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Potential Climate Impact of Retail CBDC Models

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Abstract

The expansion of digital payment services like retail Central Bank Digital Currencies (rCBDCs) built on innovative ICT infrastructure, notably datacenters, raises questions regarding potential environmental consequences due to electricity consumption. The design of such systems is critical for environmental impact as it scales with multiple actors and complex protocols as well as being influenced by server location and energy sources. In addition to other critical issues related to rCBDCs, understanding its environmental impact is therefore crucial for policymakers if they are to ensure sustainability. This study analyses one potential rCBDC, the Swedish e-krona project, by focusing on design choices and electricity consumption by comparing to existing retail payment services. Findings indicate that the energy use per transaction of the e-krona is comparable to that of card payments. There are, at the same time, significant differences in energy use depending on whether the design of the infrastructure for the e-krona is centralized or decentralized, where a centralized solution tend to be less energy consuming than a decentralized solution. The study has deployed a lifecycle perspective to explore energy consumption scenarios across various ledger infrastructures enabling a comprehensive assessment.

Keywords: Energy Consumption, Climate Impact, Digital Payment, E-krona, rCBDC

JEL classification: E58, O38, P44, Q58

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[*] Department of Industrial Economics and Management, KTH Royal Institute of Technology, Email: niklas.arvidsson@indek.kth.se

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List of Abbreviations

API	Application Programming Interface
CBDC	Central Bank Digital Currency
DLT	Distributed Ledger Technologies
DPoS	Delegated Proof-of-Stake
fBFT	federated Byzantine Fault Tolerance
iBFT	Istanbul Byzantine Fault Tolerance
pBFT	practical Byzantine Fault Tolerance
PoS	Proof-of-Stake
PoW	Proof-of-Work
PSD2	Payment Services Directive Two
rCBDC	Retail Central Bank Digital Currency
RTGS	Real Time Gross Settlement
SPOF	Single Point of Failure
TIPS	TARGET Instant Payment Settlement
tps	transactions per second

Executive Summary

The expansion of digital payment systems and retail Central Bank Digital Currencies (rCBDCs), like the Swedish prototype the e-krona, built on innovative ICT infrastructure, notably datacenters, raises questions regarding potential environmental consequences due to electricity consumption. The electricity consumed by digital payment operations, spanning data centers, servers, and transaction processing, significantly affects environmental sustainability and carbon emissions. The environmental impact of these digital technologies also rises with multiple actors, increased node usage, and adoption of complex protocols, which makes the design of the systems a critical issue. In addition, the climate impact heavily depends on server location and the energy mix of the hosting region, which emphasizes the role of location and energy sources for understanding ecological consequences.

Understanding the environmental impact of digital payments is therefore essential for central banks, regulators, and policymakers if they are to make informed decisions regarding sustainability and energy efficiency of rCBDCs. This study analyses potential designs of the Swedish rCBDC prototype, the e-krona, their potential electricity consumption and climate impact. It also compares this to existing retail payment services. Comparing the e-krona prototype design options with other payment methods allows for a relative assessment of its environmental impact.

Findings suggest that card networks and other digital payments may use comparable energy per transaction to the e-krona, especially if its design has a centralized and semi-decentralized structure. This analysis is based on a volume of the use of the e-krona that is similar to the of cash today, which means that the environmental impact of the e-krona could be lower if the use is higher, and vice versa. This is because there are both fixed energy effects related to servers and infrastructure as well as variable energy effects related to the actual use.

The study has deployed a lifecycle perspective for understanding climate impact of the e-krona based on assessments of energy use built on clear system boundaries to differentiate impacts between manufacturing aspects and usage phases. Future research directions should aim at conducting scenario analyses to evaluate the additional energy consumption levels when comparing various ledger infrastructure and consensus protocols as well as based on alternative system boundaries. This research could aim to develop a deeper understanding of the assessment of energy and climate impact across different e-krona models.

1 Introduction

1.1 Background and objective

Societies are becoming increasingly digital which brings opportunities and challenges for nation states and its policies. Retail payment services has been one of the most digitalized services for a long time which have led to more efficient systems but also challenges for those having problems accessing and/or using these digital services. Retail Central bank digital currencies (rCBDCs) is a relatively new type of retail payment service that governments around the world is launching or exploring with the aim of realizing a reliable, resilient, efficient, safe and including payment service system in a digitalized society.

In addition, as technological advancements reduce the use of physical cash in favor of digital payment services, the Riksbank's direct role in the Swedish payments system is transformed, where its role as a provider of a retail payment service, cash, may potentially disappear. This shift challenges the Riksbank's mission to maintain a secure and efficient payment system. Since 2017, the Riksbank therefore has been assessing its role in a digital world and considers the creation of an rCBDC called 'e-krona' as a digital alternative to physical cash. This initiative focuses not only on the retail payment system and the role of the Riksbank but also other aims like financial inclusivity and fostering innovation related to payment systems.

The discourse on rCBDC has primarily focused on its impact on stability in the banking system, on economic and monetary policies as well as design of technical solutions and infrastructure, while research into its environmental aspects remains comparatively limited. Understanding the environmental impact of payment systems is crucial, especially as we evaluate how digital currencies might influence both their environmental footprint and the long-term sustainability of a 'net-zero' economy. Additionally, growing concern on energy use across crypto assets associated with Distributed Ledger Technologies (DLT), as evidenced by numerous studies in recent years (Bada et al., 2021; O'dwyer & Malone, 2014; Platt et al., 2021; Wendl et al., 2023; Zhang et al., 2023), further highlights the need to explore the environmental effects of rCBDCs. Data indicates that bitcoins lead to emissions of 609 kg CO2 per transaction[1], which is a huge impact. Traditional payment methods, like cash and credit cards, already have a substantial energy consumption, as presented in Arvidsson et al. (2024)[2]. When it comes to digital payments, there's a wide range of energy linked to various technologies and components involved in their operation. The rCBDC ecosystem consists of multiple elements and functions; beyond the central clearing and settlement, or core, system, it includes a broader ecosystem of

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[1] Bitcoin Energy Consumption Index - Digiconomist

[2] Working paper nr (riksbank.se)

processing infrastructure, processing providers, and user services, which ideally should be taken into account in a comprehensive study of environmental impact of an rCBDC.

1.2 Overview of rCBDC worldwide

About 98% of the global GDP, represented by 130 countries, are exploring a CBDC, as shown in Figure 1. Of these, 64 are in advanced stages, including development, pilots, or launches, with Sweden's e-krona project being a notable example (Atlantic Council, n.d.). Eleven countries have fully launched a digital currency. China's extensive pilot reaches 260 million people, covering over 200 applications including public transport, stimulus payments, and e-commerce (Atlantic Council, n.d.). The European Central Bank is gearing up for a digital euro pilot, with over 20 countries set to pilot their CBDCs. Apart from their development status, CBDCs vary in terms of use cases (retail, wholesale, or both), architecture (such as direct or intermediated models), underlying technology (for instance, platforms like Ethereum), infrastructure, and partnerships involved.

