge the enterprises when they do not comply, this is also how the current system works (European Commission, 2021). At last, requirement F8 considers the system's use of emission allowances as an tradable asset (European Commission, 2021), this should be represented in the artefact as well.

Technical requirements	F10, F11, F12
F10 The artefact is able to implement the 'cap-and-trade principle' where a linear reduction factor is used to define the cap of emission allowances.	
F11 The artefact allows to monitor the transactions and detect anomalies in the business transactions between emission enterprises.	
F12 The artefact provides a mechanism that can automatically steer the supply of allowances and therefore guarantee a certain stability of the market (MSR)	

In the literature review, it became clear that a linear reduction factor is used to define the cap of emission allowances, this is factor is set to be 2,2% until 2030 (European Commission, 2022-a). This property of the ETS has been translated in requirement 10 for this design. Considering the security of the ETS, interviewee I2 mentioned: *"If we assume that there might be some forms of fraud in this space, where people might be reporting false numbers to get more or to pay less, this should be identified".* This condition has been translated into requirement F11. Also, from an interview with an emission enterprise (interviewee I3), it became clear that guaranteeing a stable market is important for the market growth: "*The market has experienced a surplus of allowance supply that has resulted in the price of emission allowances dropping to record lows in the past, the instability of the market inhibited market growth. "* Also, Interviewee I1 emphasized that: *"The impact of the price on the EU ETS is that a higher price result in enterprises being more sensitive about the allocation and trading of emission allowances."* From these interviews, we learn that a mechanism in the EU ETS to guarantee a certain stability of the market is necessary (requirement F12).

5.2.2 Non-Functional requirements

Non-Functional requirements	NF1, NF2, NF3, NF4, NF5
NF1 Actors is able to register and identify themselves.	
NF2 A distinction is made accounts containing different rights in the system	
NF3 The artefact allows verification and monitoring of transactions.	
NF4 The artefact allows easy integration of new entities that want to join the system.	
NF5 The artefact allows transactions with traditional systems and other blockchains.	

There are five non-functional requirements generated to define criteria to assess the operation of the artefact. For the utility of the artefact, it is specified that actors should be able to register and identify themselves (NF1) and that a distinction should be made between accounts containing different rights in the system (NF2). From the analysis on the Union Registry and EUTL, it becomes clear that this is needed to store emission data and the transaction data of emission allowances efficiently to check the compliance of installations (Abrel, 2022). Considering the serviceability of the artefact to ensure a secure system, verification and monitoring of transactions is necessary (requirement NF3). About the scalability of the system, Interviewee I2 mentioned that: *"If you want to extend the current system, this could be done in all kinds of dimensions. You could think of new industries under the ETS itself, or extension to other market players like banks, or any other interested market players."* To reach the objective for extension of the current ETS, the system needs to allow easy integration of new entities (requirement NF4). At last, we emphasize interoperability as a crucial requirement for the survivability and manageability of blockchain systems. The goal is to define an interoperable blockchain architecture, in which common components of the blockchain architecture can begin to be standardized, leading to lowering of development costs and better reusability (Al Sadawi, 2021). This has been translated in requirement NF5.

5.3 Conclusions

In this section, an overview of the design requirements is provided to answer the second sub-question: *What are the design principles and requirements needed blockchain-based design to allow extension of the current EU ETS?*. The functional requirements are divided into stakeholder, institutional, and technical requirements. Also the non-functional requirements are shown. Each requirement is related to a design principles:

1. Architecture interoperability
2. Emission trading system security
3. Emission monitoring automatization.

The sources for the engineering of the requirements are from literature (L) or from interviewee's (I1, I2, I3, I4), see Table 3 below.

Table 3 - Overview of design requirements

		Design Principle	***Source***
	Stakeholder		
F1	The artefact allows the European Commission to verify the supply of emission allowances	3	L
F2	The artefact enables the implementation of an auction house mechanism where allowances can be auctioned.	3	L
F3	The artefact is able to receive and process data from stakeholders securely	2	I1
F4	The artefact allows emission enterprises to trade their allowances with each other	3	I4
F5	The artefact enables the verification of reports by the National verification bodies.	2	I1
	Institutional		
F6	The artefact fits in the regulatory environment of the EU ETS	2	L
F7	The artefact is able to check the annual compliance of emission enterprises	3	L
F8	The artefact is able to represent the emission allowances on the blockchain.	3	L
F9	The artefact is able to charge emission enterprises when they do not comply with the regulations.	3	L
	Technical		
F10	The artefact is able to implement the 'cap-and-trade principle' where a linear reduction factor is used to define the cap of emission allowances.	3	L
F11	The artefact allows to monitor the transactions and detect anomalies in the business transactions between emission enterprises.	2	I2
F12	The artefact provides a mechanism that can automatically steer the supply of allowances and therefore guarantee a certain stability of the market (MSR)	3	I3

Non-Functional

NF1	Actors should be able to register and identify themselves	2	L
NF2	A distinction should be made between management accounts and user accounts	3	L
NF3	The artefact should allow verification and monitoring of transactions	2	L
NF4	The artefact should allow easy integration of new entities that want to join the system	1	I3
NF5	The artefact should be interoperable with traditional systems and other blockchains	1	I

6 BLOCKCHAIN ARCHITECTURE

This chapter will elaborate on the blockchain design components to answer the third research question: *How would blockchain design components be implemented in the EU ETS?* This chapter will reveal the high-level blockchain architecture design for the EU ETS, taking the design principles and requirements into account and combining it with the blockchain components. For designing a blockchain-based architecture, the blockchain design components will be addressed. The reason why certain design choices have been madewill be justified. Special attention is paid to the technical composition of the blockchain design. The design choices generated in this chapter will be demonstrated in Chapter 7.

6.1 BLOCKCHAIN DESIGN COMPONENTS

For designing a blockchain architecture for the EU ETS, a standard technical reference model for blockchain architectures is used. The work of Tasca et al., (2017) classifies the main blockchain components and their relationships, this helps to explain how blockchains works and to design or model a blockchain concept. A blockchain is a distributed database or ledger that is shared among the nodes of a computer network. As a database, blockchain stores information electronically in digital format. It uses a digital structure with a series of blocks that may contain data records with time stamps and a hash that links to the previous block (Crosby et al., 2016). In this research, six main components of blockchain architectures are considered. The main components are:

1. Identity management
2. Consensus
3. Transaction capabilities
4. Assets and tokenization
5. Extensibility
6. Security and privacy

Each main component consists of sub-components in which design choices can be made. In the next section, the different design decisions are assessed to select the blockchain architecture that best fits with the requirements of the design for the EU ETS.

6.2 BLOCKCHAIN DESIGN DECISIONS

This section explores the solution space for the to-be-designed artefact. This can be seen as a systematic exploration of the solution space based on the requirements and the blockchain components identified in the previous sections.

6.2.1 Identity management

The component identity management ensures secure access to sensitive data and establishes a suitable governance model for the blockchain (Tasca et al., 2017). This is divided in two subcomponents: Access & control and Identity.

Access & Control

The first subcomponent is Access & control where a design decision should be made between the following blockchain types: public permissionless, public permissioned, consortium and private permissioned. Hileman & Rauchs (2017) disclosed that there are three major types of permission that can be set when configuring a blockchain network: read (who can access the ledger and see a transaction), write (who can generate transactions) and commit (who can update the state of the ledger). This is used to distinguish blockchain types: public/private and permissioned/permissionless. Public/private refers to the capability to read transactions on the ledger, whereas permissioned/permissionless refers to the capability to write and commit on the blockchain, see Table 4 for an overview of blockchain types.

Table 4 - Overview of blockchain types (Adapted from: Hileman & Rauchs, 2017)

			Access & Control		
			Read	*Write*	*Commit*
Blockchain types	*Public*	*Public permissionless*	Open to anyone	Anyone	Anyone
		Public permissioned	Open to anyone	Authorized participants	All/subset of authorized participants
	Private	*Private permissionless (consortium)*	Restricted to an authorized set of participants	Authorized participants	All/subset of authorized participants
		Private permissioned	Fully private/ Restricted to an authorized set of participants	Network operator only	Network operator only

Access & control is related to the requirements F1, F4 & F10 & NF4. These requirements provide certain conditions for stakeholders to be able to read, write and commit on the data that is stored in the EU ETS. Currently, the data stored on the union registry and EUTL is accessible to the public. Therefore, the artefact will also provide 'read' capabilities to anyone. On the other hand, the 'write' and 'commit' capabilities are restricted to authorized participants (e.g. the European Commission, Central administrator, Competent Authorities). Based on these observations, it is concluded that a public permissioned blockchain type is the most suitable for the EU ETS.

Identity

The second subcomponent is Identity. Identity management solutions are generally designed to facilitate the management of digital identities and operations such as authentication and is often emphasized as a security measure (Liu et al., 2020). Multiple requirements are related to identity management. Some demand the artefact to allow specific entities to fulfill their functions (F1, F4, F5), while others require the artefact to recognize and distinct entities from each other (F2, F7, F9, NF1, NF2). In addition to this, requirements demand a reliable system that can be trusted (F3). These requirements illustrate the need for different identities in the blockchain where the information of stakeholders in the system is verified. Therefore, onboarding and offboarding of nodes in the blockchain are key aspects that need consideration. These can be achieved by implementing identity verification processes, like Know-Your-Customer (KYC) and Anti-Money Laundering (AML) to increase transparency and verify user information (Tasca et al., 2017). Each user gets a public and a private key, these are cryptographic codes used to facilitate transactions between parties. The public key is public for everyone, the identification of users can be done by the public keys. The private key is a secret number and not to be shared with anyone. The private key is used for encrypting and decrypting sensitive data so only the rightful entities are able to see the data.

6.2.2 Consensus

The second identified component is Consensus. It relates to the set of rules and procedures that allow to maintain and update the ledger and to guarantee the trustworthiness of the records in the ledger, i.e., their reliability, authenticity and accuracy (Tasca et al., 2017). In the application of blockchain, two problems need to be solved by reaching consensus: the Byzantine Generals problem and double-spending (Mingxiao et al., 2017). The Byzantine Generals problem occurs in distributed systems and describes the difficulty decentralized parties have in arriving at consensus and dealing with unreliable members without relying on a trusted central party. The double-spending problem occurs when the same currency is reused in two transactions at the same time. Blockchain solves these problems by reaching consensus through verification of the transactions while considering the consensus network topology and consensus mechanism.

Consensus network topology

Consensus network topology describes the type of interconnection between the nodes and the type of information flow between them for transactions and or validation purpose (Tasca et al., 2017). In blockchain applications, the consensus network topology could be centralized, decentralized or distributed, see figure 12.

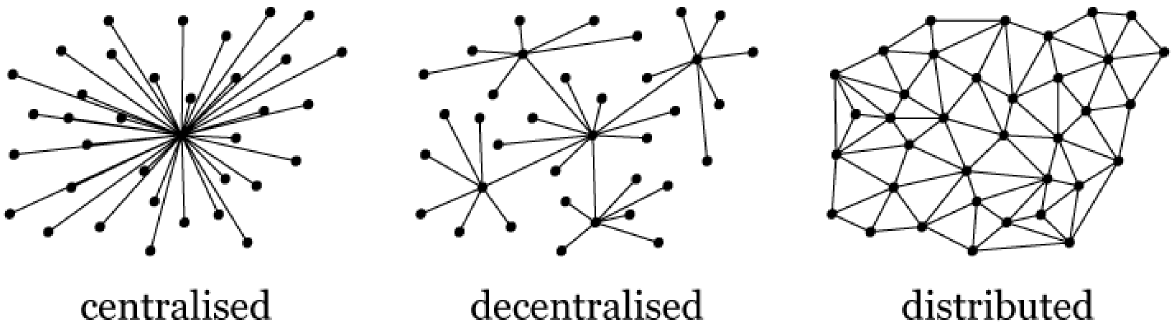

Figure 12 - Consensus network topologies (Source: Windley, 2021)

The consensus network topology relates to requirement F3 is important because it states that stakeholders need to be able to share data in a reliable way. A distributed consensus network topology allows for high performance, availability and extensibility at low costs for all the nodes in the network (Shivaratri et al., 1992).

Consensus mechanism

The consensus mechanism allows nodes in the blockchain to coordinate in a distributed setting. Consensus mechanisms vary across different blockchains, every consensus mechanism has different characteristics that result in advantages and disadvantages e.g. transaction rate, energy efficiency, scalability, and power adversary (Kumar et al., 2021 & Ashish, 2018). See appendix B for an analysis of consensus mechanisms. We compare four different consensus mechanisms: Proof-of-Work (PoW), Proof-of-Stake (PoS), Proof-of-Authority (PoA) and Practical Byzantine Fault Tolerance (PBFT), see Table 5.

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Table 5 - Comparison of consensus algorithms (Adapted from: Kumar et al., 2021 & Ashish, 2018)

	PoW	**PoS**	**PoA**	**PBFT**
Blockchain type	Open/permissionless	Open/both	Open/both	Permissioned
Transaction rate	Low	High	High	High
Energy efficiency	Less	Moderate	Moderate	High
Scalability	High	High	High	Low
Power of Adversary	Computing power	Stake	Identity	Faulty replies

The requirements related to the consensus mechanisms are F1, F3, F6, and NF4. The artefact needs to ensure that the public authorities are able to fulfill their functionalities in the cap-and-trade emission trading system (F1), also secure and reliable data exchanges are required (F3, F6). When deciding on the most suitable consensus mechanism for the EU ETS, the characteristics of the mechanisms are taken into account. For the EU ETS, we first consider the non-functional requirement NF4, which states that the artefact should allow new entities to join the system (and therefore be scalable). This excludes PBFT from the choices because this consensus algorithm has a high message complexity, which results in lower scalability (De Angelis et al., 2018). Furthermore, PoW is excluded because of low energy efficiency as well low transaction rate because of the computational power that is needed to reach a consensus (Kumar et al., 2021). PoS and PoA on the other hand use less energy-intensive mining processes to reach a consensus. The main difference between PoS and PoA is that the power of adversary is in a stake (PoS) or in the identity of an entity (PoA). When considering the functional requirements of the EU ETS (F1, F3), we conclude that the artefact needs to enable inhomogeneity of roles in the cap-and-trade principle. In proof-of-authority, a set of 'authorities' are empowered to collaborate trustlessly in a distributed registry (Mingxiao et al., 2017). This consensus mechanism allows trustworthy entities to control the network as validating nodes. This is needed in the ETS to ensure that the EU ETS regulations are aligned with the blockchain database (F6). PoA does not require heavy computational power to maintain the network so it is more energy efficient and because the mechanism is based on a limited number of block validators, it results in higher transaction rates and scalability (Kumar et al., 2021 & Ashish, 2018).

6.2.3 Transaction capabilities

The decisions made for the transaction capabilities are important to illustrate the scalability of transactions and the usability in possible applications and platforms (Tasca et al., 2017). Transaction capabilities influence the transaction throughput by changing quantitative parameters such as the data storage in the blockheader, transaction model, server storage, and block storage.

Data structure in the blockheader

In the blockchain, the validated transactions are recorded in blocks. Blockchain uses hash functions to map data of arbitrary size to fixed-size values (e.g. the hash function SHA-256 hashes all input values in 256-bit outputs).

Hash functions are known to be irreversible, meaning that there is no fast algorithm to restore the input message from the hash value. Hash functions are used in different places in the blocks of a blockchain. A block is composed of a header and a body, in the latter of which the transaction data is stored, see Figure 13.

