Integrating blockchain and microgrid technology to enable peer-to-peer energy trading:
A business process model

Thesis

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by
James Higgs
ORCid: https://orcid.org/0000-0002-8848-7188

Supervisors: Edward de la Rey and Dr. Karl van der Schyff

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Abstract

Traditional centralised energy systems are coming under increasing pressure because of decarbonisation, decentralisation, and digitisation. A lack of energy security and the inability to manage bi-directional electricity flows constitute two of the biggest challenges faced by centralised systems. Furthermore, in South Africa, the country's energy system remains monopolised with one large utility satisfying most of the country's electricity demand. This study is motivated by the need to address energy security within such a monopolised market. To redress the problems highlighted above, this study explores how blockchain and microgrid technology can be integrated to enable decentralised energy production and trading in South Africa. As such, this study develops a fully integrated blockchain-based microgrid energy trading system model. The functional requirements of the system are presented in the form of a business process model. Amongst other benefits, an active blockchain-based microgrid energy trading system provides a means to bolster energy security for the systems' users. A unique aspect of this study's approach to energy trading is the utilisation of blockchain's native tokenizing capabilities. Prosumer energy tokens are minted to create a digital currency for local peer-to-peer energy exchange. A commons-rule based approach is adopted for governing energy resources. As such, this study demonstrates that commons-based solutions provide a feasible alternative to market and profit driven trading for organizing local energy exchange. The primary deliverable of this study satisfies the request of various blockchain researchers for blockchain research to focus on holistic conceptualisations, rather than on the minutiae of blockchain technicalities. Eight core functional requirements of a blockchain energy trading system were identified prior to the construction of the process model. The functional requirements were elicited during a scoping review as a part of the secondary data collection process. Expert review was utilised to verify the functional requirements of the blockchain energy trading system. Once the experts were identified, each expert completed a questionnaire with the intention to verify the requirements. The above process constituted the expert review process for the study. Additionally, the syntactic correctness of the business process model was verified by a business process modelling expert. Weber's Theory of Evaluation constitutes the theoretical underpinning for the evaluation of the system parts. This study contributes the first publicly accessible business process models of a blockchain-based microgrid energy trading system. This study seeks to advance the discussion of a more integrative and cross disciplinary approach concerning blockchain research, particularly as it pertains to microgrid energy trading.

Declaration

I James Higgs, hereby declare that:

- The work in this thesis is my own work.
- All sources used or referred to have been documented and recognised.
- This thesis has not previously been submitted in full or partial fulfilment of the requirements for a qualification.
- I am fully aware of Rhodes University’s policy on plagiarism, and I have taken every precaution to comply with the regulation.
- Ethics number is 2021-2793-5902

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Date: 04/11/2021

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Glossary

Term	Explanation
Centralised energy system (CES)	A centralised energy system relies on large power plants to supply energy to dispersed customers according to a centralised coordination mechanism. Large transmission and distribution networks are characteristic of centralised energy systems.
Consensus Mechanism	A set of rules implemented to maintain agreement on a single state (i.e., the most up to date data record) for the digital ledger at all times of operation.
Cryptography	A security feature built into block generation. Guarantees an immutable and tamper proof data record.
Decentralised application (dApp)	A web application that has its business logic encoded in smart contracts. A dApp relies on the blockchain as a backend service for the program logic as well as for the provision of storage.
Distributed energy resource (DER)	DERs are publicly or privately owned small-scale power generation sources which can either be directly connected to the distribution network or, alternatively, on the client’s side of the electricity meter.
Digital Ledger	A distributed database that stores a continuously growing list of data records in their chronological order of issuance.
Immutability	The inability to alter or manipulate a thing (i.e., a piece of data).
Renewable energy resource (RES)	A renewable energy resource, is a more specific instance of a DER. It is a DER that is *not* fossil-fuel driven. Classic examples include solar photovoltaic panels, or wind turbines. Within the context of this study, RESs are taken to refer primarily to solar panels.
Microgrid	A microgrid is a group of interconnected DERs with a distinct electrical boundary. It provides fine grained control over the DERs, as well as allowing the microgrid to isolate itself from the main grid in the event of a power outage on the main grid. Critically, a microgrid can present itself to the main grid as a single facing customer.
Microgrid controller	The grid operator responsible for configuring and operating the physical microgrid.
Feed-in-tariff	The standard way governments attempt to involve prosumers in energy exchange. Prosumers inject electricity into the main grid in exchange for a fixed rate.
Local energy market	A newer approach to energy exchange, where energy exchange is premised on the idea that prosumers and consumers can directly exchange energy within their respective communities without relying on traditional feed-in-tariffs.

Peer-to-peer energy trading/ exchange system	A *system* which is built to facilitate decentralised energy exchange between consumers and prosumers. The system has both a physical component (i.e., the microgrid) and a cyber component (i.e., the information system enabling energy exchange).
Public grid operator	The grid operator responsible for overseeing the operator of the primary electricity network (i.e., the main grid). In this study, the public grid operator interacts with the microgrid controller.
Smart Contract	A computer program that is capable of self-executing according to predefined agreements.

Abbreviations

Abbreviation	Term
BEES	Blockchain-based energy exchange system
BPM	Business process model
CES	Centralised energy system
dApp	Decentralised application
DER	Distributed energy resource
ETS	Energy trading system
FRQ	Functional requirement
IS	Information system(s)
LEM	Local energy market
MC	Microgrid controller
P2P	Peer-to-peer
PG Operator	Public grid operator
PoAu	Proof of authority
PV	Photovoltaic
RES	Renewable energy resource
ZAR	South African

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Chapter 1: Introduction

"… the lord whose oracle is in Delphi neither speaks nor suppresses but indicates."
Heracleitos

1.1 Background information

South Africa has a centralised energy system (Eskom, 2020a; Winning, 2019). Centralised energy systems rely on large power plants to supply energy to dispersed customers, according to a centralised co-ordination mechanism (EPA, 2019; Mengelkamp et al., 2018). Centralised energy systems are also typified by a market structure that is primarily accessible only to large institutional players, which, in turn, prevents ordinary citizens from taking part in the energy production and exchange process (Andoni et al., 2019). The key feature of such a market structure is that of the consumer's passivity, who is only able to purchase and consume energy from large utilities at fixed or time-of-use price rates (Morstyn et al., 2018; Orsini et al., 2019; Zia et al., 2020). Such an institutionalised market structure is apparent in South Africa with Eskom supplying over 90% of the country's power (Winning, 2019).

However, energy sectors worldwide are undergoing structural reform that sees a transition towards an energy system that increasingly relies on decentralised energy production and exchange (Accenture, 2017; Andoni et al., 2019; Ernst and Young, 2017; Green and Newman, 2017; Kirpes, Mengelkamp and Weinhardt, 2019; Mengelkamp et al., 2018; Morstyn et al., 2018). This transition comes as a result of three trends: decarbonisation, decentralisation and digitisation (Andoni et al., 2019; Hirsch, Parag and Guerrero, 2018; Kirpes, Mengelkamp and Weinhardt, 2019; Orsini et al., 2019).

Recently, the issue of decentralisation has been receiving growing attention in South Africa. The government plans for renewable energy sources (RES) to make up approximately 24% of installed capacity by 2030, up from the current 8% (Bello et al., 2013; Felix, Cohen and Vecchiatto, 2019). The Integrated Resource Plan (IRP) of 2019 also makes provision for distributed energy resources (DERs) to be embedded into municipal distribution networks (IRP, 2019). DERs are small-scale power generation sources that are located close to the point of electricity consumption (Capehart, 2016). In South Africa, DER[1] integration has been put forward as one potential solution to combat the load shedding crisis which plagues the country (Le Roux, 2020). The integration of citizen owned DERs with the public (i.e., main) grid follows a global trend that sees traditionally passive consumers now producing, storing, and consuming their own energy. Citizens are also able to feed their surplus generated energy back into the main grid (Long et al., 2018; Morstyn et al., 2018; Orsini et al., 2019; Yang et al., 2017).

Feeding surplus energy from DERs back into the main grid poses significant challenges for traditional centralised energy systems (Ahl et al., 2019; Andoni et al., 2019; Kirpes et al., 2019; Mengelkamp et al., 2018a; Orsini et al., 2019; Zia et al., 2020). The most serious of these challenges relates to the intermittent nature of DERs (Abrishambaf et al., 2019; Andoni et al., 2019; Bello et al., 2013; Kirpes, Mengelkamp and Weinhardt, 2019; Laszka et al., 2017; Orsini et al., 2019; Siano et al., 2019; Weinhardt et al., 2019; Zhang et al., 2018; Yang et al., 2017). DER integration with the main grid becomes difficult as DERs cause voltage and frequency fluctuations which compromises the reliable supply of energy (Chen et al., 2015; Hirsch, Parag and Guerrero, 2018; Orsini et al., 2019).

Researchers are agreed on the point that microgrids provide a more promising and secure architectural solution for embedding DERs into the larger energy system (Hirsch, Parag and Guerrero, 2018; Kirpes et al., 2019; Zia et al., 2020). A microgrid is defined as:

> *"… a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the [main] grid. A microgrid can connect and disconnect from the [main] grid to enable it to operate in both grid-connected or island mode,"* (Hirsch, Parag and Guerrero, 2018, p.2).

The key benefit of connecting DERs to a microgrid is that the microgrid can be presented to the main grid as a single customer. This avoids the burden of trying to control each DER on a per unit basis (Hirsch, Parag and Guerrero, 2018). Instead, energy demand and supply is first balanced locally within the microgrid in a more controlled and visible manner and the net balance of the microgrid is then satisfied through interaction with the main grid (Hirsch, Parag and Guerrero, 2018; Kirpes et al., 2019; Li et al., 2019).

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[1] A RES is an instance of a DER. For example, a solar photovoltaic cell is a renewable energy source, but it falls within the broader classification of being a distributed energy resource.

Local energy markets (LEMs) have been put forward to reliably ensure the balance of energy generation and consumption activities within a microgrid. LEMs provide prosumers (owners of DERs) and consumers with a means to come together and actively trade energy in near real-time within their respective local communities (Laszka et al., 2017; Mengelkamp et al., 2018; Zhang et al., 2018; Zia et al., 2020). Such an energy trading process is referred to as peer-to-peer (P2P) energy trading, or exchange. This process is by definition decentralised with no central intermediary involved between the two transacting parties (Zhang et al., 2018). Essential to P2P energy trading is a secure information system (Kounelis et al., 2017; Mengelkamp et al., 2018; Zhang et al., 2018). The key function of such an information system is to provide the LEM platform that connects market participants to directly trade energy amongst each other (Mengelkamp et al., 2018 and Zhang et al., 2018). Additionally, the information system is responsible for keeping track of all ongoing market operations. The Information about ongoing market operations are then used to make operational decisions within the microgrid (Abrishambaf et al., 2019; Mengelkamp et al., 2018; Zhang et al., 2018).

Blockchain technology has been put forward as a suitable information system for enabling P2P energy trading between individuals connected to a microgrid (Abrishambaf et al., 2019; Ahl et al., 2019 and Mengelkamp et al., 2018). In its most simplistic form, blockchain is a distributed digital ledger that contains an immutable record of all system transactions stored in chronological order (Andoni et al., 2019). Blockchain technology is a natural fit for P2P energy trading as blockchain lends itself to decentralised use cases (Andoni et al., 2019). Most importantly, blockchain's consensus mechanism provides the means to reliably verify transactions between two untrusted parties absent central intermediation (Abrishambaf et al., 2019; Andoni et al., 2019; Yang et al., 2017).

Other benefits of blockchain technology for microgrid energy trading includes the provision of information transparency in the market, an easy means to financially settle energy transactions, removing a single point of failure in the P2P information system, cryptographic protection of users' data and identify and the incorporation of smart contracts to automate business processes (Abrishambaf et al., 2019; Andoni et al., 2019; Laszka et al., 2017; Mengelkamp et al., 2018a).

Previous research suggests the use of blockchain as a viable information system for decentralised energy trading. Yang et al. (2020) demonstrates that blockchain can be used to facilitate energy trading within a microgrid. Andoni et al. (2019) state that blockchains could provide a promising solution to controlling and managing increasingly decentralised complex energy systems and microgrids. Additionally, Mengelkamp et al. (2018) demonstrates the viability of a blockchain-based microgrid energy trading system.

The current state of blockchain research sees a body of literature that is overly concerned with technical details of how to implement blockchain-based solutions. This has led to researchers calling for more holistic conceptualisations and models of blockchain-based solutions, particularly in smart community settings (Ahl et al., 2019; Aggarwal et al., 2019; Kirpes et al., 2019; Mengelkamp et al., 2018a). The pre-occupation with blockchain technicalities is also found in industry. A survey of nine functional P2P energy trading systems in the DACH region reveals that business operation models remain largely unclear (Weinhardt et al., 2019). One potential solution to clarifying critical business processes and workflows in a system is the business process model (BPM). A well-defined BPM improves business coordination and strategy whilst simultaneously clarifying business processes within a system (Microsoft, 2019).

1.2 Problem statement

Given this study's context, the following problem statement was developed:

South Africa's energy system is still largely based on the traditional centralised energy supply model which sees Eskom satisfying 90% of the country's electricity supply. As such, captive consumers have no option but to rely on Eskom for the provision of electricity. Consumers are left with increasing tariffs and poor service delivery. Furthermore, such a supply model excludes other valuable energy resources (e.g., consumer owned DERs) from contributing towards the supply base. As South Africa starts moving down the path of decentralisation the increasing integration of volatile DERs with the main grid will pose significant challenges.

1.3 Research questions

For this study to address the problem statement, the following main research question was put forward:

Main Question. *How can blockchain and microgrid technology be integrated to facilitate peer-to-peer energy trading in South Africa?*

To adequately answer the main research question above, the following sub-questions were put forward:

- **Question One:** *Why is blockchain technology suited to facilitating decentralised energy trading with a microgrid?* The aim of this question was to understand why blockchain technology has been put forward by researchers as a suitable information system for peer-to-peer energy trading.
- **Question Two:** *What are the existing subsystems and processes involved in blockchain-based microgrid energy exchange systems?* The aim of this question was to identify the core actors and processes involved in a blockchain-based energy exchange system for the construction of the business process model.
- **Question Three:** *How can a blockchain-based microgrid energy exchange system be embedded into the larger South African network?* The aim of this question was to understand how the proposed blockchain-based energy exchange system could be integrated with South Africa's broader electricity network.

1.4 Research objectives

The primary objective of this study was to explore *how* blockchain technology could enable peer-to-peer energy production and trading in South Africa. As such, the final deliverable of the study was a business process model that details the operational model of a blockchain-based microgrid energy trading system[2]. In addition, the model and accompanying model narrative demonstrated how such a microgrid energy trading system could be embedded within the broader South African distribution network. This deliverable satisfied both the request of Ahl et al. (2019), Aggarwal et al. (2019) and other researchers for a process model or similar research that focuses on holistic conceptualisations when conducting blockchain research.

1.5 Methodological approach

This study was conducted within an interpretivist research paradigm, utilising a case study research strategy. A scoping review was carried out to identify the core functional requirements of a blockchain energy trading system. Qualitative data collection and analysis techniques were utilised. Data was collected from energy and blockchain experts (in both academia and the private sector) by way of open-ended questionnaires where each expert constituted a case. The data was analysed using thematic analysis, where each functional requirement of the system

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[2] This study's specific system proposed in Chapter 6 is referred to as the Blockchain-based energy exchange system (BEES). Energy trading / exchange system is synonymous. This study opted for the word exchange as clarified later in a footnote.

constituted a core theme (Nowell et al., 2017). General Systems Theory (GST) was used as the overarching theoretical framework which informed the development of the business process model. GST offers a theory for the study of interacting components that comprise the larger whole (Boulding, 1956). GST was particularly applicable to this study as it investigated the various sub-systems and processes that contributed towards the overall functioning of a blockchain-based microgrid energy trading system.

The methodological steps of the study were carried out in the following order:

1. First, a scoping review was conducted to understand and document the current processes involved in blockchain-based microgrid energy trading systems. Six core sources were selected during the scoping review for the identification of the functional requirements of a blockchain-based energy trading system. Additional (relevant) sources informed the background and context chapters of this study.
2. Once the functional requirements were identified, a use case diagram (see Appendix A) was constructed from the core functional requirements.
3. The use case diagram along with the knowledge gained from studying the internal processes of the functional requirements informed the construction of the business process model (BPM).
4. The functional requirements along with their internal processes were subject to *expert review* by means of an open-ended questionnaire (questionnaire one). This was to ensure that the business processes modelled in the BPM were verified by subject matter experts.
5. The syntactic correctness of the model was evaluated by way of a close-ended questionnaire. Questionnaire two was specifically concerned with evaluating the syntactic correctness of the business process model. *This evaluation did not form of the expert review group mentioned in point 4 above.*
6. Lastly, Weber's Theory of Evaluation (Weber, 2012) was used to evaluate the quality of the constituent parts of the model.

1.6 Contribution

This study contributes to the literature base the first publicly available business process model (BPM) of a blockchain-based energy trading system operating within the South African context. To the best of this study's knowledge, there are no publicly accessible business process models of a blockchain-based energy trading system available locally, or internationally. This study’s BPM is unique in that it captures all dimensions of a blockchain-based microgrid energy trading system. Both the cyber and physical layer of the system is discussed and modelled. Often it is the case that blockchain-based research, particularly within the confines of microgrid energy trading, focuses on one or two aspects of the system and discusses those aspects in depth. This study fills that gap where the overall interoperability of the system is presented to a wider audience. In other words, this study’s BPM answers the call of researchers within the domain for solutions that showcase the interoperability of the system, rather than simply focusing on technicalities.

Thus, this study’s BPM is aimed primarily at a popular audience covering electrical engineers, renewable energy experts, blockchain experts, information technology experts, business sustainability experts as well as any other experts from relevant fields that may have an interest in the future of blockchain-based microgrid energy trading systems. By utilizing a business process model, the system has been modelled in a universally recognized process modelling language (BPMN 2.0) to allow anyone to understand the inner workings of the energy trading system. Researchers who wish to explore the more technical aspects of the system will benefit from this study by gaining a big picture overview of the different moving parts of a blockchain-based microgrid energy trading system before exploring one aspect of the system in depth. This study’s deliverable along with the accompanying narrative can be regarded as a primer on a blockchain-based microgrid energy trading system, and as such a precursor to more technical publications and real-world implementations.

1.7 Ethical considerations

This study collected its primary data through means of open-ended questionnaires with members of the public. Research participants included academic practitioners and industry experts. All the necessary precautions were taken in this study to ensure participant anonymity and the safeguarding of participant data. This research study made sure to accurately portray the answers provided by research participants. Full ethical clearance was received from the Rhodes University central ethics committee (clearance ID: 2021-2793-5902).

1.8 Thesis Outline

In this study, Chapter 2 provides the reader with an overview of the research design and methodology adopted throughout the study. Chapter 3 explores the general energy landscape in detail. This chapter can be regarded as providing the necessary background information for the remainder of the study. Centralised energy systems are introduced to the reader along with the global move towards energy decentralisation. Lastly, the discussion is situated in the South African context. In Chapter 4, the reader is presented with a detailed discussion of microgrids and energy markets. It is explained why microgrids are an answer to many of the challenges currently faced by centralised energy systems. Local energy markets are put forward as a solution to balancing supply and demand locally within a microgrid. Chapter 5 provides a detailed overview of blockchain-based microgrid energy trading systems. Here it is explained why blockchain technology is the appropriate information system for a microgrid energy trading system. The core features of blockchain technology are discussed. The remainder of the chapter presents the core functional requirements of a blockchain-based energy trading system. In Chapter 6, this study's *specific* blockchain-based energy trading system is put forward. The system is presented in the business process model. A narrative walk through is provided, walking through each business process in detail. Chapter 7 presents the research findings of the study. In Chapter 8, the research findings are discussed. Chapter 9 concludes this study by revisiting the research questions and providing some final reflections.

Chapter 2: Research Design and Methodology

"We need a non-empirical premiss about the nature of things before we can begin to argue about the nature of things."
Stephen R.L Clark, From Athens to Jerusalem

Research is the clearly-defined process of exploring, or, expanding upon a particular domain of knowledge. (Saunders, Lewis and Thornhill, 2019, p.5). Characteristic of such a process is its purpose-driven nature, where the research data is collected and analysed in a systematic fashion (Saunders, Lewis and Thornhill, 2019, p.5). This chapter discusses the components of the research design and methodology for this study. Components to be discussed include the research philosophy, theory development, the methodological strategy selected, as well as secondary and primary data collection and analysis.

2.1 Research philosophy

The first step in the journey to formulating the appropriate research design involves selecting an appropriate research philosophy (Mackenzie and Knipe, 2006; Saunders, Lewis and Thornhill, 2019, p.130). Research is informed by an individual's ontological, epistemological and axiological assumptions of the world, and as such, different researchers may have conflicting assumptions about the nature of truth and knowledge (Saunders, Lewis and Thornhill, 2019, p.130; Žukauskas, Vveinhardt and Andriukaitienė, 2018). Within the context of academic research, a research philosophy broadly refers to a set of beliefs and assumptions about the development of knowledge. As such, a robust research philosophy is present where the researcher's assumptions about the development of knowledge are coherent and consistent (Saunders, Lewis and Thornhill, 2019), p.130). Importantly, the research philosophy underpins the entire research project, including the study's data collection and analysis procedure. As such, and due to the influential role played by a research philosophy, a coherent research philosophy is a pre-requisite for a coherent research project (Saunders, Lewis and Thornhill, 2019, p.130). The main research philosophies include: positivism, post-positivism interpretivism, pragmatism, critical realism and critical theory (Žukauskas, Vveinhardt and Andriukaitienė, 2018). This study situates itself within the interpretivist paradigm.

2.1.1 Interpretivism

Interpretivism takes subjectivism as its starting point. This stands in opposition to positivism which emphasizes that it is in principle possible to obtain objective knowledge about the world (Saunders, Lewis and Thornhill, 2019, p.148). Instead, interpretivism emphasises the position that knowledge about reality is a social construction created by human actors (Walsham, 2017). Interpretivism holds that because researchers are informed by their preconceptions and prejudices when carrying out research, it follows that no knowledge can be truly objective and value-free (Walsham, 2017). The problem of not being able to obtain value-free data is further compounded by researchers interacting with other humans when carrying out their research. Participant interaction is responsible for the introduction of further preconceptions and prejudices into the research process (Walsham, 2017).

Arguably, even a discipline closely associated with positivism (i.e., physical science) has its own preconceived ideas about the world which the discipline cannot escape. Integral to positivism is its claim that only a posteriori or tautological knowledge is valid. As Larrain, (1979, p.197) notes:

> *"One of the features of positivism is precisely its postulate that scientific knowledge is the paradigm of valid knowledge…"*

So, positivists, on the one hand reject subjectivism, and instead promote scientific knowledge as the only valid form of knowledge. Instead, interpretivists argue that subjectivism is inescapable. However, investigating positivism's claim to objective and value-free knowledge about the world, reveals that positivism is not, in the strictest sense, truly objective and value-free. All research philosophies, and more broadly philosophies in general, fall prey to preconceived ideas that are not open to rational demonstration nor empirical inquiry (Clark, 2019, p.28). In other words, at the heart of any knowledge system lies trust, or belief, rather than objective knowledge. This, by implication, means that positivism itself does not escape taking a bundle of assumptions as it's starting point. Perhaps positivism yields objective insights about the world, perhaps not, but one thing it cannot do is remove subjective assumptions from its very foundation. Thus, an 'empiricist-only' epistemology as that proposed by positivism is simply unsustainable when taken to its logical ends. (Plantinga, 2011, p.43).

Three points serve to demonstrate that empiricism (i.e., positivism) cannot survive without its own preconceptions and assumptions:

1. First, the statement that the only reliable data is that which is verifiable by the scientific empiricist method, is itself not verifiable by the scientific empiricist method (Clark, 2019). It is simply a preconceived idea, or prejudice, about what constitutes reliable data. As such, the scientific empiricist method must be a false theory of knowledge (if it is the only theory of knowledge to be true) as it is self-contradictory.
2. The fact that scientists believe their physical theories describe a rationally intelligible universe is an assumption that is not empirically, logically or mathematically demonstrable (Clark, 2020, p.35). If a positivist tries to argue that one knows physical theories accord to the physical universe by virtue of how well they work, one may simply point out that perhaps they work pragmatically, but do not 'really' describe the physical universe in an objective sense. Afterall, why would a creature that has recently evolved on the earth be capable of describing the universe in any objective sense (Clark, 2019, p.28)?
3. Third, any scientist entering the laboratory to engage in research has already assumed the reliability of his/her cognitive faculties (Clark, 2019, p.28). But, if the only reliable data is that which is empirically, logically, or mathematically verifiable, how can the scientist verify the reliability of his/her own cognitive faculties? The scientist cannot, for he/she has already presupposed their reliability, prior to attempting to verify their reliability. One could have faith in the reliability of their cognitive facilities, but proof (of a logical or empirical sort), is not available (Clark, 2019, p.28; Plantinga, 2011, p.345). But then, if it is socially acceptable to accept the validity of our cognitive faculties (as all scientists do) without empirical proof or rational demonstration, then why not so for other facts about the world?

The three examples discussed above serve to highlight the inadequacy of adopting such a stringent view of knowledge development within the context of this study. Adopting such a constrained view of knowledge development, would ultimately result in either ignoring, or reducing, the importance of certain facts about the system explored in this study. For example, a blockchain-based energy exchange system is not only a technological system, but also included individuals who interact with the system. As such, the meanings individuals ascribe to certain processes of the system need to be sought out and interpreted. Uncovering knowledge in this manner does not squarely fit in with a positivistic epistemology.

It is not being claimed that positivism is unhelpful when it comes to academic research – quite the contrary. Rather, what is being claimed is that positivism cannot claim to be the most "reliable" research paradigm due to uncovering "objective" data, as the paradigm itself is rooted in a family of preconceived ideas and assumptions hidden from rational demonstration or empirical validation. Every paradigm has at its foundation starting assumptions, and as such, interpretivism should not be diminished for including subjectivism in its first principles.

A divergent line of thought from that posited by positivism is found in a group of Information Systems (IS) scholars' work. These scholars are increasingly admitting the difficulty of attempting to reduce the socio-technical phenomena found in the IS-field to purely quantitative data (Goldkuhl, 2012). This, in turn, has signalled the need for more nuanced ways in which to study the complexities found within the IS-discipline (Goldkuhl, 2012). Interpretivism, is *one* such nuanced way, and places a particular emphasis on the social dimension of the domain under study. More specifically, interpretivism prioritises the need to understand the subjective meanings of individuals located within the studied domain (Goldkuhl, 2012; Walsham, 2017). As Goldkuhl (2012, p.4) explains:

> *"The core idea of interpretivism is to work with these subjective meanings already there in the social world; that is to acknowledge their existence, to reconstruct them, to understand them, to avoid distorting them, to use them as building-blocks in theorising."*

Naturally, subjective meanings are closely associated with an individual's cognitive makeup (e.g., meanings, beliefs, intentionality) (Goldkuhl, 2012). As such, acknowledging the cognitive dimension of the individuals located within the research domain takes on added importance for the interpretive IS researcher. It becomes the IS researcher's prerogative to understand various individuals from their own viewpoints, and in the process discover how they view the world and their role in it (Davis, 1995; Goldkuhl, 2012). Thus, by placing oneself in the position of the individual a deeper and more insightful understanding of the inner functioning of the phenomenon under study is uncovered (Davis, 1995). Within the context of this study, background information of research participants played an important role in allowing the study to better understand the lens with which each participant viewed the world.

There are various principles that should be present in a researcher's work when it comes to conducting research within the IS-interpretivist framework (Klein and Myers, 1999). One such principle is known as 'The fundamental principle of the hermeneutic circle' as introduced in the work of Klein and Myers (1999). Klein and Myers (1999) emphasize that this principle ought to be regarded as a meta-principle which all other interpretive principles should be in alignment with it. This principal suggest that a fundamental tenet of all human understanding is the process of understanding a system both from a holistic and granular perspective (Klein and Myers, 1999; Goldkuhl, 2012a). Through the process of moving between holistic and granular understanding the researcher is able to arrive at a nuanced understanding of the domain under study (Goldkuhl, 2012a). This bedrock principle has been fundamental to the way in which this study was both designed and carried out. More specifically, this research study focused on modelling a microgrid energy trading system in holistic fashion by utilising business process modelling notation. Prior to this, each of the core functional requirements of the system were studied (i.e., granular understanding) to understand their role in the system as a function of socially situated human cognition. Finally, the parts were understood in relation to the entire energy trading eco-system (i.e., a dialectical task between holistic and granular thinking).

A further IS interpretive principle of relevance to this study is ‘The principle of contextualisation.’ This principle emphasises that before conducting interpretive research, it is important for interpretive researchers to critically reflect on the social and historical background of the research setting, allowing other researchers to understand how the current topic under investigation emerged (Klein and Myers, 1999). This principle was implemented throughout the literature review (particularly in Chapter 3), where it was explored how electricity transmission systems emerged as centralised systems, what has challenged the centralised model, and why society has approached a point where peer-to-peer energy trading models can be adopted.

2.2 Approach to theory development

Theory can be defined as:

> *“… a systematic body of knowledge grounded in empirical evidence which can be used for explanatory or predictive purposes”* (Saunders, Lewis and Thornhill, 2019, p.47).

The power of a theory lies in its ability to explain the relationships between concepts. The explanations offered by a particular theory are then either confirmed, contradicted, or refined based upon the understandings that emerge from the research undertaken (Saunders, Lewis and

Thornhill, 2019, p.48). Theories (whether grand or minor theoretical contributions) are developed or tested either deductively, inductively or abductively (Saunders, Lewis and Thornhill, 2019, p.51). For this study, inductive reasoning was used during the process of analysing secondary data. This allowed for the construction of the business process model as presented and discussed in Chapter 6. Whilst analysing the primary data, inductive reasoning was again employed in the thematic analysis process. Each functional requirement evaluated in the questionnaire constituted a theme, where shared meaning was searched out under each theme.

2.3 Methodological strategy of this study

Broadly speaking, a research methodology is a plan for how a researcher will answer the study's research questions (Saunders, Lewis and Thornhill, 2019, p.189). Crucially, the role of the methodology is to provide a bridge between the study's research philosophy and methods of data collection and analysis (Denzin and Lincoln, 2018). As such, what methodology is adopted is largely determined by whether the study is qualitative or quantitative in nature. This study, being located within an interpretivist research paradigm, is qualitative in nature.
Kothari (2004, p.8) sums up the role of a methodology elegantly by stating that, ultimately, the role of the methodology is to define:

> *"… a way to systematically solve the research problem."*

There are various research strategies available to the researcher including experiment, survey, archival and documentary research, case study, ethnography, action-research, grounded-theory and narrative inquiry (Saunders, Lewis and Thornhill, 2019, p.190).

This study adopted a case study research strategy. A case study approach is particularly suitable to a research study where there is the need to obtain an in-depth understanding of a particular topic under study in its natural real-life context (Crowe et al., 2011). For example, in this study, the goal was to understand the core functional requirements of a functioning blockchain energy trading system that is connected to the broader South African electricity network. To do so, the feedback received from experts (where each expert is a case) was studied to understand the phenomena under consideration.

Case study research works particularly well for interpretivist researchers, where the researchers analyse their data, identifying patterns and themes, and then, ultimately locate their findings back within the existing literature base (Saunders, Lewis and Thornhill, 2019, p.197). Once the researchers work is located back within the extant literature base, already existing theories can either be expanded upon or refined (Saunders, Lewis and Thornhill, 2019, p.197).

2.4 Secondary data collection and analysis

This section deals with the secondary data collected and analysed during the study. Secondary data (i.e., the literature) was collected by surveying the relevant literature in the form of a scoping review. The main rationale for carrying out a scoping review is to identify and map the available evidence as it relates to a particular study. In other words, a scoping review is particularly useful for identifying the key characteristics undergirding a concept (Munn et al., 2018). Such a methodological approach coincided well with the need of this study to identify the functional requirements (i.e., the key characteristics) of a blockchain-based energy trading system. By carrying out a scoping review, the study was granted more freedom in exploring the relevant literature for any interesting or novel insights. This stands in contrast to a structured review, which is a more stringent approach to exploring the literature with predetermined inclusionary and exclusionary criteria.

2.5 Sources of secondary data

During the scoping review, several notable academic publishers were searched, including *De Gruyter, IEEE, MDPI and Science Direct*. As part of the searching process, phrases such as "*microgrid energy trading,*" "*blockchain-based energy trading,*" "*blockchain energy exchange systems,*" "*P2P energy trading,*" *and* "*distributed energy systems*" were used. Phrases were formulated based on the system that the study sought to explore and ultimately model.

Perhaps due to the novelty of the topic explored, the literature available surrounding fully integrated blockchain-based energy trading systems was scarce. Numerous papers were available that either focused on proof-of-concepts for energy trading systems (centralised and blockchain-based), or alternatively, discussed one particular aspect of an energy trading system (Abdella and Shuaib, 2019; Agung and Handayani, 2020; Han et al., 2020; Kim, Park and Ryou, 2018; Sabounchi and Wei, 2017; Yang et al., 2020). This much is evinced by the request of blockchain researchers for process models, or similar research, with a focus on holistic conceptualizations when conducting blockchain related research (Aggarwal et al., 2019; Ahl et al., 2019; Kirpes et al., 2019). As Kirpes, Mengelkamp and Weinhardt (2019, p.3) note:

> *"Most research activities evolve around the technical feasibility of blockchain-based LEM considering different aspects such as energy loss, privacy, resiliency, trust, or security by providing specific architectures and designs, verified by small-scale pilots or proof-of-concepts. Interoperability of the proposed solutions is only barely considered."*

During the scoping review, it became apparent that six research papers would constitute the core sources from which the business process model would draw. Table 1 below presents the six core sources utilised to identify the functional requirements of the blockchain-based energy trading system.

Table 1: Core sources informing the business process model

Title	Authors	Journal
1) Blockchain for decentralized transactive energy management system in networked microgrids	(Li et al., 2019)	Electricity Journal
2) Consortium Blockchain-Based Microgrid Market Transaction Research	(Zhao et al., 2019)	Energies
3) Designing microgrid energy markets A case study: The Brooklyn Microgrid	(Mengelkamp et al., 2018a)	Applied Energy
4) Design of a microgrid local energy market on a blockchain-based information system	(Kirpes et al., 2019)	Information Technology – Methods and Applications of Informatics and Information Technology
5) Peer-to-Peer energy trading in a Microgrid	(Zhang et al., 2018a)	Applied Energy
6) NRGcoin: Virtual currency for trading of renewable energy in smart grids.	(Mihaylov et al., 2014)	The International Conference on the European energy market – IEEE (conference paper)

What distinguished the above research from previously mentioned samples is their holistic research approach. All six of the research papers presented and discussed the core business processes of an energy trading system by focusing on the interoperability of the processes. Study one to four was specifically concerned with blockchain-based energy trading systems, whereas study five discussed a general centralised energy trading system. Study six discussed the minting of tokens from prosumer-injected energy. All six systems operated within the confines of a microgrid, with a connection to the public grid. Identifying functional requirements from research papers that adopted a holistic approach to blockchain energy exchange systems, whilst simultaneously explaining the constituent components was important, as it meant that as an interpretivist research study, this study was aligned with the "The fundamental principle of the hermeneutic circle," as discussed in section 2.1.

Table 2 below presents the total number of research papers read throughout the scoping review. A total of 45 papers were read that would potentially inform the construction of the business process model. Ultimately, a core set of six research papers were selected to inform the model. It is important to note that the papers listed below are only for those research papers which would inform the construction of the business process model. General research papers which informed the remainder of the literature review (i.e., background and context chapters) are not included in Table 2 below.

Table 2: Research papers read during the scoping review

Database name	Number of research papers read	Research papers included	Reason for inclusion / exclusion
De Gruyter	1	1	The research paper by Kirpes, Mengelkamp and Weinhardt (2019)[3] was identified through the *De Gruyter* database. The paper was included for its holistic approach adopted when discussing the functional requirements of a blockchain-based energy trading system (ETS). Of particular interest was the paper's discussion on escrow smart contracts.
IEEE	19	1	The research paper by Mihaylov et al. (2014) was included from the *IEEE* database. This paper was included for its discussion on blockchain-based energy tokens. Of particular importance was the paper's discussion on minting energy tokens from the process of injecting prosumer-generated energy into a microgrid.