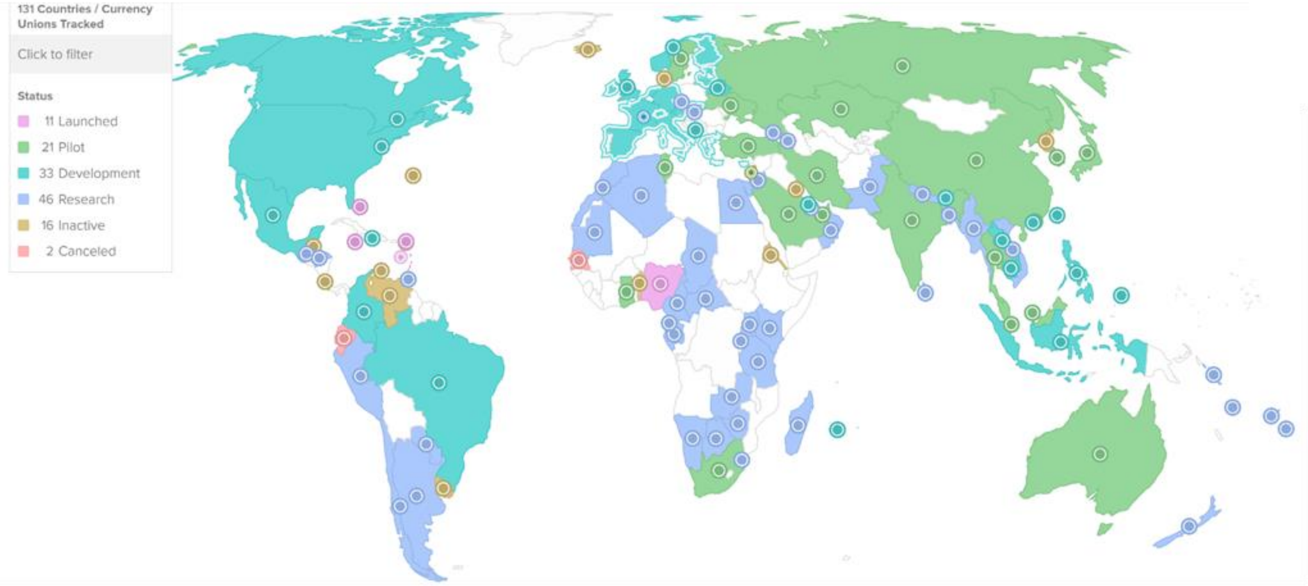

Figure 1 Overview of status of CBDC implementation worldwide.

Source: (Atlantic Council, n.d.)

Discussions about the environmental implications of CBDCs have emerged in recent years. Prominent institutions like the Group of 7 (G7), European Central Bank (ECB), and Bank of England have each outlined principles or guidelines for CBDC design, which include considering the environmental footprint (Lee & Park, 2022). Initial examinations of this environmental principle have commenced, emphasizing that a CBDC should be highly efficient and would not rely on the energy-intensive methods commonly associated with cryptocurrencies like Bitcoin (De Vries et al, 2020; Sarkodie et al, 2023). However, in-depth research on the environmental impact of CBDCs remains in the early stages, partly because it's a novel field with limited full implementations by countries.

1.3 Delimitations and limitations

There are several delimitations behind this study. The study focuses on analyzing the climate impact of potential designs of a Swedish rCBDC, the e-krona, and does not consider other critical functions of a rCBDC like its performance in relation to being a medium of exchange, a store of value and a unit of account as well as its implications for challenges related to financial inclusion and resilience. In addition, there are limitations. The design of the e-krona is not yet decided by the Riksbank, and there is not a decision made whether Sweden will introduce an e-krona or not, which means that this study is based on potential conceptual design alternatives of a future e-krona. Future decisions the Riksbank and / or the Swedish Parliament may therefore change the potential design alternatives as well as other critical conditions for the system behind the e-krona. To be clear, it is impossible to know if and when an e-krona can be launched. Given the prototype process, the study compares alternative designs of the e-krona with a study that analyzed the climate effect of retail payment services in 2021 (Arvidsson et al, 2024). Development of data servers and other technical devices between 2021 and 2024 therefore complicates the comparison but the possibility of making this comparison is still highly valuable since it puts the climate impact of a potential e-krona in a relative perspective with alternative retail payment services. A comparison with crypto-currencies is not useful since the use case of an e-krona is very different from the use case of Bitcoin.

2 Description of conceptual e-krona models

In traditional digital payment systems, trusted entities like banks and central banks play key roles in processing and settling transactions (Sandri et al., 2022). Bank transfers involve verification and settlement based on internal ledgers, compliance controls, and interbank balance settlements. Users access these services through bank websites, checks, or physical bank branches via a number of different retail payment services. For credit card payments, processing centers of card issuers and card acquirers are involved as well as the scheme providers, with users clearing their balances periodically and merchants receiving payments in their bank accounts, accessed via physical cards and point-of-sale terminals (Sandri et al., 2022). In contrast, digital currencies using DLT rely on consensus mechanisms for core processing trust, with digital wallets as the primary user access points. DLT is the infrastructure and protocol that stores transaction records in the ledger and ensures sharing of the same ledger records among the distributed network participants. DLT systems decentralize validation across validator nodes through a consensus protocol (Sandri et al., 2022). These validators form the core of DLT's processing.

The Swedish e-krona project primarily focuses on providing a digital service for domestic transactions, particularly in retail payment scenarios, such as peer-to-peer payments among individuals, or from individuals to merchants. The prototypes of the distribution model are conceptually similar to the current model for physical cash. Only the Riksbank will be able to create and redeem e-kronor, with participants playing a role in distributing e-kronor to end-users through digital wallets connected to payment instruments. The design of this system, however, includes several design challenges.

2.1 E-krona design principles

The Swedish krona (SEK) can exist in a physical form, like cash, and electronic forms, like commercial bank money or bank deposits. The e-krona, currently being piloted, is designed as a token utilizing block-chain technology. It represents a digital unit of value with attributes similar to physical banknotes but with key differences. The premise is that it is only the Riksbank that will be able to create and issue an e-krona, which thereby is uniquely identifiable and traceable to the central bank. Unlike physical cash, e-krona transactions require digital wallets and communication through network participants like banks. Each e-krona token can be designed to only be possible to use once, which implies the creation of new representations of e-kronor with each transaction. The authenticity of e-kronor will be verified digitally within the e-krona network, where the network ensures the credibility of e-kronor through their transaction history traceable to the Riksbank. However, the value of the krona will remain constant across physical, electronic, and digital forms, ensuring a one-to-one exchange rate between cash, commercial bank money and the e-krona.

Research on CBDC often makes distinctions between token-based and account-based CBDC. Token-based CBDC relies on digital tokens for transactions, offering privacy and peer-to-peer capabilities, while account-based CBDC operates through centralized accounts, offering transparency and integration with traditional banking systems. At the end-user, functional level, the distinction is not as clear (Sarmiento, 2022), and this study does not study the distinction between token-based and account-based CBDCs. However, this design feature, i.e. centralized versus decentralized, is one critical factor when designing an e-krona-system, and a central part of this study.