The block header contains the hash of the previous block, the time stamp, the nonce, and the Merkle root. The hash value in a new block is calculated by passing the header of the previous block to a hash function. When creating a new block, the hash of the previous header is used to link the new block to the previous block, resulting in a chain of blocks (therefore: Blockchain). This guarantees that tampering on the previous block will efficiently be detected (Liang, 2020). The timestamp records the time that the block is created. The nonce is used in the creation and verification of the block. The Merkle root is the root hash of a Merkle tree, which is a tree that labels each 'leaf' with a hash of the 'child leaf's' until only one root hash remains. In blockchain, the Merkle tree totals all transactions in the body of a block and hashes it until only the Merkle root remains. This generates a digital fingerprint of the entire set of operations, allowing a user to verify whether it includes a transaction in the block. This is because a tiny change in one transaction in the body can produce a significantly different Merkle root. The verification of the transaction can be completed by simply checking the Merkle root in the block header instead of verifying all the transactions in the body of the block.

The requirements related to the data structure in the blockheader are F3, F11, and NF3. The artefact should provide reliable and secure data (F3) and allow to monitor the transactions and detect anomalies in the business transactions between emission enterprises (F11). Also, the system should be able to verify and monitor the transactions (NF3). This requires flexibility in the validation of data. To fulfill these requirements, the artefact is able to use a Practical Algorithm To Retrieve Information Coded In Alphanumeric (PATRICIA) Tree. This data structure is originally introduced by Morrision (1968) and is able to use different Merkle roots in the block headers to have an extra ability to query particular data in the blockchain, for example a State Root, a Transaction Root, and a Receipt Root as used by Ethereum (Wood, 2014). The PATRICIA tree allows activities like inserting, editing or deleting information referring to the balance and nonce of accounts, which enables faster and flexible validation of transactions than the one merkle tree model (Tasca, 2017).

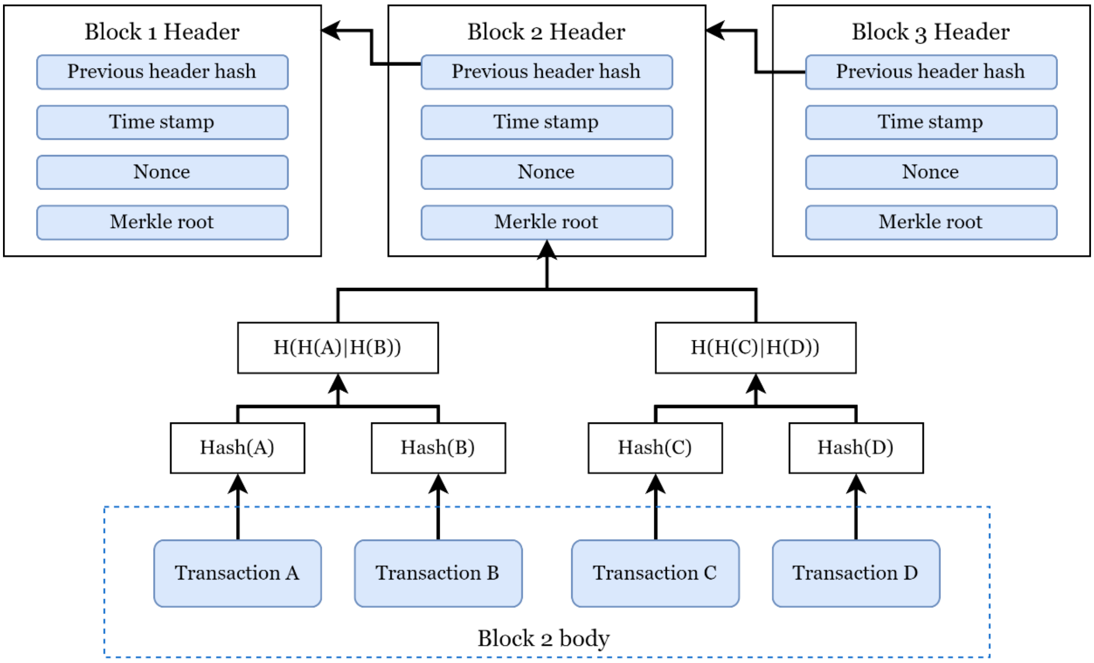


Figure 13 - Blockchain structure and Merkle tree (Adapted from: Chen et al., 2019)

Transaction model

The transaction model describes how the nodes connected to the P2P network store and update the user information in the distributed ledger. It can be imagined as an accounting ledger which tracks the inputs and outputs of each transaction (Tasca et al., 2017). To do this, we will use a traditional ledger to store the transactions. This is able to register increment and clear account balances of the EU ETS.

The blockchain will make use of smart contracts to automatize transactions. Smart contracts are programs stored on a blockchain that run when predetermined conditions are met. They can also automate a workflow, triggering the next action when conditions are met (IBM, n.d.). Execution of a smart contract is triggered via a blockchain transaction and will produce a change in the blockchain state (De Filippi, 2021). Smart contracts will be used to fulfill requirements F1, F2, F4,, F5 F7, F9, F10, and F11. First of all, smart contracts can be used in the EU ETS to manage the supply of emission allowances, the lineair reduction factor (F10) and the MSR mechanism (F11) could be applied automatically, and the European commission will verify the automatized process (F1). After this, smart contracts could enable auctioning and when prerequisites are met, the bidder automatically receives the emission allowances (F2). Also, smart-contracts enables peer-to-peer trading of emission allowances by automatizing the transaction when buyers and sellers meet the predetermined conditions (F4). Moreover, smart contracts could be programmed to use the verification of national verification bodies as a prerequisite before a transaction can be done (F5). This could also be done for the compliance of emission enterprises (F7) and when they do not comply with the regulations, they could be charged (F9). Because the EU ETS blockchain is public-permissioned, not everyone is allowed to program smart contracts. In the EU ETS chain, only the permissioned group of authorities, see chapter 6.2.1, is able to deploy smart contracts to the network. The smart contracts are written into codes and immutable when they are deployed on the network. However, when the rules about transactions changes (e.g. when the governance or laws are updated), the smart contracts need to be swapped for others so the software is ‘upgraded’.

Server storage

Server storage refers to a type of service that is used to store, access, secure and manage the data. At the core of blockchain-based systems underlies their decentralised nature of data storage, where information is copied and spread across a network (Tasca et al., 2017). We compare the following two possible blockchain server storage layouts in Table 6:

Table 6 - Comparison of blockchain server storage lay-outs (Adapted from: Tasca et al., 2017)

	Full nodes	Thin nodes capabilities
Description	All nodes connected to the network, which are part of the validation process, are of the same kind.	Some nodes connected to the network contain only a selected subset of all the information contained in the blockchain.
Information accessibility	All nodes	Selected subset of nodes
Storage needs	Higher	Lower
Scalability	Lower	Higher

We compare the information accessibility, storage needs and scalability of the layouts. This relates to the requirements F3, NF2 & NF4. Requirement F3 states that this data storage should be done in a secure and reliable way. From NF2 we understand that some users own rights as a managing account and others as user account. So, not all nodes need access to all information on the blockchain. At last, NF4 states that the design should allow new entities to join the system (storage needs & scalability). Considering this, thin nodes capabilities for the server storage will be required for the blockchain design. This enables the system to provide flexibility by letting nodes differentiate between the information that need to be accessed. Among other things, this provides more scalability for the EU ETS. Thin node capabilities result in lower information redundancy but because the nodes that form consensus use the Proof-of-Authority mechanism, they ensure redundancy of information through their 'identity'.

Block storage

The block storage contains the information that is stored in the body of the block. Here we need to make a distinction between on-chain and off-chain data. On-chain data refers to the data that is stored in the blockchain infrastructure and off-chain data are stored in traditional databases and files. For the design of the blockchain EU ETS, off-chain data will be used as the input data of the artefact. On-chain data will be stored in the block itself. For this distinction, we consider requirements F3 & NF3. Requirement F3 is about the security and reliability of the data, we need to consider how to pursue reliable off-chain data. Also, requirement NF3 states that the artefact should be able to verify and monitor the transactions, this means that the transactions of emission allowances should be stored on-chain. Based on the database of the Union Registry and the EUTL, the data is categorized in on-chain and off-chain data that will be used in the blockchain for the EU ETS, see Figure 14.

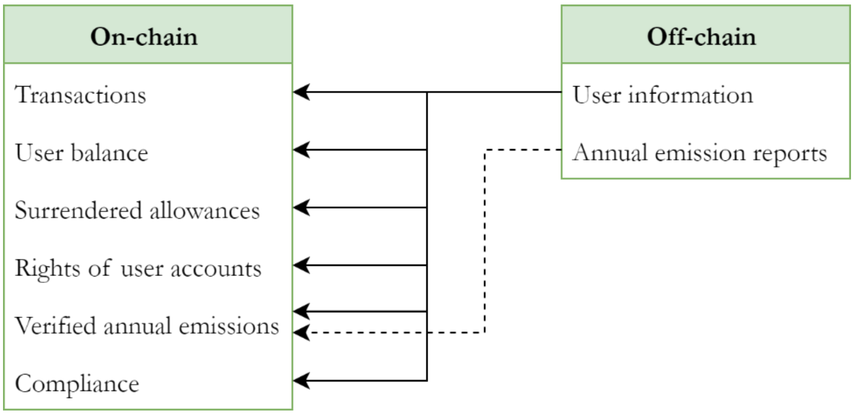


Figure 14 - On-and off-chain block storage for the EU ETS blockchain

The reason that not all data is stored on-chain is because of storage efficiency and costs. Storing all information on-chain requires more storage and therefore is more expensive. For the transactions on-chain, we take into account the functions that need to be fulfilled. Here, data about emission allowance transactions, user balances, total surrendered emission allowances, and compliance is needed. Also, the distinction of user accounts is stored on-chain. Based on the identification of users, the blockchain differentiates the emission enterprises and authorities from each other to provide rights (trading rights, verification rights, consensus rights, governing rights, etc.). On the other hand, off-chain data is used as input for the on-chain data: the user information is needed to understand all categories and verified annual emission reports are used to check the compliance of the users. The annual emission reports of the installations will be verified on-chain by the MRV-process stakeholders, see Chapter 4.2.1. To ensure that the data put on the blockchain is reliable, we keep the structure of the MRV process intact as it is now.

6.2.4 Tokenisation

Generally speaking, a token is a representation of a particular asset or utility. With the context of blockchain technology, tokenization is the process of converting something of value into a digital token that's usable on a blockchain application (Gemini, 2021). They represent assets that can be owned and has value to be incorporated in a larger asset market. In literature, there exist different kinds of classifications for digital assets, see Table 7.

Table 7 - Categorization of tokens (Adapted from: Wang et al., 2021)

	Object Class	**Key Features**
Tangibility	Tangible	Physical existence
	Intangible	Virtual existence or service
Fungibility	Fungible	Exchangeability
	Non-fungible	Uniqueness

Tangible objects refer to assets with physical existence, and they are typically unique. On the other hand, intangible objects refer to the assets that do not have a physical nature, such as services or representations of abstract objects.

Also, from the fungibility assets, fungible tokes can be interchangeable with other assets of the same category or type and non-fungible tokens are unique, non-replicable tokens which can be used to keep track of the ownership of individual assets.

Tokenization relates to the requirements F4, F8 & F12. All requirements refer the need to use 'emission allowances' as an object. By tokenization, we enable trading (F4), auctioning and distributing (F8), and managing the supply (F12) of emission allowances. Emission allowances are representations of a verifiable annual reduction or avoidance of one metric ton of GHG emissions and issued by the European Commission and are exchangeable. This makes emission allowances intangible and fungible tokens.

6.2.5 Extensibility

Interoperability

The extensibility of the design determines the future integration possibilities of the blockchain network. Blockchain interoperability is emerging as one of the crucial features of blockchain technology to enable extensibility. It refers to the ability to see and access information across various systems. Koens et al. (2019) states that interoperability can be achieved in many ways:

1. Inter: Interaction between a blockchain platform and a legacy system
2. Intra: Interaction between two blockchain platforms

Considering requirement NF5, interoperable with a legacy system as well as other blockchain platforms. There are several ways to achieve blockchain interoperability, research of the World Economic Forum (2020) proposes three approaches for interaction between blockchains: cross-authentication, API gateway, and an oracle

The first approach, cross-authentication, identifies and defines different chain interoperability strategies across public blockchains. This includes notary schemes executed by trusted parties, relays that can validate and read events and/or states in other blockchain platforms, and hash-locks that set up operations with the same trigger.

Also, application programming interface (API) gateways could be used. An API is a piece of code that governs the access point to a server and the rules developers must follow to interact with a database, library, software tool or programming language. Organizations may opt to use an API approach, where APIs are used in an additional external layer on top of the blockchain platform to connect with other systems/blockchains.

At last, an oracle is an agent that enables the transfer of external data to the blockchain for on-chain use. This is done using smart contracts that add information about real-world events to the blockchain. Once entered on the blockchain, this data can be used to automate processes based on real-world events (World Economic Forum, 2020).

For the blockchain design of the EU ETS, all different ways can be used for connections with various systems.

Governance

For blockchains to be implemented successfully and to be able to adapt, change, and interact, effective governance rules are essential. Governance as an abstract concept can be seen as all processes of social organization and social coordination. Because the deployment architecture for blockchain (public chain, private chain, consortium chain) change, so do their management practices. Two categories of governance rules are identified (Tasca, 2017) :1) technical rules of self-governance and 2) regulatory rules defined by regulatory bodies composed of regulatory frameworks. The technical rules of self-governance decides how the governance members of the system organize themselves and implement the regulatory rules in the system. Three alternatives for the governance model are identified by Tasca (2017):

1. Open-source community mode: where open communities and developers coordinate the blockchain for upgrades and adjustments
2. Technical mode: where enterprises with strong technical strength will take the responsibility of the blockchain architecture
3. Alliance mode: where the blockchain architecture is governed by entities that meet certain criteria, these entities join together and collaborate to determine the direction of the system in a decentralized way.

The requirements F1, F6, NF2, and NF4 are related to the governance of the blockchain ecosystem. First of all, requirement F1 states that the artefact should allow the European Commission to verify the supply of emission allowances. From this requirement, we conclude that the open-source community mode for governance is not applicable for this system as the system is permissioned. This also relates to requirement F6 where it is specified that the system has to fit in the regulatory environment of the EU ETS. It is not desirable that open communities regulate and coordinate the system because the system needs to comply with environmental objectives from authorities. Because the EU ETS is a policy instrument of authorities, it is also not beneficial to let technical experts take the responsibility of the blockchain architecture. The alignment between policy and governance need to be strong. Thus, a governance model in an alliance mode with policy-making authorities would fit the best. This enables technical functionalities like making distinction between accounts (NF2) and allowing for easy integration of new entities (NF4), while being compliant with policy that has been made.

Moreover, the governance in alliance mode will be decentralized. This means that all governing members will have equal voting rights in a Governance Council. This governance structure ensures that no single council member will have control, and no small group of members will have undue influence over the system as a whole. In the EU ETS, the regulatory bodies will be the same entities as the governance members of the system. These are the European Commission and the EU Member States.