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[3] See Table 1 above for the full titles of each research paper mention in this table.

MDPI	3	1	The paper by Zhao et al. (2019) was included from the *MDPI* database. This paper was included for its proposal of a microgrid blockchain-based energy trading system.
MPCE	1	0 *	The paper read did not offer any novel insights that were not already present in other papers selected.
Research Gate	5	0 *	The papers read did not offer any novel insights that were not already present in other papers selected.
Science Direct	14	3	Three research papers were included from the *Elsevier* database. The three papers included: • The paper by Li et al. (2019). This paper was included for its comprehensive overview of the various functional requirements of a blockchain-based ETS. • The paper by Mengelkamp et al. (2018a). This paper was included for its discussion on blockchain as an information system for an ETS. The paper also offered a discussion on the role and functions of the energy trading system itself. The paper by Zhang et al. (2018a). This paper was included for its thorough discussion on a platform for peer-to-peer energy trading, highlighting the various functional requirements of the system.
Springer	2	0 *	The two papers read from the *Springer* database focused on one or two technicalities of blockchain-based energy trading systems. As such the papers did not fit with the holistic approach adopted by this study.
Totals	**45**	**6**	

* Although no papers were included from MPCE, Research Gate, or Springer, it does not imply that there are no research papers present in the above-mentioned databases that discuss the functional requirements of a blockchain-based energy trading system. For this study, the six papers selected were deemed adequate to inform the business process model.

2.6 Process of secondary data analysis

The primary task of the analysis process was to identify the functional requirements of the system. Naturally, this process involved a focused re-reading of the six core articles introduced in section 2.5. To facilitate this, NVivo (a qualitative data analysis software suite) was utilized to streamline the analysis process. NVivo allows for the creation of nodes, where each node constitutes a fundamental category identified in each of the research papers. Utilising NVivo, snippets of the journal articles were categorized under each node for reference at a later stage, once the business process model was constructed. Each time a functional requirement was identified a new node was created with a descriptor for the functional requirement. Any information relevant to that node found across the six research papers would then be coded under the relevant node. At the conclusion of the analysis process, eight nodes each constituting a functional requirement were identified. Table 3 below presents the eight functional requirements identified:

Table 3: The eight functional requirements of an energy trading system

Functional Requirement	Systems included in
1. Assist in the microgrid configuration process	(Kirpes et al., 2019; Li et al., 2019; Mengelkamp et al., 2018a; Zhao et al., 2019; Zhang et al., 2018a).
2. Provide secure access control	
3. Facilitate energy trading	(Kirpes et al., 2019; Li et al., 2019; Mengelkamp etal., 2018a; Mihaylov et al., 2014; Zhao et al., 2019; Zhang et al., 2018a).
4. Carry out state estimation processes	(Li et al., 2019; Zhang et al., 2018a)
5. Carry out financial settlement processes	(Kirpes et al., 2019; Li et al., 2019; Mengelkamp et al., 2018a; Zhao et al., 2019; Zhang et al., 2018a)
6. Store all operational data pertaining to the microgrid and market related activities.	
7. Facilitate communication between system and actors	
8. Provide a streamlined and user-friendly experience (Ancillary)[4]	

2.6.1 Model building and business process modelling notation

Once the functional requirements were identified, the appropriate foundation was provided for the construction of the business process model (BPM). More specifically, by identifying all the

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[4] Functional requirement 7 and 8 are ancillary in the sense that they do not constitute core functions of the system but are rather meta-requirements. If the system carries out 1-6 correctly, 7 and 8 would be satisfied by default. This is particularly so for functional requirement 7. Perhaps, it is a bit more tentative for functional requirement 8. However, if functional requirement 8 had to be considered in detail it would takes one into the realm of user experience design, which falls outside the scope of this study.

functional requirements of the energy trading system prior to the construction of the BPM, it was guaranteed that all fundamental aspects of the system would be modelled (assuming a robust analysis process). At this stage, each of the functional requirements were studied in-depth by revisiting the relevant nodes with their coded information. Because each of the functional requirements were discussed in multiple research papers, it allowed for a more robust analysis process, seeking corroboration amongst researchers as well as seeking out differences of opinion when it came to the implementation of the functional requirements. Generally, researchers shared similar views as to how the functional requirements should be implemented. This is particularly so, given that this study worked at an intermediate abstraction level when modelling the functional requirements. Adopting an intermediate abstraction level is commonplace when conducting system analysis activities in blockchain-based energy systems (Kirpes et al., 2019; Zhao et al., 2019). Where researchers did not follow each other in implementation decisions, the differences amongst the researchers were studied, and what seemed the most appropriate design as motivated by the various researchers was modelled. For example, a state estimation process was only included in study one and five. However, such a process is necessary for this model, and it was included in the BPM.

Once each functional requirement was studied in-depth, the modelling process began. Prior to the construction of the business process model, a UML use case diagram (UCD) was constructed. A UCD is a model that describes the system's activities horizontally, rather than laterally. In other words, a UCD is the perfect high-level model for capturing all the system's functional requirements without concern for indicating the specificity of each business process flow (Dennis, Wixom and Tegarden, 2015, p.121). Modelling the system in the form of a UCD first, guaranteed a robust understanding of the various system components and users prior to the construction of the business process model. It was the task of the business process modelling process to take these components and translate them into the appropriate business process flows. As noted earlier, use case diagrams make no attempt to capture the flow of order in a system (Dennis, Wixom and Tegarden, 2015, p.121). Instead, by utilising a business process model, the system flow of events could be modelled. Two core design decisions were made during the business process modelling process: (1) first, how the model would be structured, and (2) second, how the business processes involved in the functional requirements would be modelled. The model was structured to reflect the underlying cyber-physical nature of the energy exchange system. Business process modelling notation (BPMN 2.0) was used to model the business processes involved in each of the functional requirements. BPMN 2.0 is a standardized graphical notation, that provides a robust framework for modelling business processes within a system, or organization (Object Management Group, 2012). The use of BPMN 2.0 guaranteed that the model would conform to best practice, as well as making the model accessible to a larger audience.

2.7 Primary data collection and analysis

This section turns to the primary data collected and analysed during the study. First, the sampling strategy applied to the study is discussed, including the research instrument applied to the selected sample. Once this is complete, attention is turned to the sources that constituted the research sample. Finally, the process of analysing the primary data is discussed.

2.7.1 Sampling Strategy

It is rarely possible to collect and analyse data from every possible member located within a research domain. As an alternative solution, researchers opt to select data from a particular subgroup of all possible cases (Saunders, Lewis and Thornhill, 2019, p.292). A sampling strategy guides the selection of the appropriate subgroup from which to collect data. Due to the interpretivist nature of this study, a non-probability sampling technique was utilised. Non-probability sampling techniques are a good fit for a study where the researcher is not required to make statistical inferences about the characteristics of the chosen sample (Saunders, Lewis and Thornhill, 2019, p.296). Instead, when working with a non-probabilistic sampling technique the researcher applies subjective methods to determine whether a particular element might, or might not, be included in the sample (Etikan, Sulaiman and Rukayya, 2016).

Four key sampling techniques fall under the umbrella term of non-probability sampling. These include quota, purposive, volunteer and haphazard sampling (Saunders, Lewis and Thornhill, 2019, p.297). Purposive sampling was used in this study. Purposive sampling requires a researcher to use his/her judgement to select the cases that will enable the research questions to be answered (Saunders, Lewis and Thornhill, 2019, p.321). More specifically, with purposive sampling the researcher deliberately sets out to recruit participants by virtue of their possessed qualities and characteristics (Etikan, Sulaiman and Rukayya, 2016).

Purposive sampling was especially well suited to this study due to its popularity as a sampling technique in both case study and qualitative research studies (Etikan, Sulaiman and Rukayya, 2016; Saunders, Lewis and Thornhill, 2019, p.321). As Saunders, Lewis and Thornhill (2019, p.321) explain:

> *"Purposive sampling is often used when working with very small samples such as* ***case study research*** *and when you wish to select* ***cases that are particularly informative****."*

Similarly, Etikan, Sulaiman and Rukayya (2016, p.2) note that:

> *"It [purposive sampling] is typically used in* ***qualitative research*** *to identify and select the information-rich cases for the most proper utilization of available resources."*

Similar to how there are four key techniques that fall under non-probability sampling, there are a variety of sampling strategies available when making use of purposive sampling (Saunders, Lewis and Thornhill, 2019, p.321). One such strategy is *purposive expert sampling* (Etikan, Sulaiman and Rukayya, 2016; Saunders, Lewis and Thornhill, 2019, p.321). As suggested by the name, expert sampling seeks out experts within a particular domain to participate as research participants (Etikan, Sulaiman and Rukayya, 2016). This in turn, enables the researcher to interact with a sample of highly qualified candidates as the researcher seeks to answer his/her research questions. Expert sampling is especially common in newer areas of research, or in a domain that currently lacks observational evidence (Etikan, Sulaiman and Rukayya, 2016). The blockchain energy exchange domain is a particularly unexplored area of research, with very little observational evidence apart from pilot projects. Thus, a purposive expert sampling strategy was the appropriate fit for this study.

Once a researcher has determined the appropriate sampling strategy, it becomes necessary to specify the size of the research sample. Deciding on a sample size for a non-probability sampling technique can be challenging as there are specific rules to follow when determining the appropriate sample size (Saunders, Lewis and Thornhill, 2019, p.315). This is a well acknowledged problem (Saunders and Townsend, 2018). Generally, in qualitative research, there is the notion that the sample size should grow until data saturation has been reached (Saunders, Lewis and Thornhill, 2019, 315.) However, as Saunders and Townsend (2018) explain, such a suggestion does not come without its dissidents. For example, those critical of the saturation thesis note that if it seems that data saturation has been reached, it might simply

imply that the phenomenon under study has yet to be fully explored, rather than that there is nothing new to be learnt about the phenomenon (Saunders and Townsend, 2018). Furthermore, these same authors note that they could find few authors offering any empirically based evidence regarding when data saturation is reached (Saunders and Townsend, 2018).

Whilst acknowledging the difficulties of choosing the appropriate sample size when working with non-probabilistic sampling techniques, Saunders, Lewis and Thornhill (2019, p.317) recommend between four to twelve research participants for non-probability sampling when working with a homogenous group. However, even then, the authors note that ultimately this is only a general guideline and will be dependent on the research questions and quality of data collected. Thus, this study adopted the initial guideline of between four to twelve participants as suggested as the study itself worked with a homogenous sample. Ultimately, this study ended up with seven experts who participated in the evaluation of the study. For this study, each expert that completed the study’s questionnaire constituted a case (Saunders, Lewis and Thornhill, 2019, p. 196). One further research participant evaluated the syntactic correctness of the business process model but did not form a part of the core expert review process for evaluating the functional requirements of the blockchain-based energy trading system.

2.7.2 Research Instrument

This study made use of online questionnaires to gather primary data from the research participants. Marshall (2005, p.1) defines a questionnaire as:

> *“… a method of data collection which is completed by the respondent in in written format.”*

The two question types utilised in this study’s questionnaire included (1) scale-based questions and (2) open-ended questions. Open-ended questions are particularly important for qualitative studies. To ensure that the questionnaire yields qualitative data the researcher needs to ensure the presence of a high number of open-ended questions (Marshall, 2005). Non-numerical observations and narrative data come from open-ended questions (Marshall, 2005). Within the context of this study, open-ended questions were important to understand what the different research participants thought about the business processes involved in the blockchain-based energy trading system. At the end of each question, participants were provided with an open-ended section to elaborate on each functional requirement of the system.

Two questionnaires were administered in this study, with both created in Google Forms. The first questionnaire consisted of six questions. Each question aimed to assess one functional requirement of the study's proposed blockchain energy exchange system. Importantly, these functional requirements emerged from the scoping review discussed in section 2.5. As such, the key question categories utilised in the questionnaire were a result of an in-depth scoping review and the secondary data analysis process. Accompanying each question was a use case diagram of those *specific* set of system activities that contributed to the fulfilment of a particular functional requirement (see Appendix D for the questionnaire format). Each question included a section titled "Detailed explanation of the use case," should any expert have required any further detail on the use case. For each question, experts had to answer a Likert-scale question about whether they thought the system activities modelled satisfied the given functional requirement of the system. To gather qualitative data, each question was accompanied with an open-ended section where experts could elaborate and justify why they believed the system activities either did, or did not, satisfy the functional requirements.

Accompanying this questionnaire was a detailed use case diagram (of all system activities – i.e., system level use-case diagram), and business process model that experts could consult should they wish to see more detail relating to a question. If participants wanted to view a particular business flow in depth when answering a question, participants could consult the business process model in conjunction with the already provided use case diagram. Furthermore, each use case diagram presented with the question (as well as the system-level use case diagram) was colour coded to be in alignment with the business process model, simplifying the cross-referencing process between the two presented artifacts.

The second questionnaire was administered to only one business process modelling expert. The purpose of this questionnaire was to assess the syntactic correctness of the business process model. The questionnaire took the form of closed-ended Likert scale questions. It was the role of the first questionnaire to assess the semantic content of the model, whereas the second questionnaire assessed the syntactic content of the model.

2.7.3 Sources of primary data

The sources of primary data consisted of eight research participants. Research participants were recruited through e-mail and social media outlets (LinkedIn and publicly available Slack forums). Generally speaking (and as previously alluded to) the sample group was homogenous. Seven experts had specific expertise in blockchain-based systems and system implementation more broadly. The eighth-research participant had extensive experience in business process modelling. All the experts were well qualified, with 5 holding master's degrees and two doctorates. See Chapter 7 for a detailed discussion on participant demographics and areas of expertise.

2.7.4 Process of primary data analysis

Primary data was analysed using thematic analysis. The fundamental goal of thematic analysis is to search out themes, or patterns that are present within a data set (Saunders, Lewis and Thornhill, 2019, p.651). Within the context of this study, the data set used was the participant responses from questionnaire one (i.e., the questionnaire that assessed the functional requirements) conducted. It was not necessary to thematically analyse the responses from questionnaire two, as only one participant responded. The responses for questionnaire two were close-ended, and as previously stated, simply sought to evaluate the syntactic correctness of the model.

For the questionnaire which evaluated the functional requirements of the system, each functional requirement constituted a theme. In other words, there were six core themes. The two ancillary functional requirements presented in Table 3 were not discussed. The motivation for this was that if functional requirement one through to six were well implemented in the business process model, it would follow that the two ancillary functional requirements were satisfied. Once the themes were identified, participant responses falling under each theme were analysed and compared to each other. Meaningful agreement or disagreement was documented. See Chapter 7 for a presentation of the participant responses, and Chapter 8 for a detailed discussion of the participant responses.

2.8 Summary

This chapter provided an overview of how this study was conducted. First, interpretivism was motivated as the appropriate research paradigm for the study. It was explained that inductive reasoning was applied throughout the study, with case study research constituting the appropriate research strategy for this study. Next, the secondary data sources were discussed. This included the presentation of Table 2 which presented all 45 sources involved in the scoping review, and how the study arrived at the six core sources which informed the construction of the business process model. The secondary data analysis process, including how the business process model was built was also discussed. Finally, the sampling strategy employed by this study was discussed, including an explanation of the primary data sources and primary data analysis process.

The following chapter is the first of three literature review chapters. This chapter provides an overview of the energy landscape by introducing readers to centralised energy systems and the move towards energy decentralisation. The chapter includes a discussion on South Africa’s energy sector as it pertains to all the relevant points highlighted throughout the chapter.

Chapter 3: Painting the Energy Landscape

"Eskom is in crisis and the risks it poses to South Africa are great. It could severely damage our economic and social development ambitions. We need to take bold decisions and decisive action."

President Cyril Ramaphosa, State of the Nation Address, 7 February 2019

This chapter provides readers with the necessary background information to understand the context within which this study takes place. This chapter starts by exploring traditional centralised energy systems and the move towards energy decentralisation. Lastly, the discussion centres around the current state of the South African energy sector.

3.1 Traditional Centralised Energy Systems

3.1.1 The Basic Operational Model

It was during the 19th century *"War of the Currents"* that the path was ultimately paved for the emergence of centralised energy systems (CESs). The battle saw Thomas Edison defending the position that the world should be run off direct current (DC). His opponents, George Westinghouse, and Nikola Tesla were instead arguing for the production and distribution of alternating current (AC). AC won in the end, and with that came the ability for utilities to shift the voltage of electric current (Lantero, 2014). For the first time, electricity in the form of AC could be carried over long distances at high voltages and later stepped down to lower voltages (DC) ready for consumption (Singh and Shenai, 2014). Such a process would not have been possible with Edison's promotion of using DC only (Lantero, 2014).

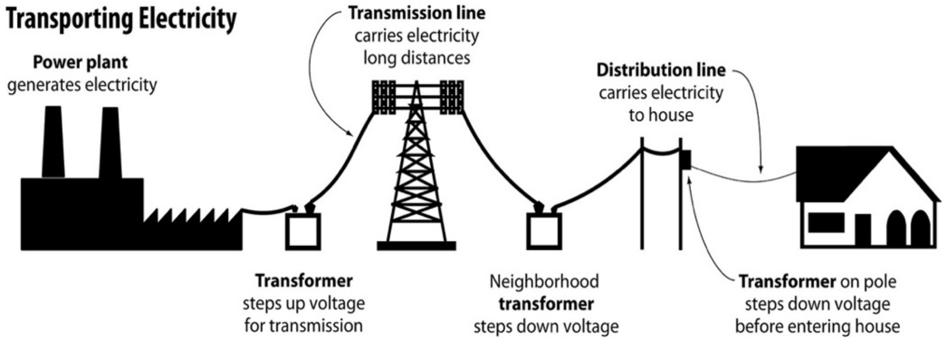

Figure 1: Centralised energy system - adapted from US Environmental Protection (2019)

Since the AC/DC battle most of the developed world has relied on a centralised energy system, including South Africa (Eskom, 2020a; Orsini, 2018; Winning, 2019). A centralised energy system's supply chain consists of four essential components: (1) generation, (2) transmission, (3) distribution and (4) retail (Buchmann, 2017; Voss et al., 2018, p10). Today, most countries' generation sectors are sustained by large fossil or nuclear driven power plants (Buchmann, 2017; Orsini et al., 2019; EPA, 2019). Typically, in such implementations, generation facilities are located in remote areas away from the point of electricity consumption (EPA, 2019; Mengelkamp et al., 2018). Generated electricity is then distributed to end consumers through a series of interconnected high-voltage transmission and low-voltage distribution networks (see Figure 1) (EPA, 2019).

In *any* energy system, it is always necessary for the main grid to maintain a real-time balance between electricity input from the generation end, and that which is drawn from the consumptive end. This balance has to be ensured to guarantee a reliable delivery of electricity to end-consumers (Orsini, 2018). In a centralised energy system, grid balance is achieved by utilising a centralised co-ordination mechanism (Hirsch, Parag and Guerrero, 2018; Mengelkamp et al., 2018a). Typically, this mechanism involves a grid operator forecasting electricity demand for the upcoming day, and then orchestrating generation facilities accordingly to meet the expected demand (Eskom, 2020c; Orsini, 2018). Grid operator roles usually vary per country. For example, in South Africa, the grid operator is an Eskom employee who is responsible for both the operation of the transmission and distribution networks (Buchmann, 2017; Voss et al., 2018, p.13). In addition to the critical role performed by the Eskom employed grid operator, distribution network operators (DNOs) oversee the distribution network. A distribution network is the section of the electricity network which is responsible for delivering electricity to the end-consumer (Hirsch, Parag and Guerrero, 2018). In South Africa DNOs carry the responsibility of performing maintenance on distribution networks, extending the network where necessary, performing metering activities and conducting billing activities (Department of Public Enterprises, 2019, p.25; Eskom, 2020b).

Up to this point, all the components of a CESs supply chain has been discussed apart from energy retail. Most often, in a CES, consumers are passive entities only able to purchase electricity from electricity retailers at fixed prices (Orsini et al., 2019; Zia et al., 2020; Zhang et al., 2018a). Such a process offers consumers little price flexibility as the price of electricity is determined on a national level without taking into account local energy scarcity or a surplus of supply (Mengelkamp et al., 2018; Orsini, 2018). Furthermore, for consumers not using prepaid meters there is no transparency concerning their consumptive data. That is, at least, not until the end of the month when they receive their electricity bill (Orsini, 2018). In liberalised energy markets the only flexibility afforded to consumers lies in their ability to choose which energy retailer to purchase electricity from (Morstyn et al., 2018; Voss et al., 2018, p.9). However, such an option remains unavailable to consumers who find themselves in a monopolised energy market such as that of South Africa (Morstyn et al., 2018; Voss et al., 2018, p.8). For South African consumers, the only place to source electricity from is their local municipality at prescribed rates.

3.1.2 Why a CES then, why not a CES now?

The economic benefit offered by the adoption of large scale energy generation plants was a primary driving force behind the development of CESs (Block, Neumann and Weinhardt, 2008; Bouffard and Kirschen, 2008; Montmasson-Clair et al., 2017, p.8). By increasing plant capacity, electricity suppliers were able to lower the marginal costs associated with electricity production (Martin and Hyafil, 2009). However, the economic benefits offered by CESs had reached their limits by the 1970s. Instead, other negative externalities set in (Hirsch, Parag and Guerrero, 2018; Orsini, 2018). Today, researchers draw attention to the fact that the monolithic CESs found in most global economies are sub-optimal solutions (operating alone) for satisfying and managing the increasingly complex requirements of *future* electricity systems (Ahl et al., 2019; Aggarwal et al., 2019; Bouffard and Kirschen, 2008; Ernst and Young, 2017; Lovins and Eberhard, 2018; Montmasson-Clair et al., 2017; Orsini, 2018). CESs face numerous challenges from an economic, security, environmental and operational perspective (Bouffard and Kirschen, 2008; Hirsch, Parag and Guerrero, 2018).

Table 4 below presents the main challenges faced by current centralised energy systems.

Table 4: Drawbacks of current centralised energy systems

Drawback	Description of Drawback
1. Aging infrastructure	A large portion of electricity supply and transportation equipment is approaching the end of its usable life (Bouffard and Kirschen, 2008). This challenge is particularly prevalent in the South African energy sector (Creamer, 2021; ZAR Department of Energy, 2019, p.16; ZAR Department of Public Enterprises, 2019, p.47).

2. Inability to manage bidirectional electricity flows	Legacy grid systems were not designed for the purpose of handling bi-directional electricity flows where consumers are also able to inject electricity into the network. Instead, CESs are built around unidirectional electricity flows (Zhang et al., 2018a).
3. Energy Security	Centralised energy systems are known for poor modular design. In the event of system failure the entire CES's network is affected and as a result shut down (Bouffard and Kirschen, 2008; Hirsch, Parag and Guerrero, 2018).
4. Environmental impact	The electricity sector is one of the largest contributors to greenhouse gas emissions (ZAR Department of Energy, 2019, p.15). This poses a serious challenge in the face of global climate change policies that aim to reduce greenhouse gas emissions (Leahy, 2019).
5. Capital costs	Building new centralised generation and network infrastructure requires an exorbitant amount of money (Orsini, 2018). CESs do not take advantage of the already 'free of charge' generation facilities available in the form of consumer-owned rooftop solar power.
6. Rural electrification	Rural electrification remains impossible with centralised energy systems as transmission and distribution networks are too costly to construct for the provision of equitable access to electricity in remote areas (Martin and Hyafil, 2009).
7. Transmission and distribution costs	Carrying electricity over long distances, via transmission and distribution networks, results in energy losses (Bouffard and Kirschen, 2008). In the US approximately 5% of energy transported is lost during this process (Orsini, 2018). In South Africa transmission and distribution losses total 8-9% per annum (Rikhotso, 2014).
8. Vulnerable to physical and cyber attack	As information and communication technologies continue to be introduced in the energy sector, systems become increasingly vulnerable to cyberattack (Bouffard and Kirschen, 2008; Daly et al., 2018; Hirsch, Parag and Guerrero, 2018). Physical attacks on CESs include the theft of copper cables as well as illegal plug-ins into the distribution network (ZAR Department of Energy, 2019, p.18).

3.2 The Changing Energy Sector

Given the shortcomings of CESs, researchers and industry practitioners are increasingly searching out more efficient solutions when considering how to satisfy a country's electricity requirements. The on-going structural reform experienced in the energy sector has come about largely as a result of three trends: decarbonisation, decentralisation and digitisation (Andoni et al., 2019; Ernst and Young, 2018; Hirsch, Parag and Guerrero, 2018; Kirpes et al., 2019; Weinhardt et al., 2019; Orsini et al., 2019).

3.2.1 Decarbonisation

Decarbonising the energy sector refers to the global movement that sees countries adopting renewable energy sources (RESs) to contribute towards the country's electricity supply (Mengelkamp et al., 2018; Orsini et al., 2019; Zhu et al., 2020). Lovins and Eberhard (2018, p.7) state in no uncertain terms that *"the renewable revolution is global"*. Tantalised by the promise of the Paris Agreement, the transition towards RESs is taking place at an enormously rapid pace in the attempt to reduce global carbon emissions (Grantham Research Institute, 2020). The Paris Agreement commits its signees (194 of them) to limiting average global temperature increases to less than 2° C degrees above pre-industrial levels by 2030 (Orsini et al., 2019).

Despite the near universal support enjoyed by the Paris Agreement, countries are still in the precarious position of having to satisfy the growing demand for electricity (Bloomberg New Energy Finance, 2019; Orsini et al., 2019). As previously discussed, CESs primarily rely on large fossil-fuel driven plants for electricity supply. Table 4 noted that such conventional generation sources are one of the largest contributors to greenhouse gas emissions. This puts signees of the Paris Agreement in a difficult position. On the one hand, the Paris Agreement beckons countries to reduce carbon emissions. Yet, on the other hand, a country's citizens expect that the growing demand for electricity be satisfied. Research from the University of California reveals that, to meet the goals as set by the Paris Agreement, no new fossil-fuel using infrastructure should be brought online (Leahy, 2019). Additionally, there is the need to shut down already extant fossil-fuel driven plants (Leahy, 2019). The implication is *clear*: if the Paris Agreement policy is to be given its full hearing, traditional fossil-fuel plants cannot remain the primary generation source for satisfying the growing demand for energy worldwide (Zia et al., 2020). The aggressive policy targets established by the Paris Agreement does not come without its detractors. For example, university professor and environmentalist, Bjorn Lomborg (2020), lays out a balanced, data-supported argument as to why such aggressive policies end up doing more harm than good. Lomborg (by no means a climate change denier) acknowledges the reality of climate change, and as a corollary of that, the need for renewable energy. However, Lomborg suggests that policies surrounding the promotion and utilisation of renewable energy be approached in a more balanced fashion, instead of being fuelled by unwarranted alarmism operating in tandem with political agendas. Alas, this study does not have the space to discuss the merits or drawbacks of aggressive climate change policies. Nor its advocates, or those regarded as its heretics.

However, it remains an indubitable fact that the Paris Agreement has spurred, globally, the installation of a whole host of renewable energy sources (Lovins and Eberhard, 2018). Policy measures, such as the one exemplified by the Paris Agreement, have irrevocably altered the traditional CES model that modern society is now so well acquainted with. For better, or worse, the result is an energy system that places a much larger emphasis on sustainability and renewable energy sources. More specifically, not only does the new energy system scorn fossil-fuel generated electricity, but it also, embraces an increasingly decentralised energy system.

3.2.2 Decentralisation

The idea of a decentralised energy system is a concept that can be traced all the way back to Thomas Edison himself (Hirsch, Parag and Guerrero, 2018; Green and Newman, 2017). A decentralised energy system is simply the opposite of a CES, and consists of small scale distributed energy resources (DERs) placed close to the point of electricity consumption (Green and Newman, 2017; Mengelkamp et al., 2018a). This removes the need to rely on large transmission networks carrying electricity from remote plants to end consumers. DERs are publicly or privately owned small-scale power generation sources which can either be directly connected to the distribution network or, alternatively, on the client's side of the electricity meter (Ackermann, Andersson and Söder, 2001; Capehart, 2016). Rooftop solar photovoltaic (solar PV) is an example of a DER, as well as an instance of a renewable energy source (RES)[5].

Today, energy systems are becoming increasingly decentralised due to the growing numbers of consumer owned RESs and battery storage solutions (Accenture, 2017; Ernst and Young, 2018; Kirpes et al., 2019). Decentralisation is further advanced by the increasing uptake of renewable energy sources as encouraged by government policy (Lawrence, 2020). The falling costs of rooftop solar and battery storage has now turned previously passive consumers into prosumers who are able to produce, store, and consume their own electricity (Green and Newman, 2017; Orsini et al., 2019; Voss et al., 2018, p.17). In addition to self-generation and

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[5] As noted, a RES (such as solar PV) is an instance of a DER. Throughout this study when a RES is mentioned, it is taken to be a small-scale DER such as solar PV or small-scale wind turbines.

storing electricity, consumers are also able to feed surplus generated energy back into the main grid (Long et al., 2018; Morstyn et al., 2018; Orsini et al., 2019; Yang et al., 2017).

3.2.2.1 Decentralisation and the Utility Death Spiral

A variety of factors have contributed to the increased uptake of consumer owned RESs. For example, globally, but more predominantly in developed countries, consumers' energy preferences have shifted towards the desire to become active participants in their respective local energy systems (Accenture, 2017; Orsini et al., 2019). Furthermore, the rising price of utility sourced electricity constitutes a core reason for the movement towards consumer owned RESs (Green and Newman, 2017; Lovins and Eberhard, 2018).

Perth, Australia, provides a good case in point where the perverse effects of a rise in the price of electricity can be observed. The price of electricity across Australia has risen dramatically over the past decade, and is now well above the Australian Consumer Price Index (CPI)[6] (Green and Newman, 2017). Australia has some of the highest electricity prices in the world, trailing only behind Denmark and Germany (Green and Newman, 2017). Unsurprisingly, as the price of any commodity or service rises, consumers search out more affordable substitute products. This substitution effect is precisely what can be observed in Perth. As of 2017, the number of households with rooftop solar photovoltaic (solar PV) in Perth is well in excess of 22.5%, approximating more than 200 000 installed systems (Green and Newman, 2017). The purchase of solar PV has continued to grow at 20% per annum (Green and Newman, 2017). In fact, in Perth, the uptake of solar PV has been so radical that its largest power station is now rooftop installed solar PV (Green and Newman, 2017). High levels of uptake continue in 2021 (Mercer, 2021).

As the price of electricity rises, the entirety of society bears the brunt. However, it is the poor and middle class that spend a larger share of their income on electricity. As such, the poor and middle class are disproportionately disadvantaged by the rise in the price of electricity (Green and Newman, 2017; Lomberg, 2020, p.11). This results in consumers (at least those able to afford to do so) turning to solar PV to reduce their electricity bills. In Perth, the adoption of solar PV has largely been a feature of the middle class, with some middle class suburbs having over 50% of its houses equipped with solar PV (Green and Newman, 2017). Surprisingly, this

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[6] CPI measures the monthly change in prices for a range of products.

transformation took place with limited government intervention, instead, it was a consumer driven transformation of Perth’s energy system (Green and Newman, 2017).

This transformation also brings along its own unique, and previously unknown, challenges. The pressing problem with large-scale adoption of solar PV can be clearly seen when the position of those consumers that are left behind (i.e., captive consumers), unable to afford solar PV, are considered. As consumers purchase less grid sourced electricity, or even worse, migrate off grid entirely, it leaves fewer customers with the burden of having to cover a larger proportion of the utilities’ costs (Green, 2019). This, in turn, leads to higher electricity prices as utilities scurry to recover their revenue. Again, a next wave of customer migration is triggered where customers again buy into solar PV and opt out of the grid (Green, 2019). This phenomenon (known as the utility death spiral) resulted in a $657 million loss for the 2018/19 financial year, for Synergy, the state-owned electricity retailer in Perth (Department of Public Enterprises, 2019; Green, 2019; Lacey, 2014; Lovins and Eberhard, 2018; Mercer, 2019). Figure 2 below illustrates the utility death spiral.

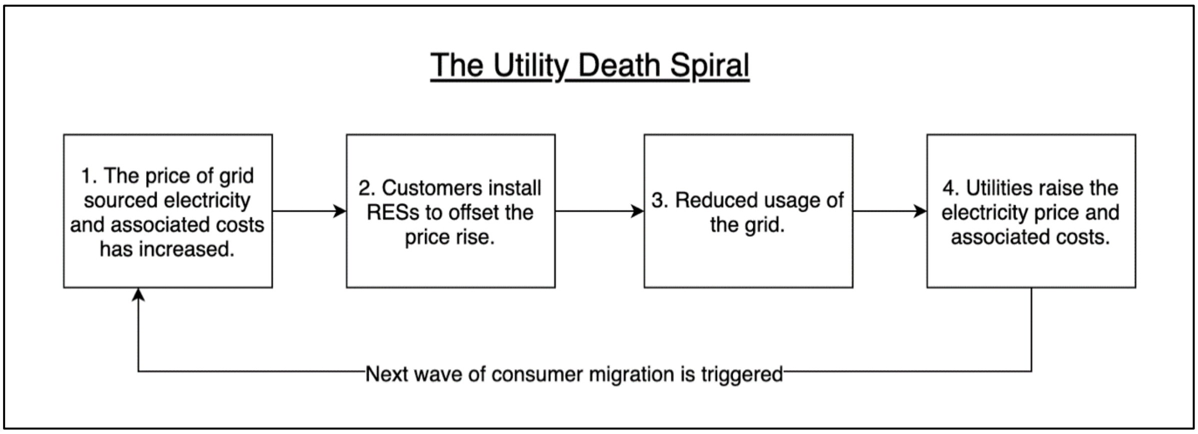

Figure 2: The Utility Death Spiral

Such an outcome is undesirable from both the utilities, and the captive consumers’ perspective, yet this is precisely what has happened in Australia as a result of rising electricity prices (Morstyn et al., 2018). Lovins and Eberhard (2018, p.17) note that the combination of rising electricity prices, plummeting demand for utility produced electricity, and the rapidly expanding renewables market in Australia points to a consumer led transition away from the traditional *“coal-based, central-plant, big-grid model”*.

3.2.3 Digitalisation

Activities that concern the day-to-day operation of the energy sector are also undergoing digital transformation. Such transformation is spearheaded by innovative information and communication (ICT) technologies (Andoni et al., 2019; Accenture, 2017; Orsini et al., 2019). Zeller et al. (2017, p.7) explain that:

> *"… digitalisation means that all processes along the whole power supply value chain are facilitated and supported through a smart ITC infrastructure."*

Investment in digital energy infrastructure and software is growing 20% per annum with the expectation that billions of devices will be connected to electricity markets in the coming decades (Orsini et al., 2019). In the United Kingdom, it is projected that 53 million electricity and gas smart meters will be installed by 2020 (Andoni et al., 2019). Digital technologies allow consumers to implement new innovative ways to reduce energy bills, engage in wholesale energy markets and provide valuable ancillary services to the grid (Orsini et al., 2019). Furthermore, digitalisation lowers the management costs of RESs by offering remote maintenance and granular control (Andoni et al., 2019; Deutsche Energie-Agentur GmbH, 2016). Importantly, the benefits of digitalisation spans the entire energy eco-system and is not restricted to one group of energy stakeholders (Andoni et al., 2019). Examples of digitalisation driven benefits include a means to improve network efficiency, streamlining billing processes, improving supply chain efficiency, the generation of data driven insights, and the introduction of automation capabilities (Andoni et al., 2019; Deutsche Energie-Agentur GmbH, 2016; Zeller et al., 2017).

3.2.4 Not either/or but rather both/and

It is an oversimplification to state that future energy systems will be either centralised or decentralised in their entirety (Bouffard and Kirschen, 2008; Funcke and Bauknecht, 2016). There are, for example, valid reasons as to why it is not desirable to have a fully decentralised energy system (Bouffard and Kirschen, 2008; Funcke and Bauknecht, 2016; Green and Newman, 2017). For example, current economic models reveal that given the still high cost of battery storage solutions, households wishing to maximise cost-savings from rooftop solar systems still require a connection to the main grid (Green and Newman, 2017). A study conducted by Green and Newman (2017) revealed that if houses were equipped with battery storage systems, only 10% of the household's electricity needed to be imported from the main grid. However, and more importantly, 75% of the renewable produced electricity still had to be exported to the main grid or stored somewhere (Green and Newman, 2017). Additionally, a traditional CES (at least in some capacity) remains necessary to ensure the provision of equitable electricity access to consumers unable to afford solar panels (Green and Newman, 2017). Other researchers also note the continuing importance of traditional centralised utilities in satisfying the majority of a country's electricity needs, particularly in developing countries (Daly et al., 2018).