2.2 Basic characteristics of e-krona models

Central banks are prototyping alternative design models for retail central bank digital currencies (rCBDCs) including the Riksbank's work to develop an e-krona in Sweden. Important lessons from this work includes, for instance, that the design must ensure that there are no negative effects for the economy as well as stimulating sufficient adoption and acceptance by consumers and merchants, which illustrates one of the dilemmas in this important work (Zamora-Pérez, 2022). In a similar vein, a Swedish study pointed to dilemmas related to trade-offs between minimalistic approaches and performance/resilience as well as how to strike a balance between decentralization and data privacy (Armelius et al., 2020). Given these inherent challenges and based on consultation with the Riksbank, the conceptual e-krona models in this study are categorized into three archetypical models: (i) highly centralized design, (ii) semi-centralized design, and (iii) decentralized design.

2.2.1 The basic principles of the three models

To sum up, the most critical differences between the three models related to the centralization vs. decentralization of access to data on accounts, legitimacy of credits, payers, payees, and other transaction data as well as clearing and settlement of transaction. The centralized model provides a minimum of this data as well as participation in clearing to actors other than the central bank while the decentralized model does the opposite, i.e. provides the highest access to data and participation in clearing to other actors than the central bank. It should be noted, however, that a similarity between the models is that it is only the Riksbank that is able to create and issue an e-krona, which thereby is uniquely identifiable and traceable to the central bank, and that it is only the Riksbank that is operating final clearing and settlement of ekrona-transactions.

2.2.2 Highly centralized design

The first model is a traditional centralized e-krona provision with centralized ledgers of transactions. It represents a typical non-block-chain, centralized system that uses a complex database and backups. The central bank is responsible for issuing and redeeming e-kronor. Further, the Riksbank provides and operates a technical platform with a core ledger that allows for instant settlement of retail payment services. This will allow intermediaries such as payment service providers who have a license to act as a financial institution and thereby a possibility to access the e-krona-system provided by the Riksbank. This will enable these actors to offer e-krona transactions to end users. All transaction information and execution are handled within the core system operated by the Riksbank, which includes backups distributed geographically but operated by the Riksbank to ensure resilience in case of server and/or infrastructure issues. This option would provide optimal control for the Riksbank as the central agency that deals with e-krona payments, hence limiting the role of other actors.

2.2.3 Semi-centralized design

The second model is a semi-centralized e-krona provision with DLT. Intermediaries operate nodes in the network in the DLT terminology and are having a copy of the ledger. The advantage of this approach is that it eliminates Single Points of Failure (SPOF). Even if one node was to go down, the other nodes having complete information of the ledger can still operate, ensuring resilience by design. Moreover, in this semi-centralized model, there is no need for extensive security measures or cryptography to protect the data, as the Riksbank is the sole entity responsible for managing and accessing the data. The nodes (e.g., payment service providers), that are relatively few, are active at all times, unlike the passive backup in the centralized model.

The semi-decentralized design could be a private permissioned network where gatekeeping strategies are applied to a network of a limited number of vetted actors (known and authorized). The access to the network is limited to these actors, thereby reducing the risk of external attacks. Each actor (except the Riksbank) will only need to run and maintain systems that relate to their interfaces and services towards the consumers as the Riksbank is hosting the core system.

2.2.4 Decentralized design

The third model is decentralized model with distributed subsets of data. The system would be decentralized, with nodes being spread out and operated by different parties, ensuring a high level of distribution and ownership. However, individual nodes only store a subset of data, i.e. information related to the intermediary that owns and operates them. To ensure the validity of each transaction, the Riksbank is responsible for verifying all transactions before completion.

This tracing process is facilitated by an ‘observation node’, allowing transactions to be traced all the way back to the initial issuance. In 2018, the Swedish central bank prototyped the e-krona on a decentralized design using Corda block-chain technology, even if these tests indicated that this technological infrastructure may not be ideal for the e-krona (Sveriges Riksbank, 2022).

The decentralized design could be a public permissioned network where the participating actors are licensed as financial institutions and classified accordingly. Each actor would need to run and host larger systems, the Riksbank will host and run its part of the total ecosystem. The decentralized nature of the model would enhance resilience to some extent by having multiple ledgers copies available, albeit likely not to the same extent as permissionless DLT solutions.

2.3 Environmental implications of a retail Central Bank Digital Currency (rCBDC)

The environmental impact of rCBDCs can vary depending on choices made in the design of the ledger infrastructure, consensus mechanism, level of control related to permissioned and permissionless network and actor involvement as well as user interfaces. In the e-krona pilot project, the e-krona network was prototyped to operate on R3's Corda platform, a decentralized private network. The participants in the network, including banks and payment service providers, run their own nodes, enabling transactions without relying on traditional payment infrastructures.

This report briefly presents qualitative analysis of how different factors affect the energy consumption and climate impact of rCBDCs, drawing insights from existing literature. While there is no preferred consensus yet, based on the consultation with the Riksbank, the discussions on the energy consumption and climate impact of rCBDCs could consider mechanisms that are being discussed internationally as a viable option. The mechanism should be able to process equal number of transactions and achieve a similar performance. The Proof-of-Work’s protocol is unlikely to be the potential solution since one of the main reasons why crypto-currencies like Bitcoin use a lot of energy is caused by the proof-of-work structure (Kohli et al, 2023). The energy efficient consensus mechanisms such as Proof-of-Stake or Byzantine Fault Tolerance variant is therefore more appealing from a climate impact perspective.

2.4 Ledger infrastructure

The decision between centralized and decentralized systems depends on priorities and objectives, impacting security, computational costs, and energy usage, which in turn affects environmental impact. Block-chain systems, compared to centralized system, need extra computations for consensus without SPOFs, affecting energy consumption. This energy requirement however varies with the chosen consensus mechanism; for instance, a centralized block-chain is likely to have similar energy usage to a centralized system like a Real Time Gross Settlement (RTGS) system. According to Sandri et al. (2022), an rCBDC that builds on a system comparable to TARGET Instant Payment Settlement[3] (TIPS), might even use less energy than credit cards. The core settlement systems using TIPS technology were found to consume only a few kilowatts of energy, effectively handling thousands of transactions per second (ECB, 2021). However, various factors beyond computation could increase its energy consumption. These include advanced features, additional security, and server backups. Central banks could optimize this by controlling the number and location of network nodes or main servers, potentially situating them in areas with sustainable and/or excess energy. The selection of environmentally friendly cloud services can benefit rCBDCs and other digital projects of central banks. While central banks may rely on private vendors for rCBDC technology, potentially limiting control over energy aspects, vendor competition and development towards lower energy and climate impact rCBDC systems can still be influenced (Sandri et al., 2022).

2.5 Consensus mechanisms

As mentioned earlier, the energy demand differs based on the consensus mechanism employed. In financial services, public block-chains commonly use Proof-of-Work (PoW), Proof-of-Stake (PoS), and Delegated PoS (DPoS), while private block-chains favor practical Byzantine Fault Tolerance (pBFT), Istanbul BFT (iBFT), and federated BFT (fBFT). The comparison of different consensus mechanisms is presented in Table 1.