6.2.6 Security and Privacy

Blockchain uses cryptography to enable validation of information storage computationally (Tasca et al., 2017). At the same time, this helps to secure the transactions by having an immutable information flow. Because the blockchain is public, meaning that everyone is able to read on the blockchain, it is important to ensure secure and privacy data. This is relevant for requirement F3 to ensure secure and reliable data transactions. This will be done by hashing with SHA-2, which stands for Secure Hashing Algorithm. In its two incarnations, SHA-256 and SHA-512, SHA is the most widely variants for hashing functions having first been used in Bitcoin (Tasca et al., 2017). When issued to hash transactions, it requires a piece of information from the issuer, i.e. the public key for the validation to take place.

Although hashing functions should ensure that only the intended recipient can read the message and have access to the content of the transaction, it is still possible to link blockchain transactions together to extract additional information of participants (Tasca et al., 2017). Therefore, we will use built-in data privacy where we obfuscate sensitive information by default. This applies for information under the European General Data Protection Regulation (GDPR). In the EU ETS, most information is not privacy-sensitive because most data relates to installations and little personal data is stored.

6.3 Conclusions

To answer the research question: *How would blockchain design components be implemented in the EU ETS?*, an overview of the blockchain architecture is given, see Figure 15. The blockchain design decisions are made based on the requirements of the EU ETS. The design decisions result in a high-level blockchain architecture for the EU ETS. The top part represents the main components and the bottom part are the sub-components and the design choices.

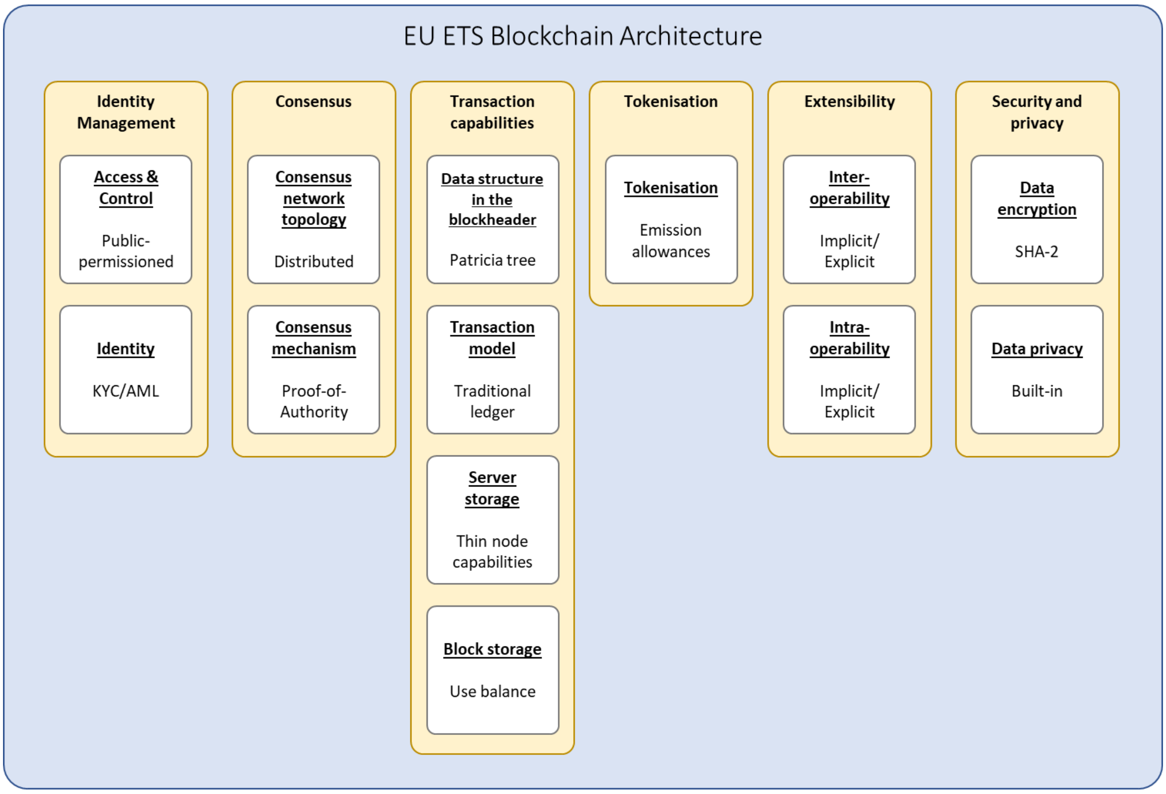


Figure 15 - EU ETS Blockchain architecture

7. A BLOCKCHAIN DESIGN FOR THE EU ETS

This chapter will demonstrate how the high-level blockchain architecture design for the EU ETS looks like, considering the stakeholders, the institutional environment, and the main processes of the system. This is focused on answering a part of the fourth research question: *How can the blockchain-based EU ETS design be demonstrated and evaluated?* After demonstrating the design in this chapter, an evaluation will be provided in chapter 8.

7.1 INSTITUTIONAL ENVIRONMENT

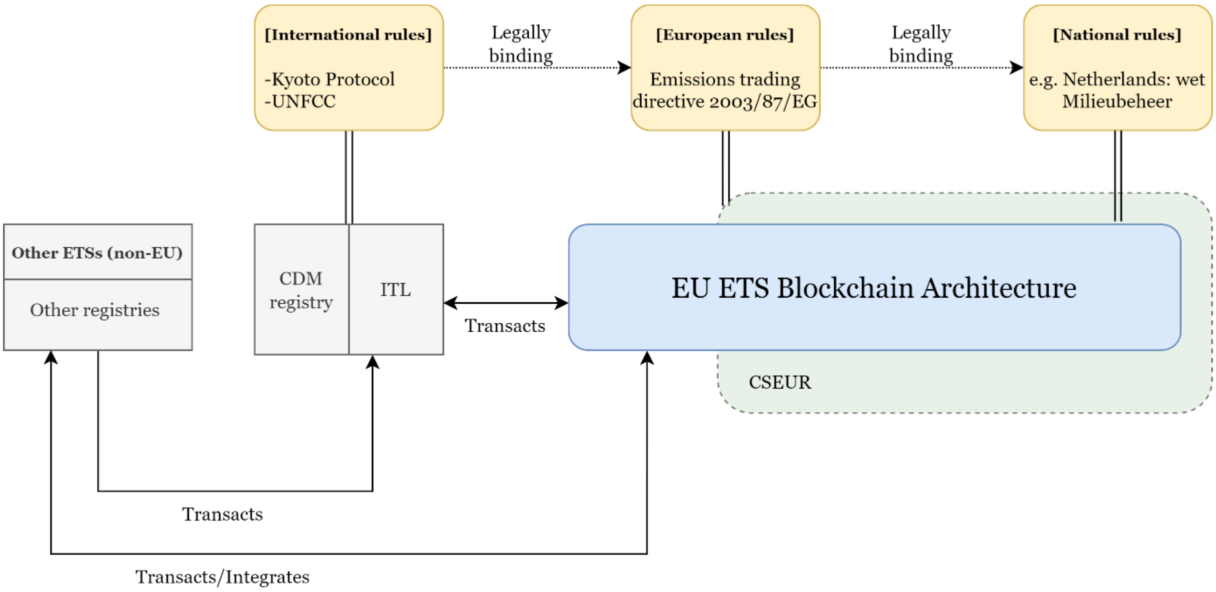


Figure 16 - Institutional environment of the EU ETS Blockchain architecture

The institutional environment of a blockchain-based EU ETS is mostly dependent on the existing rules and regulations. These consider international, European and national rules. The EU ETS blockchain architecture falls directly under European and national rules. The blockchain architecture allows transactions in the blockchain where national and European regulators will receive different rights for the verification and control of emission trading processes in their legislative environment. For example, national regulators will take the national rules into account for the verification of transactions while European regulators will focus on the European rules. These rules are also the main guidelines for the rights that each regulator gets in the blockchain architecture. Also, the architecture is legally binded by international rules. Under the Kyoto Protocol and the UNFCC, International credits are verified by the ITL. When a European member state wants to verify their international credits, it needs align with the data on the EU ETS blockchain architecture. Therefore, the ITL and the EU ETS blockchain architecture need to transact information with each other. This could be enabled by different interoperability approaches, see Chapter 6.2.5.

Also, the EU ETS blockchain, from a technical perspective, allows for transactions or integrations with other ETSs, such as the NSW GHGAS from Australia, RGGI from the Northeast United States, the WCI of 5 western US states and British Columbia, and more. Transacting with those ETSs could be enabled by interoperability approaches (see Chapter 6.2.5). Integration is possible due to the architecture design choices: the public permissioned blockchain could easily be scaled up by adding the entities of other ETSs as nodes, provide different rights to the nodes in the verification process, and form consensus through the Proof-of-Authority consensus mechanism. In the current institutional environment, there are little rules and regulations that enable these interactions between ETSs. With the extensible blockchain architecture, entities could use it as a framework to come to agreements. See Figure 16 for the institutional environment of the EU ETS blockchain architecture.

7.2 Stakeholders

All stakeholders in the network, also called nodes, receive a public and private key and will be identified by their public keys. We categorize the stakeholders in validator nodes, verification nodes, utility nodes and service providers, see Figure 17.

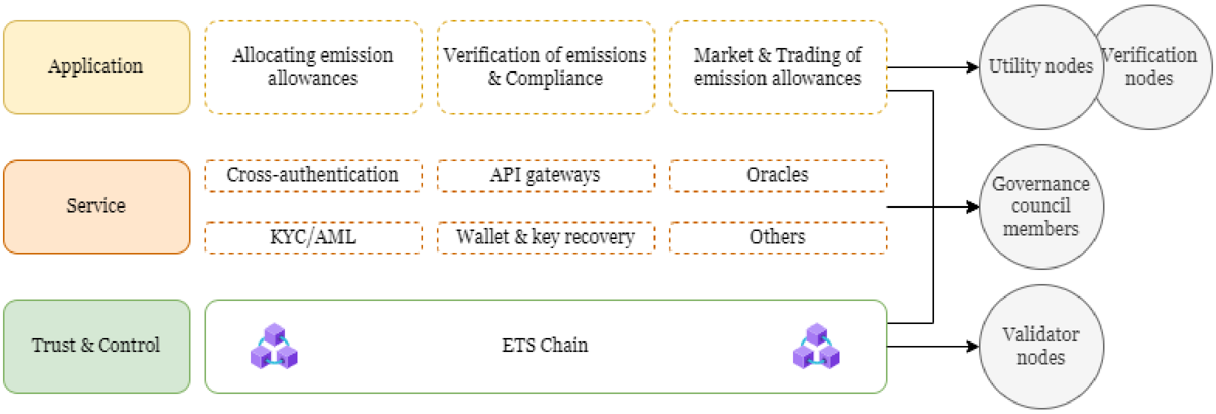


Figure 17- Stakeholders in the EU ETS Blockchain design

- Validator nodes are responsible for creating new blocks on the ETS chain, they act on the trust and control layer of the blockchain. Their responsibility is to provide network security through decentralized consensus and ensure verified transactions on the blockchain. Through Proof-of-Authority, the validator nodes will reach consensus. They are chosen based on their identity and shall be trustworthy, the validator nodes will be the central authority and the competent authorities. They secure and verify transactions to the rest of the network.
- Verification nodes are entities that are needed to verify certain processes in the EU ETS and act on the application layer of the blockchain. They support the validator nodes by signing certain transactions with their public keys. The signatures of the independent verifier and accreditation body are needed before the emission report of installations will be approved by the validator nodes.
- Utility nodes will be emission enterprises under the EU ETS. They will use the applications of the blockchain to obtain emission allowances, receive verification of their emissions and trade their emission allowances peer-to-peer with other nodes. Also, because the blockchain is public, other entities like the traders, NGO's or the public are able to become a utility node to read transactions on the blockchain and/or trade emission allowances.
- The governance council is the governing body of the blockchain and is separated from the validator nodes that form consensus. They are responsible for implementing rules and regulations in the network, ensure fair responsibilities, provide services and network stability. The governance that they decide on is applicable on the whole network. The governance council will be decentralized by design, where each

council member gets to vote on decisions. The governance council will be the ‘authorities’ of the ETS, which in the EU are the European Commission and the EU Member States.

In Figure 18 – Stakeholders and Proof-of-Authority in the EU ETS chain, it is shown how the stakeholders in the system are related to each other and how the Proof-of-Authority consensus mechanism works in the ETS chain.

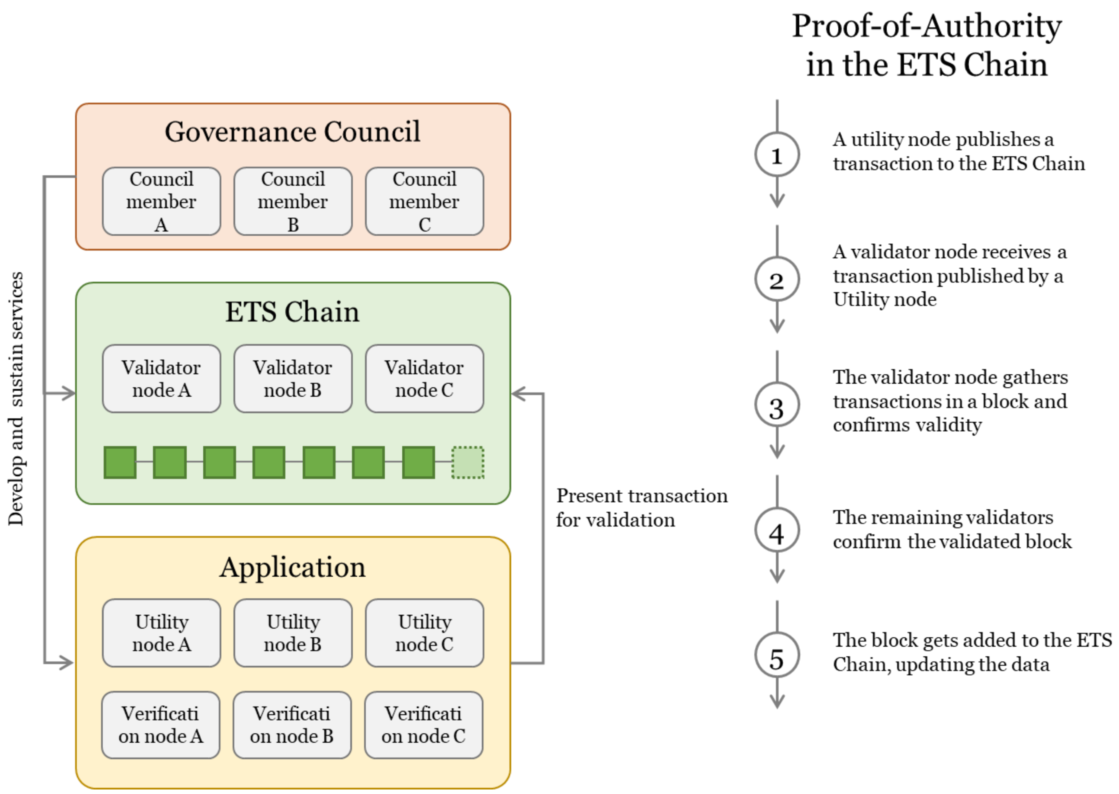


Figure 18 – Stakeholders and Proof-of-Authority in the EU ETS chain

7.3 Emission trading processes

The emission trading processes analyzed in this research are allocating emission allowances, MRV of emissions, and market & trading of emission allowances. These are continuous processes and will be executed as transactions by different nodes on the application layer of the blockchain. After validation through consensus, the transactions will be stored on the blockchain. The following section will provide cross-functional process diagrams (also: swim-lane diagrams) to present a series of interrelated work activities and resources that follow a distinct path to transform it into outputs with value (Damelio, 2011). We categorize the activities in on-chain, where the data from the activity will be stored on the blockchain, and off-chain, where the value is moved outside of the blockchain. A combination of on-chain and off-chain activities is needed to ensure the execution of emission trading processes. The cross-functional process diagrams of the three emission trading processes on the blockchain are explained in the following subsections.