As such, there lies interesting opportunities for innovation at the intersection of centralised and decentralised design approaches (Bouffard and Kirschen, 2008; Mihaylov et al., 2014). An example of this (as already previously alluded to) is the benefit that accompanies grid-tied households feeding back excess generation to the main grid. First, such a process aids a city in becoming environmentally friendly. Second, citizens feeding electricity back to the main grid provide added generative capacity to utilities, which in turn, opens more capacity for new citizen connections (Green and Newman, 2017; Zia et al., 2020). Excess capacity is unlocked without utilities needing to invest additional capital in the building of new generation plants (Montmasson-Clair et al., 2017, p.23). This is particularly significant, considering the expensive upgrades that a traditional CESs demands, as highlighted in Table 4 in section 3.1.2.

Bouffard and Kirschen (2008) believe that the successful energy systems of the future will be those flexible enough to allow for a variety of configurations that take into account the best attributes of both centralised and decentralised design solutions. Funcke and Bauknecht (2016) similarly state that future energy systems will be a simultaneous combination of centralised and decentralised design architectures where both approaches co-exist within one larger energy eco-system.

3.3 South Africa and its position in the energy transformation

3.3.1 South Africa's current centralised energy system

Like many other modern economies, South Africa has a centralised energy system. For example, the country's energy sector remains monopolised by the single state-owned utility, Eskom (Department of Public Enterprises, 2019, p.14). Eskom supplies over 90% of the country's electricity (Department of Public Enterprises, 2019, p.14; Winning, 2019). As noted in section 3.1.1, such a monopolised market structure leaves a country's citizens in the position where they are *only* able to purchase electricity from their local municipalities (Zia et al., 2020). In other words, consumers are price-takers. Such a scenario is sub-optimal, with the South African Department of Public Enterprises (2019, p.14) *itself* admitting that:

> *"Eskom's operating business model is* ***outdated*** *and based on the era of excess electricity supply and* ***captive customers****.*[7]*"*

3.3.2 Eskom as a single point of failure

The challenges faced by the South African energy sector are severe and on-going. Eskom is a critical role player in the South African energy system. Yet, at the same time, the Department of Public Enterprises (2019, p.14) notes that Eskom is a business entity publicly known for its widespread inefficiencies. A snapshot of Eskom in March 2019, would reveal that Eskom's long-term debt totals R441 billion at the time, up from R255 billion in 2014 (Department of Public Enterprises, 2019, p.11). Over the next 5 years interest payments for the state-owned utility were expected to total R148 billion and debt repayments a further R180 billion (Department of Public Enterprises, 2019, p.14). Said another way, Eskom generates less than half the cash necessary to service the principal and interest on its debt (Eberhard, 2019). Almost two years later, in 2021, Eskom has managed to cut debt to R401 billion largely due to tariff increases (Omarjee, 2021). For the 2020 period Eskom introduced a 8.67% tariff increase for electricity consumers (Comins, 2021). Although reducing their overburdening debt, Eskom still reported a net loss after tax of R18.9 billion (Comins, 2021; Omarjee, 2021).

Eskom's inability to satisfy the country's demand for electricity has led to the implementation of load shedding, in an attempt to curtail excess demand (Winning, 2019). Load shedding has cost the country as much as R1.4 trillion over the past decade, with economic indicators signalling that the situation could escalate to the point where South Africa sustains such damages on a yearly, rather than per decade basis (Lawrence, 2020). Depending on the severity of load shedding the South African economy sustains loses of R1-R4billion rand per day (Head, 2019). Eskom's inability to satisfy the country's electricity requirements shows little sign of improvement going forward. A number of Eskom coal plants reached their end of life by 2019, which in turn, requires for plants to be either retired or upgraded (ZAR Department of Energy, 2019, p.16). This is an example of a challenge faced by centralised energy systems within the

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[7] Emphasis added

context of South Africa (see Table 4). Given Eskom’s debt crisis, equipment upgrades have become increasingly difficult (Sguazzin, 2020). Additionally, the 2019 Integrated Resource Plan (IRP) notes that multiple Eskom power plants are non-compliant with environmental regulations. As such, numerous plants face impending shutdown after a 5-year deferment period granted to Eskom for ensuring compliance with state law (ZAR Department of Energy, 2019, p.36). This deferment period seems to have been largely wasted with only 1 plant being adequately upgraded by 2019 (ZAR Department of Energy, 2019, p.36). In 2021, Eskom still faces mounting pressure and threat of shutdown from both the South African environment ministerial cabinet and non-governmental organisations (Cocks, 2021; Centre for Environmental Rights, 2020; Sguazzin, 2020; Yelland, 2021). According to the IRP, non-compliance implies the following for the South African economy (ZAR Department of Energy, 2019, p.40):

> *“Assuming that non-compliant power plants are shut down, the reality of power disruptions manifests significantly from the year 2019 onwards.”*

3.3.3 A growing interest in energy decentralisation in South Africa

Given the challenges faced by Eskom, local municipalities, and the citizens of South Africa, have begun to look for alternative sources of energy. For example, at the start of 2020, the City of Cape Town announced its intention to create its own power supply grid (Le Roux, 2020). During the same period as the City of Cape Town’s announcement, municipalities with balanced books were given the go ahead from national government to source power from independent power producers (IPPs). In doing so, the City of Cape Town intends avoiding load shedding by sourcing electricity from both IPPs and residential households (Le Roux, 2020). Dan Plato, mayor of Cape Town, explains that (Le Roux, 2020),

> *“Improving access to affordable electricity is a key deliverable that we are investigating. Whatever they [IPPs] might have available, we want to know that so we can become self-sufficient so that we don’t rely on Eskom so much and get rid of this load shedding nightmare.”*

Currently, there are already nationwide policies in place that allow for certain individuals with distributed energy resources (DERs) to feed excess electricity back into the main grid (Le Roux, 2020 and Roberts and Manzini, 2017). The Department of Public Enterprises (2019, p.45) note that the IRP of 2019 assumes that increasing amounts of DERs will be connected to the main grid by households and businesses as 2030 is approached. As the number of consumer owned DERs continues to grow, it is reasonable to assume that so too will the number of consumers who wish to sell electricity back to the main grid (The Department of Public Enterprises, 2019, p.45). Other municipalities in South Africa, such as the Drakenstein and Nelson Mandela Bay municipality have already invested in incorporating consumer owned DERs with their respective municipal grids. Here, tariff schemas are available, which allows consumers to feed surplus energy back to the main grid (Montmasson-Clair et al., 2017, p.22). The City of Cape Town has similar tariff schemas in place (Montmasson-Clair et al., 2017, p.23). As wholesale and retail electricity prices in South Africa continue to rise, it is expected that increasing numbers of electricity users will look for alternative energy sources in the form of rooftop PV systems (ZAR Department of Energy, 2019, p.16). Down the road, the result may be like the trend observed in Perth, with mass migration away from the main grid (see section 3.2.2.1). It has already been pointed out that Eskom may have already triggered its own ‘death spiral’ with tariff hikes pushing more and more consumers towards self-sufficiency (Department of Public Enterprises, 2019; Lovins and Eberhard, 2018). This ‘death spiral’ can only be expected to intensify, with Eskom announcing a 15.06% tariff hike for 2022 (Comins, 2021). The National Energy Regulator of South Africa (NERSA) has already approved the proposed tariff hike (Comins, 2021).

However, even if a death spiral implies that consumers may shift their preference towards rooftop PV systems, it is not guaranteed that these migrating consumers may want to be grid-tied. A study conducted in South Africa, set out to investigate public opinion surrounding embedded rooftop solar systems in Stellenbosch (Morar, 2017). The study revealed that of the ten research participants, all were interested in, or had already purchased, rooftop PV systems but were frustrated with the government for introducing a R140 monthly grid connection fee (Morar, 2017). Participants expressed doubt in their ability to recover the monthly grid connection fee through surplus electricity sold back to the Stellenbosch municipal grid (Morar, 2017). Once research participants understood the implication that municipal feed-in tariffs potentially offered little room for profitable PV investments, their interest turned to the costs of off-grid storage solutions, as well as the process involved in being able to entirely decouple from the municipal grid (Morar, 2017). There is growing need for municipalities to reinvent and provide the requisite incentives necessary to keep citizens coupled to the main grid (Montmasson-Clair et al., 2017, p.38; Morstyn et al., 2018).

Given the current trajectory of Eskom, it is not clear whether the growing need to keep citizens connected to the main grid will be addressed. Furthermore, citizens remain captive consumers to a utility that is unable to satisfy consumers' electricity demand. As indicated by the Integrated Resource Plan of 2019, South Africa does intend on moving down the path of energy decentralisation. This constitutes a further challenge for Eskom when it comes to integrating DERs with the current energy system. Perhaps, it may be worthwhile to explore alternative solutions to incorporating DERs into the South African energy system. Such a solution would provide consumers with energy security (i.e., a safeguard against load shedding) and remove the burden of being held captive by one utility company. That, ultimately, is the task of this study.

3.4 Summary

This chapter began by exploring centralised energy systems (CESs). Importantly, it was highlighted that CESs, as a single solution, are no longer considered optimal for satisfying a country's electricity requirements. Given the challenges faced by CESs, the on-going structural reform taking place in the energy sector was highlighted. Decarbonisation, decentralisation, and digitalisation were identified as the three core trends driving structural reform. It was highlighted that future energy systems are becoming increasingly decentralised. Finally, South Africa was discussed within the context of the energy transformation. Eskom was identified as a single point of failure in the South African energy system. This has led to South African leaders and citizens alike starting to look for alternatives when it comes to guaranteeing energy security.

The following chapter considers the challenge of integrating DERs with the public grid. At this point, microgrids as a potential solution to DER integration are introduced to the reader. Finally, it is discussed how local energy markets allow for the balance of locally produced energy within a microgrid.

Chapter 4: Microgrids and Energy Markets

"To act on the belief that we possess the knowledge and the power which enable us to shape the processes of society entirely to our liking, knowledge which in fact we do not possess, is likely to do much harm."

F.A. Hayek

4.1 The challenge of decentralisation from a grid perspective

Traditional grid infrastructure (as found in a centralised energy system), was *not* designed for the purpose of accommodating large numbers of distributed energy resources (DERs) (Almasalma, Engels and Deconinck, 2017; Mengelkamp et al., 2018a; Orsini et al., 2019). Instead, these legacy grids, were solely designed to accommodate unidirectional electricity flows from centralised energy plants to consumer consumption points (Almasalma, Engels and Deconinck, 2017; Hirsch, Parag and Guerrero, 2018). Researchers agree that integrating distributed energy sources (RESs) (on a per unit basis) with the main grid poses serious challenges for centralised energy systems (CESs) (Abrishambaf et al., 2019; Andoni et al., 2019; Bello et al., 2013; Kirpes, Mengelkamp and Weinhardt, 2019; Laszka et al., 2017; Orsini et al., 2019; Siano et al., 2019; Weinhardt et al., 2019; Zhang et al., 2018; Yang et al., 2017).

Two challenges constitute barriers to the successful integration of DERs with the main grid. *First*, there is the problem of renewable energy source (RES) intermittency. Just to clarify, a RES is an instance of a DER. In other words, a DER may either be fossil-fuel driven, or driven by an alternative source such as solar energy. Most commonly, when a DER is mentioned within the context of this study, it is in reference to a RES (e.g., solar photovoltaic and wind turbines).

Technological maturity and promising energy conversion rates constitute the two primary drivers behind frequent RES installations (Zia et al., 2020). Furthermore, as mentioned in Chapter 3 (section 3.2.1), RESs penetration rates have risen globally with the widespread effort to reduce global carbon emissions. Changing consumer consumption patterns were also mentioned as an additional reason for the growing popularity of RESs (Accenture, 2017; Ernst and Young, 2017). Because RESs rely on external weather conditions to generate electricity, the energy output of these energy sources is of a volatile nature. More specifically, external weather conditions are variable, and because RES are reliant on those variable conditions for energy generation, the energy output from the RESs are thus, also variable (Orsini et al., 2019). This ‘RES intermittency’ poses grave challenges for grid operators who wish to maintain network balance in the energy system (Zhang et al., 2018a). Recall from chapter three (see section 3.1.1), the importance of an energy system maintaining a real-time balance between the load drawn from the consumptive end, and that which is generated from the supply end of the energy system (Orsini et al., 2019). For example, in an energy system, with an erratic and uncontrollable energy supply, it is highly probable that the delicate frequency bands of the main grid would be interrupted. This in turn, would result in a system wide power shutdown (Chen et al., 2015; Hirsch, Parag and Guerrero, 2018; Orsini et al., 2019).

The *second* challenge of integrating RESs with the main grid relates to the increase in bi-directional electricity flows within the grid, as more RES units are installed (Zhang et al., 2018a). An increase in bi-directional electricity flows within a grid designed for unilateral flows could result in severe voltage fluctuations. Voltage fluctuations are known for negatively impacting upon the quality of electricity received by end consumers (Almasalma, Engels and Deconinck, 2016; Chen et al., 2015; Kirpes, Mengelkamp and Weinhardt, 2019; Orsini et al., 2019).

4.2 Microgrids

4.2.1 A primer

Due to the challenges of integrating DERs (i.e., variable DERs such as solar PV) with the main grid, it is necessary for power grids to adapt on both the transmission and distribution level (Almasalma, Engels and Deconinck, 2017; Kirpes et al., 2019). If large numbers of DERs were to be integrated with the main grid on a per unit basis the process of managing each intermittent resource through a single centralised co-ordination mechanism becomes unsustainable (Hirsch, Parag and Guerrero, 2018). Some researchers believe that it would be better to take a systems approach to the challenge of DER integration with the main grid (Piagi and Lasseter, 2006). A system approach ultimately views DER electricity generation, and its associated demand, as one *sub-system* of a larger whole (the entire electricity system). One suitable avenue to realising such a systems approach is through microgrid deployment (Hirsch, Parag and Guerrero, 2018; Li et al., 2019; Piagi and Lasseter, 2006; Pullins, 2019; Zhang et al., 2018a). A microgrid is defined as:

> *"... a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the [main] grid. A microgrid can connect and disconnect from the [main] grid to enable it to operate in both grid-connected or island mode,"* (Ton and Smith, 2012, p.1).

Hirsch, Parag and Guerrero (2018) expand on the aforementioned definition by stating that:

1. A microgrid is distinct from the rest of the grid making it possible to identify the part of the distribution system that constitutes a 'microgrid'.
2. Resources connected to a microgrid are to be controlled and managed locally.
3. Physical microgrids can function regardless of whether the microgrid retains a connection to the main grid.

One core benefit of connecting DERs to a microgrid lies in the fact that microgrids are designed to handle variable electricity generation and as such provide a satisfactory answer to the question of how to manage the intermittency associated with RESs (Hirsch, Parag and Guerrero, 2018; Piagi and Lasseter, 2006). It is important to note that the argument for installing a microgrid is not that the main grid is to be replaced in its entirety by a network of microgrids. Rather, the purpose behind installing a microgrid is that a microgrid provides a feasible and sustainable solution to integrating DERs with the main grid (Cohn, West and Parker, 2017). In fact, Li et al. (2019) points out that there are benefits to having a microgrid retain its connection to the main grid. For example, if a microgrid retains a connection to the main grid it can optimise its energy management processes by actively interacting with the main grid. Similar research reveals that a properly sized microgrid is financially optimal when it supplies approximately 86% of the connected loads' annual electric needs (Pullins, 2019). Real-world microgrid implementations found in urban settlements tend to follow this rule, as evidenced by the Brooklyn microgrid where a connection between the microgrid and New York main grid is maintained (Mengelkamp et al., 2018a). It is at this interface (i.e., between the main and microgrid) where one of the core strengths of the microgrid architecture is evidenced (Zia et al., 2020). Because the demand and supply of electricity is first balanced locally within the microgrid, the microgrid can be presented to the main grid as a *single facing customer* (Hirsch, Parag and Guerrero, 2018). This, in turn, relieves the main grid from the burden of managing millions of *intermittent* DERs on a per unit basis (Hirsch, Parag and Guerrero, 2018).

Should there be an energy surplus within the microgrid, that surplus can be exported to the main grid, or alternatively, should there be an energy deficit, that deficit can be compensated for by importing electricity from the main grid (Li et al., 2019).

4.2.2 Why deploy a microgrid?

There are three core groups of drivers that lie behind the deployment of a microgrid (Hirsch, Parag and Guerrero, 2018). These three groups include energy security, economic benefit, and clean energy integration. These categories, along with their core drivers within the context of this study, are presented in Table 5 below.

Table 5: Microgrid adoption factors

Driver Category	Drivers
Economic Benefits	• Provision of ancillary services to the superordinate (main) grid. (Hirsch et al., 2018 and Mengelkamp et al., 2019) • Deferment of expensive network upgrades (Andoni et al., 2019 and Hirsch et al., 2018) • Reduction in transmission and distribution losses (Andoni et al., 2019 and Hirsch et al., 2018) • Connecting small actors for energy exchange to realise local economic gain (Mengelkamp et al., 2018)
Energy Security	• Improved network resilience and reliability of energy delivery (Ahl et al., 2019 and Li et al., 2019) • Protection against cyber- and physical attacks (Andoni et al., 2019 and Hirsch et al., 2018)
Clean Energy Integration	• Environmental sustainability (Mengelkamp et al., 2018) • Integration of RESs in a way that can facilitate interaction with the main grid (Hirsch et al., 2018)

In Europe, it is primarily the rapid uptake of RESs, and as such, the need for clean energy integration that drives the adoption of microgrids (Hirsch, Parag and Guerrero, 2018). In contrast, in the US, microgrids tend to be deployed to address specific energy security concerns or to specifically capture the economic benefits that are offered by microgrids. For example, the long-term cost profile of a microgrid is typically flat and predictable which makes for an attractive investment profile (Pullins, 2019). In other words, there are typically no erratic, or unpredictable, costs attached to the deployment of microgrids. Having said this, this does not negate the fact that there remains a cost premium attached to the initial construction of the microgrid (Pullins, 2019). However, in some instances the initial cost attached to microgrid deployment becomes less important. For example, a neighbourhood that is primarily concerned with environmental sustainability and energy security may be willing to collectively invest in a microgrid (Mengelkamp et al., 2018a; Pullins, 2019). Furthermore, a renewables-based microgrid has no variable costs (e.g. no coal procurement required), which further bolsters economic feasibility (Orsini et al., 2019; Pullins, 2019). Research reveals that deploying a microgrid does indeed result in long-term cost saving for the investors (Pullins, 2019). Additionally, locally-owned energy projects, such as renewable-based microgrids, have noticeable positive spin-offs such as delivering socio-economic and environmental benefits for communities involved (Andoni et al., 2019; Mengelkamp et al., 2018a). A group of researchers state that the integration of RESs, by restructuring the energy system into several inter-connected microgrids, would not only improve the reliability and environmental sustainability of the energy system but also provide economic benefit (Mengelkamp et al., 2018a).

Given the load shedding crisis in South Africa, special attention needs to be drawn to the fact that microgrids offer higher levels of energy security (see Table 4). Microgrids provide a hedge against system wide power cuts with their ability to remain fully functional whilst operating as self-contained entities. When a microgrid disconnects from the main grid, the microgrid is said to be ‘islanding’ (Mengelkamp et al., 2018a). Should a severe power disruption occur, due to a natural disaster, or load shedding, microgrids can stand alone and continue serving the key loads that are connected to the microgrid (Lovins, 2011). One caveat is that islanding capabilities are reserved for physical microgrids only. A physical microgrids refers to an actual physical grid built that interconnects DER loads. In contrast, virtual microgrids rely on the main grid alone for connecting loads, and as such virtual microgrids cannot island from the main grid (Hirsch, Parag and Guerrero, 2018; Mengelkamp et al., 2018a). Throughout this study, when a microgrid is mentioned, it is taken to mean a *physical* microgrid that is distinct (yet connected) from the main grid.

The importance and benefits underlying a microgrid’s islanding capabilities could hardly be understated. First, for local residential neighbourhoods (reliant on a microgrid) the convenience of retaining a continuous supply of electricity is unrivalled when compared to current centralised (e.g., CESs) configurations (Piagi and Lasseter, 2006). However, arguably more important (and interesting) are the new use cases and business processes that emerge from islanding capabilities. For example, a community microgrid could serve key loads such as hospitals, or other essential services during power disruptions on the main grid (Mengelkamp et al., 2018a). Consider the South African public health system. In a survey conducted in 2017, South Africa ranked last out of 19 developing countries based on expenditure efficiency when it comes to general health care related expenditure (Laher et al., 2019). In 2021, the national budget showed that planned spending on public health would be reduced by a further R50.3 billion over the next 3 years (McLaren et al., 2021).

Private hospitals along with secondary and tertiary level public hospitals tend to be well equipped with generator banks. However, it is the smaller healthcare facilities in South Africa that are left without electricity during load shedding as they do not have the equipment in place to maintain a stable supply of electricity (Laher et al., 2019). Hospitals face numerous complications as a result of load shedding. For example, in the case of electricity outages hospitals suffer a loss over infection control as equipment cannot be sterilised, particularly in emergency procedures (Laher et al., 2019). A community microgrid could redirect surplus electricity to hospitals in the event of electricity outages (Mengelkamp et al., 2018a). Where the surplus electricity would be sourced from, and how the electricity would be priced, is largely a question concerning microgrid governance. For example: electricity could be redirected from rooftop solar photovoltaic (PV) cells to hospitals at fixed price rates, or alternatively, there may be philanthropic prosumers connected to the microgrid who simply wish to uplift the community by freely providing electricity rather than generating profit from electricity sale (Mengelkamp et al., 2018a; Morstyn and McCulloch, 2019).

In addition to the unique operational advantages offered by microgrids, microgrids directly address the current challenges faced by CESs (see Table 4 in Chapter 3). Table 6 below presents examples of how some of the core drivers behind microgrid adoption also provide direct solutions to some of the core challenges current plaguing CESs. South African examples are provided in the table below where appropriate.

Table 6: Microgrid solutions to core challenges in South Africa's centralised energy system

Challenge faced by CES	Example of a microgrid-based solution	Relevance to South African context
Aging infrastructure and capital costs	Microgrids can defer expensive network upgrades (Andoni et al., 2019 and Hirsch et al., 2018). For example, in Brooklyn, New York a $200 million dollar microgrid was	The average age of Eskom's coal powered plants is 41 years (Mills, 2021). It will ultimately cost Eskom 300 billion rand ($20bn)

	built to utilise prosumer generated energy as opposed to building a $1 billion dollar substation (Hirsch, Parag and Guerrero, 2018).	to ensure that its aging power plant fleet is compliant with minimum emission standards (Mills, 2021).
Transmission and distribution costs	Microgrids are known for offering efficiency improvements in comparison to legacy grid systems (Andoni et al., 2019 and Hirsch et al., 2018). For example, line losses are minimised when relying on a microgrid architecture to transport electricity to end consumers (Hirsch, Parag and Guerrero, 2018).	Recent estimates place South Africa’s transmission and distribution losses at 8-9% per annum (Rikhotso, 2014).
Energy security	Microgrids provide a way in which to segment the electricity system into smaller autonomous units. As such, an outage on the main grid will not have a cascading effect where the microgrid is also left without a supply of electricity (Ahl et al., 2019 and Li et al., 2019)	As already extensively discussed in Chapter 3 and 4, load shedding poses severe threats to the wellbeing of the South African economy as well as energy satisfaction of the country’s citizens. Microgrids provide a hedge against load shedding.
Inability to manage bidirectional electricity flows	Microgrids are designed to handle bi-directional electricity flows (Hirsch, Parag and Guerrero, 2018).	The Integrated Resource Plan of 2019 (the most up to date as of 2021) mentions the need to invest in microgrids to accommodate the increase in bi-directional electricity flows as specified by the 2019 Integrated Resource Plan.
Environmental impact	Microgrids facilitate the integration of clean renewable energy resources into a country’s energy system. As such, microgrids inadvertently promote environmental sustainability (Mengelkamp et al., 2018)-	The South African government intends to increase its efforts in decarbonising the energy sector in alignment with the Paris Agreement (Farand, 2021) . Microgrids provide one avenue for the integration of clean energy into the energy sector.
Physical and cyber attack	Microgrids promote a decentralised architecture, and as such, are less susceptible to attack on critical generation	Cable theft and illegal grid connections are a contributing factor to load shedding in South Africa (Ntshidi, 2021). A

	and/or transmission equipment (Andoni et al., 2019 and Hirsch et al., 2018)	microgrid in a given community will reduce the reliance on the main grid (i.e., where theft and illegal connections most commonly occur) as well as provide more fine-grained control over where electricity is being consumed.
Rural electrification	Microgrids can connect small actors for energy exchange to realise local economic gain (Mengelkamp et al., 2018). In other words, they do not have to retain a connection to the main grid to be operational. This is especially applicable in rural areas, where it is often not possible to maintain a connection to the main grid due to inordinate infrastructural costs.	Microgrids provide a potential answer to providing rural citizens with a secure energy supply (Motjoadi, Bokoro and Onibonoje, 2020).

4.2.3 A brief word on microgrid management

There are several technical requirements that need to be satisfied for a microgrid to be considered fully operational. Microgrids must satisfy the following six functional requirements (Hirsch, Parag and Guerrero, 2018) to be considered operational:

1. The microgrid must present itself to the main grid as a single self-controlled entity. This, in turn, allows for the main grid to interface with the microgrid as if it were a standard synchronous generator.
2. The microgrid must avoid power flows that exceed line ratings.
3. The microgrid must control the DERs[8] connected to the microgrid so as to maintain energy balance within the microgrid.
4. The microgrid must be able to island smoothly.
5. The microgrid must regulate voltage and frequency within acceptable bounds during islanding.
6. The microgrid must be able to safely reconnect to the main grid once islanding is complete.

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[8] As another reminder, a DER is simply a small-scale power generation source. This can include renewable energy resources, such as a solar photovoltaic (PV) cell.

The question of how to satisfy the six functional requirements enumerated above remains an open-ended question in the literature. It is possible for a microgrid to be controlled in much the same manner as the main grid is currently managed (as discussed in Chapter 3) by utilising a centralised microgrid controller (MC) (Almasalma, Engels and Deconinck, 2017; Hirsch, Parag and Guerrero, 2018). Such microgrid implementations tend to be more commonplace. Examples of such an implementation can be found in the microgrid projects discussed by Kirpes, Mengelkamp and Weinhardt (2019) and Li et al., (2019). The study published by Mihaylov (2014) also utilises a variation of the centralised microgrid controller approach. Further examples of centrally controlled microgrids can be found in Kythonos, Greece and in the German ‘Am Steinweg’ project (Hirsch, Parag and Guerrero, 2018). The process of controlling microgrids through centralised control mechanisms is already well understood, and as such tends to receive more attention (Li et al., 2019). Alternatively, microgrids could be configured in an entirely decentralised fashion where DERs autonomously respond to local network conditions (Hirsch, Parag and Guerrero, 2018). Currently, an entirely decentralised control paradigm remains an open and on-going area of research (Almasalma, Engels and Deconinck, 2017; Andoni et al., 2019).

The centralised and decentralised control paradigms mentioned above delineate a continuum of control strategies available to microgrids. In fact, five possible architectural styles on this continuum (Almasalma, Engels and Deconinck, 2017). It is beyond the scope of this research study to discuss the merits and drawbacks of each microgrid control strategy. Instead, this study follows previous research as discussed in Kirpes, Mengelkamp and Weinhardt (2019), Li et al. (2019), Mengelkamp et al. (2018) and Mihaylov (2014) where a centralised microgrid controller is utilised. Furthermore, from a South African perspective, adopting a simple control paradigm which is already well understood by South African grid operators seems appropriate. The motivation for such a decision finds its basis in the attempt to minimise as many barriers as possible to microgrid adoption. Piagi and Lasseter (2006, p.2) draw out the overlap between the control of traditional CESs and the control of DERs connected to a microgrid:

> *“We believe that while some emerging control techniques are useful, the traditional power system provides* ***important insights****. Key power system concepts can be* ***applied equally well*** *to DG [DER] operation. For example, the power vs frequency droop and voltage control used on*

> *large utility generators can also provide the same robustness to* ***systems of small DGs [DERs]****.*[9]*"*

Additionally, current network operators (such as Eskom) already either own, control, or both own and control, grid infrastructure (Andoni et al., 2019). Given this fact, it is impractical to attempt to replace the role of these operators with privately governed microgrids. Some researchers argue that it is unnecessary, and in addition, costly to replace a group of actors that have already built up specialised domain knowledge and skills (Saxena et al., 2019). Rather, a more fruitful alternative could be to bridge the knowledge gap found in microgrid operations by standing on the shoulders of already experienced grid operators. For example: Eskom grid operators could train microgrid operators and pass on the requisite skills. In fact, this could provide Eskom with the opportunity to introduce a new facet to their current business model offering microgrid controller training services, or alternatively, to make available an employee that could be outsourced and remunerated by a microgrid community (Montmasson-Clair et al., 2017, p.38). Not only could such an approach introduce new revenue streams for Eskom, but it would also reduce Eskom's already strained expenditure on staff salaries.

In practice, getting Eskom involved in training programmes does not seem a far off prospect given the recent statement issued by the Department of Public Enterprises in the document entitled *the Roadmap for Eskom in a Reformed Electricity Supply Industry* (Department of Public Enterprises, 2019, p.45):

> *"The IRP [2019] assumes that 2,600MW of embedded electricity generation will be added by households and businesses for their own use, at a rate of 200 MW a year. This is expected to boost investment from consumers to buy technologies aimed a selling electricity back to the national grid. Investment into [the]* ***management of microgrids and bidirectional electricity flow*** *is* ***needed*** *in order to manage the flexible generation stated in the IRP*[10]*."*

Given that talk of microgrid investment has already entered mainstream consciousness in South Africa, it is the intention of this research project to adopt a microgrid control paradigm (i.e., a paradigm where a MC controller is used instead of a completely autonomous system) that is already well understood in South Africa. Up to now, it also remains the most viable technical

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[9] Emphasis added

[10] Emphasis added

solution. This also allows for a better understood discussion of microgrid integration within the South African context. As a footnote, it is important to remain cognizant of the fact that though microgrids could be managed by a centralised controller does not negate the fact that an energy system built around DER integration remains fundamentally decentralised rather than centralised. This harks back to the point raised in Chapter Three section 3.2.4 which stated that future energy systems will be a simultaneous combination of both centralised and decentralised design architectures.

Up to this point in this chapter, physical microgrids have been introduced to the reader. However, installing a physical microgrid is only one component involved in introducing more DERs into the network. To coordinate the influx of newly unlocked energy, an energy market is also required to coordinate the energy exchange. Section 4.3 begins by providing an overview of current market solutions and its associated problems. Note that the market structure discussed below does not necessarily operate within the context of a microgrid. However, it is necessary to briefly discuss how the current market operates so that the benefits underlying a microgrid-based energy market becomes more transparent.

4.3 Market-based Energy Trading

4.3.1 The current lack of flexibility offered by feed-in-tariff programs

Energy trading, or exchange, is the sale and purchase of energy from the producer to the purchaser (Ali et al., 2020). As previously mentioned, energy trading has traditionally been regarded a unidirectional process: electricity is transmitted to consumers and monetary compensation flows back to large scale utilities (Alam, Islam and Ferdous, 2019; Ali et al., 2020; Zhang et al., 2018a). Once countries introduced feed-in-tariff schemes for electricity imported to the main grid, this unidirectional trading paradigm was disrupted. A feed-in-tariff is a fixed payment made per kilowatt-hour (kWh) of generated and supplied electricity (Grösche and Schröder, 2014). As such, the feed-in-tariff is paid over to the supplier of green electricity (Grösche and Schröder, 2014). However, such feed-in-tariff schemes are not perfect and have brought about their own challenges. It is beyond the scope of this study to discuss the challenges posed by feed-in-tariffs as they relate to broader economic policy. This study does not argue for the efficacy or inefficacy of feed-in-tariff schemes in satisfying policy targets. However, one point is worth touching upon as it deals with the circumstances of the prosumer and hence bears significance within the context of this study.

Some researchers note that feed-in-tariff schemes lack flexibility as the trading process require prosumers to rely on third-parties for the importing of electricity to the main grid (Kounelis et al., 2017; Morstyn et al., 2018). The fact that prosumers are required to contract with third parties introduces additional management and transactional fees for the prosumers. This reduces potential earnings for prosumers (Andoni et al., 2019; Kounelis et al., 2017; Morstyn et al., 2018). Relying on a middleman also often leaves a prosumer without choice. For example: in South Africa, prosumers can only contract with municipalities to import electricity into the main grid (Montmasson-Clair et al., 2017, p.22). It could also be the case that municipalities do not support feed-in-tariffs (Montmasson-Clair et al., 2017, p.22). A South African study carried out by Morar (2017, p.222) revealed, that the monthly rate charged to maintain a connection to the Stellenbosch municipal grid exceeded that which residents thought they would be able to reliably recover in a single month from the sale of self-generated electricity to the main grid. This problem remains current where few, if any, prosumers are able to realise a return on their solar photovoltaic (PV) investments due to the charges municipalities levy on solar PV systems (Yelland, 2020). Municipalities charge inordinate levies in an attempt to recover their own losses in revenue with the rise of consumer owned solar PV systems (Yelland, 2020). As such, those prosumers who invest in solar PV will not realise a return on investment, given the high levies charged by municipalities – at least not in the foreseeable future.

Tangentially, prosumers are also in the unfortunate position of having the feed-in-tariff dictated to them with no ability to negotiate rates (Orsini, 2018). As such, the feed-in-tariff remains fixed, and does not reflect the scarcity or surplus of electricity in a particular localised region (Mengelkamp et al., 2018a). The discussion above does not suggest that feed-in-tariff schemes cannot be of benefit to the prosumer. Rather, the point being made is that a feed-in-tariff scheme is inherently inflexible, as both their manner of operation and the rates offered are determined in a hierarchical (i.e., top-down) fashion. And, at times, the establishment of tariffs can be to the detriment of the prosumer, as is currently the case in South Africa. Feed-in-tariffs essentially leaves the consumer in a similar position to when consumers purchase electricity in a traditional monopolised CESs – the prosumer is left with no purchasing power and must take the rate offered with no alternative available.

4.3.2 A fresh approach – Local Energy Markets (LEMs)

Given the rigidity of feed-in-tariff programs researchers have signalled the need for new approaches towards designing energy markets to facilitate the energy trading process between supplier and consumer (Kirpes et al., 2019). One approach that has gained increasing attention both in the academic literature and industry is the design of decentralised energy markets.

Decentralised markets are not a new idea – it has been discussed and argued for since the early 1900s. For example: Hayek (1945) in *the Use of Knowledge in Society*, lays out an argument for why decentralised markets and their accompanying price signals are more appropriate for a healthy economy compared to centrally determined prices which do not take into account supply and demand. Here is Hayek (1945, p.6), in the Use of Knowledge and Society:

> *"If we can agree that the economic problem of society is mainly one of rapid adaptation to changes in the particular circumstances of time and place, it would seem to follow that the ultimate decisions* ***must be left to the people who are familiar with these circumstances, who know directly of the relevant changes and of the resources immediately available to meet them****. We cannot expect that this problem will be solved by* ***first communicating*** *all this knowledge to* ***a central board*** *which, after integrating all knowledge, issues its orders.* ***We must solve it by some form of decentralization.***[11] *"*

Hayek (1945) goes on to propose decentralised markets and their accompanying price signals as one appropriate solution to effectively allocating resources within a local community. Price signals allows for the dissemnation of information amongst a community, enough so that resources could be allocated efficiently (Hayek, 1945).

Local Energy Markets (LEMs) are widely recognised as a means to decentralise energy systems (Mengelkamp and Weinhardt, 2018). A LEM refers to a market where agents to virtually trade energy within their community (Mengelkamp et al., 2018b). Fundamental to LEMs is that they are organised around a group of localised DERs (Mengelkamp et al., 2018a). For example, a group of localised DERs could be a group of solar photovoltaic panels located in a residential neighbourhood as seen in the example of the Brooklyn microgrid (Mengelkamp et al., 2018a). Because DERs (such as solar PV panels) are inherently location-dependant, the development of a localised means to balance the generation and consumption of the those

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[11] Emphasis added

DERs is a natural next step to take (Weinhardt et al., 2019). It is the role of the LEM to provide a means to balance supply and demand in a local geographical region (Kirpes et al., 2019).