Table 1 Comparison of Different Consensus Mechanisms

(Bains, 2022)

	PoW	PoS/DPoS	PoET	pBFT/iBFT	fBFT	DiemBFT
Block-chain Type	Permissionless	Permissionless	Both	Permissioned	Both	Both
Settlement Finality	Probabilisitc	Probabilisitc	Probabilisitc	Immediate	Immediate	Immediate
Transaction Rate	Low	High	Medium	High	High	High
Scalability	High	High	High	Low	High	High
Contestability	High	High	High	Low	Medium	Low
Environmental Impact	High	Medium	Low	Low	Low	Low
Security	High	High	Medium	Medium	Medium	Medium

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[3] What is TARGET Instant Payment Settlement (TIPS)? (europa.eu)

Bada et al. (2021) presented the indicative energy consumption of various consensus mechanisms which based on theoretical studies of the mechanisms and their computational overheads. Figure 2 illustrates the correlation between consensus mechanisms and their estimated energy usage, drawing from existing projects as a reference. Energy consumption increases as it moves towards a more decentralized consensus protocol.

The main reasons why energy consumption increases as systems become more decentralized are that this also increases the number of servers and computers that are part of the system as well as it often increases the volume of data that needs to be processed in one transaction. Decentralization thus necessitates systems for controlling threats of fraud, double-spending and other types of potential problems that are more data intensive than a centralized system where one actor can control these factors. In addition, the risk that some servers in a decentralized system are using non-renewable energy sources, and therefore being less environmentally friendly, increases in relation to a more centralized system where the location of servers is better known and therefore also more controllable. These factors explains the indicative energy consumption in the different types of consensus mechanisms in Figure 2.

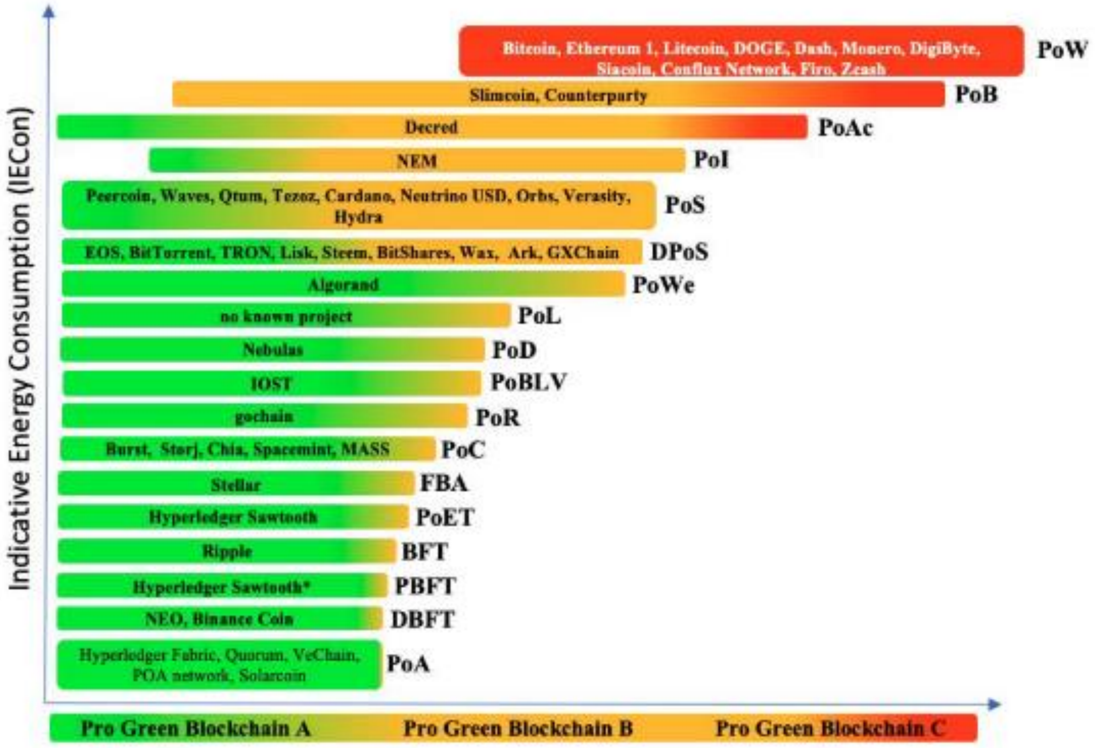

Figure 2 Indicative Energy Consumption of Consensus Mechanisms

(Bada et al., 2021: 509)

DLT systems employing PoW require substantially more energy per transaction, typically ranging from 100 to 1000 kWh/transaction, which is several orders of magnitude higher than non-PoW-based DLT systems that use between 10^{-6} – 10^{-2} kWh/transaction (Sandri et al., 2022). For comparison, the energy consumption per transaction for TIPS, as reported by the Bank of Italy, is between 10^{-6} – 10^{-5} kWh/transaction under normal load conditions (Tiberi, 2021), comparable to that of permissioned non-PoW DLT systems. Meanwhile, the clearance of existing instant payment Swish through automated clearing house in Sweden requires 6 x 10^{-5} kWh/transaction (Arvidsson et al., 2024).

Compared to permissionless DLT systems, permissioned ones have a higher potential for benefiting from energy economies of scale. Platt et al. (2021) suggest that the extent of these economies within a DLT system depends on the fluctuation in the number of validating nodes with transaction volume: a rapid increase in nodes as transactions increase reduces energy economies of scale, while maintaining a consistent number of nodes, regardless of system size, enhances them. Additionally, for non-PoW block-chains, the energy used for consensus is not substantial, so redundant operations might significantly contribute to total energy consumption. Therefore, reducing block-chain energy use should focus on both selecting alternative consensus mechanisms and implementing strategies to decrease operational redundancy (Sedlmeir et al., 2020) even if this decreases resilience. This can include reducing the number of nodes involved in processes and minimizing transaction workloads, such as through 'sharding', where network nodes are divided into groups with each handling only a portion of transactions/subsets. Moreover, the overall energy efficiency of the protocol is affected not just by the number of nodes, but also by their hardware configurations.

2.6 User interfaces

The energy costs for user interfaces including initiating payments and displaying confirmations in user interfaces are typically low. While the time usage and energy consumption of devices during transactions will influence overall consumption, these factors remain relatively minor compared to the energy used for core processing and settlement.

3 Potential climate impact of e-krona

3.1 Methods and delimitations

When considering the climate impact of digital infrastructure from a life cycle perspective to understand the climate impact based on assessments of energy use within clear system boundaries, factors beyond the direct energy used for processing and settlement of payments are crucial. These include raw material extraction, server production, other components and infrastructure manufacturing, transportation of components, and waste management. Yet, the methodologies and data needed for a thorough analysis are still in an early stage. In scenarios with numerous uncertainties or evolving factors (e.g., implemented technical solutions, number of actors and nodes, etc.), conducting a comprehensive environmental impact assessment may not yield fully accurate or meaningful results. Moreover, there is a lack of empirical data and publicly available information regarding the energy consumption of numerous consensus mechanisms. Consequently, this study should be viewed as an initial exploration rather than a definitive analysis. We recognize these limitations and anticipate the need for further research as more data related to e-krona implementation becomes accessible.

Understanding the fundamental nature of e-krona, its operational mechanisms, and its distinctions from other cryptocurrencies is crucial to assess its environmental footprint. Thus, this work examines various e-krona design choices and their potential electricity consumptions. It includes an initial evaluation of the e-krona's operational climate impacts (based on potential electricity use), comparing it with existing payment systems, to increase awareness among central banks, regulators, and policymakers about its potential environmental consequences. Additionally, comparing e-krona with other payment methods offers a chance to gauge its environmental footprint and facilitate a relative assessment of its impact level.