7.3.1 Creation and Issuance of tokens

The annual creation of tokens, which represent emission allowances, could partly be automatized by smart contracts, see Figure 19.

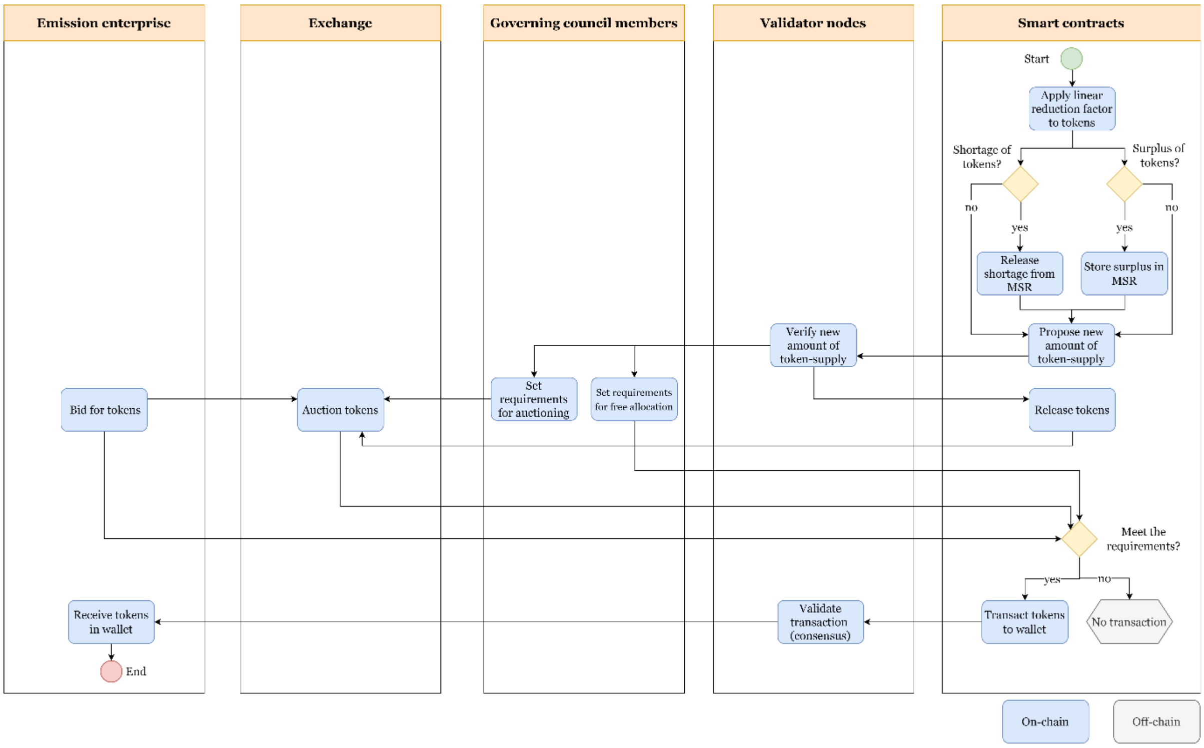


Figure 19 - Creation and issuance of tokens

The smart contract is able to check the total token-supply of the previous year and applies the linear reduction factor to the tokens to be supplied. Thanks to the pre-defined rules of the MSR, there is no need for discretion of the European Commission or Member States in its implementation (European Commission, 2021). The smart contract could use the pre-defined rules to release tokens when there is a shortage in the market or to store tokens when there is a surplus in the market. After managing the tokens in circulation, the smart contract is able to propose the new amount of token-supply for the current year. The validator nodes, which are the central authority and competent authorities, verify the new amount of token-supply based on the regulations set by the European Commission. The smart contract automatically releases the new supply of tokens. The system uses an auctioning mechanism, on which emission enterprises are able to propose bids for the new supply of tokens. The governance council members decide on a set of requirements for auctioning and free allocation. Based on this pre-defined set of auctioning requirements, an exchange is able to facilitate the auction of tokens. The smart contract will decide to reject or approve the transaction of tokens to the wallet of the emission enterprise (from free allocation or auctioning). When the bid is approved by the smart contract and validated by the authority nodes, the smart contract automatically transacts the tokens to the wallet address of the emission enterprises.

The blockchain architecture enables the automatization of using the MSR, applying the linear reduction factor, and the release of tokens. This takes away a part of the central authority's tasks as they do not have to do this manually anymore. It also reduces the responsibility of the Member States because they do not have to auction the emission allowances that are divided to them anymore. The smart contract provides an auctioning mechanism where pre-defined requirements enable release of auctioned tokens.

7.3.2 Trading of tokens

Before surrendering the tokens, emission enterprises are able to trade their tokens throughout the whole year, see Figure 20. Enterprises will have to check their balance to manage their possession of tokens.

In the situation that the enterprise has a shortage of tokens, it needs to make an order to buy extra tokens. Otherwise, it will have the risk to be non-compliant when surrendering their allowances and they will receive a fine. When an emission enterprise allocated too many tokens in their wallet, by reducing their emissions, they are able to choose to keep the tokens for the next year or sell them.

An exchange collects the orders and matches the buy- and sell-orders. After aligning the orders, the smart contract will verify this and it will be able to make a transaction for the tokens. The validator nodes validate the transactions before the tokens will be transferred to/from the wallets of the enterprises.

The blockchain enables trading of emission allowances where the transaction will be stored on the blockchain. This allows for more transparency in the market and trading of emission allowances. This also reduces the tasks of the current competent authority, who currently update the union registry when emission enterprises report their transaction. Also, the emission enterprises do not need to report their transactions anymore as the transaction is automatically stored after validation by authority nodes.

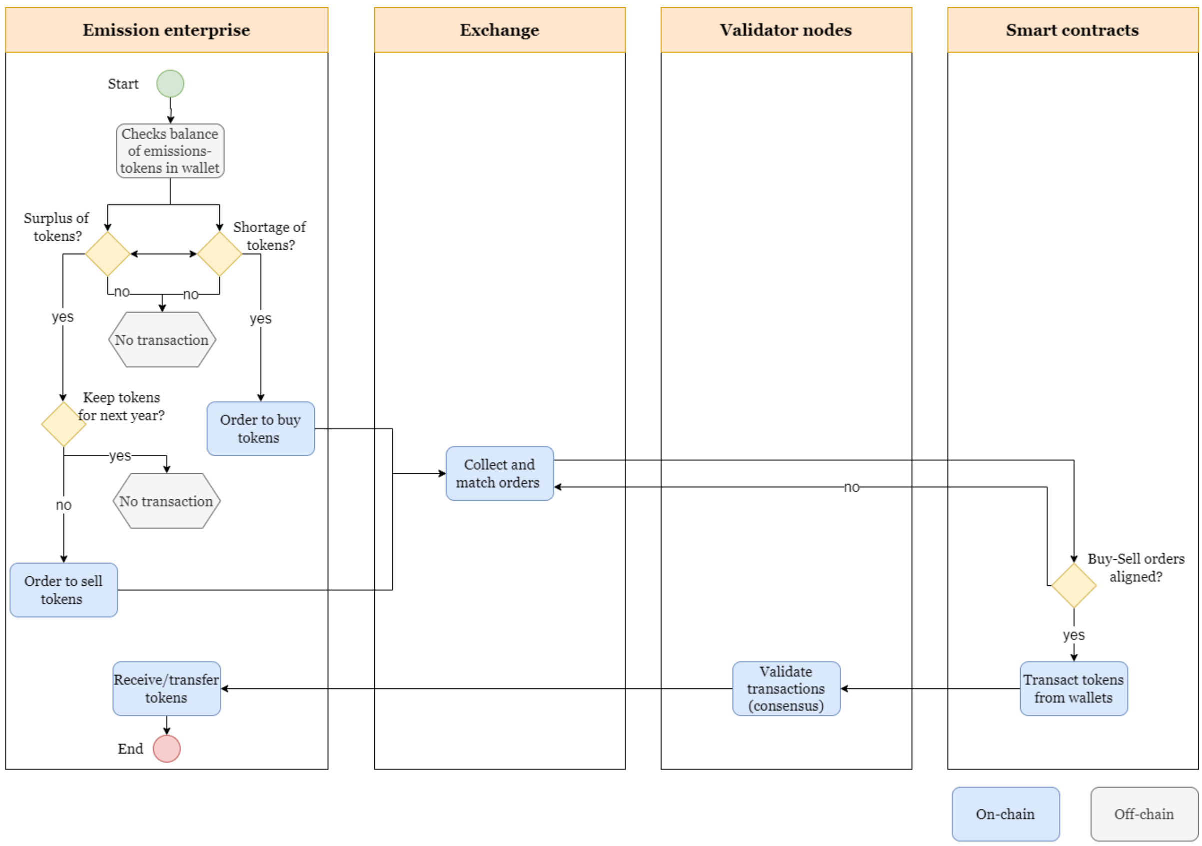


Figure 20 - Trading of Tokens

7.3.3 Monitoring, Reporting, and Verification of emissions

The annual MRV process will partly be performed off-chain and partly on-chain, see Figure 21.

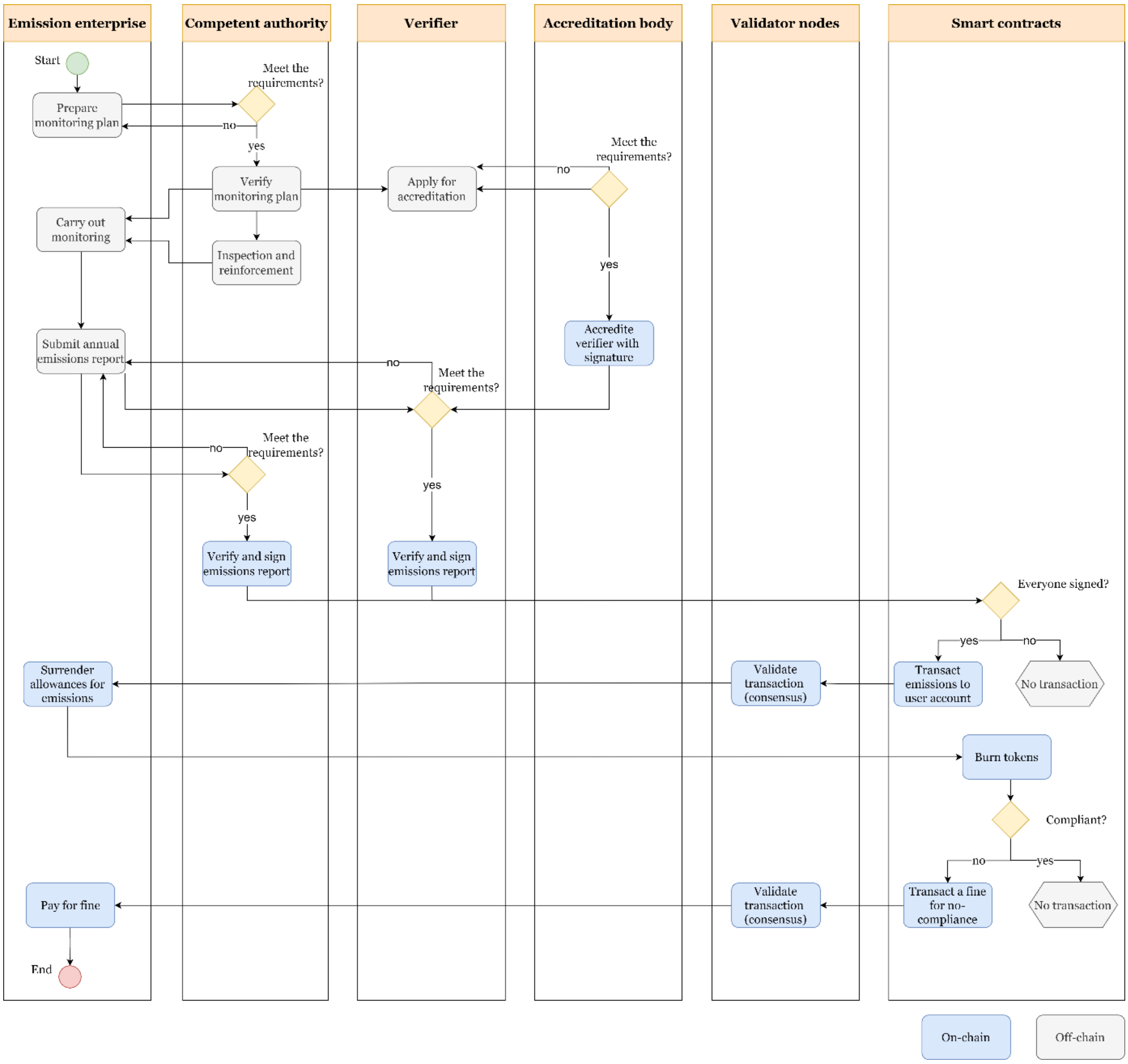


Figure 21- MRV of emissions

Emission enterprises will have to prepare a monitoring plan and carry out the monitoring of their emissions under supervision of the competent authority. Interviewee I mentioned that: *'The supervision of emission enterprises when monitoring their emissions is a time-consuming process but crucial for the system's integrity to prove that one tonne CO2 reported is equivalent to one tonne CO2 equivalent emitted.'* During the monitoring of emissions, the competent authority will be inspecting and reinforcing the enterprises. It is not needed to store this process on the blockchain because it compresences interactions between only these two entities. Interviewee I mentioned: *"Within the MRV process, blockchain (on-chain storage of transactions) is not necessarily needed because in this process, a lot of customization is needed and there are only a few entities involved."*

After this, the enterprise will submit an annual emissions report. This report needs to be signed on-chain by two verifying nodes: the competent authority, and the verifier using their private key. After this, the public key of those entities are uses to check if the right entity has signed this transaction. Before the verifier is able to sign the report, it needs to be accredited by the accreditation body. This accreditation can also be traced on-chain by the use of a signature from the accreditation body.

The competent authority verifies on requirements considering the monitoring plan and the verifier signs when it can be concluded that with a high degree of certainty, the operator reported data that are free from inconsistencies and collected according to the monitoring methodology. If both entities signs the annual emissions report, the smart contract will be able to put the emissions of the enterprise on the blockchain, after validation by the authority nodes.

Yearly, the emission enterprises will be able to surrender their emission allowances in the form of tokens to match with their verified amount of emissions. After surrendering the emission allowances, the tokens will be burned. This means that the tokens are taken out of circulation. The smart contract checks whether the emission enterprises are compliant. Compliance is achieved when the enterprise has surrendered equal or more tokens than the verified emitted amount, where one token represents one tonne of CO2. If not, the smart contract will trigger a transaction to fine the emission enterprises. After validation by the authority nodes, the emission enterprises will have to pay the fine for non-compliance.