To realise a LEM an economic layer is introduced in addition to the physical microgrid (Considine, Cox and Cazalet, 2012; Kirpes et al., 2019; Zhang et al., 2018a). Energy trading, or exchange, between prosumer and consumer is generally implemented within the confines of a local electricity distribution system, such as a microgrid (Zhang et al., 2018a). Although not a technical requirement, this energy exchange is often peer-to-peer in nature (Zhang et al., 2018a). Peer-to-peer (P2P) energy trading simply refers to the exchange of energy directly between energy consumers and prosumers (Zhang et al., 2018a). The absence of intermediation from conventional energy actors (i.e., such as a municipality, or traditional third-parties) is a fundamental tenet of P2P energy trading (Mengelkamp et al., 2018b; Zhang et al., 2018a).

4.3.4 Revisiting terminology

In this chapter many new terms and concepts have been introduced to the reader. To avoid confusion, Table 7 below presents the important terms introduced up to this point, and once again attempts to clarify how the terms relate to one another.

Table 7: Important terms revisited

Term	Explanation
Distributed energy resource (DER)	DERs are publicly or privately owned small-scale power generation sources which can either be directly connected to the distribution network or, alternatively, on the client’s side of the electricity meter (Ackermann, Andersson and Söder, 2001; Capehart, 2016).
Renewable energy resource (RES)	A renewable energy resource, is a more specific instance of a DER. It is a DER that is *not* fossil-fuel driven. Classic examples include solar photovoltaic panels, or wind turbines. Within the context of this study, RESs are taken to refer primarily to solar panels.
Microgrid	A microgrid is a group of interconnected DERs with a distinct electrical boundary. It provides fine grained control over the DERs, as well as allowing the microgrid to isolate itself from the main grid in the event of a power outage on the main grid. Critically, a microgrid can present itself to the main grid as a single facing customer.
Feed-in-tariff	The standard manner in which governments attempt to involve prosumers in energy exchange. Prosumers inject electricity into the main grid in exchange for a fixed rate.

Local energy market	A newer approach to energy exchange, where energy exchange is premised on the idea that prosumers and consumers can directly exchange energy within their respective communities without relying on traditional feed-in-tariffs.
Peer-to-peer energy trading/ exchange system	A *system* which is built to facilitate decentralised energy exchange between consumers and prosumers. The system has both a physical component (i.e., the microgrid) and a cyber component (i.e., the information system enabling energy exchange).

4.4 Conceptualising a peer-to-peer energy trading system

Given that a LEM is simply an economic layer that aims to provide a marketplace within the confines of a microgrid, it is necessary to instantiate the LEM. A system which is able to facilitate P2P energy trading (i.e., through means of a LEM) is referred to as a P2P energy trading / exchange system (Zhang et al., 2018a). Implementing an energy exchange system within the confines of a microgrid presents its own unique challenges. Many of these challenges manifest as a result of the energy trading system's cyber-physical nature. Cyber-physical systems are systems where the physical world is intertwined with the virtual world (Aggarwal et al., 2019). For example, in the context of this study, the microgrid with all its accompanying electricity flows is situated within the physical world. Yet, the local energy market finds itself in the 'virtual world.' Information and communication technologies (ICT) are used to bridge this gap between the physical and the virtual (Aggarwal et al., 2019).

To aid in understanding this conceptual divide, researchers tend to divide a P2P energy trading system into different layers. Figure 3 below, captures the different layers involved in a P2P energy trading system. This abstraction was produced by Zhang et al. (2018a), and is simply represented in Figure 3 below. Similar abstractions can be found in Kirpes, Mengelkamp and Weinhardt (2019), Li et al. (2019) and Wang et al. (2018).

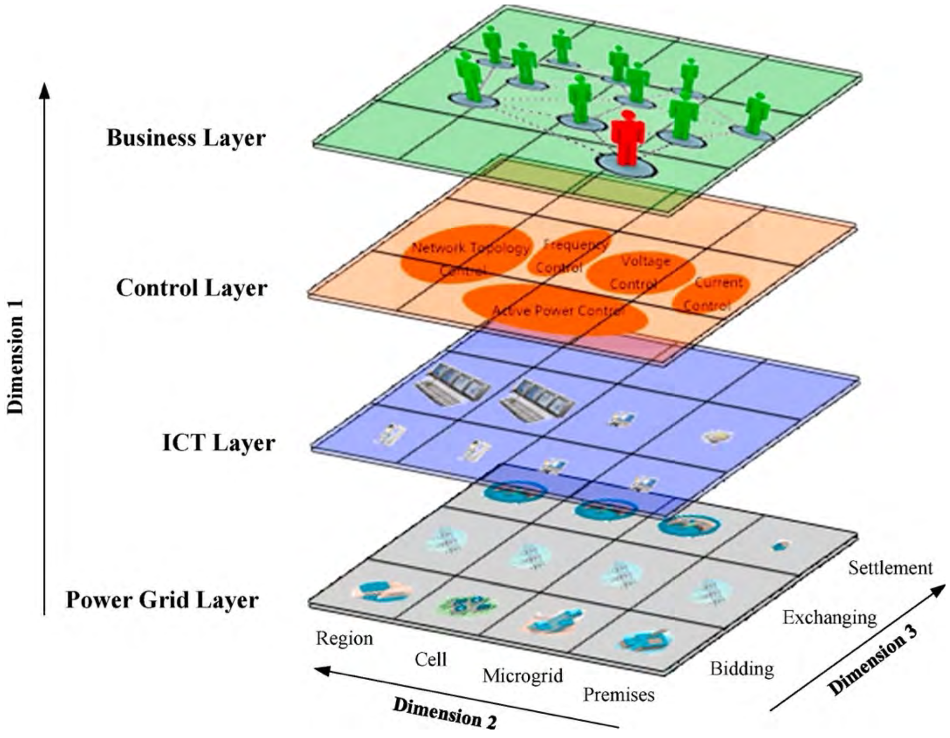

Figure 3: A four-layer architecture of a P2P energy trading system (Zhang et al., 2018a)

Figure 3 above illustrates that there are four different layers involved in P2P energy trading: (1) the power grid layer, (2) the ICT layer, (3) the control layer, and (4) the business layer. The power grid layer consists of all the physical components of the electricity system such as the physical grid, feeders, transformers, loads and DERs (Zhang et al., 2018a). A microgrid would be classified under the power grid layer. Next, the ICT layer, consists of communication devices such as smart meters and sensors, including the wireless connections that enable information transfer within the system (Zhang et al., 2018a). The control layer speaks to the control functions of the electricity system. A microgrid controller which ensures voltage and frequency balance, or which safely islands the microgrid, would be classified under the control layer (Zhang et al., 2018a). The business layer, determines how electricity is to be traded amongst members connected to the microgrid (Zhang et al., 2018a). Naturally, trading raises the two further ancillary questions of (1) how the electricity trade is to be guaranteed and settled financially and (2) to what degree the trading process could be automated. Various kinds of business models could be developed in the business layer when implementing a P2P energy trading system (Mengelkamp et al., 2018a; Zhang et al., 2018a). This study presents one such business model in Chapter 6.

4.5 Summary

This chapter introduced readers to the challenge of integrating distributed energy resources (DERs) with traditional legacy grids. Microgrids were put forward as *one* solution to integrating DERs with the public grid in a sustainable manner. The benefits underlying microgrid deployment were discussed, with specific reference to the South African context. Next, it was noted that to balance energy supply and demand within a microgrid, an energy market was required. Current feed-in-tariff schemas and their associated problems were discussed prior to introducing decentralised local energy markets (LEMs). It was pointed out that LEMs provide consumers with a more flexible solution towards facilitating the energy exchange between prosumer and consumer by moving away from traditional feed-in-tariff schemas. Lastly, it was explained that to actualise a LEM within the confines of a microgrid, a peer-to-peer (P2P) energy trading system was necessary. The cyber-physical nature of the P2P energy trading system was briefly discussed.

The following chapter is broken down into two core sections. First, the reader is introduced to blockchain technology more broadly. Essential to P2P energy trading is a secure information system. Blockchain is put forward as this secure information system. Following on from this, the core functional requirements of a blockchain-based microgrid energy trading system is discussed.

Chapter 5: Blockchain-based Microgrid Energy Trading System

"Security is the most crucial part of any system. It enables the machine to possess an initial 'state' or ground position and gain economic traction. If security is not integral to an information technology architecture, that architecture must be replaced."

George Gilder, Life after Google

This chapter introduces the reader to blockchain technology. First, the core components of blockchain technology are introduced and discussed. The second part of this chapter highlights the core functional requirements of a blockchain-based energy trading system. Each functional requirement is discussed in depth.

5.1 Blockchain: a secure information system architecture

Without an information system, energy trading (i.e., exchange) between prosumers and consumers is impossible. An efficient and secure information system constitutes the heart of peer to peer (P2P) energy trading (Tushar et al., 2020). Broadly speaking, such an information system is responsible for connecting all market participants and in doing so, provides the software platform necessary for the energy trading process to take place (Mengelkamp et al., 2018a; Zhang et al., 2018a).

P2P energy trading systems are technology agnostic, and as such, can be designed and implemented in a variety of ways (Li et al., 2019; Zhang et al., 2018a). For example, an energy trading system (ETS) could be designed around a centralised architecture which relies on a single database to house all system data. Alternatively, a decentralised architecture could be utilised, where system data is distributed and stored across multiple computers (i.e. nodes) (Abrishambaf et al., 2019; Tushar et al., 2020). Blockchain technology is one way to realise such a decentralised architecture, and is regarded by researchers as a viable information system for implementing an energy trading system (Alam, Islam and Ferdous, 2019; Kirpes et al., 2019; Li et al., 2019; Mengelkamp et al., 2018a; Tushar et al., 2020; Wang et al., 2019; Zhao et al., 2019).

5.1.1 What is blockchain?

Blockchain technology rose to prominence with the widespread attention received by Bitcoin (BTC) in 2008. Blockchain technology made it possible, for the first time, to carry out BTC P2P transactions within the confines of a trust-less network environment (Nakamoto, 2008). In essence a blockchain is a database that is duplicated amongst nodes, rather than stored in a single digital location (Andoni et al., 2019). Blockchain's distributed architecture is its most fundamental feature (Kirpes et al., 2019; Zhu et al., 2020). This distributed database (or in 'blockchain terminology' *digital ledger*) stores a continuously growing list of data records in their chronological order of issuance (Andoni et al., 2019).

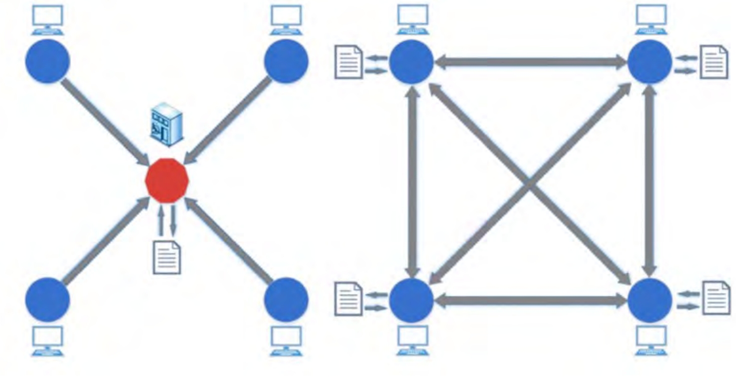

Figure 4: Centralised vs Distributed System (Andoni et al., 2019)

Figure 4 above illustrates the difference between a centralised database architecture and a distributed digital ledger. On the left, the centralised system[12] (what type of system remains irrelevant for now) has all its data stored in one location. In such an architecture, a central figure of authority is responsible for both managing and safeguarding the system data. Conversely, the distributed system (on the right) has no single data storage location. Rather, each node in the system network stores its own copy of the system data (Andoni et al., 2019). The system data is collectively maintained by the distributed nodes within the system (Andoni et al., 2019). The distributed digital ledger as illustrated in Figure 4 is fundamental to blockchain, yet blockchain technology consists of more than just the digital ledger. All blockchain-based systems are a combination of (1) distributed ledger technology, (2) a decentralised consensus mechanism and (3) asymmetric cryptography (Johanning and

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[12] **Note:** Wherever reference is made to a **centralised system** in this chapter, it refers to a **centralised information system**, **not** a centralised **energy** system. **These two concepts are distinct and should not be conflated**. If reference is made to a centralised **energy** system, it will be spelt out in full.

Bruckner, 2019; Mengelkamp et al., 2018b). Although (4) smart contracts are not an *inherent* feature of blockchain technology, they too, are generally to be found in most blockchain-based systems (Kim, Park and Ryou, 2018). Smart contracts are responsible for introducing automation capabilities. The four features listed above are often colloquially referred to as 'blockchain' (Andoni et al., 2019). The three inherent blockchain features, functioning together, make it possible for transactions to be carried out securely between peers, as well as for system data to be written to the digital ledger. This becomes possible without requiring a central intermediary to guarantee the integrity of the data, nor, the authenticity of the transaction (Mengelkamp et al., 2018a; Zhao et al., 2019). The above point is important: blockchain is not only effective in conducting transactions between two parties (though it does that particularly well), but it is also effective in simply storing system data as one would do with an ordinary centralised database system.

5.1.2 Blockchain Fundamentals

5.1.2.1 A typical blockchain transaction

This section begins by discussing the core steps involved in a typical blockchain transaction. Here, transaction is broadly construed as either a financial transaction between two parties, or simply writing data to the digital ledger. Discussing a typical transaction, clarifies the interoperable nature of the four key components of blockchain technology prior to discussing each component in greater detail. In this discussion, each of the four blockchain components are bolded to draw attention to what role they play in the typical transaction process.

Figure 5: A typical blockchain transaction (Andoni et al., 2019)

To a large degree, how a blockchain transaction is processed is determined by the consensus mechanism of the blockchain implementation (Hartnett et al., 2018; Mengelkamp et al., 2018a). A consensus mechanism is the set of rules implemented to maintain agreement on a single state (i.e. the most up to date data record) for the digital ledger at all times of operation (Agung and Handayani, 2020). Performing valid CRUD (create, read, update, delete) operations and establishing the validity of transactions on the blockchain network is the responsibility of the consensus mechanism. In the discussion about to follow, a Proof of Authority (PoAu) consensus mechanism is utilised. The five essential steps of a typical blockchain transaction are as follows (Aggarwal et al., 2019; Andoni et al., 2019; Deutsche Energie-Agentur GmbH, 2016; Hartnett et al., 2018):

1. First, a transaction request is transmitted to the network containing specific information that is of importance to the transaction being processed. For example, in a Bitcoin transaction this information would include the number of coins to be transferred from party A to party B and the recipient's public address (**cryptography used here**). The message is signed by the sender's private key (**cryptography used here**) which serves as a 'digital signature', used to confirm the legitimacy, and stamp the point of origination, of the transaction. A transaction can be either triggered automatically, **by a smart contract**, or manually by a user in the network.
2. As previously illustrated in Figure 4, the P2P network is comprised of nodes (devices with unique IP addresses). A subset of these nodes (validator nodes) continuously receives transaction requests (**consensus mechanism applied here**). Upon receiving each transaction, the digital signature that signed the transaction is validated by referring to its public key counterpart (**cryptography used here**). This is to ensure that the transaction was initiated by a trusted node in the network. If the transaction is considered valid, the authenticated transaction is placed in a pool of pending transactions (**consensus mechanism applied here**).
3. Next, an algorithm assigns one validator node as the primary validator node (**consensus mechanism applied here**). This primary validator node aggregates pending transactions into a block and confirms the validity of each transaction (**consensus mechanism applied here**). Confirming the validity of a transaction, could, for example, involve ensuring that the 'buyer' node has enough cryptocurrency to spend for the given transaction.
4. Upon completion of this step, the block is broadcasted to the remaining validator nodes, who confirm the primary node's validation (**consensus mechanism applied here**).
5. If the other validator nodes agree with the primary validator node that all the transactions in the block are indeed valid, the block is appended to the **digital ledger.** Once a new block is appended, the new state of the **digital ledger** is communicated to all the nodes in the network. Blocks are timestamped and cryptographically linked to

each other, which forms both an (1) immutable and (2) tamper-proof digital ledger (**cryptography used here**).

5.1.2.2 Different types of consensus mechanisms

Blockchain technology can remove the need to rely on a central intermediary to validate the data stored and transactions processed within a distributed system. Ultimately, it is the role of the consensus mechanism to ensure that a particular piece of information is correct, and that this agreement is shared amongst most of the nodes on the blockchain network (Bains and Melo, 2022). There are a variety of consensus mechanisms available[13], each catering to a specific outcome (Bains and Melo, 2022). For example, Proof of Work (PoW) consensus mechanisms can provide a secure and tamper-proof digital ledger within a low-trust environment by forcing validator nodes to engage in computationally heavy tasks. In contrast to this, a Proof of Authority (PoAu) consensus mechanism is best implemented in a relatively high-trust network environment (two-thirds honest nodes), and as such, can prioritise transaction speed and network efficiency by pre-determining a group of validator nodes based on their identities (Bains and Melo, 2022; Zhang et al., 2019). Table eight below presents *a few* of the popular consensus mechanisms that are available to govern digital ledgers. Due to the breadth of the topic at hand, it is not possible to discuss all the consensus mechanisms available today. For example, one study surveys 25 consensus mechanisms available for use in cyber-physical systems alone (Bodkhe et al., 2020). The goal of the table below is simply to provide a bird's eye view of some of the more popular consensus mechanisms available to blockchain-based systems.

Table 8: Blockchain consensus mechanisms

Consensus mechanism	**Explanation**	**Public or permissioned blockchain**[14]
Proof of Work (Pow)	The Proof of Work (PoW) consensus mechanism was popularised by Bitcoin (Bodkhe et al., 2020; Zhang et al., 2019). The fundamental premise underlying PoW consensus mechanisms is that validator nodes must complete a computationally intensive algorithm to ensure	Public

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[13] Section 5.1.2.3 elaborates on the factors that go into selecting the appropriate consensus mechanism for a given system context.

[14] The distinction between public and permissioned blockchains is drawn out in the following section (section 5.1.2.3). However, in a nutshell, public blockchains allow any member of the public to become a validator node, whereas in a permission blockchain only a select group of nodes are authorised to validate transactions.

	that transactions are valid, and as such, may then be written to the digital ledger. By introducing a computationally heavy algorithm, attackers are deterred from polluting the blockchain with invalid or malicious transactions (Zhang et al., 2019). Common problems faced by PoW includes computational cost and the infamous 51% attack (Andoni et al., 2019; Zhang et al., 2019).	
Proof of Stake (PoS)	Proof of Stake (PoS) was introduced to reduce the energy consumption introduced by the PoW consensus mechanism's computationally intensive puzzle. PoS is premised on the fact that the next eligible block is appended to the digital ledger by miners who have 'staked' their own cryptocurrency tokens on the block (Bains and Melo, 2022; Zhang et al., 2019). With a PoS consensus mechanism, nodes are incentivised to be honest since they have staked their own tokens, and as such, stand at risk of losing their tokens, not being rewarded with transaction fees, and furthermore, from being banned from future participation in transaction validation (Zhang et al., 2019). A common criticism levied against PoS is that the consensus mechanism is fundamentally unjust as miners are selected based off the size of their stake (i.e., how much cryptocurrency they own of a particular digital ledger). This in turn, implies that the wealthy miners remain wealthy, whilst validator nodes with smaller stakes stand a much smaller chance of being selected and rewarded with the appropriate transaction fees.	Public
Delegated Proof of Stake (DPos)	Delegated Proof of Stake (DPoS), like PoS offers a public consensus mechanism that improves network efficiency and scalability over Bitcoin's PoW mining (Zhang et al., 2019). DPoS places a larger emphasis on decentralised governance, where validator nodes are selected in a democratic fashion (Bodkhe., 2020). This stands in contrast to a PoS governance structure which is premised on the idea that the wealthiest nodes, in essence, become de-facto validator nodes. In a DPoS system, stakeholders vote for other nodes in the network (often referred to as witnesses) to perform critical tasks such as validating transactions (Bains and Melo, 2022; Zhang et al., 2019). Stakeholder votes are proportional to the number of tokens owned (Bains and Melo, 2022; Zhang et al., 2019). Like PoS, DPoS is also prone to centralisation over time, as tokens within the network are distributed disproportionately amongst the different stakeholders (Zhang et al., 2019).	Public
Proof of Elapsed Time (PoET)	Proof of Elapsed Time (PoET) requires nodes to wait for a random period prior to validating transactions and appending a block to the	Permissioned

	digital ledger (Bains and Melo, 2022). With PoET, each node on the network generates a randomised waiting period and is then required to wait for the time to elapse. More specifically, the node with the shortest wait time gains the privilege of appending a new block to the digital ledger (Bains and Melo, 2022). PoET promotes network efficiency as nodes are able to go offline, or engage in other network related tasks whilst waiting for their allotted time to elapse. This, in turn, results in energy and cost savings.	
Proof of Authority (PoAu)	Proof of Authority is built upon the same design philosophy as Proof of Stake but tries to optimise the mechanism even further (Zhang et al., 2019). PoAu works best in a network environment with at least partial trust. With PoAu, a validator node stakes its own identity as opposed to solving a computationally heavy puzzle (PoW) or staking cryptocurrency (i.e., PoS or DPoS) (Bains and Melo, 2022). With a PoAu system, validator nodes are often pre-determined and as such, transactions can be processed much more efficiently at a fraction of the computational cost Zhang et al., 2019). The downside of this approach is that the means to guarantee the integrity of the digital ledger is ultimately more centralised than decentralisPoAu is particularly suited towards system environments with strict regulatory requirements where an emphasis is placed on user trustworthiness and reputation (Zhang et al., 2019).	Permissioned

5.1.2.3 Blockchain taxonomies and consensus mechanisms

The decision as to which consensus mechanism to implement is never made within a vacuum. Key system parameters such as (1) system scalability, (2) transaction speed, (3) security and (4) resource expenditure are all determined by the type of consensus mechanism implemented (Andoni et al., 2019). Thus, special attention needs to be given to the task of assessing which consensus mechanism is most suited to a particular system (Andoni et al., 2019; Johanning and Bruckner, 2019). When assessing the suitability of a consensus mechanism for a particular blockchain-based system, it is often the *type of blockchain* implemented, that plays a large role in determining which consensus mechanism gets adopted (Abdella and Shuaib, 2019; Mengelkamp et al., 2018a). A blockchain can be one of two types: (1) public, or (2) permissioned (Abdella and Shuaib, 2019; Li et al., 2019). In a public blockchain, any user is able to join the network, and consequently take on any role, including that of a validator node (Nakamoto, 2008). Conversely, a permissioned blockchain has predefined rules stipulating precisely who is allowed to join the network, including the read/write privileges assigned to each node (Abdella and Shuaib, 2019). Permissioned blockchains are further divided into private and consortium blockchains (Aggarwal et al., 2019). For a private blockchain, the digital ledger is maintained and updated by a *single* validator node (i.e. high degree of centralisation), whereas for a consortium chain, it is governed by a *set* of pre-selected validator nodes (Abdella and Shuaib, 2019).

Consortium and private blockchains tend to operate in medium to high trust environments respectively (Mengelkamp et al., 2018a). In contrast to this, a public blockchain operates in a low trust environment, and as such, the consensus mechanism used has to guarantee a secure system that leaves no room for any malicious node to manipulate the digital ledger (Mengelkamp et al., 2018b). This scenario is illustrative of how the blockchain *type* (i.e., public) has certain requirements (high levels of system security), and therefore, determines the nature of the to be implemented consensus mechanism. Take the example of Bitcoin, for example. Bitcoin is a public blockchain. To maintain a *high degree of information* integrity, Bitcoin implements a *computationally intensive* consensus mechanism known as Proof of Work (see Table 8 above). Computationally intensive consensus mechanisms ensure validator nodes incur personal costs when validating transactions, and as such, are discouraged from engaging in fraudulent activity (Andoni et al., 2019; Mengelkamp et al., 2018b). When deciding which consensus mechanism to implement there is always a trade-off between maintaining a high degree of information integrity vis a vis computational cost (Mengelkamp et al., 2018a). As noted in Table 8, the main criticism faced by consensus mechanisms, such as PoW, is its resource intensiveness and slow transaction verification speeds (Andoni et al., 2019; Zhao et al., 2019). Given this resource intensiveness, it is self-defeating to suggest that an energy trading system utilise a consensus mechanism that consumes 200 kilowatt hour of electricity per transaction (as Bitcoin does), whilst the trading platform simultaneously has as one of its fundamental pillars energy sustainability and renewable energy sources (Andoni et al., 2019; Mengelkamp et al., 2018a).

Instead, researchers propose that consortium blockchains are best suited towards the development, and implementation of blockchain-based energy trading systems (Andoni et al., 2019; Hartnett et al., 2018; Tushar et al., 2020; Zhao et al., 2019). The *first reason* for this conclusion is rooted in the consensus mechanisms most often utilised by consortium blockchains (Hartnett et al., 2018; Wang et al., 2019; Zhao et al., 2019). Proof of Authority

(PoAu), as introduced in section 5.1.2.1 above, is an example of a consensus mechanism commonly used in conjunction with a ‘consortium-chain’. In a PoAu blockchain, CRUD operations, and the verification of transactions, becomes the responsibility of a pre-determined group of nodes that possess a specific and trustworthy digital identity (Andoni et al., 2019). Because validator nodes are presumed to be trustworthy, consortium blockchains utilise simple and lightweight consensus mechanisms, which speeds up the process of verifying the validity of blockchain processes (Li et al., 2019). By implication, PoAu has proven particularly fruitful in the blockchain energy domain as blockchain-based energy systems typically have high-frequency data recording requirements (Andoni et al., 2019; Wang et al., 2019; Zhao et al., 2019). For example, one such successful implementation is the Energy Web Foundation’s PoAu blockchain, where transaction processing speeds of 3-4 seconds have been achieved (Andoni et al., 2019; Hartnett et al., 2018). To put this into perspective, Bitcoin takes approximately 10 minutes to process and clear a transaction (Andoni et al., 2019). An energy trading system utilising a slow consensus mechanism (like that of Bitcoin) could result in system bottlenecks whilst processing numerous real-time transactions. Speedy transaction processing times are vital for a near-real time energy trading system where energy bid and purchase offers have to take place in successive 15-60 minute intervals, depending on the system configuration (Li et al., 2019; Zhang et al., 2018a). Table 8 below presents the benefits of a PoAu mechanism as opposed to a more computationally intensive consensus mechanism, such as Proof of Work.

Table 9: Proof of Authority (PoAu) Consensus Mechanism Benefits

Benefit	Explanation
1. More consistent and trustworthy 2.Significantly improved resource efficiency 3. Increased throughput	By using pre-determined validator nodes, the integrity of their identities is established in advance. Thus, there is a certain level of trust inherent to PoAu not known to other consensus mechanisms. As a result of this, resource efficiency is enhanced, as less resource intensive consensus mechanisms are used. This, in turn, increases transaction throughput.
4. Reduced transaction costs	Reduced computing and energy requirements for validator nodes lowers the operating cost for validator nodes. In turn, this lowers the cost of each blockchain transaction for end users.
5. Minimal network latency	Because validator nodes are known in advance, they can install dedicated hardware and high-speed Internet connections for transaction validation. This is not possible with Proof of Work where the selection process for validator nodes is randomised.

6. Simplified protocol upgrades	Upgrading the core protocol of the blockchain network and ensuring validator compliance is much simpler with a few known entities, rather than pseudo anonymous entities as found with a typical Proof of Work mechanism.

The *second reason* for the applicability of a consortium blockchain to an energy trading system has to do with how well suited consortium blockchains are for systems operating in highly regulated environments (Li et al., 2019; Wang et al., 2019; Zhao et al., 2019). For example, in a microgrid peer-to-peer energy trading system there are numerous stakeholders, including: (1) prosumers, (2) consumers, (3) the microgrid controller (MC), (4) the public grid operator, (5) the blockchain platform provider, and possibly even an (6) energy regulator (such as NERSA) in South Africa. Each of these stakeholders share similar goals (for example, to increase energy security in the neighbourhood), but inevitably, these special interest groups also pursue their own, and often conflicting, economic interests (Zhang et al., 2018a). For example, prosumers want to maximise their profits when selling energy, whereas consumers wish to purchase the cheapest electricity possible (Kirpes et al., 2019). Another example: individuals connected to the microgrid may not be satisfied if the energy trading system is configured in such a manner that financial transactions are automatically billed for electricity imported from the main grid via the public grid operator, without any regulatory mechanism in place. If there is no way in which these stakeholders could be held accountable to one another the potential for corruption and dishonest use of the system exponentially increases (Aggarwal et al., 2019). The advantage of consortium blockchains lies in their ability to accommodate stakeholders from each competing interest group to collectively act as validator nodes for energy transactions – see section 5.1.2.1 above (Hartnett et al., 2018; Mengelkamp et al., 2018a). Consensus mechanisms that are able to be configured to such granular level (i.e., to accommodate for complex regulatory schemas) are simply not possible with public or private blockchains (Wang et al., 2018; Zhao et al., 2019). Energy blockchain researchers are in agreement that a consortium blockchain that utilises a PoAu mechanism is both technically viable and preferable for a blockchain-based microgrid energy trading system as can be seen in Andoni et al., 2019; Hartnett et al., 2018; Kirpes, Mengelkamp and Weinhardt, 2019; Wang et al., 2019 and Zhao et al., 2019. This is of particular importance as both Mengelkamp et al., (2018a) and Wang et al. (2019) advocate the use of consortium blockchains (utilising PoAu) in small community-based microgrid energy trading systems – given that this is the context for this study.

5.1.2.4 Cryptography

Blockchain is strongly dependent upon cryptography for establishing a secure system. Importantly, cryptography enables (1) authentication and authorisation, (2) immutability, (3) information integrity, (4) auditability and (5) non-repudiation in blockchain-based systems (Aggarwal et al., 2019; Li et al., 2019). By leveraging blockchain-technology such features are easily integrated into a peer-to-peer (P2P) energy trading system. Conversely, a traditional centralised system would not be able to provide the security features as easily nor as efficiently in a smart-community setting (Aggarwal et al., 2019).

Cryptography is primarily active in two areas of blockchain-based systems. The first area concerns block generation. Abstracting away from the intricacies, every time a new block is appended to the digital ledger it is linked to the previous block with a cryptographic pointer (Andoni et al., 2019; Li et al., 2019). Information in each block is also encrypted with a one-way hash-function (Li et al., 2019). As such, compromised information becomes worthless to a malicious node, as the node cannot restore the information to its pre-encrypted state (Li et al., 2019). The main point to take away from cryptography and block generation is the following: *cryptography is built into block generation, and as such, guarantees an (1) immutable and (2) tamper proof data record. If data held by one node is compromised it is not a problem, as all other nodes on the network hold their own copies. Any breach is easily identified and rectified due to cryptographic hashing* (Alam, Islam and Ferdous, 2019; Andoni et al., 2019). Guaranteeing an immutable and tamper evident data record is, in principle, not possible with a centralised database architecture (Andoni et al., 2019).

The second area where cryptography is utilised in blockchain-based systems is in enabling authentication and authorisation processes in blockchain-based systems (Aggarwal et al., 2019; Li et al., 2019). Authentication concerns establishing a node's identity in contrast to authorisation which concerns itself with establishing a node's permissions levels in the system (Aggarwal et al., 2019). All nodes that participate in the energy trading system have both a public and private key (Li et al., 2019). To provide an analogy, regard the public key as a post-box, and the private key as the physical key used to unlock that post-box. On the blockchain network, the public keys of all nodes are available to all other nodes. This allows for each node to become an addressable entity on the blockchain network (Li et al., 2019). Consequently, this enables messages to be sent amongst nodes, or for two nodes to engage in a financial transaction (Li et al., 2019; Zhao et al., 2019). On the other hand, each node holds its own private key, inaccessible to any node on the network. The private key is used to decrypt information sent to its public key (i.e. unlocking a post-box to get the mail), or alternatively the private key (because it is unique and in single possession by its owner) can be used to sign transactions, which in the process guarantees non-repudiation (Li et al., 2019). One of the most important features of blockchain, is that it allows for users to prove that they did or did not do something, and as such, 'signing' transactions with a private key leaves an immutable record of user activity (Gilder, 2019). For example, in the context of an energy trading system, if prosumer A disputes that prosumer B did not pay for the energy transacted, a simple lookup can be done on the immutable digital ledger to see if both private key signatures are present when the exchange took place. The system could be configured in such a manner that if party B's signature is present on the transaction, it implies that indeed financial compensation was received by party B (Li et al., 2019). Such configurations are done via smart contracts, the next topic of discussion.

5.1.2.5 Smart Contracts

Smart contracts are said to be the *summum bonum*[15] of blockchain technology (Andoni et al., 2019; Cohn, West and Parker, 2017; Kirpes et al., 2019; Li et al., 2019; Sabounchi and Wei, 2017; Wang et al., 2019). Through the implementation of smart contracts, and only then, can blockchain technology's full potential be realised (Andoni et al., 2019; Li et al., 2019; Zhu et al., 2020). A smart contract is defined as:

> *"… a computer program that is capable of [self] executing or enforcing a predefined agreement using a blockchain, when and if specific conditions are met. Its main goal is to enable two parties to perform a trusted transaction [automatically] without having the need of intermediaries"* (Kounelis et al., 2017, p.2).

Several important points emerge from the above definition, including the fact: (1) that smart contracts are computer programs, (2) that smart contracts are executed upon the satisfaction of specific conditions, and (3) that smart contracts enable automated trusted transactions between parties, without the need for central intermediaries. Points 1-3 are briefly discussed below. Regarding point one, smart contracts are simply if/else statements (i.e. predefined rules)

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[15] The highest or ultimate good

implemented as self-executable computer scripts (Cohn, West and Parker, 2017). These if/else statements are executed once certain conditions are satisfied via the provision of either internal or external information. Internal information originates from within the blockchain network, whereas external information is provided by way of *oracles* (Cohn, West and Parker, 2017). An oracle is an external data source, either in the form of a personal agent (e.g. the public grid operator), or alternatively, a digital device (e.g. a smart meter) (Cohn, West and Parker, 2017). It is the responsibility of an oracle to monitor the external conditions that are encoded within a smart contract, and in turn, feed information back into the smart contract that is of relevance to those conditions. Depending on the information provided, and what the conditions of the smart contract are, particular state changes are triggered in the blockchain-based system (Voshmgir, 2019). Oracles are necessary given that a blockchain implemented with native features only, is in principle, incapable of accessing information that lies outside the blockchain network. Hence, there is need for an external source to pass information into the blockchain network (Voshmgir, 2019). Not all smart contract implementations require oracles, rather, it depends whether there is need to access external data for the process that is automated by the smart contract. Below are examples of typical use cases for smart contracts within a blockchain energy trading system:

1. Smart contracts could be used to automate the trading hours for users of the blockchain-based energy trading system. For example, smart contracts could contain the following conditional for prosumers: *if* the local time for prosumers is between 8AM – 4PM on a weekday enlist all surplus self-generated electricity on the energy trading system’s energy market portal (Yang et al., 2020).
2. Smart contracts could be used to announce each iteration of a specific energy bidding and selling window by notifying each node in the network 5 minutes prior to the trading window opening (Sabounchi and Wei, 2017).
3. Smart contracts could be used to automate the financial settlement process between users of the blockchain energy trading system (Mengelkamp et al., 2018a; Li et al., 2019).
4. Smart contracts in conjunction with smart meters could be used to automatically record the amount of energy consumed and produced by individual households on the blockchain’s digital ledger (Andoni et al., 2019). For example, a smart meter (oracle) could be configured to push electricity readings to a smart contract every 5 minutes, which would then trigger the recording of the data onto the digital ledger.