The study of the potential climate impact of conceptual e-krona models is done in relation to another study of climate effects of existing retail payment services like cash, cards, Swish, giro-payments and payment apps, where the year of study was 2021 (Arvidsson et al., 2024). This means that the comparison of the results in this study to the results in the other study (ibid) must be made with caution since there is a time difference regarding data collection between these two studies. The analysis of the e-krona builds on characteristics of systems in 2024 while the analysis of other retail payment services are based on the characteristics of payment systems in 2021. Had the analysis of other retail payment services than the prototype of the e-krona been made in 2024, it is likely that the climate impact could be lower than what was found in Arvidsson et al (2024). This is because technological development of infrastructure and servers tend to reduce climate impact over time.

The study explores the climate impact of three distinct proposed e-krona models, each varying in its design as discussed in Section 2:

1. A highly centralized design.
2. A semi-centralized design.
3. A decentralized design.

The payment system of each proposed e-krona models for estimating electricity use is divided into three layers or components i.e., core layer, nodes/actor layer, and user layer. The comparison of layers of existing payment methods and conceptual e-krona models is illustrated in Table 2.

Table 2 Components of several payment methods

	Traditional payments			Conceptual e-krona models		
	Cash	Card	Credit transfers (Giro/Swish)	Highly centralized design	Semi-centralized design	Decentralized design
Core layer	Creation, distribution, use, and disposal of banknotes and coins	Card issuers' and banks' data centers, RTGS	Banks' data centers, RTGS	The Riksbank data centers, RIX INST with major role in transaction initiation, verification, validation, confirmation, record	The Riksbank data centers, RIX INST for transaction initiation, verification, confirmation	
Nodes/actors layers				Commercial banks for forwarding the payment	Authorized actors/banks except the Riksbank that join the network to validate the transactions	Trusted/approved nodes except the Riksbank that join the network to validate the transactions
User layer		Physical cards, point-of-sale terminals, online payment, payment app	Online payment, paper-based payment	Online payment		

3.2 Potential architectures of conceptual e-krona designs

The study explores e-krona designs and their potential consumption of electricity. This can be estimated by considering various factors, such as hardware needs, traffic volume, and the geographical positioning of the core layer (inclusive of backups) and the nodes/actors layer, in addition to device's electricity use. Based on the consultation with the Riksbank, the type of hardware and expected hardware utilization in the conceptual e-krona designs can be derived from industry recommendations. Considering the basic characteristics of e-krona designs, outlined in Section 2.2, the possible infrastructures of each model are summarized in Table 3.

Table 3 Possible infrastructures for different conceptual e-krona designs

Infrastructure	Highly centralized design	Semi-centralized design	Decentralized design
Servers at Riksbank	High-capacity server	Low to medium power computing but high storage capacity	Low power computing but high storage capacity
Server nodes	Low power severs	Low to medium capacity, high storage power severs	Medium to high capacity, high storage power severs
Back-up servers	The Riksbank manages master data. High-capacity server.	All actors have back-ups incl. the Riksbank. Low to medium power computing but high storage capacity	All actors have back-ups incl. the Riksbank. Low power computing but high storage capacity

Subsequent subsections provide a framework for estimating energy usage across three different layers (i.e., core, node/actor, and user).

3.3 Estimating electricity use of core layer

The core layer of the system could be composed of the following components:

- RIX INST: As the core settlement system built on the TIPS-platform, it is capable of facilitating up to 2000 transactions per second (tps). TIPS energy consumption is 128 MWh/y with PUE (energy use per transaction) of 1.6 The climate impact of this system is estimated at 0.00429 grams of CO_2 per transaction, as reported by the Bank of Italy in 2021 (Tiberi, 2021).
- Application Programming Interface (API) Gateway: This serves to connect different nodes with the core and includes considerations of typical hardware requirements or servers, traffic volume, and geographic location. The API is expected to align with prevalent industry standards, like RESTful APIs, similar to those used in PSD2 (Payment Services Directive Two) APIs[4] currently offered by banks and Payment Initiation Service Providers.
- RIX RTGS: This is the current core system clearing and settlement of batch transaction operated by the Riksbank, and it will still have a role in managing transfers between e-krona and traditional bank accounts, i.e. e-krona to and from commercial bank money, functioning in a manner similar to current systems. This role therefore relates to potential final gross settlements that relate to but go beyond instant settlements made

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[4] PSD2 APIs are used in the financial industry to facilitate secure and regulated access to bank account information and initiate payments.

in the RIX INST system which could be settlements of transactions involving the e-krona as well as commercial bank money deposited in a bank account. However, if all transactions occur directly from e-krona to e-krona there would be no involvement of the RIX RTGS system.

- Backup core layer: This is an archive to store the historical transaction.

3.4 Estimating electricity use of nodes/actor layer

The energy use related to nodes/actors layer in semi-centralized and decentralized designs depends upon four main factors:

- The consensus protocol of which should have the capacity to process a number of transactions equal to that of TIPS while maintaining a comparable level of performance. The TIPS system is currently sized to handle an average volume of 500 tps which corresponds to NTIPSNormal = 15.7 × 109 transactions per year. In addition, the system is currently able to absorb traffic peaks of 2000 tps (Tiberi, 2021).
- The number of validator and back-up nodes in addition to the core which includes bank, payment service providers, that have been authorized by the Riksbank to participate in e-krona transactions.
- Minimum hardware requirement, utilization of that hardware and their energy consumption.
- Traffic volume (number of transactions).

The electricity use can be estimated using a linear mathematical model that includes the core metrics of a DLT system. For DLT, the key factors affecting electricity consumption are the ability to control participation and the consensus algorithm. Estimates for prospective non-DLT digital currencies match the lowest energy consumption of the DLT-based designs (Agur et al., 2023).

Different calculations can be employed for different block-chain types due to variations in protocols, number of validator nodes, recommended hardware, and throughput requirements. Platt et al. (2021) presented a mathematical framework for estimating the energy consumption of PoS' block-chain systems. The framework focuses on the energy requirements associated with the operation of validator nodes, which play a central role in the consensus mechanism of PoS block-chains.

Framework for estimating the energy consumption of PoS' block chain systems:

1. **Energy consumption model**: this model considers the average power consumed by a validator node (denoted as p) and the number of validator nodes (denoted as $n$val). The overall average power the DLT system consumes (denoted as pt) is expressed as the product of p and $n$val, providing a straightforward way to estimate the energy needs of the consensus mechanism.

$$pt = p \cdot n\text{val} \qquad ..(1)$$

2. **Transaction-Based Energy Consumption:** The framework also incorporates a consumption function (denoted as fctx) that calculates the energy consumption per transaction based on the overall system throughput (measured in transactions per second). This function takes into account the number of validator nodes and their power consumption, providing insights into the energy requirements associated with processing transactions on the block-chain.

$$f_{c_{tx}}(l) = \frac{n_{val} \cdot p}{l} \; ..(2)$$

For simplicity it can be assumed that the correlation is perfect,

i.e., $n\text{val} = \kappa + \lambda \cdot l$ for some $\kappa, \lambda \in$ R, $\lambda > 0$, and using (2) we obtain

$$fc\text{tx}\ (l) = \{(\kappa + \lambda l) \cdot p\} / l$$

This model assumed a fixed energy consumption per server, a known number of servers for block-chain operations, and a specific volume of network throughput. The type of hardware used by validators is derived from industry recommendations (Table 4). It should be noted that actors could have different minimum hardware requirement depending on their role in the e-krona transaction.