To prevent the quality of data entry leading to unreliable data output, off-chain verification is performed in the MRV-process. Signatures of assigned stakeholders enable verification of the transaction on-chain without needing to store all the monitoring data on the blockchain. This results in better scalability of the system. Also, by using this design for the MRV-process, only the annual emissions of a company is stored on chain, and less company-sensitive data. In this process, the competent authority has two roles: verifying the enterprise's emissions as a verification node and validate transactions as a validator node. At last, the blockchain enables automatization of fining emission enterprises when they are not compliant with the regulations.

7.4 Conclusions

This subsection answers the first part of the fourth research question: *How can the blockchain-based EU ETS design be demonstrated and evaluated?* In the institutional environment, three main observations are made. The first observation is that the system compresses the European and National registries into one system. The second observation is that on the International level, the blockchain architecture needs to interact with the ITL. The third observation is that the blockchain architecture is able to transact or even integrate with other existing ETSs technically.

The stakeholders are categorized in different roles in the blockchain architecture: validator nodes, verification nodes, utility nodes, and governance council members. The roles function on different layers in the blockchain architecture. Here, the European Commission and National Member States are the governance council members, the validator nodes are the central authority and the competent authorities, independent verifier and accreditation body are represented as verification nodes, and emission enterprises & other users fit as utility nodes.

The blockchain architecture enables the automatization of the following processes: using the MSR, applying the linear reduction factor, annual release of tokens, providing an auctioning mechanism, fining emission enterprises when they are not compliant with the regulations. This takes away a part of the competent authority's and the national Member States' tasks as they do not have to do this manually anymore. To prevent the quality of data entry leading to unreliable data output, off-chain verification is performed in the MRV-process. Signatures of assigned stakeholders enable verification of the transaction on-chain without needing to store all the monitoring data on the blockchain. This results in better scalability of the system. Also, by using this design for the MRV-process, only the annual emissions of a company is stored on chain, and less company-sensitive data. The design enables trading of emission allowances where the transaction will be stored on the blockchain. This allows for more transparency in the market and trading of emission allowances. This also reduces the tasks of the current competent authority, who currently update the union registry when emission enterprises report their transaction. At last, the emission enterprises do not need to report their transactions anymore as the transaction is automatically stored after validation by authority nodes.

8. EVALUATION

This chapter will evaluate the high-level blockchain architecture design for the EU ETS. The second part of the fourth research question will be answered: *How can the blockchain-based EU ETS design be demonstrated and evaluated?* The evaluation is divided in two parts: the fulfillment of the design requirements (8.1) and an inventory of implementation challenges (8.2). In 8.1, the fulfillment will be analyzed based on the design choices that have been made. In the inventory of implementation challenges, section 8.2, semi-structured interviews with experts are conducted to analyze the implementation possibilities of the system.

8.1 FULFILLMENT OF DESIGN REQUIREMENTS

The design choices made for the blockchain architecture (chapter 6) were based on the requirements (chapter 5). This section iterates over every individual requirement and evaluates if the designed architecture fulfills it. Also, it is reflected which design choices resulted in the fulfillment of a requirement, see Table 8. The substantiation for design choices to fulfill requirements is provided in chapter 6.

Table 8 – Fulfillment of design requirements

Require-ment	Description	Design choice	Fulfill-ment
F1	The artefact allows the European Commission to verify the supply of emission allowances	• KYC/AML (6.2.1) • Public-permissioned (6.2.1) • Smart contracts (6.2.3) • Decentralized governance (6.2.5)	✓
F2	The artefact implements an auction house mechanism where allowances can be auctioned.	• KYC/AML (6.2.1) • Smart contracts (6.2.3)	✓
F3	The artefact is able to receive and process data from stakeholders securely	• KYC/AML (6.2.1) • Distributed network (6.2.2) • Proof-of-Authority (6.2.2) • Patricia tree (6.2.3) • Thin node capabilities (6.2.3) • Use Balance block storage (6.2.3) • Hashing with SHA-2 (6.2.6) • Built-in data privacy (6.2.6)	✓
F4	The artefact allows emission enterprises to trade their allowances with each other	• Public-permissioned (6.2.1) • KYC/AML (6.2.1) • Smart contracts (6.2.3) • Tokenization of emission allowances (6.2.4)	✓
F5	The artefact enables the verification of reports by the National verification bodies.	• KYC/AML (6.2.1) • Smart contracts (6.2.3)	✓
F6	The artefact fits in the regulatory environment of the EU ETS	• Proof-of-Authority	✓

		• Decentralized governance (6.2.5)	
F7	The artefact is able to check the annual compliance of emission enterprises	• KYC/AML (6.2.1) • Smart contracts (6.2.3)	✓
F8	The artefact is able to represent the emission allowances on the blockchain.	• Tokenization of emission allowances (6.2.4)	✓
F9	The artefact is able to charge emission enterprises when they do not comply with the regulations.	• KYC/AML (6.2.1) • Smart contracts (6.2.3)	✓
F10	The artefact is able to implement the 'cap-and-trade principle' where a linear reduction factor is used to define the cap of emission allowances.	• Public-permissioned (6.2.1) • Smart contracts (6.2.3)	✓
F11	The artefact allows to monitor the transactions and detect anomalies in the business transactions between emission enterprises.	• Traditional ledger (6.2.3) • Smart contracts (6.2.3) • Thin node capabilities (6.2.3)	✓
F12	The artefact provides a mechanism that can automatically steer the supply of allowances and therefore guarantee a certain stability of the market (MSR)	• Smart contracts (6.2.3) • Tokenization of emission allowances (6.2.4)	✓
NF1	Actors is able to register and identify themselves	• KYC/AML (6.2.1)	✓
NF2	A distinction is made accounts containing different rights in the system	• KYC/AML (6.2.1) • Decentralized governance (6.2.5)	✓
NF3	The artefact allows verification and monitoring of the transactions	• Use balance block storage (6.2.3) • Thin node capabilities (6.2.3)	✓
NF4	The artefact allows easy integration of new entities that want to join the system	• Public-permissioned (6.2.1) • Proof-of-Authority (6.2.2) • Thin node capabilities (6.2.3) • Decentralized governance (6.2.5)	✓
NF5	The artefact is interoperable with traditional systems and other blockchains	• Cross-authentication, API gateway, oracles (6.2.5)	~

From this analysis, we conclude that all functional requirements are fulfilled. This means that the proposed blockchain architecture cover the tasks to be executed in the EU ETS. By fulfilling all requirements that have been defined as objectives for a solution of the identified issues, the artifact provides a blockchain-based solution that is able to cover the core functions of the system while actively improving system compatibility, preventing security issues and non-transparancy, and enable automatized monitoring of transactions (See section 5.1 Design principles). The non-functional requirements specify criteria that can be used to judge the operation of a system, rather than specific behaviors. This includes the utility (NF1, NF2), serviceability (NF3), scalability (NF4), and interoperability (NF5) of the system. All are fulfilled, except for NF5, which is partially satisfied. In this research, it is shown that there are several ways to achieve blockchain interoperability from a technical perspective including cross-authentication, API gateways, and oracles, see chapter 6.2.5. This allows for interoperability despite the differences in, for example, data structures, digital signature schemes, consensus mechanisms, token issue mechanisms and more. However, the existing solutions allow interoperability between blockchains and systems in the medium term, since the used approaches are not universally used (Belchior et al., 2021). Therefore, to allow interoperability in the current situation, the blockchain architecture needs to redesign the solution for each system that they want to be interoperable with, based on the specific standards of that system. This promotes the development of blockchain interoperability standards for the long term. Research of Belchior et al. (2021) states that multiple standards will likely arise and be used, for each vertical industry, as there is a lack of generalized interoperability standards. Standards are then reused across industries. These developments of interoperability are outside the scope of this research, therefore the requirement NF5 is only partially fulfilled taking only the current available solutions into account.

8.2 PRACTICAL LIMITATIONS AND IMPROVEMENTS

This section uses expert validation to evaluate on the proposed blockchain-based EU ETS design and inventorize on the practical limitations and improvements when implementing such a design. This has been done in the form of a semi-structured evaluation in which the design is demonstrated and questions are asked while there is still room to explore relevant other topics, see Appendix B for more details about the expert evaluations. Experts in this domain include academics and experts from the working field that could evaluate the blockchain-based EU ETS design and the content of the design. The data retrieved from the evaluation interviews are qualitative evaluations. The evaluations are used to provide an overview of limitations and improvements of the design. The evaluations could be divided in two categories: about the proposed design for implementation (Chapter 8.2.1) and about the feasibility to extend the system to other ETSs (Chapter 8.2.2). The following subjects have been proposed considering practical limitations and improvements:

8.2.1 Limitations and improvements of the proposed design

The limitations and improvements of the blockchain EU ETS design are identified by experts in semi-structured expert evaluations, see Appendix B. The two subjects proposed by the experts are Technical design improvements and the identification of Implementation costs and benefits. This section quotes the evaluations of the experts and elaborates further on both subjects.

Technical design improvements

Expert E2 reflects on the technical design: *"The framework provides a good overview of blockchain architectures. Considering the fast-developing blockchain environment and that the framework is published in 2017, I think that there might be other innovative design options that could be considered for the future."*

The proposed EU ETS blockchain design provides a high-level architecture of the system, based on Tasca's ontology (2017). Currently, the EU ETS uses the Union Registry and the EU ETL as their technical system. With this blockchain design, the EU ETS is able to improve the current system by:

- Automatizing manual processes,
- Extending to/integrating with other ETSs

- Providing medium-term interoperability

The automatization of manual processes is enabled by the use of smart contracts. This takes away a part of the tasks of some stakeholders and even removes some intermediaries from the system, such as auction platforms. The ability to extend to/integrate with other ETSs is fulfilled by allowing easy integration of new authorities through scalable design choices and decentralized governance. At last, interoperability is provided on a medium-term by cross-authentication, API gateways, and oracles. See 8.1 for the fulfillment of the design requirements. This research focused on improving these aspects of the system. For the future, the technical design could be enhanced by other design components such as the use of native currencies, rewarding systems and slashing systems (Tasca, 2017). Native currencies are assets classes used in blockchain solutions that can be transacted in the system. They allow to run daily activities on the platforms, In the current design, we do not use native currencies because the European Union already uses their own native currency, the euro. For global implementations, it might become interesting to use a native currency for the ETS to avoid the entanglement of various currencies and high transaction fees due to the exchange of currencies. Rewarding systems could be put in place to nudge users into certain behavior. Slashing systems could be used to discourage malicious behavior. As an example, these systems could be used for finding inconsistensies in the system (rewarding) or for being faulty (slashing).

In this research, the most established design options are analyzed for the blockchain design to ensure more reliable comparisons and better information retrieval. On the other hand, recent developments in blockchain technology are focused on more energy-efficiency. New promising concepts of blockchain solutions with significantly lower power consumption are being tested (Sedllmeir et al., 2021). When these innovative solutions prove to be realizable, they could be used to improve the technical design of the EU ETS blockchain.

Hence, the proposed blockchain design for the EU ETS is able to improve the current system while covering the tasks to be executed in the EU ETS. To enhance the current design, design components such as native currencies, rewarding systems, and slashing systems could be used. Considering the fast-developing blockchain environment, innovative solutions are rising rapidly in the domain. When these solutions prove to be realizable, they could be incorporated in the EU ETS blockchain.

Implementation costs and benefits

The research aimed to explore the required technical components to improve an existing ETS. The architecture implementation costs have thus been left aside during the requirement generation phase. Expert E1 recommended: *"A cost-benefit analysis could be done to check the financial feasibility of the proposed system".*

Some financial benefits resulting from the design could be from the automatization of processes. This takes away tasks of some stakeholders and removes intermediaries (e.g. auctioning platform & exchanges) from the system. Implementation costs are complex aspects of information systems that could help identify hidden design assumptions (Barreau, 2001). See Table 9 for an overview of implementation costs.

Table 9 - Overview of implementation costs (Adapted from: Barreaau, 2001)

Type	*Category*	*Description*
Preliminary	Testing and planning	Project management costs to plan and monitor the implementation progress
	Conversion of legacy systems	Migration of data and redesign of processes
	Documentation and training	Preparing documentation, manuals, white papers, protocols and training activities for users
Operational	Hardware	Vendor selection, purchase and installation of new equipment
	Supporting infrastructure	Providing support to the architecture (servers, energy supply)
	Overhead	Overhead of management structure and user staff
Maintenance	Performance monitoring	Analyse information from the system to measure performance
	Updates and improvements	Developments and improvements
	Support staff	Technical staff and support centers

Thus, the costs and benefits are of the implementation of an EU ETS design could be analyzed. Doing this could help to decide whether the proposed design is feasible from a financial perspective. This could be a topic for future research, see Chapter 9.4.

8.2.2 Feasibility of extension to other ETSs

To take the next step for the blockchain design of the EU ETS and to be able to implement this design, we evaluate on the feasibility of extension to other ETSs of the blockchain EU ETS design, identified by experts in semi-structured expert evaluations, see Appendix B. The subjects proposed by the experts are Standardization, Convergence of market mechanisms and prices, and Politics and governance. This section quotes what the experts evaluated and elaborates further on these subjects.

Standardization

While the design takes the standards of the EU ETS as a starting point, from the expert evaluation it became clear that standardization is still an important factor to take into consideration when extending the system to other ETSs. Expert E1 said: *"Also with the Clean Development and Joint Implementation mechanisms (baseline-and-credit principles), we cope with the challenge that it is not sure whether the emission reduction is actually realized. There is a lot of attention and regulation to deal with this challenge and technology would not directly solve this fundamental problem."*

Expert E2 explains that: *"When integrating with other systems, the garbage in = garbage out principle still is a problem. Other systems use other standards to measure their emissions and if the quality difference of those measurements is high, it results in a unreliable system."*

At last, Interviewee I4 mentioned that: *"Technology is a means and not a solution. By providing a decentralized design of the EU ETS based on blockchain might contribute to designing a framework for setting standards while cooperating with other ETSs. This might be very interesting for CBAM as the European Commission is currently challenged by how to estimate and tax the carbon emissions of goods imported to the EU."*

In this research, two different types of carbon markets were explored: baseline-and-credit principle and cap-and-trade principle. For both types of carbon markets, there is a need for standardization to ensure effective carbon pricing with uniform methodologies and approaches (Keane et al., 2021). Currently, there are no carbon standards in use. The EU ETS blockchain design proposes a technical option to link and integrate with other ETSs but according to experts, to achieve this in practice within the existing carbon markets, carbon standards need to be defined first. The EU ETS currently uses a very decentralized approach to verify emission reports (with competent authorities, independent verifiers and accreditation bodies). But globally, there are no uniform, mandatory standards for this certification. Also, even if there is a standard for the certification of emissions, there might still be inconsistencies in interpretation of guidelines among different verifiers.