A recurring theme found in all the examples provided above, is that smart contracts are the primary mechanism for instilling operational intelligence in the energy trading system (Andoni et al., 2019; Li et al., 2019). Recall from Chapter 3 section 3.2.3 that one of the key trends for the future of energy systems lies in automation. Furthermore, as can be seen by the range of examples offered, smart contracts are not restricted to the settlement of financial transactions only, but are also useful for streamlining the day to day operation of the physical microgrid as well as in the utilisation of other ancillary services of the blockchain energy trading system (Li et al., 2019; PwC, 2016). The above examples also delineate how smart contracts are executed only once certain conditions are satisfied, as per point (2) of the smart contract definition provided above. Taking point (3) of the smart contract definition, the reason why smart contracts allow for trusted transactions between parties is because smart contracts inherit blockchain's property of immutability, and therefore, by implication are guaranteed to execute given that certain conditions are satisfied (Agung and Handayani, 2020; Li et al., 2019). Figure 6 below illustrates a *high-level* business process model for a *financial settlement* smart contract. The process model highlights the steps performed by a smart contract once a particular condition is satisfied (party B receiving 5 units of electricity from party A). The purpose of Figure 6 is to demonstrate the automation capabilities offered by smart contracts.

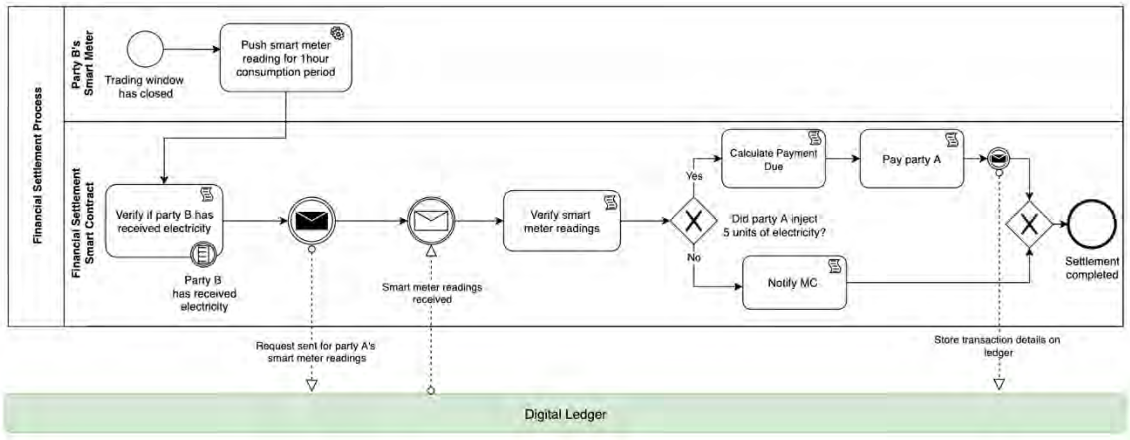

Figure 6: Role played by smart contract in financial settlement

The above discussion on smart contracts, particularly in conjunction with Figure 6, suffices in demonstrating the potential, and applicability, of smart contracts for designing and implementing 'smart' blockchain-based energy trading systems (Zhu et al., 2020). More will be said about the role of smart contracts when the actual design of the blockchain-based energy trading system is discussed below.

As noted at the start of this section, researchers have put blockchain technology forward as a suitable information system for peer-to-peer (P2P) energy trading. This section demonstrated that blockchain is a natural fit for P2P energy trading as blockchain’s consensus mechanism provides a means to reliably verify transactions between parties without a central intermediary (Andoni et al., 2019; Yang et al., 2017). This is the core, and *unique*, benefit offered by blockchain technology (Andoni et al., 2019). Furthermore, it was noted that blockchain technology provides cryptographic protection of users’ data and identity. A further benefit of adopting blockchain technology within the context of P2P energy trading is the provision of smart contracts as means to automate critical business processes.

5.2 The Blockchain-based microgrid energy trading system

Up to this point, the four core components of blockchain technology have been surveyed from a bird’s eye view, and at certain critical junctures discussed in greater depth. The next section lays out the various sub-systems and processes involved in a blockchain-based energy trading system (ETS). Each process, or sub-system, is discussed by explaining *what* purpose each process / sub-system serves and *how* each sub-system / process functions.

5.2.1 Some preliminaries

In the paper *‘Designing Microgrid Energy Markets’* by Mengelkamp et al. (2018a) (now regarded in some measure as seminal) seven essential components for microgrid energy markets were identified. One such component identified was an *energy management trading system* (EMTS) (Mengelkamp et al., 2018a). In a nutshell, the goal of the EMTS is to automate the process of securing energy supply on behalf of the market participants by implementing specific bidding strategies (Mengelkamp et al., 2018a). To ascertain what precisely such a system is expected to achieve in a given business context, system analysts engage in a requirement elicitation process (Satzinger, Jackson and Burd, 2016, p.5). Ultimately, such a process reveals the functional requirements of the system (Satzinger, Jackson and Burd, 2016, p.5). Functional requirements are those activities that a system must perform in order to accomplish the system goals that emerge from the business context within which the system operates (Satzinger, Jackson and Burd, 2016, p.5). For example, suppose it is a requirement that the EMTS must allow for a prosumer and consumer to communicate via private messaging. This would be determinative of a functional requirement for the system. In broad outline, the primary purpose of this study’s energy trading system is as follows: the system is expected to automate the energy trading process between various individuals in a microgrid tied neighbourhood. To enable such a process, the system has a two-pronged task of (1) facilitating the trading process via an energy market platform, as well as (2) facilitating and supporting the operation of the physical microgrid.

As hinted at above, researchers such as Mengelkamp et al. (2018a) and Tushar et al. (2020) construe the purpose of the EMTS narrowly: the system is solely responsible for facilitating the trading of energy at a market level where automated bidding, selling and financial settlement constitute the system’s primary activities. In such a schema, almost no attention is paid to the physical layer aside from incorporating smart meter readings into the bidding strategies of consumers. One possible reason for the more narrow and focused approach adopted by Mengelkamp et al., (2018a) is that the study was implemented in a New York suburb, where prosumers were ultimately being paid by their neighbours for injecting electricity into the New York national grid – with the microgrid only acting as a backup on the physical layer (Mengelkamp et al., 2018a). In other words, the project still in its infancy at the time, was not a microgrid implementation in toto. Naturally, there would be less room in such an implementation for exploratory and theoretical ideas to be put forward as seen can be found in the studies of Li et al. (2019), Yang et al. (2020) and Zhao et al. (2019). These latter research efforts envision the role of the EMTS as something broader and more intricate. This broader view encompasses the narrow conception of the EMTS (as construed by Mengelkamp et al. and Tushar et al.). In other words, the broader view does facilitate and automate bidding, selling and financial settlement processes. However, the broader view also includes the process of supporting the physical operation of the microgrid, as well as engaging in other ancillary activities such as authentication and authorisation processes (Li et al., 2019). Perhaps, it would be more accurate to refer to this latter system not as an electricity management trading system (EMTS), as defined by Mengelkamp et al., (2018a), but rather as *a transactive energy management system solution*, as it is referred to in the research of Abrishambaf et al. (2019) and Li et al. (2019). As Li et al. (2019) note: their system is designed to address both (1) *operational* and (2) *financial* challenges posed by the emergence of distributed energy resource (DER) based microgrids. However, it must be added, that both system conceptions undeniably share considerable overlap as both are *primarily* focused on energy trading (i.e., facilitating energy exchange between prosumers and consumers). Yet, the distinction between the two system conceptions is also clear: the EMTS is solely focused on *automating* trading and settlement, whereas the TEMS is trading focused, but includes the management of other system related activities too.

This study will refer to its proposed system simply as a ‘blockchain-based energy exchange system’ (BEES)[16]. However, when reference is made to this BEES throughout the study, it is to be construed in the broad sense of being a member of *transactive energy management system solution*. In the discussion to follow, the system under consideration will simply be called an energy trading system (ETS). In the next chapter, this study’s system (i.e., the BEES) which implements the above discussed functional requirements is presented. To see what an ETS is expected to achieve the following functional requirements (FRQ) were identified in the relevant literature sources:

1. FRQ1: The ETS is required to facilitate and provide support for the configuration of the physical microgrid prior to energy trading taking place within a specific window of time (Kirpes et al., 2019; Li et al., 2019; Zhao et al., 2019).
2. FRQ1 continued: The ETS must assist in the microgrid islanding process (Hirsch, Parag and Guerrero, 2018).
3. FRQ2: The ETS requires an access control sub-system that handles all authorisation and authentication processes for prosumers and consumers registering on the ETS the first time (Li et al., 2019; Mengelkamp et al., 2018a; Zhao et al., 2019).
4. FRQ3: The ETS has to enable prosumers and consumers to engage in their respective buy and sell orders during each particular trading interval (Li et al., 2019). This has to take place in a democratic and non-discriminatory fashion (Mengelkamp et al., 2018a). The ETS is expected to aid in the electricity balancing process within the microgrid by either suggesting that the microgrid controller export or import electricity to the public grid as necessary (Kirpes et al., 2019; Li et al., 2019).
5. FRQ4: The ETS must handle various state estimation processes. During such a process, smart meters are used to ensure that the electricity procured by party A, was indeed delivered by party B (Zhang et al., 2018a). In the event that electricity was not delivered, or there was a discrepancy in the amount of electricity delivered, the ETS is expected to take remedial action (Li et al., 2019; Zhang et al., 2018a).

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[16] The word ‘exchange’ was adopted instead of ‘trading’ to get away from the image of trading that is generally associated with the idea of a direct exchange between two parties only. This will become clearer in the following chapter.

6. FRQ5: The ETS must automate all financial settlements for each individual energy transaction between two parties, as well as automatically handling and resolving financial disputes between parties (Li et al., 2019).
7. FRQ6: The ETS must store all on-going operational data pertaining to both the physical operation of the microgrid (i.e. concerning energy flows), as well as the data pertaining the market activities (i.e. bid and sell offers, as well as financial transactions) (Mengelkamp et al., 2018a). This must be achieved in a satisfactorily secure manner (Kounelis et al., 2017).
8. FRQ7: The ETS must be able to communicate with all nodes via public broadcast messages, as well as communicate with individual nodes where appropriate (Andoni et al., 2019; Tushar et al., 2020). This includes announcing the opening of energy trading windows and other important state changes on the microgrid (Yang et al., 2020).
9. FRQ8: The ETS must automate as many of its processes as possible, not only to increase the user friendliness and customer retention rates of the system, but also to streamline the operational efficiency of the overall system (Mengelkamp et al., 2018a; PwC, 2016; Yang et al., 2020).

These functional requirements define the various activities to be carried out by this study's ETS. When conducting system analysis and design related research, it is commonplace to adopt an *intermediate* abstraction level when considering the functional requirements (Kirpes et al., 2019; Li et al., 2019; Zhao et al., 2019). A similar approach is employed in this study. Below, each functional requirement that constitutes a clear business process is discussed as *found in the literature base*. The discussion is discursive rather than systematised. This sets the study up for the business process model (BPM) to be introduced and discussed in following chapters. The BPM itself, preceded by other analysis-based activities will demonstrate how the system operates in a more formalised and sequential manner.

5.2.2 Functional Requirement 1 (FRQ1): Configuring the physical microgrid

Electricity, by virtue of its physicality, is distinct from other 'virtual' commodities (e.g., cryptocurrency) exchanged over blockchain infrastructure. As such, the physicality of electricity, acting in accordance with certain physical laws, impose constraints on the operational flexibility of the ETS (Li et al., 2019; Mengelkamp et al., 2018a). For example, electricity line flows are restricted by thermal or stability requirements and if not adhered to leads to power flow congestions (Li et al., 2019; Zhang et al., 2018a). As a result, an indeterminate quantity of electricity cannot be injected into the microgrid without compromising the secure delivery of electricity. Rather, the quantity of electricity to be injected into the microgrid has to be predetermined in a reliable and predictable fashion (Zhang et al., 2018a). Researchers have proposed a number of solutions towards addressing the problems posed by the physicality of electricity (Hirsch, Parag and Guerrero, 2018). The end goal of all such proposals is to guarantee both a (1) reliable and (2) secure supply of electricity within the confines of the microgrid and broader electricity system (Zhang et al., 2018a). There are essentially two phases involved in the process of configuring the microgrid network (Li et al., 2019). Phase one takes place prior to the opening of a given electricity trading window. During this first phase, the microgrid operator considers the general physical limitations of the microgrid (Li et al., 2019). Typical factors considered by the microgrid operator includes (1) whether the distributed energy resources (DERs) owned by prosumers are reliable enough to participate in a given trading window, (2) how best to ensure quality electricity services through appropriate voltage and frequency control measures, and (3) perhaps even, how to maximise the environmental and economic well-being for the microgrid community (Li et al., 2019; Zhang et al., 2018a). In short, the primary purpose of phase one is to determine what the microgrid network's operational constraints are. The second phase takes place at the conclusion of the trading window (and thus falls under FRQ3 – see section 5.2.4). Here the purpose is simply for the MC to reject or accept (or appropriately modify) trading offers based on the microgrid's operational constraints as determined during phase one.

For this study's BEES (i.e., this study's implementation of an energy trading system), the grid operator responsible for configuring and operating the physical microgrid is the microgrid controller (MC) (Li et al., 2019; Kirpes et al., 2019). It is assumed that the MC is outsourced via Eskom, as briefly discussed in Chapter 4 (see section 4.2.3). Importantly, the MC is assisted by machine learning techniques that are applied to historical configurations, which then, accordingly suggest the appropriate voltage and frequency parameters for a given electricity exchange window (Kirpes et al., 2019; Li et al., 2019). For this study's BEES, three further assumptions are made concerning the physical layout of the microgrid:

1. Firstly, each prosumer has a battery storage solution locally installed to increase the robustness of the microgrid (Hirsch, Parag and Guerrero, 2018; Kirpes et al., 2019; Mengelkamp et al., 2018a; Kounelis et al., 2017). Battery storage solutions in European countries such as Germany are already experiencing mainstream adoption via municipal lease models (Green and Newman, 2017; Zeller et al., 2017, p.18).

2. A second assumption is that the physical microgrid includes a large-scale community battery, as suggested in the study of Yang et al. (2020). The purpose of the community battery is for grid-stabilisation purposes as the battery is capable of being dispatched at peak load times (Zeller et al., 2017, p.18; Zhang et al., 2018). Large-scale batteries are already being tested in small microgrid set-ups in Germany, as discussed by Zeller et al. (2017, p.18).
3. The third assumption made is that the microgrid interfaces with the main grid in the event where surplus electricity needs to be exported to the main grid, or alternatively, a deficit needs to be compensated via the main grid (Li et al., 2019; Kirpes et al., 2019; Zhao et al., 2019). This process was discussed in detail in section 4.2.1. In microgrid energy trading research, the main grid tends to be modelled as both an unlimited supplier and consumer, either purchasing or supplying electricity at a fixed rate (Kirpes et al., 2019). More to follow at a later stage on how the main grid in South Africa is contextualised appropriately in this study (see section 5.2.5).

The process of configuring the physical network (i.e. phase one discussed above) takes priority over every other trading activity in the research of Li et al. (2019). In another study, phase one (i.e. determining the microgrid network's operational constraints) and phase two (i.e. tailoring trading bids/offers to accommodate microgrid constraints) appear to be combined into one process at the conclusion of each particular trading window (Zhang et al., 2018a). Another study, *seemingly,* ignores the problem all together of taking network constraints into consideration (Zhao et al., 2019). Lastly, the study conducted by Kirpes, Mengelkamp and Weinhardt (2019) does not make it explicit *when* physical configuration of the microgrid takes place. Nor does it clarify whether it adopts a two-phase approach or not. There seems to be good reason to adopt the two-phase approach advocated for by (Li et al., 2019). Firstly, if there is no awareness of the microgrid's operational constraints prior to an energy trading window opening, necessarily it follows that the ETS will not place a limit upon the quantity of electricity traded during the trading window. This provides a potential source of conflict, as the amount of electricity offered on the market and purchased on the market might not be able to be accommodated by the physical limitations of the microgrid. However, perhaps more alarmingly, is the fact that if the pre-configuration process (i.e., phase one) is foregone, unreliable DERs could be allowed to inject electricity into the microgrid, and as such, potentially compromise the microgrid's stability. Thus, this study's BEES rejects any approach that does not favour a two-phase configuration process and instead gives the configuration of the physical network utmost priority, as per the design of Li et al. (2019). Only once the physical network has been configured, and then finally the orders accepted or rejected in phase two, can the electricity be dispatched into the microgrid by a ‘dispatch’ sub-system. The dispatch sub-system refers to those collection of activities involved in transporting electricity from party A to party B on the microgrid. In addition to configuring the microgrid and dispatching electricity, the MC also must island the microgrid during interruptions on the main grid in secure fashion. It is the role of the ETS to announce to microgrid-tied users that an islanding process is anticipated (once the message is received from the MC). The ETS must then be able to assist the MC in reducing user consumption accordingly (mainly by suggesting appropriate consumption rates as determined by machine learning algorithms), to ensure that prosumers’ personal batteries are charged for the islanding period. Finally, in the event of islanding, it is assumed that the community battery is charged for those in need of electricity, and as such the ETS should assist the MC in the process of providing those in need with electricity. This concludes the discussion surrounding FRQ1. An answer can now be provided to the two questions that are going to be posed to each functional requirement throughout this section.

What is the purpose of FRQ1? FRQ1 is concerned with the physical configuration and operation of the microgrid. More specifically, the purpose of FRQ1 is for the microgrid controller (MC) to configure the physical network prior to *each* electricity trading interval (i.e., this is an on-going process) to guarantee the secure and reliable delivery of electricity to each member connected to the microgrid. Safely islanding the microgrid is a further task of FR1. ***How does this process unfold?*** The MC is responsible for configuring the physical distribution network prior to each trading window opening by taking various physical parameters into consideration. The MC is assisted by machine learning techniques that analyse historical configurations stored on the blockchain’s immutable digital ledger.

5.2.3 Functional Requirement 2 (FRQ2): Access Control

As noted in section 5.1.2.2, when implementing a consortium blockchain, a group of pre-determined nodes validate the blockchain transactions. Theoretically, it is possible for validator nodes to collude and perform CRUD operations on the digital ledger. For example, colluding to delete sensitive information from the digital ledger. Thus, it is important to ensure that the nodes connected to the network are ‘honest’ nodes, particularly if members from the public (i.e., a given prosumer or consumer) are also validator nodes in the network. Researchers suggest that one viable means to establish a secure ETS involves a centralised entity issuing appropriate market-identities to each energy stakeholder connected to the microgrid (Li et al., 2019; Mengelkamp et al., 2018a; Zhang et al., 2018a; Zhao et al., 2019). The purpose behind the issuance of market-based identities by a central entity is not restricted to only safeguarding the digital ledger from potential collusion given its consensus mechanism. Issued identities also allow for the ETS to keep track of the various system user groups, and in turn, issue users with appropriate system privileges. For this study's BEES, a government department (call it the *Identity Issuance Department*) is responsible for allocating users with the appropriate market-based identities according to users' potential roles and responsibilities in ETS (Li et al., 2019; Mengelkamp et al., 2018a). A government department is required to act as an identity issuance authority due to the high barriers of entry (i.e. regulatory requirements) common to electricity trading (Li et al., 2019; Mengelkamp et al., 2018a).

Market based identities include a (1) prosumer-identity or (2) a consumer-identity. One fruitful development in the blockchain domain relates to digital identities, which are known as self-sovereign identities (SSI). In a nutshell, a user of a self-sovereign identity service has his/her personal information tied to one digital account (this constitutes the self-sovereign identity), which can then be exposed to other users of the same service when requests are made for personal particulars (Sovrin, 2020). Furthermore, because a self-sovereign service is enabled by a blockchain network, it inherits blockchain's security features (Sovrin, 2020). Thus, it is impossible for a self-sovereign identity to be of a fraudulent nature (Sovrin, 2020). It is important to note that such a service is run on its own blockchain network, in other words, it is not strictly part of this study's BEES but is rather a third-party service included in the design plan of the BEES. The strength of smart contracts lie in their ability to interact with third party services, and as such, include third-party functionality within the design of the ETS (Li et al., 2019). Third-party functionality can be introduced into the ETS to assist in completing complex tasks in a cost-effective manner (Li et al., 2019). Figure 7 below illustrates a UML domain model class diagram, which models both a prosumer and consumer self-sovereign identity inheriting from a self-sovereign identity superclass.

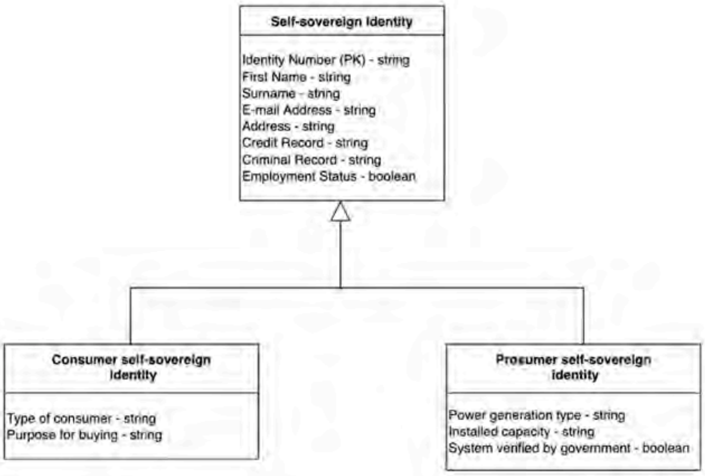

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Figure 7: Self-sovereign identity particulars

A core reason for adopting a self-sovereign identity service is that it simplifies the process of issuing potential system users with market-based identities (Zhao et al., 2019). This can be seen in the fact that ETS users are no longer required to supply personal particulars through a tedious manual process, but rather, users can simply expose their self-sovereign identities as needed. This study assumes that the governmental Identity Issuance Department and each user of the ETS are registered on a self-sovereign identity service (see Sovrin[17] if interested), and furthermore, that the third-party service provided is reliable.

The business process for the issuance of market-based identities is as follows:

1. First, a new user requests to join the ETS via a web or mobile application. The system requests the role the user wishes to register for, as well as requesting permission to access the user's self-sovereign identity for the remainder of the business process (Aggarwal et al., 2019). Tied to this self-sovereign identity, is the fact whether a government accredited service provider installed the solar photovoltaic (PV) system for a prosumer (assuming it is a prosumer registering). One could imagine this information as a simple Boolean (true / false) value (see Figure 7 above). This verification step is necessary to ensure that the solar PV system installed by a new potential prosumer matches quality standards so as not to compromise the energy security of the microgrid.
2. Next, the government identity issuance department is notified about the role the user wishes to register for and is asked to verify the user's self-sovereign identity. At this point, the government department validates the identity via the self-sovereign identity service. This includes the government department doing a background check (e.g.,

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[17] https://sovrin.org/

credit and criminal record check) to determine whether the user is deemed trustworthy to join the ETS.

3. If the identity is considered trustworthy, the governmental department assigns the appropriate ETS market-based identity to the user. For example, an individual wishing to register as a prosumer, will be assigned the ‘prosumer-identity,’ (authentication) which in turn, grants the user with the appropriate access privileges as a prosumer (authorisation).
4. This market-based identity is sent back to the ETS and then linked to the user’s private / public key combo.
5. The market-based identity is recorded in the digital ledger and signed by the user’s private key (to establish an audit trail), along with a reputation score of 5.
6. Next, the user’s cryptocurrency wallet is configured.
7. Finally, the user is provided with his/her private key. The public key is added to the ETS’s public register should the need arise to contact that user (as discussed in section 4.1.2.3).

The business process unpacked above from step 1 - 7 is by nature repetitive. Thus, the process lends itself to automation via a smart contract implementation (Li et al., 2019; Zhao et al., 2019). In such an implementation, the governmental department acts as an oracle, receiving the self-sovereign identity, and sending back the appropriate market-based identity into the smart contract. The smart contract could automatically perform steps 2-7 highlighted above. Automating the business process of identity issuance eliminates the possibility of human error (i.e., simple capturing errors). Furthermore, automation secures the system from the issuance of fraudulent identities, and therefore, eliminates a potential point of failure in the system (Li et al., 2019). For example, if the identity issuance process was conducted manually an actor could assign a legitimate market identity to a malicious node, and in doing so, compromise the security of the entire ETS.

The attentive reader would have noticed that a reputation score of 5 was assigned in step 7 above. Reputation scores aim to mitigate irresponsible or malicious user behaviour (Li et al., 2019). Suppose that a prosumer lists electricity that is available for sale during a particular trading window. At the conclusion of the trading window, the prosumer fails to deliver on the promise, and as such the consumer who purchased the electricity, is left without electricity. Not only is this individual consumer affected, but the electricity balance of the entire microgrid would be compromised threatening system-wide shut down (Li et al., 2019; Zhang et al., 2018a). To rectify this situation, the microgrid controller (MC) would be forced to import electricity from the main grid on emergency procurement. To discourage nodes from engaging in such behaviour Li et al. (2019) and Zhang et al. (2018a) introduce two different solutions. Li et al. (2019) favours using reputation scores in an attempt to mitigate irresponsible user behaviour. This ETS assigns a new user with a reputation score of 5. For every failure to deliver upon a promise, be it a prosumer failing to deliver electricity, or a consumer failing to consume his/her electricity, 1 point is subtracted from the reputation score. Additionally, subtraction of reputation points may also issue in financial punishment. In other words, market participants risk both their revenue and reputation when engaging in energy trading (Li et al., 2019). Once the reputation score reaches 0, the consumer is banned from the system for a period of time. The operating assumption is that if users (prosumers and consumers) do not intentionally set out to disrupt the functioning of the system, there will be no need to subtract reputation points, as the system is fully automated. However, it remains a possibility for a prosumer to, for example, disconnect his/her solar PV system, at the conclusion of a trading window, in an attempt to receive funds without transferring the actual electricity. The prosumer’s attempt to obtain illegitimate funds will fail as the system is designed to counteract such a move (see section 5.2.5), but nonetheless, a reputation mechanism must be in place to mitigate and reduce behaviour that threatens system-stability. Similarily, a consumer may fail to consume what was procured on behalf of the consumer. Though this would be less of a problem for the system (as electricity surpluses are easier dealt with), the intention of this reputation mechanism is to bring *unexpected* behaviour to a minimum (Li et al., 2019). The severity of the punishment scales with the number of reputation points lost. For example, if the user has lost more than 15 points in total since joining the ETS, the punishment is more severe compared to a user who has only lost the first batch of 5 reputation points (Li et al., 2019). If warranted by the circumstances, a user may be permantently banned from accessing the ETS. Reputation scores are also reset after an agreed upon period of time (Li et al., 2019). As an alternative to reputation scores, Zhang et al. (2018a) suggest that if a prosumer fails to deliver electricity, and the electricity has to be imported from the main grid at a higher price rate, the burden falls on the prosumer who failed to deliver electricity to cover the charges. Both suggestions will be incorporated into the business process model to follow in Chapter 6.

Attention can now be turned to answering the ‘what’ and ‘how’ of FRQ2. ***What is the purpose of FRQ2?*** The purpose of FRQ2 is to introduce authentication and authorisation processes into the ETS in a secure, and reliable manner. The task of keeping track of users’ reputation scores is also subsumed under this business process. ***How does this process unfold?*** In a nutshell, the process utilises a third-party self-sovereign identity service to confirm the integrity of user's identities. Smart contracts do the heavy lifting by automating the issuance of the appropriate market-based identities and linking it with the user's private and public key combinations.

5.2.4 Functional Requirement 3 (FRQ3): Energy Trading

As discussed in Chapter 4, a localised energy market provides the 'platform,' or locale, for prosumers and consumers to come together and trade energy (Mengelkamp et al., 2018a). Naturally, this raises the question: *Where is this market platform to be hosted?* Afterall, blockchain technology is just a distributed database with some unique functionalities. Yes, it acts as the underlying information system of the ETS, but there is nothing inherent in blockchain's features (the digital ledger, the consensus mechanism and cryptography) that could plausibly provide a front-end facing market platform for the ETS. Ethereum, a leading blockchain platform provider, noticed this opportunity for improving upon the fundamental features of blockchain early on in the development lifecycle of the technology (Kim, Park and Ryou, 2018). Ethereum introduced the concept of a decentralised application (in blockchain jargon – a dApp). In a nutshell, a dApp is a web application, that has its business logic encoded in smart contracts (Ethereum, 2020). Uniquely, a dApp relies on the blockchain as a backend service for the program logic (i.e., smart contract functionality) as well as for the provision of storage (i.e., the digital ledger). The dApp, as a collection of smart contracts and other enabling technologies, is designed to satisfy one overarching purpose within a particular business context (Kirpes et al., 2019). Since Ethereum's introduction of dApps, other alternatives dApp-supporting blockchain platforms have also become available. For example, EOSIO is an open-source platform that provides developers with the opportunity to develop distributed applications in C++ (EOSIO, 2022). Due to the performant nature of C++, EOS offers scalability, with the ability to process thousands of transactions per second (Bhardwaj, 2020). In contrast, Ethereum only processes 25 transactions per second (Bhardwaj, 2020).

In the context of this study, the overarching purpose of the dApp is to facilitate energy trading amongst microgrid tied prosumers and consumers by providing an energy market platform. Ordinarily, a dApp includes a front-end, however, it remains optional, and as such, is contingent on the functional requirements of the system (Kirpes et al., 2019). For purposes of this system, a front end is assumed (see step 2 below).

Given that a dApp makes it possible to provide a front-end for the blockchain-based application, it is the ideal candidate for implementing an energy market portal (i.e., platform) for this study. As mentioned above, the dApp's primary purpose is to facilitate energy trading amongst prosumers and consumers. An instance of such a dApp implementation can be found in the study of Kirpes, Mengelkamp and Weinhardt (2019). It is beyond the scope of this study to address the question of *how* to implement a secure dApp, and which blockchain platform is most appropriate. It is simply assumed that (1) this study's consortium blockchain supports dApps, (2) that the dApp is securely implemented, (3) that user data is handled responsibly by the front-end facing server and (4) that the server is secured with more traditional system security approaches via methods such as firewalls and intrusion detection and prevention systems.

There are different approaches towards facilitating the energy trading process, yet, most blockchain energy trading systems share considerable overlap in their approach (Kirpes et al., 2019; Li et al., 2019; Zhang et al., 2018a; Zhao et al., 2019). Below, the energy trading business process is presented as found in the relevant literature. A reminder that this study is working at a medium level of abstraction when considering business processes. As such, it is impossible to cover all detail involved in the intricate processes discussed. The example below unpacks the trading process between one prosumer and one consumer:

1. The physical exchange of energy takes place once the energy trading window closes. A common trend amongst trading systems is for the trading window to last anywhere from 15 minute to 1 hour intervals (Mengelkamp et al., 2018a; Zhang et al., 2018a; Zhao et al., 2019).
2. A preliminary activity prior to the energy trading process involves consumers and prosumers setting price parameters via the energy market dApp (Andoni et al., 2019; Mengelkamp et al., 2018a). Consumers set the highest price they are willing to pay (WTP) *per unit* of electricity. Conversely, prosumers set the lowest price that they are willing to sell (WTS) *a unit* of electricity for. Apart from setting parameters, the ETS automates the remainder of the trading process, as the ETS has access to each user's blockchain account (Mengelkamp et al., 2018a; Yang et al., 2020). In other words, the only time prosumers and consumers interact with the energy market dApp is when setting WTP and WTS amounts (Mengelkamp et al., 2018a). Consumers and prosumers can change their parameters when they wish to do so. Additionally, by

utilising machine learning techniques the ETS will reveal average WTP and WTS amounts to guide prosumers and consumers in their choices (Li et al., 2019). This raises interesting ethical implications as the algorithms may, for example, mislead users by recommending overstated WTP amounts. In current centralised energy systems (i.e., a citizen sourcing electricity from the municipality) citizens are not burdened by the need to trade energy throughout the day. Thus, such a burden should not be introduced with the ETS, if it is avoidable. The rationale for this is that by automating the trading process the social acceptance of the microgrid energy market increases significantly (Mengelkamp et al., 2018a; Yang et al., 2020).

3. The first major activity of the energy trading process involves the ETS determining whether consumers who wish to join the trading window have enough cryptocurrency in their wallets, as well as positive reputation scores (Li et al., 2019). To calculate how much cryptocurrency a given consumer is expected to have, machine learning algorithms analyse the average historical bidding price of the consumer and see whether the consumer has enough cryptocurrency to cover the cost of the anticipated bid. For the user to join the market, the funds are deposited as ‘collateral,’ to be kept to one side, until the conclusion of the state estimation process.
4. Next, the ETS determines and places a bid for electricity based on the consumer’s pre-defined WTP parameters. Machine learning techniques analyse the historical consumption patterns of the consumer to determine the quantity of electricity to be covered by the bid (Li et al., 2019; Kirpes et al., 2019). As Mengelkamp et al. (2018a) notes, for this to take place, the ETS requires access to the consumers smart meter readings (available via the digital ledger) to forecast consumer consumption by analysing historical consumption patterns.
5. Whilst consumer bidding takes place, the ETS is collecting all the prosumer bids from prosumers.
6. Once all consumer bids are placed, along with prosumer offers, the initial bids are written to the digital ledger. This is done due to the fact that in step 8 (below) the microgrid controller (MC) has authority to modify the orders, and as such, an auditable trial needs to be established to see how orders were modified should the need arise to see why a given decision was taken by the MC. Say, for example, to identify whether a particular prosumer or consumer is being favoured consistently in each trading round by the MC during trading modifications.

7. The process of placing bid and sale offers lasts for the period of the exchange window as noted above in Step 1. At the conclusion of this bidding and selling window, the market platform utilises its built-in market mechanism and pricing strategy to determine an efficient allocation between buy and sell orders (Li et al., 2019; Kirpes et al., 2019; Mengelkamp et al., 2018a). It is beyond the scope of this study to discuss the various market and pricing mechanisms for microgrid energy markets. This remains a critical area of on-going area of research (Mengelkamp et al., 2018b; Zhao et al., 2019). As such, the assumption for this study is simply that such a mechanism exists and is functional. The goal of this mechanism is to determine the correct electricity quantities to be exchanged, at the correct price (Mengelkamp et al., 2018a). Chapter 6 elaborates briefly on the market and pricing mechanism employed in this study. Here, the microgrid controller (MC) is also involved, ensuring that the mechanism takes into account the microgrid's operational constraints (Li et al., 2019; Zhang et al., 2018a).
8. Once the official market allocations are finalised, the consumer's funds for that bid is locked into an escrow smart contract (Kim, Park and Ryou, 2018; Kirpes et al., 2019). The funds deposited as collateral (in step 3 above) are transferred into the escrow fund. If there is not enough cryptocurrency in the collateral fund, additional currency is taken from the consumers cryptocurrency wallet via smart contract automation. If there is surplus currency in the collateral fund, the funds are returned to the consumer. The escrow smart contract only releases the funds to the relevant prosumer's cryptocurrency wallet at the conclusion of the state estimation process (see section 4.2.5 below), which, roughly speaking, is responsible for determining whether the electricity was indeed injected into the microgrid by the prosumer[18].
9. At this stage, one of the two possible scenarios emerge:
    a. First, the possibility that supply exceeds demand **(S > D)**: If it is the case that supply exceeds demand (i.e., more sale offers than purchase offers) the public grid operator on the main grid is notified that surplus electricity is available. If the main grid requires electricity, the electricity is transferred over (in step 10),

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[18] **Electricity cannot be routed directly from prosumer A to consumer B**. The details behind this constraint are well explained by Mengelkamp et al. (2018a) for the curious reader. In a nutshell, the solution to this is that consumer B pays prosumer A for electricity, but prosumer A only injects electricity into the main grid. This increases the **net amount of electricity** flowing within the microgrid, and as such makes surplus electricity available for consumption by consumer B.

   and the microgrid controller will in turn receive the appropriate compensation at the moment of transfer. The payment is then appropriately distributed to the various prosumers. If the main grid does not require electricity, the electricity is routed to the community battery (at step 8). The battery may also be topped up prior to consulting the main grid, the order in which these events unfold remains the prerogative of the MC. It is assumed that the physical configurations are in place to facilitate the above discussed processes.

   b. Or, secondly, the possibility that demand exceeds supply **(D > S)**: If demand exceeds supply (i.e., more purchase offers than sale offers) much the same principle applies as highlighted above, just in reverse. In brief, either the main grid imports electricity into the main grid (at step 8) and is financially remunerated, or alternatively, electricity is dispatched from the community battery to compensate for the microgrid deficit. It is possible that the main grid does not have electricity, given the South African context, and thus the community battery will need to compensate the shortfall, or else the microgrid will inevitably shutdown until electricity is available again. Thus, it is imperative to keep the community battery always charged and ensure that prosumer's personal solar PV batteries also remain charged for such emergency periods. The MC may also curb consumption as deemed appropriate.