In the design of a semi-centralized or decentralized system for rCBDC, the role of participating actors varies significantly. In a semi-centralized design, the participating actors, acting as validators, are primarily responsible for operating and maintaining systems that facilitate their interfaces and services for consumers. In this model, the Riksbank hosts and manages the core system, reducing the infrastructural burden on individual actors. Conversely, in a decentralized design, the participating actors need to manage and host more substantial system components. Each actor, including the Riksbank, is responsible for hosting and running their respective segments of the overall ecosystem, leading to a more distributed and shared infrastructure responsibility.

Platt et al. (2021) indicated that a realistic energy consumption estimate for a validator node needs to factor in both the minimum hardware requirement (i.e., how many CPU cores or what amount of memory is required) as well as the utilization of that hardware. Most of traditional permissionless block-chain systems with comparatively large numbers of validators running full nodes that verify every transaction, demand comparatively low-powered hardware. For the permissioned system (e.g. Hedera) which constitutes a high-tps system and characterized by a small number of nodes maintains consensus, the network performance is determined by the lowest-performing validator node. Therefore, to achieve the postulated maximum throughput values, highly performant server hardware is demanded by the network operator.

Table 4 Possible upper and lower bounds for the power demand of a validator machine for semi-centralized and decentralized designs

(Platt et al., 2021)

Configuration	Hardware Type	Exemplar	Demand (W)
Minimum	Small single-board computer	Raspberry Pi 4	5.5
Medium	General purpose rackmount server	Dell PowerEdge R730	168.1
Maximum	High-performance server	Hewlett Packard Enterprise ProLiant ML350 Gen10	328

3. **Consideration of Network Throughput:** The mathematical framework acknowledges the impact of network throughput on energy consumption, highlighting the relationship between the number of validator nodes, their energy consumption, and the overall system throughput. This consideration allows for a more comprehensive assessment of the energy demands of PoS block-chain systems. The mathematical framework thus reflects the previous discussion of energy consumption by consensus mechanisms in Figure 2 by identifying the critical factors influencing energy consumption in these systems, i.e. energy consumption per server, the number of servers, volume of network throughput, and type of hardware used by validators.

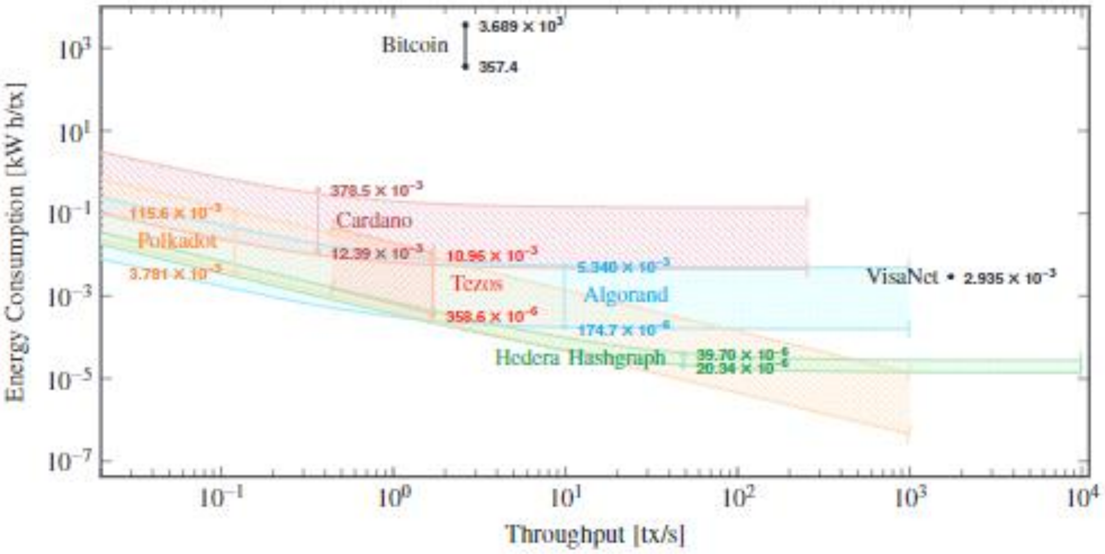

Figure 3 Energy consumption vs throughput for each system where the lower mark indicates optimistic validator hardware assumption while the upper mark represents the pessimistic model

(Platt et al., 2021)

3.5 Potential electricity use of conceptual semi-centralized and decentralized designs of the e-krona

Electricity consumption per transaction is often used as a key metric for comparing block-chain protocols. However, its complexity lies in different calculation methods and variations in transaction definitions across networks. Some metrics simulate full-speed networks, while others measure transaction rates directly (Gallersdörfer et al., 2022). Additionally, attributing electricity solely to transactions is challenging, as networks have base consumption for consensus. Thus, running a node during low-transaction periods may inflate electricity per transaction costs since there are economies of scale in energy use related to transaction volumes. While this metric offers insights, its assumptions must be understood, and results treated cautiously.

In this study, the choice of consensus mechanism to represent the nodes/actor layers of the semi-centralized and the decentralized designs considers the basic characteristics of the mechanism (e.g., private or public permissioned network), the ability to process equal number of transactions to that of TIPS (i.e., average volume of 500 tps and peak volume of 2000 tps), as well as the data availability of the specific energy use in the literature.

Hedera, the private permissioned network that uses a directed acyclic graph (DAG)-based data structure to store the transaction history and applies PoS (Platt et al., 2021) is chosen to represent the semi-centralized model in terms of the electricity use per transaction. Hedera as a private permissioned network has gatekeeping strategies that are applied to a network of a limited number of vetted actors (known and authorized). The access to the network is limited to these actors, thereby reducing the risk of external attacks. Each actor (except the core host, i.e. the Riksbank) will only need to run and maintain systems that relate to their interfaces and services towards the consumers as the Riksbank is hosting the core system. Hedera also constitutes a high-tps system. Hedera's protocol currently had 21 number of validators with contemporary throughput of 48 tps and the max postulated sustainable system throughput is 10000 tps. Platt et al., (2021) estimated per transaction electricity consumption of Hedera's protocol in the range of 0.00002 – 0.00004 kWh/transaction.

For representing the decentralized design, Algorand's protocol, a PoS type, is chosen. It is a public permissioned network where the participating actors are licensed as financial institutions and classified accordingly. Each actor would need to run and host larger systems. The Riksbank will run and host its part of the total ecosystem. The decentralized nature of the model would enhance resilience to some extent by having multiple copies of the ledgers available, albeit likely not to the same extent as permissionless DLT solutions.

Algorand also constitutes a high tps system. Currently, it has 1126 validators with contemporary throughput of 9.85 tps and the max postulated sustainable system throughput is 1000 tps (Platt et al., 2021). The range for the electricity consumption per transaction for contemporary throughput of Algorand consensus is between 0.00017 – 0.00534 kWh/transaction (Platt et al., 2021). The estimation of Algarond's electricity per transaction from Gallersdörfer et al. (2022) of 0.0027 kWh/transaction, is within that range presented in Platt et.al. (2021). The overall electricity consumption per transaction further depends on the number of nodes connected to the respective network.