Furthermore, carbon standards are necessary to support the development of market mechanisms under Article 6, secure environmental integrity and create monitoring, reporting and verification framework (Keane et al., 2021). One of these market mechanism that could be supported by standardization is the Carbon Border Adjustment Measure (CBAM) imposed by the EU. The EU aims to implement the initial reporting phase of CBAM in 2023. The EU CBAM is a mechanism supporting the EU ETS to reduce some of the risks of carbon leakage. It will require importing nations to join in the EU's carbon market by subjecting the import of products to the EU with a carbon levy. Individual countries are moving at different speeds regarding the development of their own carbon markets and ETSs (Keane et al., 2021). Trade tensions may be heightened as countries seek to level up carbon ambitions with trading partners by imposing CBAMs (Mendez-Parra et al., 2020). The European Commission is planning to use product benchmarks to estimate the carbon intensity of goods. This results in a carbon price being transmitted along the value chain, but the price is not well connected to actual carbon emissions. The result is a lack of incentives for producers to decarbonize their processes (Marcu et al., 2020). Some have argued that the CBAM will increase the costs of trade while having limited impact on global emissions. In research of Keane et al (2021), the following two options are proposed for suppliers to the EU market: 1) Participate/integrate in the EU ETS and paying the price of carbon to enter the EU market, 2) Implement equivalent measures such as an EU ETS or a carbon tax and seeking recognition by the EU. For the first option, the EU ETS blockchain design is able to provide a solution to easily participate and integrate in the existing EU ETS. Currently, the countries that are linked or integrated with the EU ETS are exempted from CBAM. When considering the second option, the creation of carbon standards in the MRV process could be used in CBAM to prove the carbon emissions of importing nations. So instead of estimating the carbon intensity of goods, the EU could tax levy's based on standardized and verified emissionsCurrently, the countries that are linked or integrated with the EU ETS are exempted from CBAM.

To conclude, standardization is needed in carbon markets to be able to certificate emissions in a uniform way which is a great challenge in carbon markets. These carbon standards are also necessary to support the development of market mechanisms, like CBAM. However, even when these standards are set, inconsistencies in interpretation of guidelines among different verifiers could still occur. While standards develop and blockchain matures, industries and businesses will tend to incorporate blockchain technology in their processes (Belchior et al., 2021). Only then, mass-adoption of the EU ETS blockchain design could be followed after.

Convergence of market mechanisms and prices

The EU ETS is a market mechanism intended to reduce carbon emissions, including the cap-and-trade principle, the allocation of emissions allowances, MRV of emissions, and trading of emission allowances. To strengthen the EU carbon market, a concerted effort is required across a number of fronts. About this effort, E3 said: *"So just thinking about processes, you know, it's not just about trading. It's also about how to manage the future markets, how to how to manage the financial risk, the counterparty risk, even the risk to the exchange itself, and how to fulfill all the obligations from a reporting perspective and from a financial stability perspective."* This same expert E3 also mentioned that: "*When integrating emission trading systems, the prices will be converged. It is the question what this development results as one standardized price will have different impact on countries. When this happens, this impact on countries needs to be analyzed."* Also, Expert E1 indicates that: *"The advantage of integrating emission trading systems is that the price of allowances can be converged, resulting in less carbon leakage."*

In the past years, emission allowance prices, which have been exchanged on the European CO2 market, alternated in the range [0, 30] euros and mostly at low values and surged dramatically in 2021 to almost 60 euros, see Figure 22. A few factors can explain this sudden price surge, but the most impactful one is the shortage of natural gas. While a high carbon price increases the viability of low-carbon technologies (ING, 2022), the volatility shown in the market indicates an immature market.

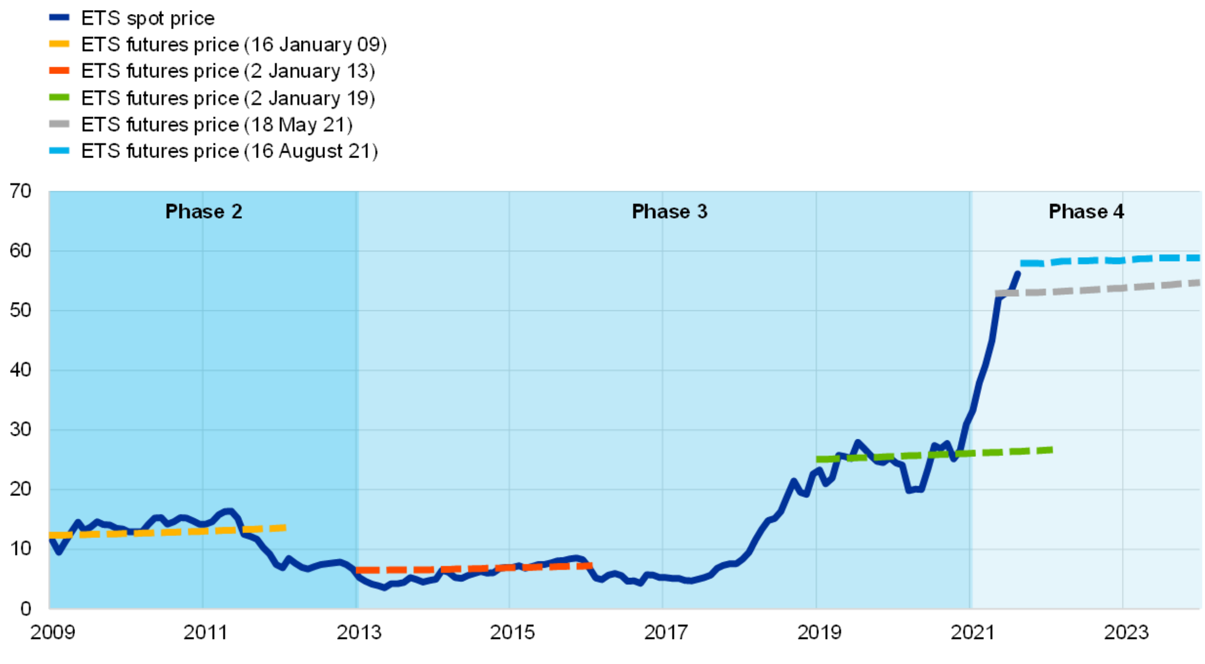


Figure 22 - EU ETS CO2 allowance prices in Euro/tonne CO2 and future prices (Source: ECB, 2021)

Currently, over 60 pricing policies are in place in 45 UNFCCC jurisdictions (Haited, 2020). Multiple interacting policies will cause carbon prices to vary across jurisdictions and reduces the potential economic benefit of price coordination (Haites, 2020). Price coordination will result in a more stable and mature carbon market (Haites, 2020). This research proposes a blockchain design for linking and integration of ETSs to enable price coordination.

Converging the market mechanisms could results in less carbon leakage. Carbon leakage usually occurs when businesses transfer their production to other countries with laxer emission constraints to avoid the costs of climate policies. When carbon pricing policies are set globally, businesses will less likely be able to escape the emission regulations. The goal of the EU is to use the ETS as a tool to achieve carbon neutrality but it is not achieved yet. The volatility of carbon prices make it challenging to manage the future carbon markets. Therefore, price coordination is needed to get a more stable and mature carbon market. The integration of ETSs could enable price coordination and prevent carbon leakage, but to realize this in practice, it is very dependent on standardization (8.2.1) and politics and governance (8.2.4).

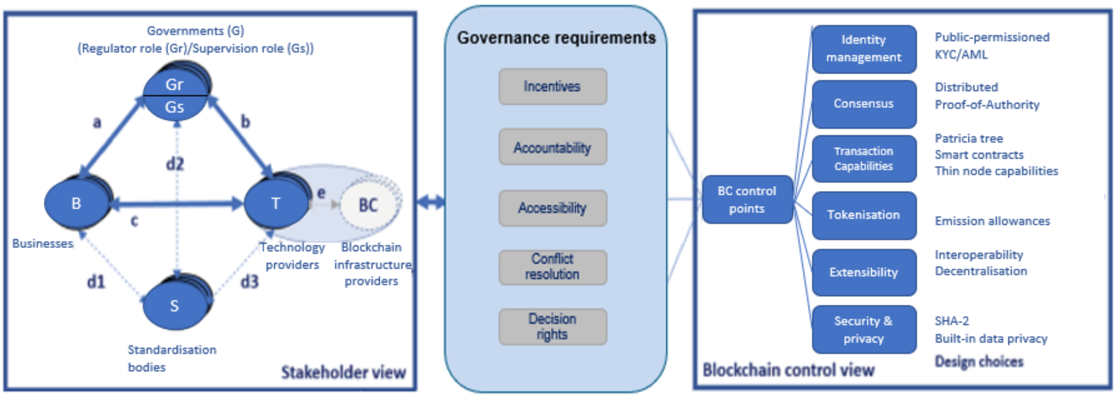
Politics and governance

This research has focused on providing a technical solution for the European emission trading system based on the policy of the European Commission. The requirements of this research were therefore not accounting the governance requirements needed when extending/integrating with other ETSs. Expert E4 mentions that: *"I think that this design is quite complete and that it can actually work on a blockchain. To implement this, of course, all kinds of Member States and countries are involved and that is a very large project from a political point of view"*. Expert E1 comments: *"The design proposes a good technical instrument. However, (for extension/integration) the first step will still be policy. In Europe, the European Commission has a certain authority in Europe to provide policy and when another ETS integrates with this system with an authority that has power over another region, there will be political consequences to such an integration."* This indicates that the stakeholder politics should aligned with the governance of the system. As part of a larger social coordination system, governance is a design factor closely linked to the alignment of interests between stakeholders (Engelenburg et al., 2020). An additional comment of Expert E2 is: *"Trust between authorities is very important, even with standards, we know that a lot of countries deal with problems such as conflicting geopolitical interests or corruption. So when an authority claims that they meet the standard, you still need to be able to trust that authority."*

Governance is an abstract concept that can be seen as all processes of social organization and social coordination. Research of Engelenburg et al. (2020) provided a framework to analyze the relationship between governance requirements in Business & Government (B&G) communication settings and the design of blockchain systems. This could be applied for the EU ETS because the proposed design architecture allows public entities to communicate with emission enterprises through rules and regulations. Figure 233 shows the blockchain governance framework of Engelenburg et al(2020), combined with the Behavioral drivers as governance requirements from research of Van Haaren-Van Duijn (2022), and the blockchain design components from the framework of Tasca (2017) used in this blockchain EU ETS design.

Figure 23 – Blockchain governance framework for B2G communication (Inspired by: Engelenburg et al., 2020, Van Haaren-Van Duijn, 2022 & Tasca, 2017)

The first view is the stakeholder view where the interests, relations, and potential tensions of the stakeholders are mapped (Engelenburg et al., 2020).. The second view is the governance requirements, they act as an intermediary between high-level governance considerations and low-level technical design choices. Governance requirements



describe decision rights that parties should be able to exercise explicitly. Research of Van Haaren-Van Duijn (2022) identified five behavioral drivers of blockchain governance: incentives, accountability, accessibility, conflict resolution, and decision rights. The determination of the behavioral drivers for the stakeholders involved starts in the stakeholder view and leads to agreements (e.g., specified in policies or contracts). On the other hand, what rights parties can exercise depends on the technological design choices made (Tasca, 2017), see the blockchain control view.

The framework can be used to align politics with the governance of the EU ETS blockchain design. In this case, the blockchain control view (right side of the framework) is designed so that the governance can be decentralized and flexible (see chapter 6.2.5). Thus, when the relations in the stakeholder view change, for example when adding authorities and enterprises of other ETSs to this system, the governance requirements in the blockchain ecosystem will have to be realigned in a decentralized way. After the realignment, the design decisions in the blockchain control view could be adjusted.

Hence, the current EU ETS blockchain design proposes a technical solution in which systems can be integrated with each other without having to throw away the existing principles. However, for allowing linking and integration with other ETSs, politics and governance of the system need to be aligned. The presented framework, see figure 20, could be used to align politics with governance. Moreover, before being able to link or integrate with other ETSs, trust between authorities need to be ensured.

8.3 Conclusions

This chapter evaluated on the blockchain design in two ways: by checking the fulfillment of design requirements and by semi-structured expert evaluations to answer the second part of the sub-question: *How can the blockchain-based EU ETS design be demonstrated and evaluated?* The objective of the first evaluation, see Chapter 8.1, was to assess whether the current design is functional and fulfills the non-functional conditions to be interoperable, secure, and enables automatization. The objective of the second evaluation with the experts, see Chapter 8.2, was to inventorize on a possible implementation of the design. The following conclusions are derived from the evaluations:

First, from the evaluation on the design requirements, we conclude that all requirements in the scope of this research are fulfilled. By fulfilling all requirements that have been defined as objectives for a solution of the identified issues, the artifact provides a blockchain-based solution that is able to cover the core functions of the system while actively improving system compatibility, preventing security issues and non-transparency, and enable automatized monitoring of transactions (See section 5.1 Design principles).The inventory of the possible implementation of the design resulted in two categories: limitations and improvements of the proposed design, and the feasibility of extension to other ETSs. Based on the expert evaluation, we conclude that the evaluations include the following topics: Technical design improvements, Implementation costs and benefits, Standardization, Convergence of market mechanisms and prices, and politics and governance.

9. CONCLUSION & FUTURE RESEARCH

In this last chapter of the research, a reflection on the work done is covered to answer the main research question. The conclusions of each sub-question is provided in 9.1. Next, the scientific relevance of this research is discussed in section 9.2. Furthermore, societal relevance is considered in section 9.3. The recommendations for future research are covered in section 9.4. Finally, a link between this research thesis and the CoSEM programme is made in section 9.5

9.1 CONCLUSIONS

The main objective of this research is to explore what a Blockchain-based EU ETS design with the possibility to extend/integrate with other ETSs would look like, including the requirements, and possible configurations. To achieve this objective a Design Science Research approach and a systems engineering perspective are used with the intention to answer the main research question:

What blockchain-based design can be used by the European Union to improve the technical design of the EU ETS while allowing for the extension to other Emission Trading Systems?

To answer this main research question five sub-questions were proposed to gain adequate knowledge to answer the main research question. The research questions were divided over the phases of the DSR approach: Explicate problem, Define requirements, Design and Development, Demonstration, Evaluation and Communication (Ramraika, 2015).

1. What is the current socio-technical composition of the EU ETS?

This sub-question is related to the first phase of the DSR approach, Explicate problem. To answer this question, desk research was conducted with a complex systems engineering, dividing the socio-technical system into technical, institutional, and stakeholder subsystems.

In the *stakeholder subsystem*, insight is provided on stakeholders about the way (in)formal relationships shape hierarchy and the definition of stakeholders' power comparison to each other. In the EU ETS, the European Commission is the key player as the executive arm of the system. Together with the Member States, they fill in the context of the ETS such as the creation and issuance of allowances, the rules for trading allowances and the monitoring, reporting and verification of emissions. The other authorities (the central administrator, national accreditation body, verifier and competent authority) play a crucial role to ensure that the processes are done correctly, also following the regulations from the European Commission and the Member States in the EU ETS. The emission enterprises are subjects in the context of the EU ETS as they are obligated to comply with the regulations. The auction platforms and exchanges are parties that are needed to ensure the possibility of allocation of allowances and emission trading.

The EU ETS registries are dependent on *institutional environment* of the EU ETS. In Europe, greenhouse gas registries are established to conform to provisions of international, European, and national rules. The Union Registry and the EUTL operate under the European emission trading directive, Directive 2003/87/EG of 13 October 2003. These registries need to transact with EU national registries under national regulations and the ITL under international regulations. This is enabled by the hierarchical structure and legal bond of regulations, from international agreements translated into European directives, and converted into national laws. While the EU ETS is well organized under European supervision and compliant with international agreements, a legal connection between the EU ETS and nations outside the EU currently does not exist.

At last, *the technical composition* of the EU ETS consists of the European registries which are the Union Registry and the EUTL. The Union registry functions as the database of the EU ETS where all relevant data is stored, such as the countries participating in the EU ETS, the installations covered (in each country), accounts of companies or individuals holding allowances, transfers of allowances performed by account holders, the annual verified CO_2 emissions from installations and aircraft operators, and annual reconciliation of allowances and verified emissions. On the other hand, all transactions between accounts in the Union Registry are automatically checked, recorded, and authorized by the EUTL. Data published in the Union Registry are consistent with the data provided by the EUTL.