10. Once electricity allocations are complete, the primary validator node of the ETS system receives all transactions (see section 4.1.2.2), groups them into a block, processes them via the consensus mechanism and then the verified transactions are stored in the digital ledger (Kirpes et al., 2019). It is assumed that the electricity quantity requested by the consumer has been determined by the machine learning algorithm in such a manner that it will last the consumer until the conclusion of the following trading window (i.e., just little over an hour from the dispatch sub-system being called).
11. It is at this point that the physical electricity transfer takes place by calling the 'dispatch' sub-system as discussed in FRQ1.

Two footnotes to step 1 - 8 above: (1) It must be again stressed that the process highlighted above is entirely automated from steps 2 - 8, and secondly, (2) it is possible to substitute a prosumer into the consumer's role above, where one has the scenario where prosumer A, is purchasing additional electricity from prosumer B.

The ‘what’ and ‘how’ for FRQ3 can now be answered. ***What is the purpose of FRQ3?*** FRQ3 constitutes the heart of the ETS. Its purpose is to facilitate energy trading between participants and ensure that each consumer in the microgrid is allocated electricity for consumption, and that the relevant funds are locked in escrow for payment to the prosumers. Furthermore, communication takes place with the main grid via the microgrid controller in situations where there are electricity surpluses or deficits in the microgrid. ***How does this take place?*** First, prosumers and consumers set up their initial willingness to sell and willingness to pay parameters via the energy market dApp. The rest of the trading unfolds automatically through using blockchain’s smart contract to infuse the trading process with operational intelligence.

5.2.5 Functional Requirement 4 and 5 (FRQ4 and FRQ5): State Estimation and Financial Settlement

In the final step of FRQ3, (step 10), the ‘dispatch’ sub-system is called without releasing the cryptocurrency funds held in escrow. It is, once again, due to the physicality of electricity that an additional constraint is introduced with regards to *when* the funds may be released from escrow. This constraint emerges as a result of a synchronicity problem between the cyber and physical layer of the ETS (Li et al., 2019; Zhang et al., 2018a). On the one hand, the ETS is expected to ensure that financial settlement takes place between prosumers and consumers at the conclusion of each trading window. Yet, the ETS implementation, as discussed up to this point, has no way to guarantee that the quantities of electricity procured during each trading window are delivered to each respective consumer, in those precise pre-determined quantities (Zhang et al., 2018a). This potential mismatch between that which is procured (i.e. the cyber layer), and that which is delivered (i.e. the physical layer), stems primarily from (1) the unreliability of DERs and (2) the physical constraints and limitations of the microgrid, as well as, (3) the unreliability of prosumers and consumers (Li et al., 2019; Zhang et al., 2018a). As a result of the potential mismatch, it is possible that the payments made at the conclusion of each trading window do not accurately reflect the actual physical transfer of electricity on the microgrid. To solve this synchronicity problem, researchers suggest that the ETS must be able to determine (1) whether prosumers injected the correct quantities of electricity into the microgrid, and secondly, (2) whether each respective consumer received the electricity that was procured on his/her behalf by the ETS. This process is known as state estimation (Li et al., 2019). Ultimately, state estimation ensures that the financial settlement process for energy exchanges between prosumers and consumers accurately reflects the physical exchange of electricity that takes place on the microgrid. It provides a means to synchronise to physical and cyber layer of the ETS. Li et al. (2019, p.12) note:

> *"After state estimation results become available, financial settlements are made automatically via smart contracts."*

However, not all researchers appear attentive to this synchronicity problem, as summarised above, or at least, do not regard it noteworthy. Consequently, some researchers fail to build state estimation processes into their energy trading systems. Note, for example, the explanation offered by Zhao et al. (2019, p.7):

> *"… when the transaction [communications with the main grid] is completed, transaction data is recorded and settled [financially], then the Dispatch System is called to complete the energy dispatch."*

A similar design decision appears in the paper by Kirpes, Mengelkamp and Weinhardt (2019). As Kirpes, Mengelkamp and Weinhardt (2019, p.5) note:

> "As soon as *Market Clearing and Settlement* are executed, the actual physical *Electricity Transfer* happens.[19]"

Notice the commonality between the system designs of Kirpes, Mengelkamp and Weinhardt (2019) and Zhao et al., (2019): trading amongst prosumers and consumers are *first* settled financially, and only *then*, is electricity injected into the microgrid. In other words, financial settlement takes place prior to energy dispatch in both system designs. This seems to present a problem, in fact, it seems to be mistaken design. If this procedure were to be followed, a new scenario emerges where it is becomes in principle possible for there to be a *complete* mismatch between what takes place in the cyber layer (i.e., the market platform and financial settlement) and what takes place on the physical layer of the ETS (i.e., the microgrid). Other researchers, cognizant of the problem of settling transactions prior to dispatching electricity, devote considerable attention to state estimation processes (Li et al., 2019; Zhang et al., 2018a). This is particularly true for the research of Li et al., (2019). Instead of placing the financial settlement process prior to the physical exchange of electricity, the latter researchers delay financial settlement until the state estimation process has been concluded, which takes place,

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[19] Emphasis original to the authors

after the physical exchange of electricity on the microgrid (Li et al., 2019; Zhang et al., 2018a). Zhang et al. (2018, p.3) explain the importance of the state estimation process:

> *"The difference between **promised** and **actual** electricity generation or consumption quantity **needs to be calculated** and charged during the settlement.*[20]"

As a matter of fact, for the ETS to guarantee accurate financial payments, it does not seem at all clear how synchronisation could be established between the two disparate layers (i.e., cyber, and physical) except by the presence of a state estimation process as described above. Thus, it seems a significant oversight of above-mentioned researchers to not include a state estimation process in their respective energy trading systems. Unless, of course, their respective energy systems will *never* encounter a mismatch between the physical and virtual layer - which seems an ambitious assumption to make - particularly given the volatile microgrid context within which the researchers' systems are situated. Furthermore, a fundamental system design principle, particularly when working with automated systems, is to assume that aberrant system behaviour *will* manifest (Flanagan, 2014; Norman, 1990). Working from this assumption, appropriate system feedback mechanisms can be designed to rectify undesirable system behaviour (Flanagan, 2014; Norman, 1990). A feedback mechanism is a system process that (1) gathers information from a given state of the system, and then, (2) using that information, applies system controls to obtain a desired outcome, and eventually, move the system back to a desirable state (Flanagan, 2014). Given the more than reasonable assumption that aberrant behaviour will manifest in the ETS, it seems wise to exercise caution when designing the ETS, and assume that, at times, there may be a mismatch between the cyber and physical layer.
Norman (1990, p.1) captures the heart of the state estimation process:

> *"Appropriate designs [i.e., automated designs – such as the ETS] should **assume the existence of error**, it should continually provide feedback, it should continually interact with operators [smart meters in this context] in an effective manner, **and it should allow for the worst situations possible**.[21]"*

Should an ETS wish to implement state estimation, smart meters play a critical role in implementing such a process (Li et al., 2019; Zhang et al., 2018a). As previously discussed, each prosumer and consumer connected to the microgrid has a smart meter installed at the

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[20] Emphasis added

[21] Emphasis mine.

premise of electricity generation and/or consumption (Monacchi and Elmenreich, 2016). Smart meters provide energy data readings which relate the quantity of electricity each respective prosumer has injected into the microgrid. These readings are written to the digital ledger. Similarly, once consumers, consume energy from the microgrid, this is also recorded by smart meters, and ultimately recorded on the digital ledger (Zhang et al., 2018a). For this research study, consumption and generation data is pushed to the microgrid controller (MC) continuously throughout the lifecycle of the ETS (Pipattanasomporn, Kuzlu and Rahman, 2018). The MC is responsible for grouping the energy readings into blocks, validating each reading (e.g., ensuring that the energy data is not tampered with), and then, finally, writing the generation and consumption data to the digital ledger.

In microgrid energy trading systems (at least from a theoretical perspective), it is commonly assumed that when electricity of quantity X is procured by a certain consumer A, the electricity is delivered in precisely that quantity X to the given consumer A. Or, to state it less formally, in the ideal energy trade, all participants exchange energy exactly as scheduled during the trading window. Thus, it is guaranteed that the payments and revenues reflect scheduled quantities (Li et al., 2019; Zhang et al., 2018a). If it were the case, that electricity was *always* delivered in the exact quantity procured, a state estimation process would indeed be obsolete. All the ETS would have to do is release the funds from escrow, as the funds are guaranteed to match the physical transfer of electricity (Li et al., 2019). Perhaps, this is one reason behind Kirpes, Mengelkamp and Weinhardt (2019) and Zhao et al., (2019) exclusion of state estimation processes from their system designs. However, this assumption that the energy exchange and settlement process will function properly, is in direct contrast to the recommendation made above that the worst possible scenario should always be assumed (Norman, 1990). It does remain a possibility for the physical transfer of electricity to deviate from the scheduled amount due to either generation or load variations, or, as a result of the electricity travelling along physical power lines susceptible to power loss (Hirsch, Parag and Guerrero, 2018; Li et al., 2019; Zhang et al., 2018a). It might not be the case that it will happen *often,* nonetheless, the ETS should be able to handle *corner cases* of any given business process. For example, a corner case could be that consumers fail to consume (i.e. load variation) that which they promised to consume, or alternatively, prosumers fail to inject electricity (i.e. generation variation) into the grid as promised (Zhang et al., 2018a). This, in turn, poses two problems, (1) one that affects the stability of the microgrid, and the other in (2) terms of accurately settling financial payments as alluded to throughout this section. Each problem is addressed in turn below.

A quick note on microgrid stability (point 1 above). Recall from earlier discussions (see Chapter Two) that for an electricity grid to remain stable it is imperative that there remains a balance between the electricity drawn from the consumptive end and that which is injected from the generative end. Researchers propose relying on the main grid to act as a ‘buffer’ in an unlimited capacity to maintain microgrid stability for this business process (Kirpes et al., 2019; Li et al., 2019; Mengelkamp et al., 2018b; Zhao et al., 2019). In other words, if there is a shortage due to a prosumer failing to deliver electricity as expected, the main grid compensates the shortfall to maintain grid stability. Conversely, if there is an oversupply (due to a consumer failing to consume his/her procured electricity) in the microgrid, the main grid relieves the microgrid of the surplus to maintain grid stability. This in a nutshell, entails that the main grid steps in on an emergency basis, with the payment process resolved by the ETS after the main grid has assisted in the balancing process. This solution is put forward by both Li et al. (2019) and Zhang et al. (2018a). This solution is essentially just a further iteration of the same proposal implemented during the trading window to compensate for a short fall or surplus in electricity (see section 5.2.4 above). However, with the caveat that here the solution is implemented on an emergency basis. However, given the South African context it appears rather tentative to assume that the main grid will always be available to step in during a shortfall of electricity. In other words, it is unrealistic to model the South African main grid as an unlimited supplier as is done in the study of Kirpes, Mengelkamp and Weinhardt (2019), which was appropriately contextualised for a European setting. Conversely, it is more plausible that the main grid could be modelled as an unlimited consumer. As discussed in depth in Chapter 3, Eskom is incapable of satisfying electricity demand in South Africa, on both a consistent, and reliable basis. The South African energy economy is one that generally faces a shortage in supply, whilst facing excess demand from the country’s citizens (Lawrence, 2020). As such, this study, will model the main grid as a limited supplier, and unlimited consumer. In the event that Eskom does not require surplus electricity to compensate the deficit on the main grid, Eskom would still able to sell the surplus electricity to other countries tied to the South African Power Pool (SAPP) (Eskom, 2016). SAPP countries include Botswana, Lesotho, Mozambique, Namibia, Swaziland, Zambia and Zimbabwe (Eskom, 2016).

In terms of accurately settling financial payments, the financial settlement process of the ETS must be designed to adequately deal with energy trading complications. Critically, the ETS's financial settlement process must be attentive to the financial settlement problem from a variety of angles, factoring in the positions of prosumers, consumers as well as the public grid. Judging from the literature base, three core payment and electricity balancing scenarios have been identified (Li et al., 2019; Mengelkamp et al., 2018a; Zhang et al., 2018a; Zhao et al., 2019):

1. ***The prosumer injects electricity into the microgrid, and the consumer consumes the correct quantity of electricity:***

   This scenario is the 'no-problem route' for the ETS. Here, the state estimation process reveals that the prosumer injected precisely what was promised during the trading window, and similarly, the consumer received what was determined during the trading window (Zhang et al., 2018a). As such, the funds held in escrow can be released and sent to the prosumer's cryptocurrency wallet.

2. ***The prosumer injected the electricity, and the consumer did not consume the electricity:***

   Suppose that the consumer does not consume that which was procured on behalf of the consumer. This would complicate the balancing process of the microgrid. As discussed in FRQ2, the system proposed by Li et al. (2019) subtracts reputation points from consumers in this instance, whereas in Zhang et al. (2018a) a penalty charge is issued that the consumer is expected to settle to continue making use of the ETS. This system will adopt the 'reputation points' approach as discussed in FRQ2.

3. ***The prosumer did not inject the electricity, the consumer requires electricity:***

   Suppose the ETS (on behalf of the prosumer) offers to inject X units of electricity into the grid at the conclusion of the 1-hour trading window but fails to do so due to a reason unrelated to ETS failure. In turn, the ETS now must satisfy that shortage from the main grid, as previously discussed. The cost of the electricity procured from the main grid will most likely be higher than what was initially offered by the prosumer due to it being procured on short notice (Zhang et al., 2018a). In this case, the funds locked in escrow that was supposed to go to the prosumer, is instead routed to the public grid operator through a smart contract implementation. The excess fees that still need to be paid over to the public grid operator to compensate the difference in the higher price, falls on the shoulder of the prosumer who failed to deliver the electricity. Furthermore, a reputation point is subtracted from the prosumer (Li et al., 2019; Zhang et al., 2018a).

Lastly, suppose the prosumer injected the electricity and the consumer received some of the electricity, yet there is still a deficit because of electricity losses taking place as the electricity is transported through the microgrid (Hirsch, Parag and Guerrero, 2018). Here, the main grid again must compensate the shortage in the microgrid, albeit to a much lesser extent. The suggestion for this study is that this cost is spread across all microgrid connected users, including both prosumers and consumers. Afterall, it is an inherent disadvantage of the system, and as such, no one party can take responsibility for these transportation losses. Thus, for the sake of remaining as egalitarian as possible, the responsibility should be spread evenly out amongst all users of the microgrid ETS. This too, can be achieved with a smart contract implementation. That, at least, is one solution: an alternative is for the system to keep running a positive balance of electricity. This could be achieved by having prosumers ensure that their personal solar PV batteries are charged above a certain threshold for emergency consumption, whereas consumer (i.e., those without solar PV and battery systems) deficit can be compensated by the community charged battery. A combination of both these business processes could be combined.

All the functional requirements of the ETS have now been explored and discussed. The question of *what* and *how* can now be answered for the final two functional requirements here discussed. ***What is the purpose of FRQ4 and FRQ5?*** The purpose of FRQ4 and FRQ5 is to guarantee that the financial payments made to prosumers and the public grid operator align with the physical exchange of electricity that takes place on the physical layer of the system (i.e., the microgrid). ***How is this achieved?*** This is achieved by placing an emphasis on state estimation, the process of tracking how much electricity each consumer has consumed, and how much electricity each prosumer has injected into the main grid. Auditing the generation and consumption figures allows the ETS to reconstruct consumption and generation patterns, and as such, orchestrate the financial settlement process accordingly.

5.3 A Use Case Diagram

Figure 8, on page 96 provides a use case diagram that highlights the energy actors involved the ETS with their specific activities. This use case summarises all the functional requirements discussed in this chapter. The use case diagram was used to inform the design of the business process model which is to be presented in the following chapter.

5.4 Summary

Much has been said in this chapter, much had to be covered. First, the various components of blockchain technology were introduced and explained. It was noted *why* blockchain technology is particularly applicable to decentralised peer-to-peer energy trading systems. The bulk of the chapter was concerned with the various functional requirements of a blockchain-based energy trading system. Each functional requirement was discussed in-depth. At certain points reference was made as to how this study’s blockchain-based energy exchange system would implement the functional requirements (i.e., BEES).

The next chapter presents this study’s blockchain-based energy trading system (i.e., the BEES) in the form of a business process model. First, the structure and components of the model are discussed followed by an in-depth discussion of the various business processes in the system.

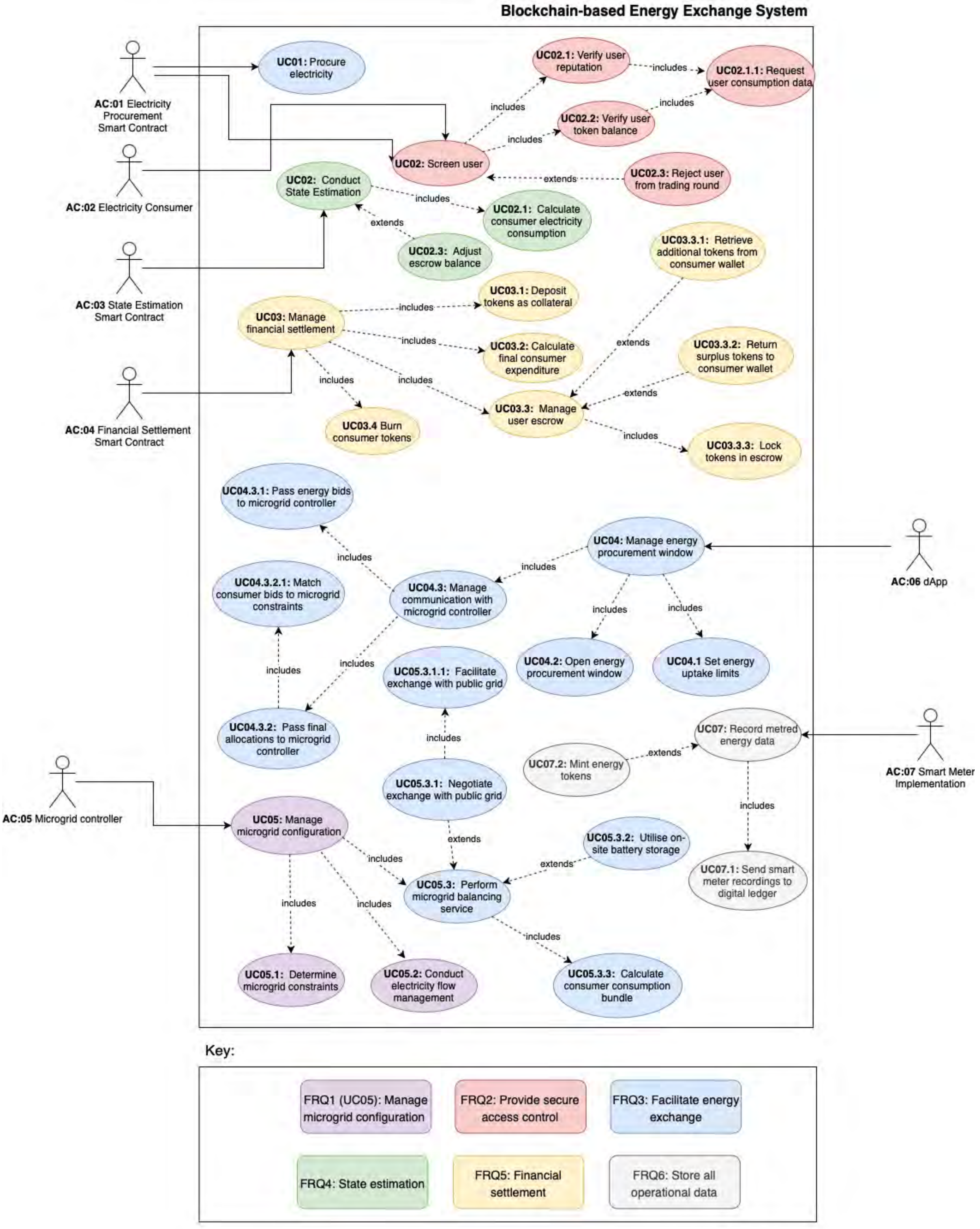

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Figure 8: A use case diagram of this study's blockchain-based energy exchange system

Chapter 6: The blockchain-based energy exchange system

"Thus, the commons was no utopian ideal; it reflected the historical and everyday experience of cooperation and mutual aid."

"Under the medieval cope of heaven, property had to be directed toward the common good, not employed or aggregated for private gain."

Eugene McCarraher, The Enchantments of Mammon

In the previous chapter, the *eight* core functional requirements of an energy trading system (ETS) were identified and discussed. This was a necessary step, as the functional requirements formed the foundation for the construction of this study's blockchain-based energy exchange system (BEES)[22]. This chapter presents this study's iteration of an energy trading system in the form of a business process model. First, the key components of the model are introduced. Once the components have been introduced, a discussion ensues about how the components are structured in the layout of the BPM. At this point, specific attention is paid to how the layout of the BPM reflects the underlying intricacies of a cyber-physical system. Finally, the core business process flows of the model are discussed. Throughout this chapter it is assumed that readers are familiar with the content discussed up to this point in the thesis.

6.1 The business process model components

Three core entities are modelled in the *BEES BPM*. These entities include the Public Grid Operator (PG Operator), the Blockchain-based energy exchange system and the Digital Ledger.

6.1.1 The public grid operator (PG Operator)

As noted earlier, the public grid has an operator (PG Operator) who is responsible for interacting with the BEES's microgrid controller (MC). Should there be a surplus or deficit of energy within the microgrid at the conclusion of a trading window, the MC interacts with the PG Operator to rectify energy imbalances. There are various configurations available for facilitating the interaction process between the MC and the PG Operator (Faia et al., 2019;

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[22] From this point onwards this study's energy trading system is referred to as the BEES.

Tohidi, Farrokhseresht and Gibescu, 2018). For this model, it is enough to assume that an operational communication link exists between the MC and PG Operator. In other words, the *BEES BPM* is agnostic about how the link is implemented. Ultimately, the imperative lies with grid designers to decide upon the specific implementation based on the operational environment of each respective energy system.

6.1.2 The blockchain-based energy exchange system and the digital ledger

The BEES is a cyber-physical system, and as such, has both a physical, as well as cyber layer (see Figure 9 below).

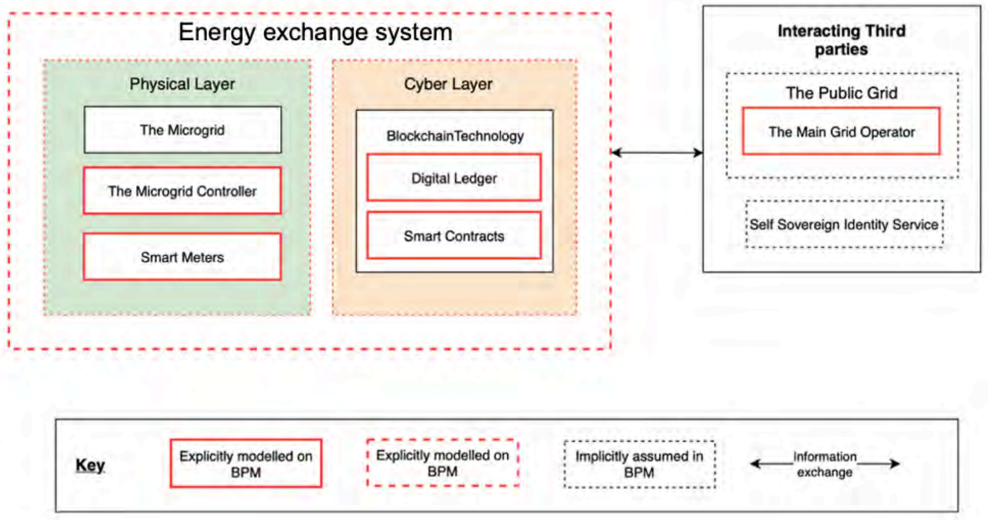

Figure 9: Core BEES components and third-party interactions

As illustrated in Figure 9, the microgrid, the microgrid controller, and the BEES users' smart meters form the physical layer of the BEES. The BEES's cyber layer is comprised of two blockchain technologies, namely smart contracts, and the digital ledger. The public grid and PG operator constitute a third-party that only interacts with the BEES but is not strictly part of the BEES. The self-sovereign identity service is also a third-party that only interacts with the BEES. However, the SSID service *is not included* in this BPM, as it is assumed that BEES users have already gone through the appropriate registration process prior to trading energy (see section 5.2.3 for a discussion on a typical registration process). The motivation for excluding the registration process from the *BEES BPM* is that pre-registration is tangential to the primary focus of the process model (i.e., facilitating energy exchange amongst prosumers and consumers). There is an access control business process included in the model, but it *assumes* that pre-registration has already taken place.

6.2 The model structure

Figure 10 on page 101 illustrates the *BEES BPM*. Located at the top of the model is the PG Operator. The PG Operator is modelled as a *collapsed pool*. In business process modelling notation 2.0 (BPMN 2.0), a *pool* is a graphical representation of a system actor, or entire system (Object Management Group, 2012). A *collapsed pool*, is a more specific instance of a *pool*, and denotes an actor whose internal processes are not of direct concern to the BPM (Object Management Group, 2012). Third parties are often modelled as *collapsed pools*. As such, a *collapsed pool* is a useful construct for indicating that there is communication taking place between the primary system (i.e., the BEES) and the PG Operator, whilst simultaneously indicating that the intricacies of the PG Operator's internal business processes are not known.

Located at the bottom of the business process model is the digital ledger. By digital ledger we are referring to the blockchain's distributed digital ledger. The digital ledger is also modelled as a *collapsed pool*. However, in contrast to the MG operator, the digital ledger is modelled as a *collapsed pool* to indicate a separation of concerns between the internal processes of the digital ledger and the remaining internal processes of the cyber-layer (see Figure 9 above). In other words, for purposes of the *BEES BPM* it is not necessary to model how the digital ledger stores and makes available energy related data to the rest of the BEES. Instead, it is only necessary to model that the digital ledger can do so.

Located in the middle of the BPM is the BEES (excluding the 'digital ledger sub-system,' which is also a part of the BEES – again see Figure 9 above). The BEES is contained by a *pool* labelled as 'Blockchain-based energy exchange system.' There are two core *swim lanes* nested within the BEES, namely the 'Physical Layer' and the 'Cyber Layer'. *Swim lanes* are used to organize and categorize the business activities that unfold within a *pool* (Object Management Group, 2012). Modelling the *BEES BPM* with two core *swim lanes*, indicates the cyber-physical nature of the BEES (Tushar et al., 2021). Nested within the physical layer are two further *swim lanes*: a smart meter *swim lane*, and a microgrid controller (MC) *swim lane*. These swim lanes denote the actors that operate within the physical layer of the BEES. Nested within the cyber layer of the BEES is a *swim lane* labelled 'Smart Contract Layer'. This *swim lane* indicates that out of the two technologies that constitute the cyber layer of the BEES, it is the 'Smart Contract Layer,' with its nested *swim lanes* that is of primary interest to the *BEES BPM*.

Nested within the ‘Smart Contract Layer,’ are four additional *swim lanes*. The four *swim lanes* include:

1. The Energy Procurement Smart Contract **(lane 1)** – This *swim lane* is responsible for the execution of all system activities that relate to the procurement of energy for consumers, including access control measures.
2. The State Estimation Smart Contract **(lane 2)** – This *swim lane* is responsible for the execution of all system activities that relate to state estimation.
3. The Financial Settlement Smart Contract **(lane 3)** - This *swim lane* is responsible for the execution of all system activities that ensure an accurate financial settlement process between prosumers and consumers.
4. The dApp **(lane 4)** – This *swim lane* is responsible for the execution of all system activities that relate to the operation of the energy procurement window. Tasks carried out by the dApp includes setting energy uptake limits (as informed by the microgrid controller), opening the energy procurement window as well as managing communication with the microgrid controller at critical points throughout the system’s lifecycle.

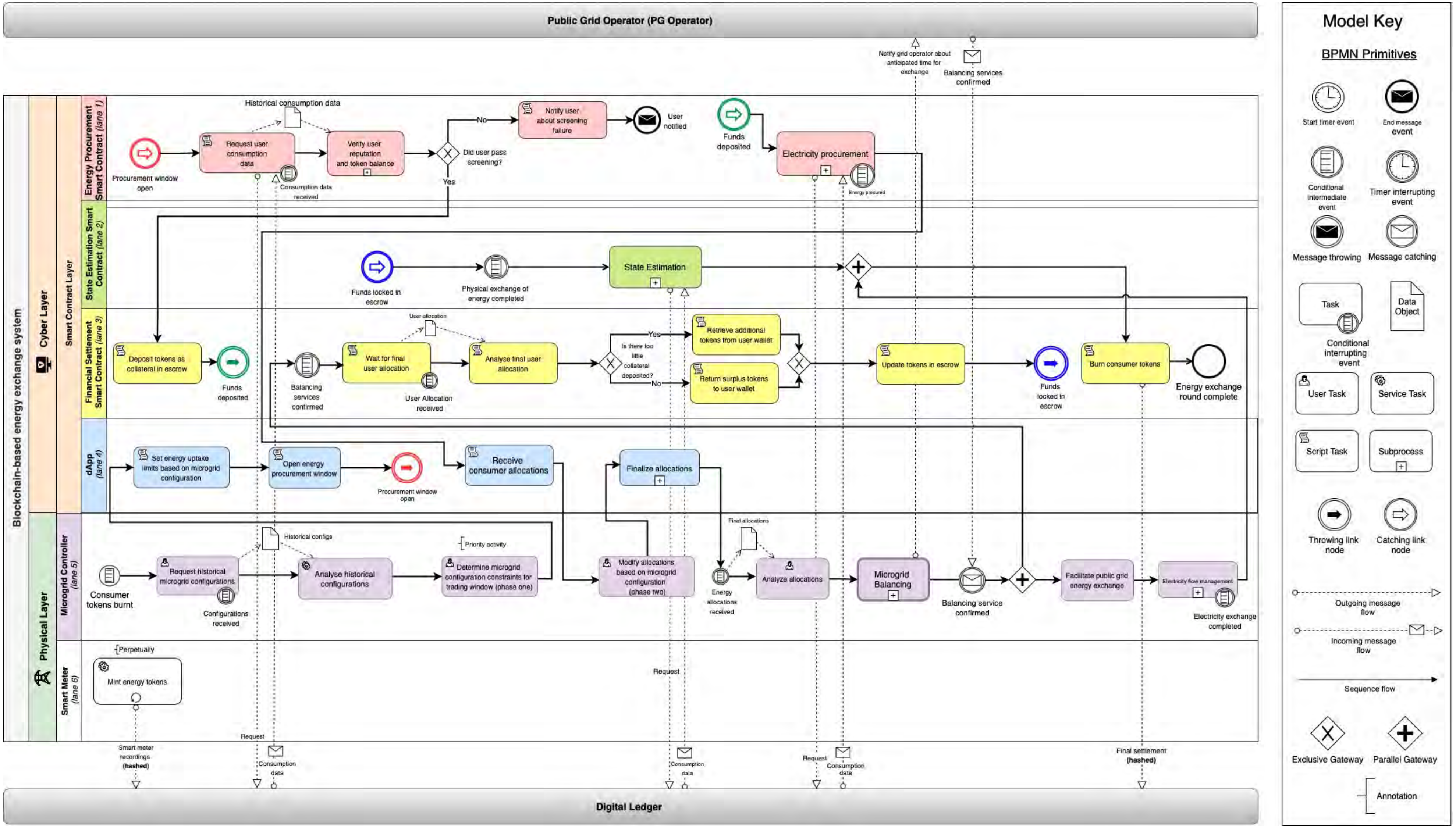

Figure 10: The BEES business process model

6.3 The business process model explained

There are four distinct phases involved in bringing the energy exchange process to completion. These phases include market initialization, energy procurement, state estimation and financial settlement (Li et al., 2019; Zhang et al., 2018a; Zhao et al., 2019). For this study, these four phases are envisaged as microprocesses of the BEES. More specifically, the time within which these four phases can be brought to completion is primarily limited by how quickly the microgrid controller is able to complete the business processes situated in swim lane five on the physical layer. Here one can note the interdependency between the physical and cyber layer of the ETS, and how the physical layer influences the overall efficiency of the cyber layer of the BEES (Sridhar, Hahn and Govindarasu, 2012).

6.3.1 Community rules: a commons-rule based approach

For energy related research to be truly influential, proposed solutions must suggest genuine alternatives to modern day organizational and production systems (Giotitsas et al., 2020; Meyer, 2020). Earlier it was noted why current centralised energy systems are both unsustainable and incapable of meeting the growing demands of energy decentralisation amongst other challenges. Furthermore, capitalist economies driven by commodification, accumulation and consumption alone provide inadequate solutions to modern day climate challenges (Giotitsas et al., 2020; Mengelkamp et al., 2018a). Thus, this research model situates itself within the commons paradigm as introduced by the seminal work of Ostrom on common-pool resource management (Field and Ostrom, 1992). With the emergence of information and communication technologies the concept of the commons has been expanded to include commons-based peer production (Giotitsas et al., 2020; Meyer, 2020). Giotitsas et al. (2020, p.2) describe commons-based peer production as:

> *"… the Internet-enabled free engagement and cooperation of the people, who coalesce to create shared value according to community-defined governance mechanisms."*

Importantly, a system informed by commons-based peer production governs shared resources without the intervention of traditional hierarchical organizations (Rozas et al., 2018). For a commons-based production system, profit and accumulation does not constitute the main drivers for production (Giotitsas et al., 2020). Instead, sustainable collaboration amongst community members becomes the goal, where the common resource is to be shared according to predefined rules and norms as defined by the participants of the community (Giotitsas et al., 2020). Blockchain-based governance can be utilized to architect a BEES that is informed by a commons-influenced protocol (Risius and Spohrer, 2017).

For this study, we have designed a commons-influenced protocol for the BEES. This is only one of many scenarios and possible configurations[23]. Each community will vary these rules based on their own preferences and as agreed upon communally.

The commons-influenced protocol assumed for this *BEES BPM* scenario is as follows:

1. The microgrid is located within a residential neighbourhood and has a connection to the public grid.
2. Each prosumer that joins the BEES has the appropriate solar photovoltaic (PV) system installed to inject energy into the microgrid. Consumers and prosumers have local battery storage systems installed. When tokenizing energy, the BEES is only concerned with actual energy injected into the microgrid.
3. The issuance of energy tokens is coordinated by smart meters that operate in conjunction with the blockchain. Every time prosumers inject energy into the microgrid prosumers are rewarded with energy tokens. One energy token is the equivalent of 100 watts of electricity injected into the microgrid. Because the model operates within a commons-paradigm, energy tokens do not appreciate or depreciate (i.e., they are 'stable energy tokens')[24].
4. The microgrid has two large scale community batteries installed (Yang et al., 2020; Zeller et al., 2017; Zhang et al., 2018a). One community battery is specifically geared towards handling emergency energy dispatch (Li et al., 2019). This battery is geared towards facilitating grid stabilisation by acting as a temporary buffer (Zeller et al., 2017; Zhang et al., 2018a). The other community battery acts as a storage unit capable of being dispatched at peak load times (Zeller et al., 2017).
5. As a community rule, all prosumers must contribute to the emergency dispatch battery to always keep it above 80% capacity.
6. If the storage battery is above 75% capacity prosumers may exchange energy with the public grid.

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[23] This stands also stands in contrast to a free-market system. This design consideration is further discussed under the limitations of the study.

[24] Here a free-market system would instead opt for a variable pricing structure.

7. As a community rule, 10% of the revenue generated from electricity sold to the public grid goes to a community fund for the maintenance and upgrading of the physical microgrid.
8. If there is an energy deficit within the microgrid prosumers and consumers may purchase energy from the public grid with energy tokens. It is assumed that the amount of energy tokens required for 100 watts of electricity from the public grid will be higher than what is ordinarily paid to prosumers within the local energy market (Green and Newman, 2017). The process of having prosumers and consumers pay the public grid in energy tokens constitutes one of the mechanisms for burning (i.e., spending) tokens in the BEES. The other mechanism involves the purchase of energy directly within the local energy market. Once a consumer has purchased energy in the local energy market the tokens for that quantity of energy consumed are burnt.
9. There is an energy token exchange managed by the public grid operator. BEES users may purchase energy tokens in exchange for fiat currency from the public grid. BEES users may then use the energy tokens to purchase energy within the local energy market.
10. Prosumers are permitted to act as consumers in the BEES. A prosumer may switch from production to consumption mode from within the BEES web application.