It is important to note, however, that this study does not exclude the possibility that the final design of a system could be centralized without consensus.

3.6 Estimating electricity use of user layer

The electricity usage in the user interface layer or device is presumed to be similar to that of the Swish payment system. Based on climate impact assessment of retail payment services per transaction of Swish, which is comparable to an e-krona since it is the only existing instant payment service in Sweden, requires 0.00023 kWh/transaction (Arvidsson et al., 2024). This assumption is made since there is no actual data of electricity use in the user layer of the e-krona, and the best available data is that related to Swish-transactions in the previous study (ibid). It should be noted, however, that electricity use in the user layer of the e-krona is likely to be lower than that of the user layer of Swish-transactions given that servers and devices tends to become less energy-consuming over time.

3.7 Estimating number of e-krona transactions

The future demand of e-krona is still being discussed. Assuming that e-krona will replace half or entire cash payments, this translates to 110 – 219 million of e-krona transactions. The upper range of e-krona transactions is equal to number of cash transactions in 2021. While the value of transaction is assumed to be 300 SEK/transaction, which is similar to the average value of a transaction based on a debit card in 2021. All in all, we assume the volume of e-krona transactions will be similar to that of cash based transactions, which is in line with Segendorf (2018). This implies that our models are based on two scenarios where one is that the e-krona replaces 50 percent of cash payments and the other is that the e-krona replaces 100 percent of cash payments. We do not assume the e-krona will replace other types of retail payment services.

4 Comparing e-krona's electricity use with other payment services

The climate impact of e-krona will depend on a range of design parameters, which are expected to be decided in the upcoming years. This involves understanding how these design elements could influence the carbon footprint of rCBDCs, and to what degree central banks can tailor these aspects to meet environmental objectives. These design elements must of course consider other critical functions of a rCBDC like medium of exchange, store of value and unit of account as well as challenges related to financial inclusion and resilience.

The selection of ledger infrastructure is a crucial decision that impacts various aspects such as security level, computation cost, and energy consumption (Lee & Park, 2022). The choice between centralized infrastructure and decentralized infrastructure depends on priorities and objectives, but will have implications for these factors. No matter which design that is chosen, however, final settlement will always be made in a centralized system operated by the Riksbank. Although the adoption of block-chain technology can enhance resilience by eliminating SPOF, the additional computations required to achieve consensus without SPOFs have an impact on the energy consumption of the system. The other factor that influences energy consumption is related to the degree of control achievable over the underlying architecture, including aspects such as the number of nodes that constitute the network, participant role assignment, node location and the ability to optimize power consumption through code and node updates (Sandri et al., 2022). Moreover, as the number of nodes increases, the computation energy can rise linearly or exponentially depending on the consensus protocols (Lee & Park, 2022).

The comparison between e-krona models and other payments is based on the use of electricity in various stages of transactions, see Table 5. For the retail payments (card, Giro, and Swish), the estimation does not include the electricity consumption of data center of the clearing counterparts (RIX system) of the Riksbank (Arvidsson et al, 2024). For fair comparison, the e-krona's electricity use also excludes the core layer where the Riksbank has a central role. The electricity use of semi-centralized and decentralized designs are represented by the lower and upper bound to anticipate the range of various hardware requirements and number of nodes. In other words, uncertainty regarding hardware requirements and number of nodes leads to a potential range of outcomes where the upper bound is a pessimistic model with high energy consumption while the lower bound is an optimistic model with low energy consumption (see Section 3.4). Per kWh transaction of different payment services is illustrated in Figure 4.

For the overall electricity consumption of different payment services, the average per kWh of transaction is multiplied by the number of transactions. The number of transactions of card, Giro and Swish payments in 2021 were respectively 3825 million, 488 million and 340 million

(Arvidsson et al., 2024). Whereas the range future e-krona demand is between 158 - 315 million transactions per year (see Section 3.4). The estimated electricity use is illustrated in Figure 5.

Table 5 Electricity use of different payment types

Payment type		Electricity use (kWh/tx)	Total (kWh/tx)
Card	Payment service provider	0.000030	0.000361
	Clearing system	0.000100	
	Payment terminal	0.000227	
	Merchant	0.000004	
Giro	Payment service provider	0.000031	0.000091
	Clearing system	0.000056	
	Merchant	0.000004	
Swish	Payment service provider	0.000015	0.000914
	Clearing system	0.000570	
	Merchant	0.000002	
	User	0.000328	
Concept. Highly centralized	User	0.000328	0.000328
Concept. Semi-centralised (lower bound)	Network (nodes/actor layer)	0.000020	0.000348
	User	0.000328	
Concept. Semi-centralised (upper bound)	Network (nodes/actor layer)	0.000040	0.000368
	User	0.000328	
Concept. Decentralised (lower bound)	Network (nodes/actor layer)	0.000170	0.000498
	User	0.000328	
Concept. Decentralised (upper bound)	Network (nodes/actor layer)	0.005340	0.005668
	User	0.000328	

Notes:

- Electricity use in datacenters for card, Giro and Swish is from Arvidsson et al., (2024)
- Electricity in user layer of the e-krona is assumed to be similar to Swish (see Section 3.6)
- Electricity use by network (nodes/actor layer) of e-krona models is obtained from (Platt et al., 2021) (see Section 3.4). For the semi-centralized model this is between 0.00002 – 0.00004 kWh/transaction (based on Hedera protocol) and for the decentralized model this is between 0.00017 – 0.00534 kWh/transaction (based on Algorand protocol).