Thus, the existing EU ETS provides a well-regulated system with roles and interdependencies between stakeholders which are interconnected with the institutional and technical environment. However the system still copes with challenges such as Lack of system compatibility, security issues and non-transparency, and manual monitoring of transactions, see Chapter 2.4.This system analysis serves as an input for the generation and elicitation of the design principles and requirements, see sub-question 2.

2. What are the design principles and requirements needed blockchain-based design to allow extension of the current EU ETS?

The second sub-question is answered by combining the insights of the system analysis with interview results. The design principles form the general guideline for the design and are developed into specific design requirements, see Table 10.

Table 10 - Overview of design principles

	Name	Description
1	Architecture interoperability	The design provides features that support the compatibility of data exchanges between Emission trading systems and different blockchain platforms
2	Emission trading system security	The design provides features that allow secure transactions across the emission trading domain
3	Emission monitoring automatization	The design provides features that ensure the automatization in the monitoring of the data used for emission trading.

Functional requirements cover the tasks to be executed and drive the application architecture. The non-functional requirements provide criteria to assess the operation of the artefact and define its technical architecture. An overview of the Functional requirements (F) and Non-Functional requirements (NF) is provided in Table 11.

Table 11- Overview of functional and non-functional requirements

Requirement	Description
F1	The artefact allows the European Commission to verify the supply of emission allowances
F2	The artefact implements an auction house mechanism where allowances can be auctioned.
F3	The artefact is able to receive and process data from stakeholders securely
F4	The artefact allows emission enterprises to trade their allowances with each other
F5	The artefact enables the verification of reports by the National verification bodies.
F6	The artefact fits in the regulatory environment of the EU ETS
F7	The artefact is able to check the annual compliance of emission enterprises
F8	The artefact is able to represent the emission allowances on the blockchain.
F9	The artefact is able to charge emission enterprises when they do not comply with the regulations.
F10	The artefact is able to implement the 'cap-and-trade principle' where a linear reduction factor is used to define the cap of emission allowances.
F11	The artefact allows to monitor the transactions and detect anomalies in the business transactions between emission enterprises.
F12	The artefact provides a mechanism that can automatically steer the supply of allowances and therefore guarantee a certain stability of the market (MSR)
NF1	Actors is able to register and identify themselves
NF2	A distinction is made accounts containing different rights in the system
NF3	The artefact allows verification and monitoring of the transactions
NF4	The artefact allows easy integration of new entities that want to join the system
NF5	The artefact is interoperable with traditional systems and other blockchains

3. How would blockchain design components be implemented in the EU ETS?

The third sub-question is answered by conducting a literature review about multi-criteria architecture frameworks for blockchain technologies. Here, the ontology of Tasca (2017) is chosen to find the relevant design components of blockchain architectures. The following design components are considered: Identity management, Consensus, Transaction capabilities, Tokenisation, Extensibility, and Security and privacy. The design decisions are made based on the functional and non-functional requirements for the EU ETS blockchain architecture.

For identity management, a public-permissioned blockchain type will be used. This means that the artefact will provide 'read' capabilities to anyone because the EU ETS currently also provides this. On the other hand, the 'write' and 'commit' capabilities are restricted to authorized participants (e.g. the European Commission, Central administrator, Competent Authorities). Also, KYC and AML are used to provide reliable onboarding and offboarding of nodes. This is essential for the EU ETS to recognize entities and their roles.

The consensus in the blockchain will be distributed with a Proof-of-Authority mechanism. The distributed consensus topology allows for high performance, availability and extensibility at low costs for all the nodes in the network. The Proof-of-Authority consensus mechanism allows trustworthy entities to control the network as validating nodes. PoA does not require heavy computational power to maintain the network so it is more energy efficient and because the mechanism is based on a limited number of block validators, it results in higher transaction rates and scalability.

The transaction capabilities are important to illustrate the scalability of transactions and the usability in possible applications and platforms. Using a PATRICIA tree in the block header allows activities like inserting, editing or deleting information referring to the balance and nonce of accounts, which enables faster and flexible validation of transactions (Tasca, 2017). The use of smart contracts in the traditional ledgers enables automatization of processes. Furthermore, to increase the scalability and lower the storage needs of the design, thin node capabilities are provided. This enables some nodes to contain only a subset of all the information stored in the blockchain.

Tokenization result in the possibility to convert something of emission allowances into a digital token that is usable on a blockchain application. By tokenization, we enable trading, auctioning and distributing, and management of the supply of emission allowances. Emission allowances are representations of a verifiable annual reduction or avoidance of one metric ton of GHG emissions and issued by the European Commission and are exchangeable. This makes emission allowances intangible and fungible tokens.

The extensibility of the design determines the future integration possibilities of the blockchain network. Interoperability could be enabled by different approaches, such as cross-authentication, API gateway, and an oracle. Also, a decentralized governance in alliance mode ensures that no single Council Member will have control, and no small group of members will have undue influence over the system as a whole.

Finally, to enable validation of information storage computationally and to secure the transactions, hashing will be performed with the SHA-2 function. Although hashing functions should ensure that only the intended recipient can read the message and have access to the content of the transaction, it is still possible to link blockchain transactions together to extract additional information of participants. Therefore, we will use built-in data privacy where we obfuscate sensitive information by default.

4. How can the blockchain-based EU ETS design be demonstrated and evaluated?

The demonstration of the blockchain-based EU ETS design is done by showing the institutional environment, the stakeholders in the system, and the emission trading processes.

In the institutional environment, three main observations are made. The first observation is that the system compresses the European and National registries into one system. The second observation is that on the international level, the blockchain architecture needs to interact with the ITL. The third observation is that the blockchain architecture is able to transact or even integrate with other existing ETSs technically.

The stakeholders are categorized in different roles in the blockchain architecture: validator nodes, verification nodes, utility nodes, and governance council members. The roles function on different layers in the blockchain architecture. Here, the European Commission and National Member States are the governance council members, the validator nodes are the central authority and the competent authorities, independent verifier and accreditation body are represented as verification nodes, and emission enterprises & other users fit as utility nodes.

The results of the proposed blockchain architecture are:

- Allowing extension to other ETSs
  The blockchain architecture is able to transact or even integrate with other existing ETSs due to technical design choices that are made by allowing easy integration of new entities in the system and interoperability of the system. Easy integration of new entities in the system is enabled because the blockchain is public-permissioned (Chapter 6.2.1), it uses a proof-of-Authority consensus mechanism (Chapter 6.2.2), it has thin node capabilities (Chapter 6.2.3), and it has a decentralized governance structure (Chapter 6.2.5). Interoperability of the systems is enabled by Cross-authentication, API gateways, and oracles (Chapter 6.2.5)
- Taking the existing environment into account
  The blockchain architecture takes the existing environment into account to increase the feasibility of the design implementation and it takes a part of stakeholder's tasks away to increase the efficiency of the processes. The stakeholders are categorized in different roles in the blockchain architecture: validator nodes, verification nodes, utility nodes, and governance council members. The roles function on different layers in the blockchain architecture. Due to technical efficiency, a part of the competent authority's and the national Member States' tasks are taken away as they do not have to do this manually anymore.
- Automatization, encryption, and transparency
  The blockchain architecture enables the automatization of the following processes: using the MSR, applying the linear reduction factor, annual release of tokens, providing an auctioning mechanism, fining emission enterprises when they are not compliant with the regulations. This takes away a part of the competent authority's and the national Member States' tasks as they do not have to do this manually anymore. To prevent the quality of data entry leading to unreliable data output, off-chain verification is performed in the MRV-process. Encryption is used to enable verification of the transaction on-chain without needing to store all the monitoring data on the blockchain. The design enables trading of emission allowances where the transaction will be stored on the blockchain. The blockchain architecture provides transparency in the market and trading of emission allowances. This also This reduces the tasks of the current competent authority, who currently update the union registry when emission enterprises report their transaction. Also, the emission enterprises do not need to report their transactions anymore as the transaction is automatically stored after validation by authority nodes.

The design is evaluated through two methods: 1) an analysis for fulfillment of requirements, and 2) an expert evaluation for limitations and improvements of the design.

This research concludes that the artifact provides a blockchain-based solution that is able to cover the core functions of the system while actively improving the current EU ETS by enabling system compatibility, preventing security issues and non-transparency, and enable automatized monitoring of transactions (See Chapter 2.4 Challenges in the EU ETS and Blockchain as an option). The operation of the blockchain EU ETS design covers the utility, serviceability, and scalability of the system. Limitations of the proposed EU ETS design that need to be considered are concerning Technical design improvements, and Implementation costs and benefits. Additionally, this research identified topics to consider when taking this design to the next step which is the implementation of the design. The topics to consider are Standardization, Convergence of prices and market mechanisms, and Politics and governance.

9.2 SCIENTIFIC RELEVANCE

This research positively contributes to the scientific community in several ways. First, this research provides an overview of academic research in the domain of Blockchain and emission trading, which currently is scarce in the scientific world. This research proposes a method to use socio-technical elements of emission trading principles to create a blockchain design. In general, this can be interpreted as an approach to model distributed ledgers in multi-actor systems. The research uses the DSR approach to provide an additional use case of blockchain in which relevant functional and non-functional requirements are generated. These requirements provide an overview of the system's specifications which can be used when gathering empirical data. Furthermore, this research linked technical design choices with requirements. This provides insight in the impact of technical design choices on certain objectives. By fulfilling the requirements, the research was able to demonstrate a functional blockchain-based design for the EU ETS enabling extension to other ETSs from a technical perspective. From an engineering perspective, this research shows how on-chain and off-chain processes can be combined in a blockchain architecture to ensure the execution of processes using identification methods (KYC/AML) and cryptography (public and private keys). From a governance perspective, this research shows how blockchain technology enables differentiation of centralized and decentralized decision making on different levels, because overall the rules in the EU ETS are centrally organized and verified by authorities of the system, but these authorities are able to work together and form consensus in a decentralized way. This differentiation of governance on several levels of a system can be applied to blockchain governance research. At last, this research provides a specification of an existing blockchain governance framework to align policy and stakeholder interests with governance and technical blockchain control points in the emission trading sector.

9.3 SOCIETAL RELEVANCE

Besides contributing to closing a gap in a growing research field, the use of the architecture provides benefits to society in different ways. The blockchain architecture offers a technological solution in which systems can be integrated with each other without having to throw away the existing principles. This is beneficial because these existing principles have been developed after a great amount of learnings, investments, and experience. The research uses the EU ETS as a starting point, making it easy for the European Commission to understand how a blockchain design would look like in the EU ETS. Also, the design enables more authorities to join a system that is already running while also able to have a say in the governance. This could lead to convergence of market mechanisms and prices where as a result, a more efficient and unified carbon market will emerge. Carbon markets try to mitigate the effects of global warming and climate change, more efficient carbon markets lead to achievement of the CO_2 emission objectives from the Kyoto Protocol and Paris agreement.

9.4 FUTURE RESEARCH

This research has focused on designing a blockchain architecture for the EU ETS to allow extension with other emission trading systems. Linking offers several potential benefits, including reducing the cost of cutting emissions, increasing market liquidity, making the carbon price more stable, levelling the international playing field by harmonizing carbon prices across jurisdictions, and supporting global cooperation on climate change (European Commission, 2022-c). This design is highly relevant because it is able to demonstrate on a high-level how the core functions of the systems are covered and improved by a blockchain-based system. Also, it provides a technical alternative to enable linking and integration with other ETSs. However, the blockchain environment is rapidly developing and the technology can still be considered to be in its infancy and the connection with other ETSs is not only a technical challenge. Thus, this section is dedicated to recommendations for future research regarding 1) the expansion of the proposed design for implementation, and 2) the possibilities to link or integrate with other ETSs.

9.4.1 Future research for the expansion of the design for implementation

In order for a blockchain based EU ETS to be implemented, future researchers have to research the market mechanisms on the blockchain, see Section Technical design improvements. A surplus of emission allowances has built up in the EU emissions trading system since 2009 and the European Commission proposed the MSR to manage the surplus of allowances, which is integrated in the blockchain design of the EU ETS. Future researchers have to define the effects of the MSR on the blockchain and provide requirements to manage the future markets. Currently, it is not clear what the financial risk, the counterparty risk, and even the risk of an exchange itself are when trading emission allowances. Also, the tokens of emission allowances do not expire and only evaporate when tokens are surrendered. Future researchers have to analyze the effects on carbon markets when using a 'retirement' market mechanism on the blockchain. This retirement market mechanism could include an expiration date of emission allowances.

Moreover, future researchers should expand the current design by looking into the effects of using native currencies, rewarding systems, and slashing systems in the blockchain EU ETS design, see Chapter 8.2.1. For global implementations, it might become interesting to use a native currency for the ETS to avoid the entanglement of various currencies and high transaction fees due to the exchange of currencies. Also, blockchains often use rewarding and slashing systems to incentivize users into certain behavior. As the MRV process of the ETSs is a big challenge, it is interesting to research how rewarding or slashing will enhance the trust in the ecosystem by rewarding nodes that find inconsistencies in the monitoring reports of emission enterprises and slashing nodes when they provide faulty information.

Also, the current design is taking the existing standards in the EU ETS as a starting point to implement a blockchain design for further improvements that enable extension with other ETSs, see Chapter 8.2.1. While on a smaller scale, other innovative technologies could enhance the processes in the ETS. For instance, in the MRV process emissions of enterprises are monitored and purely based on calculations. The emergence of IoT devices and satellite measurements could result in more accurate reporting of emissions. Researchers have to take the core processes of the blockchain design and research the use of emerging technologies to strengthen certain processes in the current blockchain.

9.4.2 Future research for linking or integrating with other ETSs.

To enable the linking and integrating with other ETSs and enabling a uniform carbon market, there is a need for standardization to ensure effective carbon pricing with uniform methodologies and approaches, see Chapter 8.2.2.

This includes standardization in monitoring, verification, and long-term interoperability. Future research has to provide a comparison of existing methodologies and approaches in carbon markets to support stakeholders on creating standards in this sector.

Also, when linking and integration with other ETSs can be established, the effects of converged market mechanisms and prices have to be thoroughly researched, see Chapter 8.2.2. Price coordination is needed to get a more stable and mature carbon market. The integration of ETSs could enable price coordination and prevent carbon leakage, but to realize this in practice, it is very dependent on standardization and politics and governance (8.2.2). Future researchers have to research how standardization and politics and governance influence the price coordination in emission trading systems.

At last, an analysis has to be done on the alignment of politics and governance. This can be done by using the proposed framework of Section Politics and governance. Research about the political environment (including stakeholder interests) of the ETS can be translated into governance requirements and transformed in blockchain control points in the design.