With the commons-influenced protocol laid out, the next section discusses the BEES system activities as modelled in the *BEES BPM*. If need be, see the attached glossary (Appendix C) for an explanation of the italicised words that relate to BPMN 2.0.

6.3.2 The role of the smart meter

Swim lane six in the *BEES BPM* is dedicated to smart meter related activities. As indicated by the ‘mint energy tokens’ task, throughout the lifecycle of the BEES, each user’s smart meter pushes energy readings to the digital ledger. For prosumers, readings include consumption data and the quantity of electricity injected into the microgrid. For consumers, readings include consumption data. All smart meter readings are timestamped. Smart meter readings constitute the only data written to the BEES’s digital ledger. The smart meter readings are passed to a smart contract that issues the appropriate number of energy tokens to each respective prosumer’s wallet[25]. This is how energy tokens are created in the BEES and can be *likened*[26]

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[25] Here the smart meter acts as an oracle. See section 5.1.2.4.

[26] Likened. It is not the same, it is only to provide a mental map for how prosumers are rewarded.

to the Bitcoin mining process where miners are rewarded for solving a computational puzzle (Mihaylov et al., 2014). For consumers there is no issuance of tokens. Instead, consumer tokens are burnt (i.e., spent) at the conclusion of each round of trading. Pushing data to the digital ledger takes place every interval as specified by a configurable parameter. For this study we assume that energy is dispatched into the microgrid *continuously*, with energy tokens issued to prosumers every five minutes. Importantly, smart meter readings are cryptographically hashed each time prior to being stored on the digital ledger. Hashing the energy readings guarantees that users' sensitive information is protected (Laszka et al., 2017; Kounelis et al., 2017). The hashing process is indicated on the *BEES BPM* by the *outgoing message flow* extending from the task to the digital ledger.

Lastly, it is assumed that smart meters and the other requisite physical infrastructure is installed at each BEES users' site of consumption to effectively regulate energy uptake[27]. This physical implementation would be similar to what is required for current demand response configurations in microgrid energy systems (Zia et al., 2020; Monacchi and Elmenreich, 2016; Mihaylov et al., 2014). For example, if the BEES has procured 500 kilowatts of electricity on behalf of the consumer, the consumer will not be able to draw more than 500 kilowatts from the microgrid until the next energy exchange window.

6.3.3 The market initialization phase

The market initialization phase is geared towards configuring the microgrid prior to the energy procurement window opening. This configuration process takes place in a two phased approach. Phase one takes place during market initialization. In *swim lane* 5, the *conditional start event* is triggered once consumer tokens are burnt from the previous energy exchange round. Once triggered, the microgrid controller (MC) requests all previous microgrid configurations from its own on-site database. It is assumed that this database is adequately secured. Once the configurations have been received, they are passed to the next task as *a data object*. At this point, utilizing artificial intelligence and machine learning techniques the historical configurations are analysed identifying trends and patterns that may be of assistance to the MC for configuring the microgrid during phase one. Once the historical configurations have been analysed, the MC considers the results and determines the appropriate microgrid

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[27] It is extremely important to understand that energy is being continuously dispatched into the microgrid for circulation whilst there is physical infrastructure present to regulate uptake.

configuration for the energy procurement window that is bound to open. In short, phase-one provides the MC with an opportunity to determine the base-line operational constraints for the microgrid prior to the opening of the next energy procurement window. For example, suppose that during the configuration process, the MC determines that the physical microgrid can only accommodate a hypothetical 50 units of electricity to avoid power line congestions. In this instance, the MC might notify 10 prosumers to switch to consuming electricity from their on-site batteries for the next 30 minutes instead of procuring energy via the local energy market (LEM). Recall prosumers may act as consumers or prosumers during a given trading window. Absent a phase one configuration process, this operational constraint would go unnoticed until later in the trading process and as a result cause a system complication. Once the MC is satisfied with the identification of the operational constraints, the MC locks in the system constraints. Upon confirmation, the constraints are passed to the market decentralised application (dApp). This concludes phase one of the microgrid configuration process. Once the dApp receives the operational constraints, the energy uptake limits are set for the energy procurement window that is bound to open. Once the energy uptake limits have been set, the dApp opens the energy procurement window.

6.3.4 The energy procurement phase

Once the energy procurement window has opened, the next task is carried out by the Energy Procurement Smart Contract (EP smart contract). The shift to *swim lane* 1, is indicated by the *throwing link node* in *swim lane* 4 (i.e., the red element) and the *catching link node* in *swim lane* 1 (i.e., the other red element). Given that the energy procurement window is now open, the EP smart contract requests each consumer’s consumption data that is stored on the digital ledger. It is assumed that once prosumers and consumers have registered for the BEES, each user is coupled with the *one* smart contract responsible for managing energy procurement (the same applies to the financial settlement and state estimation smart contract instances). The smart contracts can store state for multiple users. Figure 11 below illustrates a UML domain model class diagram, which models how one user (the consumer in this instance) is linked to all three smart contract instances.

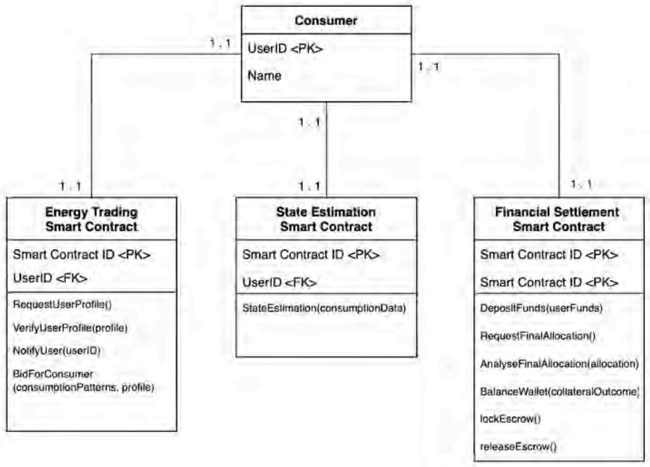

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Figure 11: Consumer link to smart contracts

For the remainder of this discussion, the processes are discussed as if they were carried out for one consumer to simplify the discussion. In the actual system implementation, these processes would be carried out for multiple consumers at once.

Once the EP smart contract receives the consumers' consumption data from the digital ledger, it passes the consumption data as a *data object* to the next task. Next, the consumer's reputation score and token balance are calculated and verified via a smart contract implementation as a form of access control. On the *BEES BPM* this process is modelled as a *sub-process*, as indicated by the '+ element'. To verify the consumer's reputation score, the EP smart contract determines whether the user's reputation score is above a pre-defined threshold by analysing whether the consumer has consumed the appropriate quantities of energy as procured by the BEES in previous trading rounds. Verifying the consumer's energy token balance constitutes a more complicated verification process. The EP smart contract computes the mean quantity of energy tokens spent on energy consumption over a specified period (e.g., two weeks). If the user's current energy token balance is above or equal to the calculated mean (i.e., token balance >= mean quantity spent) the user will qualify to partake in the energy trading window. Furthermore, the EP smart contract will not place a bid for an electricity quantity that exceeds what can be purchased with the user's energy token balance (i.e., electricity bid <= token balance).

Next, the EP smart contract makes a decision that is mutually exclusive in outcome (indicated by the *exclusive gateway* in *swim lane* 1). If the user did not pass the screening process, the EP smart contract notifies the user about the screening failure, including the reason for failure. Alternatively, if the user did pass the screening process, the user's financial settlement smart contract (FS smart contract) in *swim lane 3* deposits the consumer's energy tokens (i.e., the anticipated quantity to be spent on energy) as collateral. This is a built-in safety mechanism that the BEES uses to safeguard itself from consumers withdrawing from energy exchange mid-way through an open procurement window (Kirpes et al., 2019).

Once the consumer's energy tokens are deposited, the EP smart contract connected with the specific user procures electricity on behalf of the user. This shift back to *swim lane* 1 is indicated by a *throwing link node* (i.e., the green element) in *swim lane 3* and a *catching link node* (i.e., the other green element) in *swim lane 1*. The bidding process lasts until the BEES has procured the energy currently available in the microgrid *for each consumer connected to the microgrid*[28]. Once energy has been procured for each consumer, the *conditional interrupting event* terminates the procurement process. Electricity bidding is a *sub-process*, as indicated by the '+ element' on the *BEES BPM*. The background processes hidden by this sub-process relates to the EP smart contract's behaviour to determine the appropriate bidding strategy on behalf of the user. To do this, the EP smart contract puts in a data request from the digital ledger, for the user's historical consumption data (*as indicated by the outgoing message flow*). Once the EP smart contract has received the data (*as indicated by the incoming message flow*), the EP smart contract considers the consumer's past consumption patterns and then procures the appropriate quantity of energy based on anticipated consumption until the next trading round. The consumer is only able to draw the exact procured quantity of energy from the microgrid until the next exchange window. Energy uptake is regulated by the physical infrastructure operating in conjunction with the users' smart meters. Should the consumer not have enough energy tokens to purchase energy to last until the next trading, or exchange, round (given current consumption rates), the user will be notified to purchase more energy tokens as well as to cut back energy consumption to a level that can be accommodated by the user's remaining energy tokens balance.

Once energy has been procured for all consumers, dApp (*swim lane* 4) receives all consumer allocations (i.e., the procured energy for each consumer) and passes this information to the microgrid controller in *swim lane* 5. At this point, phase-two of the microgrid configuration process begins. Here, the MC again checks the operational constraints of the microgrid to see if any constraint threshold has altered since the initial calculation process carried out during

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[28] It is assumed that a mechanism exists to equitable procure electricity on behalf of each user. This is a domain for future research.

phase-one. Once this is complete, the MC modifies the bids to match the operational constraints of the microgrid. How to modify the bids in an equitable manner remains an open area of research. For example, one study utilizes a ‘last on, first off’ principle, that sees the latest electricity bids removed first if electricity trading has to be scaled down due to operational constraints on the physical layer of the system (Zhang et al., 2018a). For this study, it is simply assumed that such a mechanism exists, and is equitable in practice. The *BEES BPM* is agnostic to the specific design implemented. However, it is argued that if a microgrid that has been adequately designed for a specific context the MC should not need to modify bids on a regular basis. Rather fringe cases may present themselves during periods of overconsumption where microgrid users could rather be advised to cut back on electricity consumption instead of excluding consumers from the electricity procurement process (Monacchi and Elmenreich, 2016). Once the MC has modified the consumer allocations to match the constraints of the microgrid, the final bids are passed back to the dApp.

Here, the dApp finalises consumer allocations, calculating whether there is a deficit or surplus of energy within the microgrid to satisfy consumer demand for energy until the next energy exchange round. In traditional market-based energy trading here the market would be cleared by the dApp. Two commonly deployed mechanisms in market-based trading include the (1) continuous double auction and (2) combinatorial double auction mechanism (Kirpes et al., 2019). Another popular market mechanism is one that is built around utilizing Bayesian Equilibrium (Zhao et al., 2019). However, these mechanisms are associated with a synchronous bidding and offer process. Our system is asynchronous when it comes to bidding for electricity (as prosumers are continuously injecting electricity into the microgrid). Furthermore, the price for LEM procured energy is not determined through a market clearing mechanism, but rather calculated during microgrid balancing (see section 6.3.5). Once consumer allocations have been finalized the energy procurement phase of the *BEES BPM* is complete.

6.3.5 The state estimation and settlement phase

Once the energy allocations have been finalized, the microgrid controller (MC) receives the allocations from the dApp. Once the MC receives the allocations they are passed to the next task as a *data object*. After analysing the market allocations, the ‘Microgrid Balancing’ sub-process starts. The goal of the ‘Microgrid Balancing’ sub-process is to manage a potential energy mismatch within the microgrid at the conclusion of finalizing the energy allocations. It would rarely be the case that all consumer bids exactly match the energy balance in the microgrid at the time when the energy procurement process ends. Instead, it is likelier that one of the following two scenarios will emerge at market clearance:

(1) There is a surplus of electricity within the microgrid. This happens when the total quantity of energy requested by consumers is less than the energy balance within the microgrid (Energy balance > Energy requested),

(2) Or there is a deficit of electricity within the microgrid. This happens when the total quantity of energy requested is greater than the balance within the microgrid (Energy balance < Energy requested)

When analysing the final allocations, the MC is informed of the mismatch (assuming there is one). At this point, the MC decides how to rectify the imbalance. For purposes of discussion, it is here assumed that there is a deficit of electricity within the microgrid (instead of a surplus) and that the main grid does have electricity to supply the energy deficit within the microgrid. During the ‘Microgrid Balancing’ sub-process, the MC contacts the public grid operator (PG operator), and requests to import the quantity of electricity needed to compensate for the energy deficit within the microgrid. Once negotiations are complete between the PG operator and the MC controller, final consumer allocations are calculated including the number of tokens to be spent on energy by each consumer. Here it is anticipated that the number of energy tokens required to procure electricity from the public grid will exceed the price of local energy market (LEM) procured electricity. For example, whereas in the LEM one energy token is worth 100 watts of energy, procuring energy from the public grid could result in one energy token being worth only 50 watts. If a consumer’s consumption rates are too high to be satisfied by the microgrid alone, the surplus electricity is contracted from the public grid at a higher rate for the consumer. Here it is assumed that there is a mechanism in place that equitably distributes the available energy within the microgrid, where additional energy needed by the consumer is satisfied by the public grid. Calculating the consumer’s anticipated token expenditure is performed by a microgrid balancing smart contract. The specific process flows have been abstracted away, as indicated by the ‘Microgrid Balancing’ sub-process. Once the total tokens to be spent by each consumer has been calculated, the PG operator is notified about the anticipated time of energy exchange that is bound to take place between the microgrid and the public grid. This is indicated on the *BEES BPM* by the *outgoing message flow* from the ‘Microgrid balancing sub-process’ to the PG operator at the top of the *BEES BPM.* Once the PG operator has reviewed the request of the MC controller to import electricity to the microgrid, the PG operator confirms the balancing service. Upon receiving confirmation, the

MC facilitates the energy exchange with the public grid, appropriately coordinating the physical microgrid to allow for the importing of energy from the public grid. Once the electricity has been imported, the MC engages in electricity flow management, as indicated by the ‘Electricity Flow Management’ sub-process. In a nutshell, during electricity dispatch, it is a possible that there is an unanticipated surplus or decrease of electricity within the microgrid due to consumers failing to consume their procured energy, or alternatively, or due to prosumers failing to inject energy into the microgrid. This will cause balancing issues for the MC. For purposes of discussion, it is here assumed that there is a surplus of energy within the microgrid due to the failure of three consumers to act on their promise to consume a specific quantity of electricity. During the ‘Electricity Flow Management’ sub-process, the MC identifies that there is an electricity surplus within the microgrid and remedies the situation by utilizing the emergency dispatch battery. Here, the MC will reroute surplus energy to the batteries to restore energy balance within the microgrid.

Whilst all the above discussed activities are unfolding in *swim lane* 5, the Financial Settlement (FS) smart contract (*swim lane 3*) has been waiting for the completion of the Microgrid Balancing sub-process (*catching intermediate message event* in *swim lane 5*). At this point, the FS smart contract is buffering waiting to receive the final user allocation after the microgrid balancing sub-process. Once the user allocation has been received, the allocation is passed as a *data object* to the next task, where the allocation is analysed. More specifically, the consumer’s total tokens to be spent is compared to how much collateral is currently deposited. Once the consumer allocation has been analysed, two mutually exclusive scenarios emerge (indicated by the *exclusive gateway*):

1. The user’s deposited collateral is less than the total tokens to be spent. If this is the case, then the remaining tokens are retrieved from the consumer’s wallet.
2. Or the user’s deposited collateral is more than total tokens to be spent. If this is the case, the surplus tokens are returned to the consumer’s wallet.

Once the surplus tokens have been returned, or the remaining tokens retrieved, the tokens are locked in escrow until the completion of the state estimation process. Next, the state estimation process is carried out by the state estimation smart contract (SE smart contract). The shift to *swim lane* 2 is indicated by the *throwing link node* (i.e., the blue element) in *swim lane* 3 and the *catching link node* in *swim lane* 2 (i.e., the other blue element). In *swim lane* 2, there is a *conditional intermediate event* labelled as ‘Physical exchange of energy complete.’ Once the physical exchange of energy for the exchange round is complete, the condition is satisfied[29].

As a result, the ‘State Estimation’ sub-process can begin. At the heart of the ‘State Estimation’ sub-process lies the need to *guarantee* an accurate financial settlement process (see section 2.4.3). First, the State Estimation (SE) smart contract requests the smart meter readings for the consumer from the BEES’s digital ledger. This is indicated by the *outgoing message flow* form the task to the digital ledger. The SE smart contract also receives as an input the number of tokens currently in escrow for the consumer the smart contract is linked to. Once the consumption data has been received (indicated by the *incoming message flow*), the SE smart contract calculates how much electricity the consumer consumed and what the consumer must pay based on actual electricity consumed. Once the SE smart contract has calculated this, the consumers escrow balance is adjusted accordingly. The details of this process have been abstracted away as state estimation is a sub-process. This concludes the state estimation process. Suppose the SE smart contract determines that there is no discrepancy between the number of tokens held in escrow and how much energy the consumer consumed during the energy exchange round. This will allow the financial settlement smart contract to burn and release the exact quantity of tokens as currently held in escrow (*swim lane 3*). In swim lane 3, the consumer’s tokens are burnt, and the portion of tokens owed to the public grid released to the PG operator. Next, the final settlement is written to the digital ledger. The entire energy exchange round is now complete. This leads to the next cycle of microprocesses working in conjunction to carry out market initialization, energy procurement, state estimation and financial settlement for the next energy exchange round.

6.4 Summary

This chapter introduced this study’s Blockchain-based energy exchange system (BEES). The system was presented in the form of a business process model. First, the core components and structure of the model were discussed. This was followed by a presentation of the busines process model. The remainder of the chapter provided a detailed narrative walk-through of the

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[29] Between state estimation being carried out and the next round of physical energy transfer, system users’ energy demand is either satisfied from their own on-site batteries (both prosumers and consumers as per the assumption of this study). The larger community battery can also assist in acting as a temporary buffer until the next energy dispatch process starts under the “electricity line flow management” sub process in swim lane 5.

business process model. In the following chapter, a detailed presentation of this study’s research findings is provided. Both the secondary and primary research findings are presented.

Chapter 7: Research Findings

"Research is formalised curiosity. It is poking and prying with a purpose."

Zora Nearle Hurston

This chapter focuses on the research findings that emerged from both the secondary and primary data collected during this study. First, the secondary research findings are presented. Next, the primary findings of the study are presented. Discussion of the findings follow in Chapter 8.

7.1 Findings of secondary data analysis

As previously discussed, Chapter 5 constituted the requirement elicitation process of the study, where various functional requirements of a blockchain-based energy trading system were identified. Chapter 5 included a detailed discussion on each of the core functional requirements identified.

Once the requirements were identified, each requirement was mapped to a use case diagram (see Appendix A or page 96). The use case diagram ultimately informed the construction of the business process model (BPM). The BPM presents this study's iteration of a blockchain-based energy exchange system (BEES) operating within the confines of a microgrid. Chapter 6 was exclusively devoted to discussing the BPM. This included highlighting both the key components and structure of the model, presenting the model and providing a narrative walkthrough of each business process contained within the model.

The BPM presented in Chapter 6 is the first research finding of this study. More specifically, the business process model is the *main* finding of the secondary data analysis process.

7.2 Findings of primary data analysis

This section presents the research findings that emerged from the primary data. For a discussion on the design and purpose of the primary research instrument see Chapter 2. Note that the findings are only presented in this chapter, an in-depth discussion of the findings can be found in Chapter 8.

7.2.1 Participant contextual background

Because of the cross-disciplinary nature of the study, cross-disciplinary experts were required to effectively verify the functional requirements of the blockchain-based energy exchange system. By verifying the functional requirements (FRQs) which constitute the BEES, one can determine whether the FRQs have been correctly specified at a medium abstraction level. Furthermore, it provides the opportunity to identify whether any core functional requirements were missing from those initially presented in Chapter 2, and fully discussed in Chapter 5. In total, eight experts participated in the primary data collection process. Figure 12 below presents the educational background of the research participants.

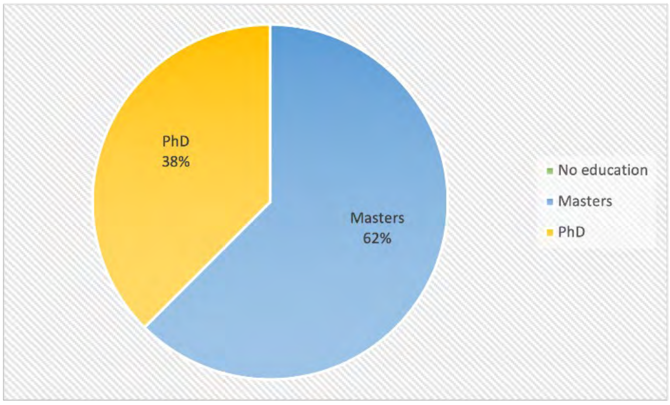

Figure 12: Educational background of research participants

Of the eight experts, three participants held doctorate degrees with the remaining five all holding at minimum master’s degrees. Seven participants completed the questionnaire aimed at evaluating the functional requirements of the blockchain-based energy exchange system (i.e., the system presented in the business process model). One expert completed the questionnaire which aimed to evaluate the syntactic correctness of the business process model.

Reading from Figure 12 above, the research participants were all well qualified from an educational standpoint. More specifically, the qualifications held by the participants are qualifications that are held in high regard in both industry and academia. This is due to most participants qualifications’ being intimately tied up in the various STEM fields. Furthermore, it was often the case that the degrees were cross-disciplinary in nature. For example:

- **Participant 1,** a current PhD candidate, noted that his/her:

> *“… current PhD dissertation is about Blockchain in Smart Metering Systems.”*

- **Participant 2** noted that:

  > *"I have a PhD in blockchain-based local energy markets."*

- **Participant 5** mentioned that he/she holds a master's degree in electrical engineering.

Thus, not only did the participants possess sought after qualifications, but they also brought a host of cross-disciplinary expertise. From the eight research participants alone, the following *general* areas of expertise were identified.

1. Blockchain expertise including
    a. Blockchain business analysis,
    b. Blockchain digital assets,
    c. Blockchain energy trading,
    d. Blockchain entrepreneurship in the energy ecosystem,
    e. Blockchain web integration,
    f. Smart contract development (Solidity, Alogrand, Stellar),
2. Business analysis and system implementation,
3. Business analytics,
4. Business process modelling,
5. Electrical engineering,
6. Energy smart metering systems,
7. Energy systems,
8. Local energy markets.

As previously explained, often one participant would have expertise that stretched more than one of these domains. For example: **participant 2** comments:

> *"I have been implementing Practice Management Systems (including the financial components) for 15 years. I also lecture in Business Analysis and Business Analytics."*

Similarly, **participant 5** notes that he/she has experience in:

> *"… blockchain and energy systems based on previous work experience and [an] electrical engineering background."*

Again, **participant 7** comments that:

> *"I have worked as a systems analyst prior to becoming an academic. I have taught systems development for many years."*

Participant 4 noted that he/she specialises in blockchain development with a specific focus on smart contract implementation. Additionally, **participant 4** has experience in blockchain web integration and the management of blockchain digital assets.

The next seven sections (7.2.2 – 7.2.8) summarise the findings from the questionnaire responses. See Appendix D for the questionnaire presented to research participants. Research findings are reported thematically as they relate to each of the functional requirements (FRQs). The findings are also reported in the same logical sequence in which they appeared in the questionnaire.

7.2.2 Findings related to FRQ6 (The system must store all operational data)

The first question of the questionnaire evaluated whether the blockchain-based energy exchange system (BEES) satisfied FRQ6 (i.e., that the system must store all operational data).

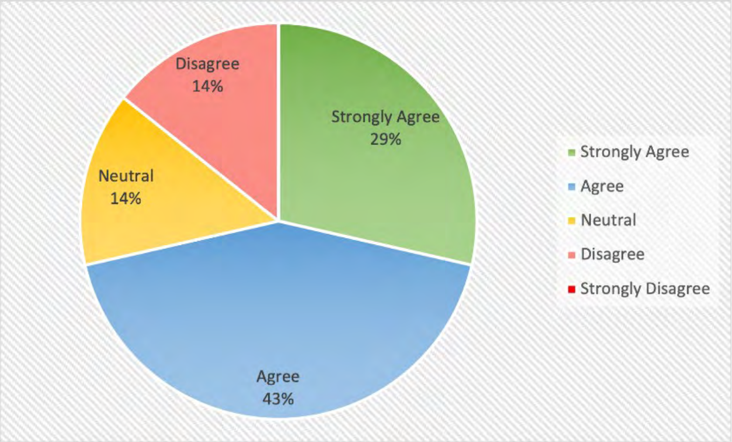

Figure 13: Participant responses for FRQ6

Reading from Figure 13 above, approximately 72% of the respondents agreed that the BEES satisfies FRQ6 (either agreeing, or strongly agreeing). Participant 2 remained neutral in his/her opinion. Participant 6 disagreed that the BEES does satisfy the FRQ.

Noting his/her reason for dissonance, participant 6 explains that:

> *"Storing data is not a value add blockchain use case but rather identifying data points / storing aggregate transactions that serve a function or enabling [sic] a decentralised data marketplace."*

Relating to the storage of operational data, participant 2 and participant 5 make a similar observation about the availability of other storage mechanisms that can be used in conjunction with the digital ledger. For example, participant 2 notes that:

> *"Other data storages [sic] are also available. Note [sic] everything needs to be on chain."*

Participant 5 asks:

> *"Is there consideration of storing some of the data outside of the digital ledger, for regulation reasons maybe?"*

Although **participant 5** raises a query about the data storage mechanism of the BEES, the respondent still believed that the BEES does satisfy FRQ6. **Participant 2**'s query ultimately resulted in the participant remaining neutral about the system's ability to satisfy FRQ6.

Although both **participant 2** and **participant 5** raise observations about the availability of other storage mechanisms, they do so for differing reasons. For **participant 2,** alternative storage is suggested to ultimately enhance the efficiency of the BEES. In contrast to this, **participant 5** raises the possibility of alternative storage for regulatory reasons. It is possible that the two similar, yet differing suggestions were given due to the participants' divergent backgrounds. **Participant 2** is a practicing academic with PhD in blockchain-based local energy markets. **Participant 2**'s current academic interests include the *analysis* of blockchain technology as an information system for energy markets. Presumably, **participant 2** is well acquainted with the body of research that relates to blockchain-efficiency within the context of energy systems. As such, participant 2's analysis-based background hints towards the participant's observation that other storing mechanisms exist which can enhance the efficiency of the overall information system.

On the other hand, **participant 5** has *practical* work experience in relation to blockchain and more broadly, energy systems. As such, it is probable that **participant 5** has encountered practical implementation challenges where sensitive data had to be stored in a specific matter to comply with local legislation. Thus, it is possible that participant 5's practical experience informed his/her comment that regulation may dictate that not all data can simply be stored on the digital ledger itself.

Participant 3 raised a similar concern to **participant 5** with regards to regulatory concerns by noting that:

> *"I am not sure how much personal information is being stored but I am assuming minimal as these are subject to strict laws."*

Participant 3 has been implementing practice management systems (including the financial components) for 15 years. Thus, it seems that participant backgrounds which are largely dominated by practical experience (i.e., **participant 3 and 5**) is a probable contributing factor to the suggestions that relate to regulatory concerns over the storage of system data. Today, it is standard for system implementors to consider the various legal requirements which aim to protect specific types of data. The necessary business rules are then enforced in the businesses' information systems to comply with legislation (Guarda, Ranise and Siswantoro, 2017).

Participant 4 agrees that the FRQ is satisfied, and comments:

> *"Operational data comprises of production and consumption data, as well as minted tokens for production so this largely satisfies the requirement. I am not sure if you should also be tracking the movement of tokens here as well (i.e., the movement of tokens from the producer to the consumer but I assume this is covered in a transactional use case)."*

Participant 7 comments that he/she is:

> *"… satisfied with the detailed explanation given."*

7.2.3 Findings related to FRQ1: The system must assist in the microgrid configuration process

The second question of the questionnaire evaluated whether the blockchain-based energy exchange system (BEES) satisfied FRQ1 (i.e., that the system assisted in the microgrid configuration process). Figure 14 below presents the participant responses for question two.

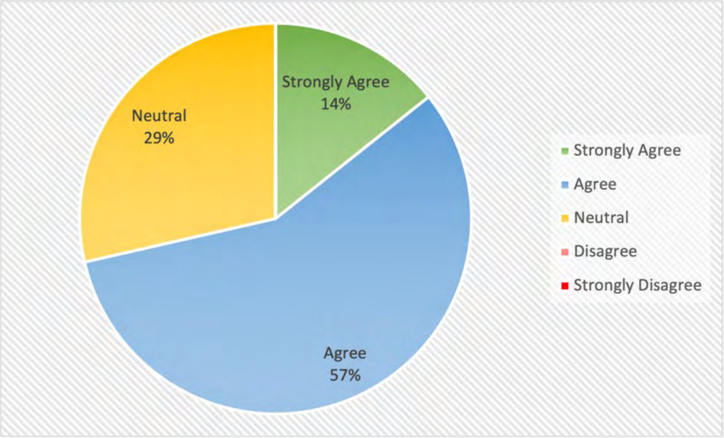

Figure 14: Participant responses for FRQ1

Reading from Figure 14 above, approximately 71% of the respondents agreed that the BEES satisfies FRQ1. **Participant 5 and 6** remained neutral in their opinions. Not one participant disagreed with the fact that the system assists in the microgrid configuration process.

Participant 3 and participant 4 felt the system satisfied the FRQ well enough and did not feel the need to further elaborate as to why this is so. **Participant 1** re-emphasised the important role played by smart meters when configuring the microgrid. On a similar vein, **participant 2** highlights the importance of this functional requirement by stating that:

> *"… without configuration/set up support the microgrid and market will not be successful."*

Participants 5 and **6** do not highlight any key reasons for their neutrality in relation as to whether the BEES satisfies FRQ1. However, **participant 6** does comment that:

> *"You can simulate this [i.e., the configuration of the microgrid] without a blockchain and use blockchain to manage clearing and settlement."*

7.2.4 Findings related to FRQ2: The system must provide secure access control

The third question of the questionnaire evaluated whether the blockchain-based energy exchange system (BEES) satisfied FRQ2 (i.e., that the system must provide secure access control). Figure 15 below presents the participant responses for question three of the questionnaire.

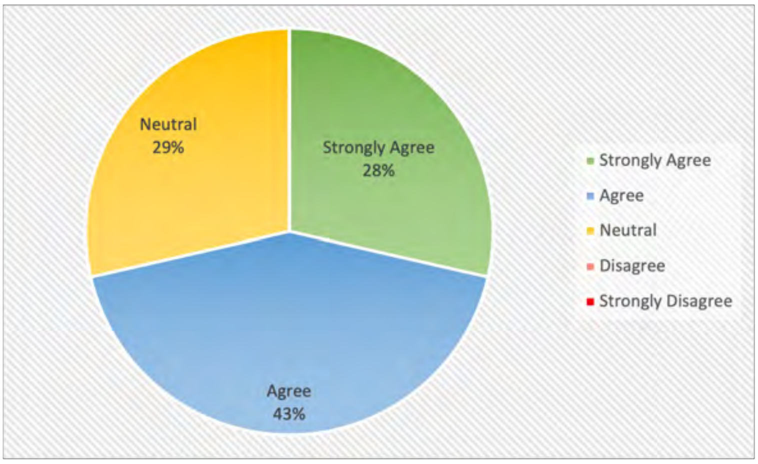

Figure 15: Participant responses for FRQ2

Reading from Figure 15 above, approximately 71% of the respondents agreed that the BEES satisfies FRQ2 (i.e., either agreed or strongly agreed). Noteworthy is the fact that **participant 1** and **participant 2** strongly agreed that the BEES satisfies FRQ2. **Participant 5 and 6** remained neutral in their opinions. Not one participant disagreed with the fact that the system provides secure access control.

Participants 1 and 2 felt that the BEES satisfied FRQ2 well enough and did not feel the need to elaborate. **Participant 3,** who agrees that the BEES satisfies FRQ2, comments:

> *"… my only mention would be around reputation data and permission to access this."*

Participant 3 also expresses that:

> *"The use case is satisfied by the BEES."*

Later, **participant 3** raises a query regarding the system's implementation of the electricity procurement smart contract. **Participant 3 notes:**

> *"… However, I am not sure I understand what you mean that each consumer is coupled with their own smart contract instance? Do you not have 1 Electricity Procurement Smart Contract that maintains state for each user based on their address (i.e., public key)? This state can include the quantities consumed in previous energy exchange windows (perhaps tracked via a struct and a mapping of an address to the previous energy exchange window struct – assuming a Solidity smart contract)?"*

This is a valid query about the design of the electricity procurement smart contract and is addressed in Chapter 8.

Participant 5 (neutral about the system's ability to satisfy FRQ2) comments:

> *"…Is there perhaps some onboarding process outside of BEES, that includes some form of "KYC" verification checks (e.g., Hanis checks, Experian credit check) to have baseline data about the consumer?"*

Participant 6 (neutral about the system's ability to satisfy FRQ2) comments:

> *"Yes [i.e., yes it does satisfy FRQ2], but should be decentralised to benefit from blockchain value e.g., EWF Switchboard."*

7.2.5 Findings related to FRQ4: The system must facilitate energy exchange

Due to the complicated nature of this functional requirement question four was broken down into three sub-questions (4.1 - 4.3), with each question addressing a specific component of the functional requirement.

- Question 4.1 addressed the electricity procurement process.
- Question 4.2 addressed the management of the energy procurement window.
- Question 4.3 addressed the microgrid balancing process.

Question 4.1

Question 4.1 addressed whether any key aspects were neglected in the energy procurement process. Figure 16 below presents the participant responses.

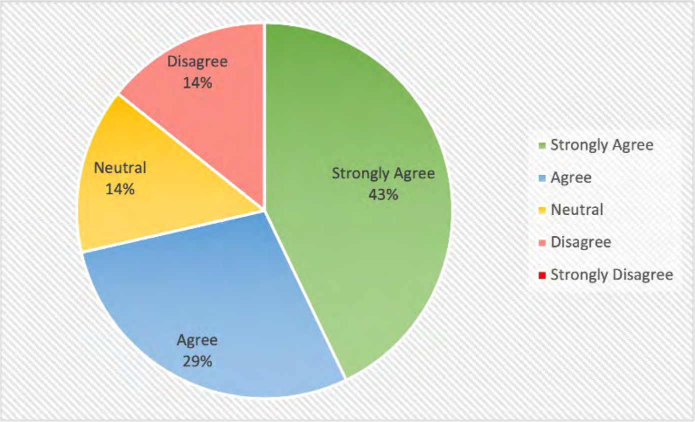

Figure 16: Participant responses for FRQ4 (component one)

Reading from Figure 16 above, approximately 72% of the respondents agreed that no key aspects were neglected in the energy procurement process. **Participant 2** remained neutral. In contrast to all other respondents, **participant 6** believed that the system did indeed neglect key aspects in the energy procurement process.

Most participants simply agreed that the above process did not neglect any key aspects. For example, **participant 3** notes:

> *"Process sufficiently outlined,"*

Participant 7 noted that:

> *"This is satisfactory."*

Similarly, **participant 4** states:

> *"No further comment, sounds good."*

Participant 5, although agreeing that no key aspects are neglected in the procurement process, raises the following concern:

> *"What if the producer does not have sufficient capacity to provide enough energy to last the consumer to the next exchange window?"*

Participant 6 explaining the reason for his/her dissonant opinion states that:

> *"Trade should be market-driven and not have a predetermined price and matching; moreover, blockchain enables more preferences, not just price and hence this would be a very limited use of blockchain."*

Question 4.2

Question 4.2 addressed how well the management of the procurement window was handled by the decentralised application. Figure 17 below presents the participant responses.