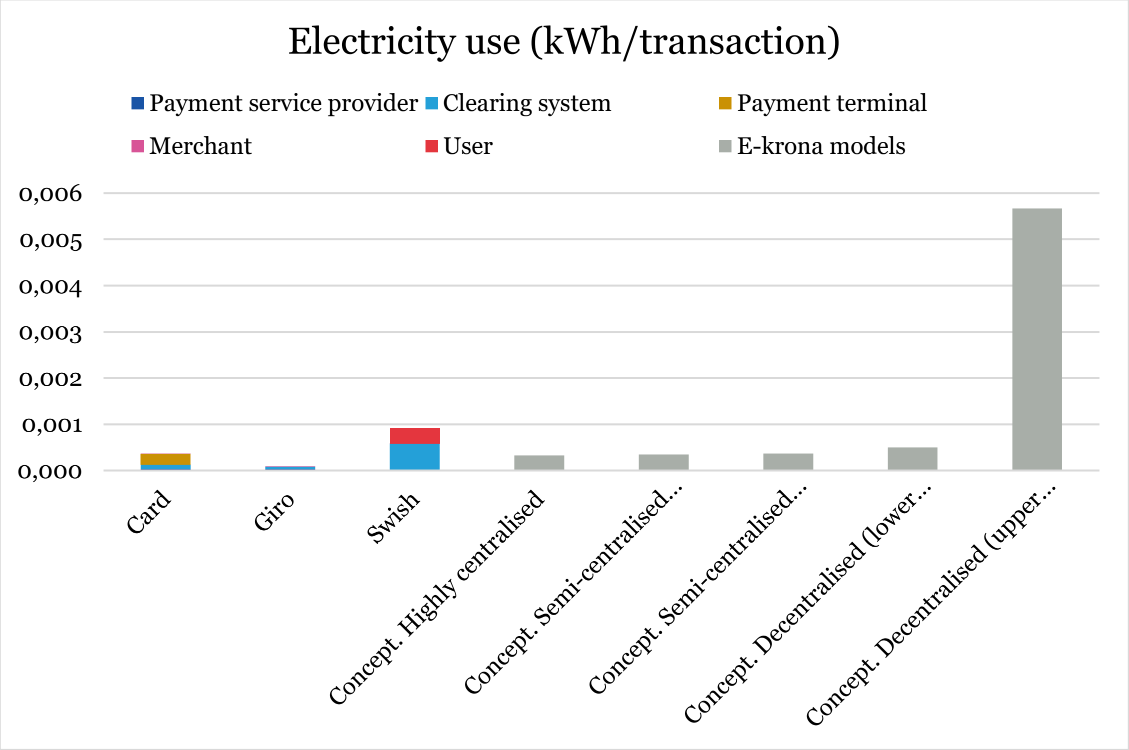

Figure 4 Per kWh transaction of different payment services

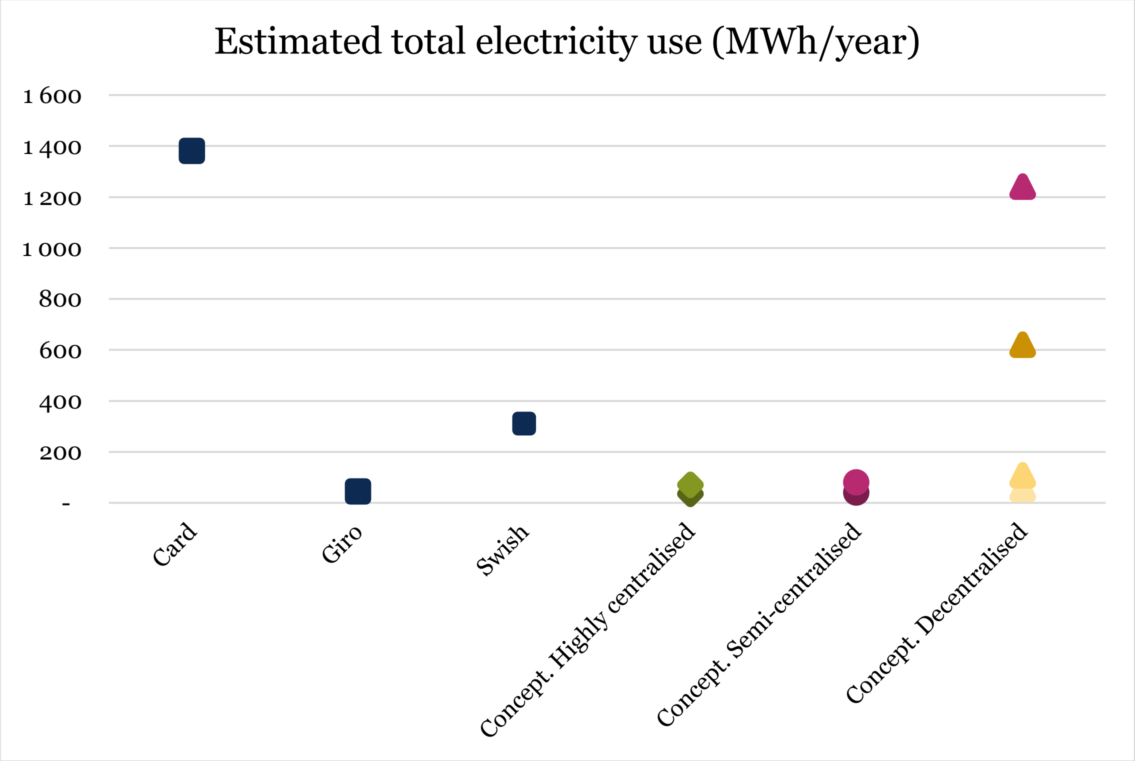

Figure 5 Total electricity use of different payment type

Note: The conceptual models of e-krona considers the lower and upper bound of electricity consumption (see Table 5) as well as future e-krona demand of between 110 and 219 million of transaction per year (see Section 3.7).

5 Conclusions

Retail Central Bank Digital Currencies, like the e-krona, are built on ICT infrastructure that will consume energy, especially via data centers that are known for their significant environmental footprint, which makes it important to understand which climate impact a rCBDC may have. The operation of rCBDCs, encompassing data centers, servers, and transaction processing, is likely to consume a substantial amount of electricity but still significantly less than, for instance a cryptocurrency like Bitcoin which is having as high annual emissions as entire countries. The source of this electricity, i.e. the characteristics of the grid and its energy sources, directly impacts the environmental sustainability and carbon footprint. Transitioning to renewable energy sources, like hydro, wind and solar, instead of non-renewable sources, like coal and oil, will enhance the overall sustainability of digital payments by reducing carbon emissions and environmental impacts associated with energy production. Additionally, as many companies choose to outsource their IT operations, and thereby relocate servers to environmentally efficient data centers in other countries with a Power Usage Effectiveness (PUE) lower than the European average, the climate impact may increase. The choice of where to locate servers as well as the control of this decision should consequently be a strategic issue if central banks and financial companies are to reduce the climate impact associated with IT operations.

We also conclude there are climate impact that is independent of use – like the impact of manufacturing and transportation of servers – and impact that is directly connected to the use of systems when processing a transaction, which is called operational energy use. This implies the climate impact is not a direct linear function based on the number of transactions. Instead, the climate impact per transaction will decease as the number of transactions increase.

Thus, considering the climate impact during the usage phase, adopting a lifecycle perspective and carefully defining system boundaries during assessments are vital, as the impact may be considerably lower than during the manufacturing of equipment in some cases. Future research directions should aim at conducting scenario analyses to evaluate the additional energy consumption levels when comparing various ledger infrastructure and consensus protocols as well as based on alternative system boundaries. This research could aim to develop a deeper understanding of the assessment of energy and climate impact across different rCBDC models.

All in all, the environmental footprint of digital technologies escalates with the involvement of multiple actors, increased usage of nodes, servers, and backup servers, and the adoption of more intricate protocols. Furthermore, the climate impact is profoundly influenced by the geographical location of servers and the energy mix of the hosting region. For instance, situating servers within a decarbonized electricity system like Sweden drastically reduces emissions compared to if the data centers are located in areas where electricity production is reliant on fossil fuels, exemplified by the comparison with the EU central bank digital euro project. Such considerations underscore the critical role of location and energy sources in mitigating the ecological consequences of digital infrastructure. Even though our study has not studied this, another factor related to location is that one should expect a longer response time in transactions if servers are located far away from the actual transaction site. There is also a scale effect since some climate impact factors will be the same independently of transactions while others are directly related to the number of transactions of a particular service.

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Sveriges Riksbank
Visiting address: Brunkebergs torg 11
Mail address: se-103 37 Stockholm

Website: www.riksbank.se
Telephone: +46 8 787 00 00, Fax: +46 8 21 05 31
E-mail: registratorn@riksbank.se