9.5 LINK WITH COSEM MASTER PROGRAMME

This thesis project is part of the graduation requirements of the Master for Complex Systems Engineering and Management (CoSEM). The research focuses on the design of a socio-technical system in a setting with various stakeholders and different interests. The differentiation of stakeholders in the blockchain architecture of the EU ETS results in different power play, e.g., current powerful stakeholders will have to take other roles within the system and shift their power and interests. For example, the European Commission will have to consider the decentralized attribute of the system in the decision-making. Therefore, an interdisciplinary multi-actor perspective is needed to address relevant policies in this complex system. According to Janssen et al. (2020), to adopt blockchain technology, the complex relations between institutional, market, and technical factors should be captured. In this case, institutional factors refer to the rules that regulate the interaction between the market parties and the entrance rules in the EU ETS. Market factors refer to the structures and processes to buy and sell carbon credits. At last, technical factors are dependent on the type of blockchain technology used, involving information transactions, distributed ledgers, and shared infrastructures. The interventions of these factors prove that this problem fits in the domain of a CoSEM engineer.

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Appendix A: Interviews

List of interviewees

Table 12 shows the list of interviewees in this research. The organization type, the roles of the interviewee's in the ETS and the expertise of each interviewee is described below. The conversations with the interviewees were executed with a semi-structured interview protocol.

Table 12 - List of interviewees

	Organization type	**Role**	**Expertise**
I1	National emission authority	Competent authority in EU ETS	Independent national authority for the implementation and supervision of market instruments that contribute to a climate neutral society.
I2	Blockchain energy solution provider	Blockchain & Energy expert	Provides blockchain solutions in the energy domain. Also, interviewee 2 has experience in the EU ETS as the interviewee had discussions with the European Commission as a stakeholder working for an industrial company.
I3	Integrated energy conglomerate	Emission enterprise in EU ETS	Works on Energy Markets Analyses at a utility in Europe. The utility is involved as an emission enterprise under the EU ETS, starting from the early stages of the system.
I4	Consultancy	Global trade expert	Institutional expert in the EU ETS, specialized in the Carbon Border Adjustment Mechanism, a supplementary mechanism of the EU ETS to prevent carbon leakage. Also worked on projects using blockchain.

SEMI-STRUCTURED INTERVIEW PROTOCOL

The objective of this interview is to test the requirements for a blockchain-based EU ETS design by obtaining a more in-depth understanding of ETSs and the issues that businesses and companies face in the system with/without using the new technology. The interviews will be used to elicit and validate requirements in three dimensions: technical, institutional and stakeholders.

This interview will be a semi-structured interview in which I would ask pre-determined questions while there is still room to explore relevant other topics. This allows for objective comparison of interviewees (structured part), while also providing a personalized approach and allowing a free-flowing conversation (unstructured part). The interview will consist of 4 parts: introduction, questions about technology, stakeholders and institutions. The results of the interview will be anonymized.

Pre-interview:

- Do you give permission to record the interview?
- Do you give permission for me to use an anonymized quote from this conversation for the research?

Introduction:

An introduction will be given about the research and the main objective of this interview. The introduction can be shortened by doing research about the interviewee and the ecosystem that the interview is about.

1. Could you tell me about yourself and describe your background in brief?
2. What kind of experience do you have with emission trading/carbon credits/allowances?
3. What is the biggest challenge that you experienced 88et he88?
4. In practice, what are for you the main differences of ETSs in the mandatory and voluntary market, and do you see a chance for these markets 88et h linked 88et he88 other?
5. What do you think about the use of blockchain in ETS? Could It be relevant 88et he88 mandatory market (cap-and-trade systems)?
6. What are the main advantages of using blockchain in ETS?

Technology

For my research, I distinguished 3 core processes in the ETS that I will focus on:

- Creation and issuance of emission allowances
- Monitoring, Reporting, and Accreditation of emissions -> cancellation of the emissions (market/aggregation and trading)
- Market and trading of emission allowances (monitoring/cancellation/retirement)

7. From these 3 processes, where do you see the most relevance of blockchain technology? How could this be implemented?
8. Within a cap-and-trade system, emission allowances are currently created and issued through free allocation and auctioning. What is important to take into account when considering this process?

9. What are the challenges in the monitoring/reporting/accreditation of emissions and what would 89et he requirements needed to ensure that this process is done correctly?
10. Market and trading: which other risks are there currently? (double spending?) What, do you think, is needed to mitigate those risks?
11. In these 3 processes, is there any sensitive data that needs more consideration?

Stakeholders

12. Can you describe or list the different types of participants or stakeholders of Emission trading systems?
13. How do you think that the roles/responsibilities of these participants will change when going to a blockchain-based system? Is that advantageous or not for these participants?
14. If you would be a user, trading emission allowances, what would be important requirements for you regarding the ETS?

Institutions

15. How do you take institutions/laws/regulations into consideration when working on a project with emission trading systems?
16. What are the biggest challenges/chances that you see?
17. What are important institutional requirements?

INTERVIEWEES' CONTRIBUTION TO THE RESEARCH & QUOTES

	Role	Contribution to the research	Quotes
I1	Competent authority in EU ETS	• Validation of EU ETS system analysis • Input for requirements engineering from a stakeholder's perspective (as an authority)	"All kinds of mechanisms are in place in the EU ETS to enable safe and secure transactions and processing of data from stakeholders" "Current development is focused on the fit for 55, which includes cbam, for example." " There is still a lot of work to be done. The allocation of allowances is becoming more dynamic. we spend a lot of time on granting allowances, but actually a lot more on measuring emissions. The allocation of allowances is mostly focused on benchmarking while the measurements of emission enterprises is very time-consuming" "The supervision of emission enterprises when monitoring their emissions is a time-consuming process but crucial for the system's integrity to prove that one tonne CO2 reported is equivalent to one tonne CO2 equivalent emitted." "We are increasingly becoming a data-driven organization in phase 4 of the dynamic allocation of emission allowances." "The impact of the price on the EU ETS is that a higher price result in enterprises being more sensitive about the allocation of emission allowances." "Within the MRV process, blockchain is not necessarily needed because in this process, a lot of customization is needed and there are few entities involved." "At the moment few parties are asking for emissions of enterprises, but it is possible that in the future emissions will become interesting for banks and insurers, for example." "Private independent verifiers must sign that the emission reports of enterprises are reliable, they are not under the authority of an instance but are accredited by the accreditation body."
I2	Blockchain & Energy expert	• Possible implementation possibilities of blockchain in the EU ETS • Input for requirements engineering from a stakeholder's perspective (as an emission enterprise)	"So once it (Blockchain technology) is proven at scale, from various angles and not necessary from all angles…… I would expect that at some point in time, the ETS or its future design will be replaced or expanded. Then it would make sense for anyone to agree to move on to blockchain. Because it's more resilient. It's more fraud resistant, it's more democratic."

		• Input for requirements engineering considering institutional factors • Input for requirements engineering considering technical factors	"In some form, the ETSs are managed by a different entities, and these entities can exchange on blockchain the blockchain. But how do we manage it? Could illicit behavior be proved because if it is not possible, that would discredit the whole system." "But now we do have like more much political data, like third party data, which could be used for cross validation. I think that in the end, as blockchain matures, the process of creation, issuance and distribution allowances could be improved by blockchain. Specifically, with KYC/AML. That's a thing where I think blockchain will have big impact, positive impact." "if we assume that there might be some forms of fraud in this space, where people might be reporting false numbers to get more or to pay less, this should be identified"
I4	Emission enterprise in EU ETS	• Validation of the EU ETS system analysis • Explanation of market concerns in the EU ETS • Input for requirements engineering considering technical factors	"The market has experienced a surplus of allowance supply that has resulted in the price of emission allowances dropping to record lows in the past, the instability of the market inhibited market growth. " "If you want to extend the current system, this could be done in all kinds of dimensions. You could think of new industries under the ETS itself, or extension to other market players like banks, or any other interested market players. "
I5	Global trade expert	• Validation of the EU ETS system analysis • Input for requirements engineering considering institutional	"Technology is a means and not a solution. By providing a technological design of the EU ETS based on blockchain might contribute to a framework for setting standards while cooperating with other ETSs. This might be very interesting for CBAM as the European Commission is currently challenged by how to estimate and tax the carbon emissions of goods imported to the EU." "In the EU ETS, trade must be made possible between emission enterprises for economic efficiency"

APPENDIX B: EXPERT VALIDATION

LIST OF EXPERTS

The experts are

	Organization type	Role	Expertise
E1	Scientific/Educational institution	EU ETS expert	Simulation modelling, in particular agent-based modelling on the domain of energy systems. Focuses on developments in modelling methodology to an understanding of complex socio-technical energy systems in order to better understand how to model, analyse and design of the energy transition. His primary interests are to unravel the possible long-term dynamics of energy systems and how they are shaped by energy policies, and in contributing to the modelling methods that address important academic and societal questions in this area.
E2	Scientific/Educational institution	Technical blockchain expert	Focuses on information sharing systems including blockchain and researches blockchain-based architectures from the technical perspective for implementations for among other things governance and circular economy.
E3	Consultancy	Global trade expert	Institutional expert in the EU ETS, specialized in the Carbon Border Adjustment Mechanism, a supplementary mechanism of the EU ETS to prevent carbon leakage. Also worked on projects using blockchain.
E4	National emission authority	Competent authority in EU ETS	Independent national authority for the implementation and supervision of market instruments that contribute to a climate neutral society.

SEMI-STRUCTURED EVALUATION PROTOCOL

The objective of this conversation is to evaluate the blockchain-based EU ETS design and inventize on the practical limitations and improvements when implementing such a design.. This will be done in the form of a semi-structured evaluation in which I would demonstrate the design and ask questions while there is still room to explore relevant other topics. The interview will consist of 4 parts: introduction, demonstration of the institutional environment, demonstration of the stakeholders, and demonstration of the emission trading processes.

Pre-interview:

- Do you give permission to record the conversation?
- Do you give permission for me to use an anonymized quote from this conversation for the research?

Introduction:
An introduction will be given about the research and the main objective of this evaluation.

1. Do you have any questions about the research objective or this evaluation?

Institutional environment
A demonstration of the institutional environment is given. We focus on the three biggest observations of the institutional environment when using a blockchain architecture for the EU ETS:

2. The first observation is that the system compresses the European and National registries into one system. Do you think that this is a good change and why? Will there be any challenges resulted by this change?
3. The second observation is that on the International level, the blockchain architecture needs to interact with the ITL. Does this result in any challenges?
4. The third observation is that the blockchain architecture is able to transact or even integrate with other existing ETSs technically. What challenges do you see to enable this?

Stakeholders
The stakeholders are categorized in different roles in the blockchain architecture: validator nodes, verification nodes, utility nodes, and governance council members. The roles function on different layers in the blockchain architecture.

5. Do the central authority and the competent authorities fit as validator nodes?
6. Do the independent verifier and accreditation body fit as verification nodes?
7. Do the emission enterprises & other users fit as utility nodes?
8. Do the European Commission and National Member States fit as governance council members?
9. What changes/challenges occur when assigning these roles to these stakeholders?

Processes
The emission trading processes demonstrated are allocating emission allowances, MRV of emissions, and market & trading of emission allowances.

10. The MSR and the linear reduction factor are implemented in smart contracts and automatized, are there any considerations that are missing?

11. Does the automatized auctioning mechanism result in implementation challenges?
12. Does the distinction of on-chain and off-chain data collection in the MRV process result in any challenges?
13. Is this MRV-process able to cope with *garbage in = garbage out*?
14. Does the fact that the competent authority has two roles in the MRV process conflict any interests?
15. How does the on-chain ‘exchange’ used for trading of tokens work? Are there any challenges?

EXPERTS' CONTRIBUTION TO THE RESEARCH & QUOTES

	Role	Contribution to the research	Quotes
E1	EU ETS expert	• Evaluation of designed processes from the perspective of the current EU ETS • Possible implementation challenges of the blockchain architecture in the EU ETS for: politics & governance • Possible implementation challenges of the blockchain architecture in the EU ETS for: convergence of prices and market mechanisms • Possible implementation challenges of the blockchain architecture in the EU ETS for: Technical design improvements	"The realization of integration between Emission Trading System is a complex problem but very desired thinking about topics such as a Global carbon price. " "With the Clean Development and Joint Implementation mechanisms, we also cope with the challenge that it is not sure whether the emission reduction is actually realized. There is a lot of attention and regulation to deal with this challenge and technology would not directly solve this fundamental problem. " "To realize a global solution, maybe an institutional solution would be to take a step back and think whether a cap-and-trade solution is actually the most applicable. Maybe additional to the cap-and-trade system, you could use a pricing mechanism for emission allowances. Is that possible? " "The advantage of integrating emission trading systems is that the price of allowances can be converged, resulting in less carbon leakage. " "The design proposes a good technical instrument. However, the first step will still be policy. In Europe, the European Commission has a certain authority in Europe to provide policy and when another ETS integrates with this system with an authority that has power over another region, there will be political consequences to such an integration." "The auctioning as a responsibility of member states result is currently a kind of market mechanism influencing the price of emission allowances" "The expiration of allowances could be a mechanism added to the design to regulate the allowances in circulation." "A cost-benefit analysis could be done to check the financial feasibility of the proposed system"
E2	Technical blockchain expert	• Evaluation of designed processes from a technical perspective • Possible implementation challenges of the blockchain	"Dependent on your requirements, there are different access control mechanisms in blockchain, such as encryption, but for every choice you make

		architecture in the EU ETS for: politics & governance • Possible implementation challenges of the blockchain architecture in the EU ETS for: standardization • Possible implementation challenges of the blockchain architecture in the EU ETS for: technical design improvements	for a design, there are advantages and disadvantes. ” The framework provides a good overview of blockchain architectures. Considering the fast-developing blockchain environment and that the framework is published in 2017, I think that there might be other innovative design options that could be considered for the future.” “Scalability is a good consideration for combining on-chain and off-chain data storage” “Often, there are use-cases using blockchain where I think that it is not necessary to use blockchain. But with this case, it provides value because it is able to cope with the balance of power between authorities on a decentralized way. “ “When integrating with other systems, the garbage in = garbage out principle still is a problem. Other systems use other standards to measure their emissions and if the quality difference of those measurements is high, it results in a unreliable system.” “Trust between authorities is very important, even with standards, we know that a lot of countries deal with problems such as conflicting geopolitical interests or corruption. So when an authority claims that they meet the standard, you still need to be able to trust that authority.”
E3		• Evaluation of designed processes from an institutional perspective • Possible implementation challenges of the blockchain architecture in the EU ETS for: politics & governance • Possible implementation challenges of the blockchain architecture in the EU ETS for: convergence of market mechanisms and prices	“the EU CBAM is a mechanism supporting the EU ETS and will require importing nations to join in the EU's carbon market. CBAM is intended to reduce some of the risks of carbon leakage” “So just thinking about processes, you know, it's not just about trading. It's also about how to manage the future markets, how to how to manage the financial risk, the counterparty risk, even the risk to the exchange itself, you know, as a sort of like a centralized counterpart to operate, and how to fulfill all the obligations from from a reporting perspective and from a financial stability perspective.” “When integrating emission trading systems, the prices will be converged. It is the question what this development results as one standardized price will have different impact on countries. When this happens, this impact on countries needs to be analyzed.”

			"Transparancy of data between countries might be a sensitive topic. "
		• Evaluation of designed processes from an overall perspective • Possible implementation challenges of the blockchain architecture in the EU ETS for: politics & governance	"The European Commission is currently accountable for the allocation of the emission allowances, and each Member State is responsible for dividing these emissions in the market. In parallel, the processes of allocation are free allocation and auctioning." "Take a note that the verified emissions also can be corrected by the competent authority within 5 years" "I think that this design is quite complete and that it can actually work on a blockchain. To implement this, of course, all kinds of Member States and countries are involved and that is a very large project from a political point of view"