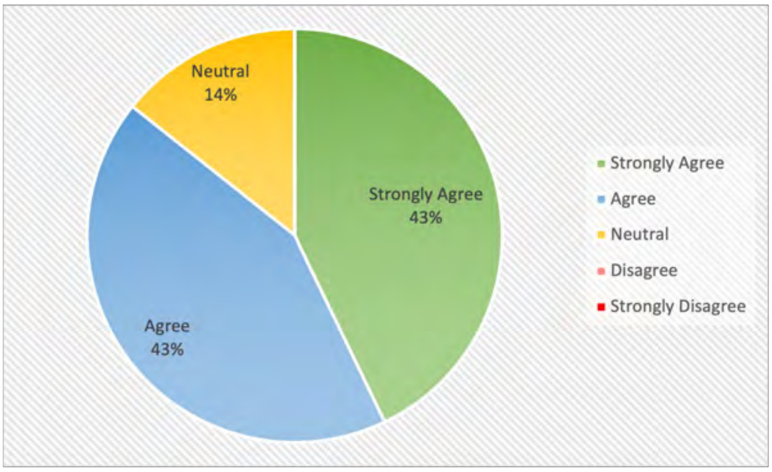

Figure 17: Participant responses for FRQ4 (component two)

Reading from Figure 17 above, approximately 86% of respondents believed that the management of the procurement window is well handled by the decentralised application (dApp).

Participant 2 remained neutral about the business process. Importantly, no participants disagreed or strongly disagreed with the assertion.

Most participants were satisfied with the dApp's role in FRQ4 and did not provide any further feedback. **Participant 2** does not provide a direct reason for his/her neutrality but rather states:

> *"My evaluation is missing a detailed look into the options of the dApp."*

It is possible that **participant 2's** hesitancy to comment stems from the specific domain knowledge required to understand the intrinsic characteristics of decentralised applications. **Participant 4,** an expert in blockchain development (i.e., decentralised application development), as well as blockchain web integration's opinion would presumably carry weight when assessing this business process. **Participant 4** strongly agreed that the procurement window was well handled by the dApp**,** noting**:**

> *"No further comment. Presumably [the dApp integration] this is via a web front end?"*

Thus, **participant 4** was satisfied with the implementation as well confirming the implementation's design by noting that it ought to be implemented via a web-front end as specified in Chapter 4. **Participant 5**, also agreeing that the procurement window was well handled by the dApp raises the secondary concern:

> *"This may be outside of the scope of this exercise, but how is the app managed, how will it be hosted and most importantly how will the integration [sic] to other layers?"*

Although valid concerns, these are ultimately concerns which relate to the non-functional requirements of the BEES. The intention for this evaluation was to focus on the functional requirements of the system.

Question 4.3

Question 4.3 addressed whether any key aspects were neglected in the microgrid balancing process. Figure 18 below presents the participant responses.

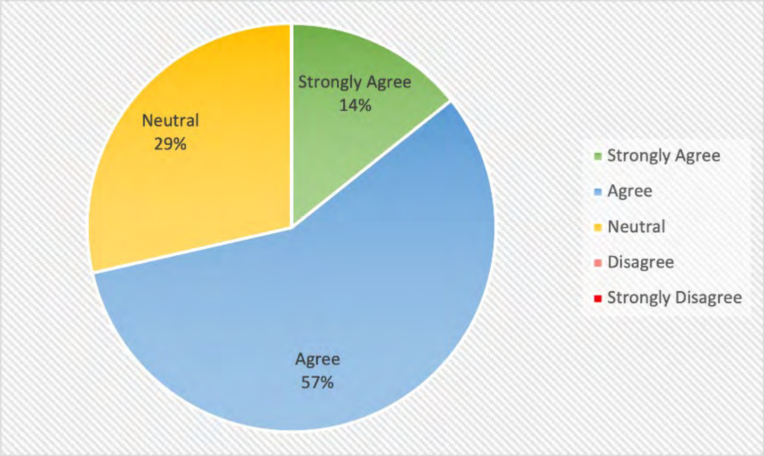

Figure 18: Participant responses for FRQ4 (component three)

Reading from Figure 18 above, approximately 71% of the respondents believed that no key aspects were neglected in the microgrid balancing process (i.e., either agreeing or strongly agreeing). Two participants remained neutral in their opinion. No participants disagreed or strongly disagreed with the assertion that no key aspects were neglected in the microgrid balancing process.

Participant 2, expressing the reason for his/her neutrality notes:

> *"The marketing and acting on the balancing markets seem to be missing."*

Participant 4, also neutral in his/her opinion states:

> *"… Perhaps what is missing is where is the MC getting the current grid status from i.e., whether in energy deficit or in surplus – is this from the final allocations?"*

Participant 3 and **5** raise questions about the balancing process itself. **Participant 5** asks:

> *"To an earlier comment, do you cater for having multiple prosumers that a consumer can buy energy from?"*

Similarly, **participant 3** wants to know whether:

> *"… this balancing is batched, with brief time windows, and also whether any priority coding is factored in."*

Participant 6 believes that the balancing process does not neglect any key aspects by stating:

> *"Can work but how do you satisfy reporting requirements?"*

Question 4.4

At the conclusion of evaluating each of the three individual components which constitute functional requirement 4, participants were asked their opinion about the functional requirement from a holistic perspective. In other words, participants had to consider whether the use cases presented in question 4.1 – 4.3, taken collectively, are satisfactory for the BEES to facilitate energy exchange (FRQ4). Figure 19 below presents the participant responses for this question.

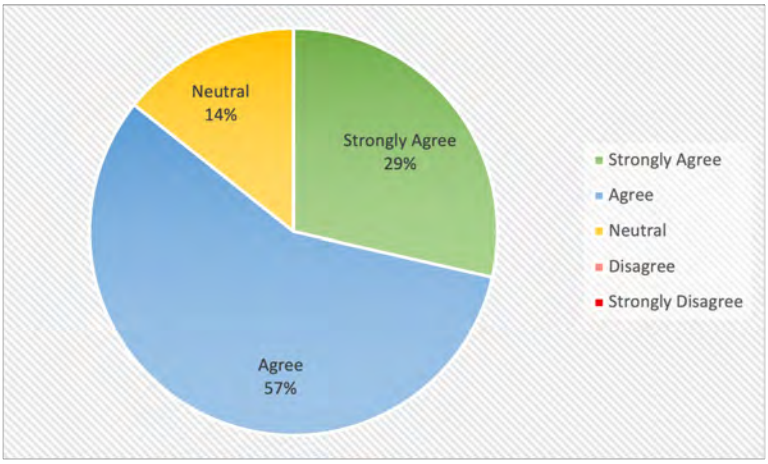

Figure 19: Participant responses for FRQ4 from a holistic perspective

Reading from Figure 19 above, approximately 86% of respondents believed when taking component 1 – 3 collectively, the BEES satisfies FRQ3 (i.e., that the system must facilitate energy exchange). This is a strong affirmation of the BEES's success in satisfying FRQ4.

Interestingly, for question 4.1 – 4.3 the average rate of respondents agreeing (i.e., agree or strongly agree) that the business process was well handled was only 76%. It seems to suggest that when the business processes are viewed from a holistic angle their ultimate purpose becomes more transparent.

Only **participant 6** remained neutral about the system’s ability to satisfy the functional requirement. **Participant 6**’s neutrality is rooted in the reason earlier noted:

> *“Trade should be market driven and not have predetermined price and matching; moreover, blockchain enables more preferences, not just price and hence this would be a very limited use of blockchain.”*

From a strictly technical point of view **participant 6’s** comment is not a direct challenge to the system’s ability to satisfy the functional requirement (i.e., to facilitate energy exchange). It is rather an ideological viewpoint challenging how energy exchange is facilitated, not that it is being facilitated. In an elaborate comment provided at the end of the study **participant 6** clarified that he/she feels that:

> *“…. There is a range of prices [available in an energy market] and that they shouldn’t even be set by the government, that they should just be what the market needs. And obviously we have to work with the government to set a feed in tariff, but the range is bigger than just saying let’s choose a certain price in the middle.”*

For **participant 6**, if the market price is not determined by supply and demand, the full potential of blockchain is not being unlocked. **Participant 6**, comments on pre-determined pricing and matching by noting:

> *“… If everything is pre-set then you wonder, why are they [i.e., fixed price implementations] even using blockchain? … If everything is pre-set, you are using blockchain to just automate a contract that is a precept, right. Which is really, a very minimalist use of a blockchain.”*

For **participant 6**, blockchain should rather be used to solve the exchange of energy at various levels. For example, participant 6 comments:

> *“Because it [i.e., the energy exchange] also depends on the time, when the exchange happens and the needs of that person at a specific time, and then we can make it even more interesting. We can say, it’s not just about the price, but maybe I care to buy first from our hospital generator because they have a surplus. Maybe I don’t like wind generated energy, and I like solar. I only want to buy solar energy.”*

Towards the end of **participant 6’s** comment, the participant explains that if the purpose of the study was to see how blockchain technology could function in one specific system implementation at a simplified level (i.e., a fixed-price model) then how the study approached to problem of decentralised energy exchange was appropriate. In other words, if it was consciously decided that price would be fixed to simplify the model there is no problem with the way the system is specified and modelled in the business process model.

Participant 6 notes:

> *"… If as long as you say that [i.e., specify that the model is operating with a fixed price approach] then it's absolutely correct what you did. You analyse a certain segment, which, for a master's thesis is more than enough. You were still ambitious in my opinion."*

7.2.6 Findings related to FRQ5: The system must provide financial settlement

The fifth question of the questionnaire evaluated whether the blockchain-based energy exchange system (BEES) satisfied FRQ5 (i.e., does the system provide financial settlement). Figure 20 below presents the participant responses.

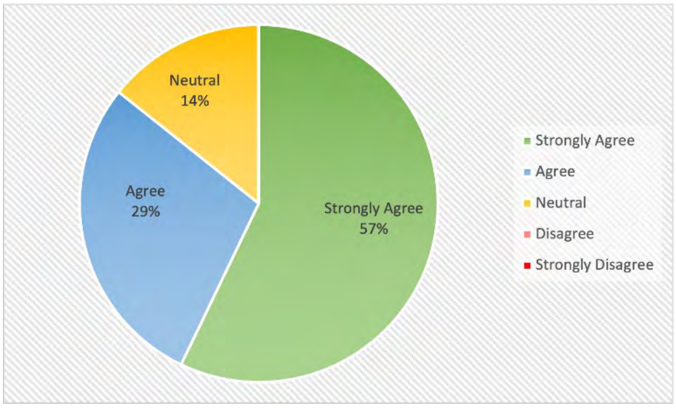

Figure 20: Participant responses for FRQ5

Reading from Figure 20 above, approximately 86% of the respondents agreed that the BEES satisfies FRQ5. Fifty-seven percent of the participants strongly agreed that this was the case.

Participant 6 remained neutral by stating:

> *"… no mention of grid fees here, how are they resolved?"*

Participant 6's comment on grid fees is addressed in Chapter 7.

Participant 1 reemphasises the importance of financial settlement in transactional energy systems (TES) by noting:

> *“The financial aspect is so important in TES.”*

Participant 2 and 3, both agreeing that the system provides financial settlement, simply raise two queries. **Participant 2** asks:

> *“Not quite sure on which data the financial settlement is finally decided on: only the post “real” data?”*

Participant 3 wonders whether:

> *“… any alerts have been built into the system to warn customers of impending caps to be breached i.e., 80% warning.”*

Participant 4 finds the settlement process appropriate by noting:

> *“Sounds good – the idea of burning tokens is similar to an electricity meter counting down – makes sense!”*

On a similar vein, **participant 5** believes that:

> *“The settlement process is very clear.”*

7.2.7 Findings related to FRQ4: The system must provide state estimation

The sixth question of the questionnaire evaluated whether the blockchain-based energy exchange system (BEES) satisfied FRQ4. Figure 21 below presents the participant responses for question two of the questionnaire.

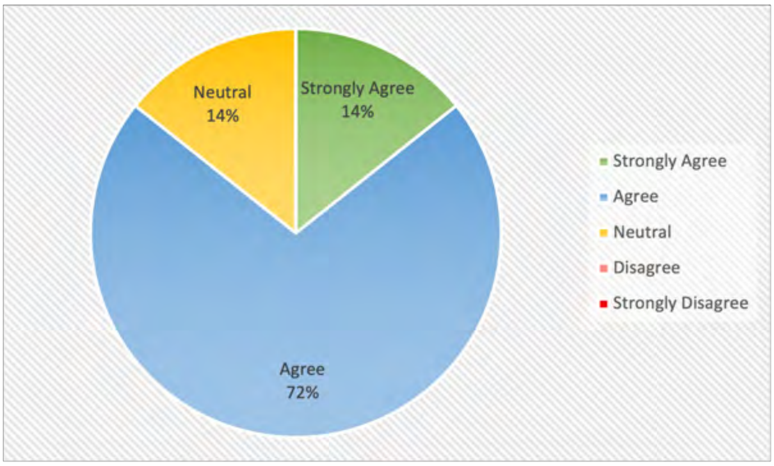

Figure 21: Participant responses for FRQ4

Reading from Figure 21 above, approximately 86% of the respondents believed that the functional requirement was satisfied by the BEES. **Participant 6** remains neutral in his/her opinion by noting:

> *"Could work but based on the assumption that limited options will be made available to individual users."*

Participant 6's comment is once again open for debate. Here it will simply be noted that it is this system's implementation specific design to only have a set number of options available to individual users. Further discussion will be deferred to the next chapter.

Participant 2 notes that the system does provide state estimation, but whether it will be successful:

> *'Depends on the calculation method..."*

Participant 4 raises an interesting point by stating:

> *"Makes sense. That said, a downside of pre-state estimation and post-state estimation is that this is sending at least 2 transactions which will incur fees."*

Participant 5, also agreeing that the system provides state estimation notes that:

> *"This is essentially a reconciliation process."*

7.2.8 Findings related to FRQ1-FRQ6: Blockchain energy exchange system (BEES)

Question seven constituted the final question of the questionnaire. The final question of the questionnaire asked whether taking all six functional requirements (FRQ1-FRQ6), including the two ancillary functional requirements mentioned in the introduction of the questionnaire, included all the functional requirements for a blockchain-based energy exchange system. Figure 22 below presents the participant responses for this question.

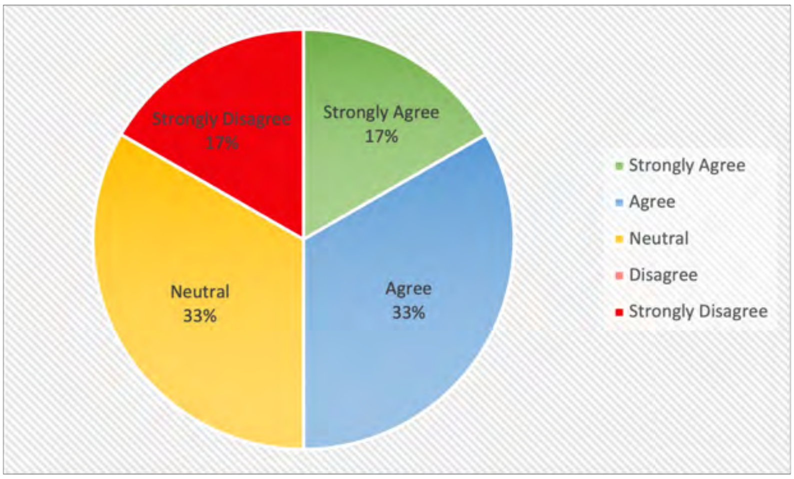

Figure 22: Participant responses for FRQ1-FRQ6

Overall, 50% of the respondents felt that the BEES was not missing any core functional requirements. Thirty-three percent of participants were neutral about the system missing any core functional requirements.

Participant 6 strongly disagreed with the fact that no core functional requirements are missing for the blockchain energy exchange system.

Participant 6 notes:

> *"Various issues noted in previous answers."*

Participant 6's response, does not explicitly invalidate the claim that there are no core functional requirements missing for the system. Rather, **participant 6** is emphasising that he/she is not happy with how some of the already present functional requirements are presented and specified in the BEES.

With regards to functional requirements that may potentially be missing from the current BEES's implementation, **participant 2** suggests:

> *"All requirements seem to have been addressed. Providing analytics data to anticipate potential bottlenecks may be useful."*

Participant 5 also believes that some functional requirements may be missing with regards to:

> *"The initial onboarding process (KYC)."*

7.3 Syntactic Findings

The research findings related to the evaluation of the business process model was straightforward. In terms of the expert's background related to process modelling, the participant commented that:

> *"I have ten years of experience in business process modelling and as such I have implemented numerous BPM related projects in both State-Owned Enterprises and Governmental departments."*

Four core parts of the model were assessed for their syntactic correctness namely the:

1. Use of gateways,
2. Use of events,
3. Description of activities,
4. Use of sub-processes.

For all the four core parts mentioned above the expert commented that:

> *"The use of [gateways/events/activities/sub-processes] in the model are represented fairly."*

As a concluding remark, the participant noted that:

> *"I think you have demonstrated a fair understanding of process modelling using BPMN 2.0 notation."*

The process modelling expert also noted that he/she agrees that the process model does conform to modelling best practices as specified by BPMN 2.0. Additionally, the expert mentioned that that future work on the model may include clarifying a few of the activity descriptors and decomposing the model further.

7.4 Summary

The goal of this chapter was to provide a detailed overview of the research findings of this study. First, the business process model presented in Chapter 6 was identified as the main finding of the secondary data analysis process. Next, the findings from the primary data analysis process were presented. In the next chapter, the primary research findings are discussed in greater detail.

Chapter 8: Discussion

"The aim of argument, or of discussion, should not be victory, but progress."

Joseph Joubert

This chapter provides an in-depth discussion of this study's research findings. First, Weber's theory of evaluation is introduced and briefly explained. Next, using Weber's Theory of evaluation, it is shown how this study's business process model (BPM) satisfies the necessary preconditions to be considered a high-quality model as specified by Weber. Next, the findings from the primary data analysis process are discussed within the context of this study. Where appropriate the findings are further contextualised and applied to the South African context.

Throughout this chapter, interpretivist epistemological and ontological principles are utilised. Goldkuhl (2012, p.4) summarises the involvement of the above-mentioned principles in the work of the interpretivist IS researcher:

> *"The core idea of interpretivism is to work with these subjective meanings already there in the social world; that is to acknowledge their existence, to reconstruct them, to understand them, to avoid distorting them, to use them as* ***building-blocks*** *in* ***theorising***[30]*."*

8.1 Weber's theory of evaluation

8.1.1 A primer on Weber's theory of evaluation

Weber introduced his 'theory of evaluation' in a research paper published in 2012 titled *"Evaluating and Developing Theories in the Information Systems Discipline."*

In this paper, Weber (2012, p.2) proposed:

> *"… a framework and criteria that can be used to evaluate the* ***quality of a theory***[31]*."*

For the discussion to be fruitful going forward, various terms (as defined by Weber) need to be introduced. First, it is important to understand Weber's conceptualisation of what constitutes a valid theory.

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[30] Emphasis added

[31] Emphasis added

For Weber (2012, p.4) a theory is:

> *"… a **particular kind of model**[32] that is intended to account for some subset of phenomena in the real world. A theory is a social construction, it is an artifact built by humans to achieve some purpose. It is a conceptual rather than a concrete thing."*

Weber, (2012, p.5) elaborates on his understanding of a model by noting:

> *"By model, I mean an **abstracted, simplified, concise** representation of something else (phenomena) in the world. Models help us to comprehend the world by representing only those **major features** of the world that are **important for our purposes**. Often, they provide only an **approximate account** of the complexity that exists in the real-world phenomena they cover.[33]"*

In other words, a model is a simplified representation of some subset of phenomena located within the real-world. Assuming that the model possesses certain characteristics it can be deemed a theory (Weber, 2012).

8.1.2 Theorising with business process models

Given Weber's understanding of a theory, it is important to address the question of whether a business process model (BPM) in general (and more specifically this study's BPM) could be a valid theory. See Appendix B for this study's business process model.

At first glance, it seems self-evident that a BPM is a model as defined by Weber. However, to substantiate this claim, this study's BPM will be compared to Weber's definition of a model. To do this, Weber's definition is decomposed into sentences and applied to this study's BPM. First, working from within an interpretivist paradigm, Weber's sentences are *interpreted* to highlight the core sentiments expressed about what constitutes a model. This is followed by an investigation as to whether this study's model satisfies the identified sentiments. Table 8 below presents the comparison of Weber's definition of a model to this study's business process model.

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[32] Emphasis added

[33] Emphasis added

Table 8: Weber's definition of a model compared to this study's business process model (Weber, 2012, p.5)

	Sentence from definition	**Weber's sentence interpreted**	**Applicability to the study's business process model**
1	"By model, I mean an **abstracted**, simplified, **concise representation** of something else **(phenomena)** in the world."	**1.** For Weber, a model is an **abstraction**, or **simplified** version of reality. **2.** The model **aims to capture** this simplified version of reality. **3.** Reality is depicted by modelling some **subset of phenomena**.	**1.** This study's BPM is a **simplified version** of a complex and multidimensional energy eco-system. **2.** A BPM, more broadly, is simply an abstracted version of reality being **captured in model form**. Often, multiple BPMs may be required to capture all dimensions of the modelled reality (Smirnov et al., 2012). **3.** This study's **subset** of phenomena **includes all the elements found within a blockchain-based energy exchange system**.
2	"Models help us to **comprehend** the world by representing only those **major features of the world** that are important for **our purposes**."	**1.** For Weber, a model is there to **aid understanding**. **2.** A model only focuses on the **primary features of the modelled reality**. **3.** The major features included in the model are in part **determined by the purpose of the model**.	**1.** The **primary goal of a BPM is to aid understanding** (Becker, Rosemann and von Uthmann, 2000; Aguilar-Savén, 2004). **2 and 3.** This study aimed to investigate the role of **blockchain technology in a blockchain-based energy exchange system**. As such, the **purpose of the model dictated** that the core focus of modelling activities was centred around the cyber layer (i.e., smart contract layer) of the system.
3	"Often they provide only an **approximate account** of the **complexity that exists** in the real-world phenomena they cover."	**1.** Models provide only an **approximate account** of the modelled reality. **2.** Real-world phenomena are **too complex to be entirely captured** by a model.	**1.** Once again, it is the **intention of a BPM to provide an approximate**, and not a complete account (Smirnov et al., 2012). **2.** Many of the processes involved in energy exchange are far **too rich to be completely detailed in a single business process model**.

Table 8 above highlights the close congruence between this study's BPM and Weber's definition of a model. As such, it seems reasonable to conclude that this study's BPM satisfies Weber's definition of a model. This claim is further supported by the already established consensus in the literature base that a BPM is a model (Aguilar-Savén, 2004; Becker, Rosemann and von Uthmann, 2000; Smirnov et al., 2012).

Given the fact that this study's BPM satisfies Weber's definition of a model, the question of whether the BPM satisfies Weber's definition of a theory can be addressed. Recall, for a model to be a theory, it has to be a *particular kind* of model. Weber (2012, p.5) explains:

> *"Theories are particular kinds of models, however. All theories are models, but not all models are theories. A model must satisfy certain conditions before I deem it to be a theory – conditions that relate to rigorous specification of its "parts" and particular qualities of its "whole." Thus, the existence of a model is a* ***necessary condition*** *for the existence of a theory, but it is not a* ***sufficient condition****.*[34]*"*

The quote above explains that a model's parts, including the whole model itself, needs to possess certain qualities to be deemed a theory. This study *does not* argue that the business process model ought to be regarded as a theory. The intention behind the design of the business process model was *not* for it to be a considered a theory. Rather, it is to provide an initial 'blueprint' of the blockchain-based energy exchange system. However, by utilising Weber's criteria for the 'parts' of a model (when assessing whether a model is a theory) allows for a direct inference about the quality of the business process model itself (Weber, 2012, p.26).

8.1.3 Applying Weber's framework to the business process model

In this section Weber's evaluation framework is applied to this study's business process model (BPM). More specifically, the purpose of applying Weber's evaluation framework to the BPM is to determine the quality of the parts of the model. The section of Weber's framework which considers the holistic qualities of a given model is largely only relevant to models which aim towards being regarded as generalised theories. Holistic qualities include the importance, novelty, parsimoniousness, level and falsifiability of the model. The above-mentioned characteristics (i.e., qualities of the whole) will not be used to assess the quality of the model.

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[34] Emphasis added

Instead, the parts of the model will be assessed according to Weber's framework. There are four core parts that need to be present in a model for it it's parts to be considered high-quality (Weber, 2012, p.6). These parts include constructs, the associations shared between constructs, states, and events (Weber, 2012, p.6). Table 9 below presents the above-mentioned parts along with an explanation of each part.

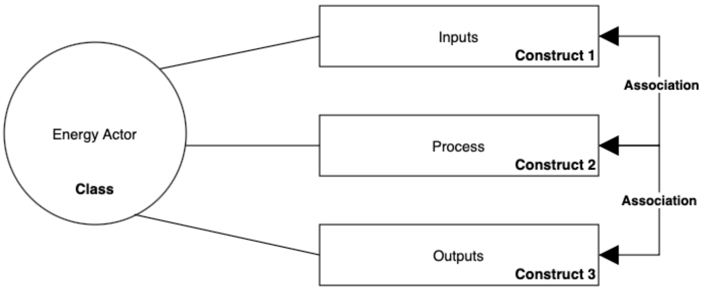
Table 10: Weber's parts defined

Part	Explanation
Construct	A construct represents an attribute in general of some class of things in its domain (Weber, 2012, p.7). Weber defines a 'thing' as something either concrete (i.e., a smart meter), or conceptual (i.e., machine learning algorithm utilised by a smart meter) (Weber, 2012, p.4). For Weber, a class is constituted by 'things' that at minimum hold one property in common (Weber, 2012, p.4).
Association	Weber (2012, p.8) explains that associations in a theory can have multiple meanings. To accurately identify and define associations, it is important to determine whether the theory under consideration is of a static, or dynamic nature. For a theory of dynamic nature (such as this study's BPM), an association between two constructs demonstrates that a set of values of one construct is conditional on a set of values from another construct (Weber, 2012, p.8). Later in the research paper, Weber explains that these associations can be pointed out with varying levels of precision. Of particular relevance to this study is when the direction of the association between two constructs is shown (Weber, 2012, p.9). By pointing out the direction of the association between the constructs, the relation implies the existence of causality where one construct causes a change in the value of another construct (Weber, 2012, p.9).
State	For Weber, the state of a *thing* is a family of attributes (along with their associated values) captured at a given moment of time (Weber, 2012, p.4).
Event	For Weber, an event takes place when the state of one thing changes to another one of its states (Weber, 2012, p.4). In other words, an event occurs when the current values associated with a thing change (Weber, 2012, p.4).

Table 10 below presents examples (from this study's BPM) of the four parts specified by Weber. It is not the intention of Table 10 to present *all* the examples of each of the parts present in the model. Instead, Table 10 demonstrates that the BPM does contain *robust* examples of each of the four core parts presented above. Assuming this is the case, by implication, it would mean that the model satisfies Weber's criteria that the parts of the model are to be considered high-quality.

Table 11: Parts present in the business process model

Part	Example(s) from this study's business process model
Construct	Prior to identifying constructs within the model, it is necessary to identify the appropriate class(es) present in the model (Weber, 2012, p.7). The discussion below centres around the primary constructs of the model. A clear example of a class in the BPM is an **energy actor**. This includes all the energy actors located in swim lane 1 to 6. Energy actors hold in common the fact that they are all participants in the blockchain-energy exchange system, performing important roles to guarantee the exchange of electricity between prosumers and consumers. From this class, strong candidates for constructs would be a transformation **process, input,** and **output** values. These are good candidates to be the central constructs of the model for three reasons: (1) First, inputs, outputs and a transformation process are fundamental to General systems theory (GST), and as such have strong theoretical backing for being identified as the three core constructs in the business process model (Kast and Rosenzweig, 1972; Orr, 2015). One cannot do system modelling of any sort without taking inputs, outputs and a transformation process into consideration at some base level (Orr, 2015). (2) Second, each actor in the model (i.e., the general actor class) has at its own foundation a set of inputs which are transformed and results in a certain set of outputs. Thus, inputs and outputs plus a transformation process are fundamental to the model itself, and thus make good candidates for being identified as primary constructs of the business process model. (3) Third, throughout the model outputs from one actor often serve as an input to a second actor's transformation process. Thus, the constant interaction between the three potentially identified constructs point towards strong association relationships. Once again, this provides reasonable ground for the identified constructs to be regarded as the core constructs of the model.

	Thus, from the three justifications provided above inputs, outputs and a transformation process are three suitable examples of the primary constructs located within the model.
Association	Once the appropriate constructs have been identified in the model, the next step is to identify the associations shared between the constructs. As previously stated, associations can be defined with varying levels of precision (Weber, 2012, p.9). For sake of brevity, the example used here will specifically focus on defining an association where the direction of the relationship is specified. Weber (2012, p.9) notes that such a relationship implies that: *"… changes in the value for an instance of one construct cause a change in the value for an instance of the other construct."* For this example, the three constructs discussed above are used to identify and explain two instances' associations present in the model. Figure 23 below presents the constructs along with the associations shared by the constructs.  **Figure 23: Constructs and associations** Consider swim lane 1 in the BPM. Once the user's reputation and token balance has been confirmed, there is an output from that specific process which takes the form of a message. For this example, it is assumed that the user has passed the screening process. Once the message is received as an input by the financial smart contract, the smart contract deposits the tokens as collateral. The result of this process is an output message to the energy procurement smart contract. This starts the next phase of the electricity procurement process. From the above narrative, a direction-based association can be identified in two places: 1. The input value to the ***'deposit tokens as collateral process'*** is initially null. Once the value of the input changes (i.e., the procurement process finishes and the input is now an active message), the deposit token process starts and as such its value changes (from pending to active).

	2. Similarly, once the value of the process changes to complete (i.e., the tokens are deposited) the output changes from null to a new message that is sent to the energy procurement smart contract noting that the funds are deposited. This is one example of a multitude of direction-based associations present in the BPM. As previously noted, not all examples will be discussed here. However, this example does demonstrate the presence of the most common association relationship shared between the constructs of the model.
State	Recall that for Weber, a state refers to the attributes of a thing at a given moment in time (Weber, 2012, p.4). State is present all over in the process model. The example discussed above will be continued down below to provide an example of state in the model. The process 'deposit tokens as collateral in escrow' (swim lane 3) is a conceptual *thing*. Presumably, this process has different attributes. For example, one attribute could be whether the process is currently active or not. If it is not active, it would be pending. Let's call this attribute *active*, and it is a Boolean true/false value. Prior to the message arriving from screening process in swim lane 1, this process is in a 'pending state' with the *active* attribute being equal to false (i.e., bool active = false). This is **one state** present in the model. Once the message arrives the process is triggered and its state now changes to pending (i.e., bool active = true). This is an example of **another state** present in the model.
Event	Events are closely related to both state and associations. Associations specifically define relationships shared between constructs in the model. Earlier it was noted that the associations shared between the core constructs of the model are all associations which imply causality (Weber, 2012, p.9). Events are more general than this and are technically the 'causal happening' that takes place when the state of a thing changes. In other words, the message arriving to the financial smart contract and causing a state change from pending to active is itself an event.

8.1.4 A final word on the business process model

Section 8.1.2 demonstrated how the business process model satisfies Weber's definition of a model. Next, it was discussed that for a model to be considered high-quality, the model must possess certain characteristics. Following on from this, it was shown how the model satisfies all the requirements of the ‘parts’ (section 8.1.3). Table 10 presented examples of how this study’s business process model has examples of each of the parts as required by Weber’s framework of evaluation. As such, the model stands up well to the assessment criteria put forward by the framework. Given this, the business process model has all the necessary parts to be considered a high-quality model.

8.2 Research findings with a practical implication

The section below discusses the practical implications of the research findings. Specific attention is paid to the implications that relate to the functional requirements and associated expert feedback.

8.2.1 Functional requirement 6: The system must store all operational data

See Figure 13 for a reminder of the participant responses for this functional requirement. Overall, majority of the participants (72%) agreed that this functional requirement was satisfied by the blockchain-based energy exchange system (BEES).

Interestingly, three of the seven experts all commented on the need for integrating off-chain storage solutions with the BEES as opposed to storing all the operational data on the digital ledger itself. As explained in Chapter 7 section 7.2.2 the two core motivations behind the suggestion for off-chain storage relates to either system efficiency or regulatory concerns.

The suggestion to integrate off-chain storage solutions (to enhance system efficiency) raises interesting design questions for system architects. There is already a body of literature available that investigates the benefits behind incorporating off-chain storage solutions as a means to scale blockchain-based systems (Mühlberger et al., 2020; Zamani, Movahedi and Raykova, 2018). However, this question ultimately falls outside the research scope of this study as this considered is more aimed at system design than system analysis. Future researchers may wish to explore the merits of an on-chain only blockchain-based energy exchange system and compare it to adopting a hybrid approach (i.e., a combination of on and off chain).

Having said that, there is value in addressing this question briefly, as it does touch on the general value of digital ledgers. It seems that for a small-scale system such as the one proposed by the BEES, a hybrid-based approach (i.e., introducing off-chain storage) would provide unnecessary overhead. For example, an energy exchange system that is accommodating minimal energy exchange transactions would not necessarily face read/write bottlenecks from the digital ledger. It is not the fact that integrating off-chain storage is a complex process, it is rather a question of whether it is truly worth introducing the additional complexity of managing two or more data sinks, as opposed to having one immutable source.

For systems that are concerned with scalability, off-chain solutions might be mandatory. However, this is a question open for future research. It is impossible to state here which solution is better without some empirical grounding and further research. There are many approaches towards lightening the transactional load on the digital ledger, and they would need to be compared to one another. For example, sharding is another solution (as opposed to off-chain solutions) that aim to solve scalability issues faced by blockchain-based systems. Sharding, instead of utilising off chain data storage, is a technique that attempts to utilise the nodes on the blockchain network to work in parallel to process transactions (Zamani, Movahedi and Raykova, 2018). Future research may wish to explore which storage and consensus mechanisms are most efficient for a blockchain-based energy exchange system. In the literature review it was pointed out that current literature tends to favour proof of authority based mechanisms (Andoni et al., 2019; Wang et al., 2019; Zhao et al., 2019).

Importantly, it must be noted that none of the details discussed above have any *significant* impact on the current iteration of the business process model. The business process model does not attempt to model nor directly address consensus mechanisms and off-chain solutions. In-fact, in the model the microgrid controller does utilise its own data source during the configuration period. The model has been designed in such a manner that it is adaptable to a variety of system implementations. If an off-chain solution had to be incorporated into the model it would be the simple introduction of another external actor that would interact with the model in a manner similar to the digital ledger’s interaction already present in the model.

Regarding energy regulation, this too is an important point that system implementors need to take into consideration. Although regulatory issues concerning blockchain-based systems does not directly touch on the *technical* focus of the study (i.e., the functional requirements), because of its current importance in blockchain-based systems it is worth discussing. This discussion will be kept brief. A primary challenge currently faced by blockchain-based systems (more broadly) is correctly interpretating and understanding the regulatory environment within which the system is to operate (Charles et al., 2019). It is often the case that regulatory agencies have not provided blockchain stakeholders with clear guidelines for ensuring regulatory compliance in their given implementation context (Charles et al., 2019). Most researchers are of the opinion that the only manner in which this challenge can be solved is through multi-stakeholder discussion (Charles et al., 2019; Staples et al., 2017). For example, to foster an environment where blockchain-based systems are compliant with local regulatory requirements Charles et al. (2019) recommend:

1. Active engagement between researchers and regulators, where early and open-ended discussion between system designers and regulators shape the design of the blockchain-based system.
2. The introduction of blockchain pilot projects, where regulators can see the value of the technology, including how the technology operates.

Staples et al. (2017) also provide a list of recommendations for blockchain-developers in their efforts to ensure that their systems are compliant with local regulatory requirements. Some of the key recommendations made by Staples et al. (2017) include that:

1. Regulators must be transparent in how the plan to evaluate whether there is sufficient evidence that a blockchain-based system satisfies regulatory requirements.
2. Regulators and the broader enterprise should be neutral in framing their criteria for the acceptance of a blockchain-based system (i.e., there should be no discriminatory factors against the use of blockchain-based systems).

From the above examples provided, there is a definite need for collaboration between various system stakeholders. Possible system stakeholders in the context of this study may include the blockchain-development team, the South African government, the National Energy Regulator of South Africa, local communities, and Eskom. The question of how to adequality address such regulatory concerns highlights the merit behind this study’s proposed business process model. As noted above, answering questions and coming up with solutions to ensure regulatory compliance for a blockchain-based system will require a multitude of stakeholders (Charles et al., 2019). Each group of stakeholders will come from various disciplines, and presumably, not all stakeholders will have an intricate understanding of blockchain-based energy exchange systems. It seems reasonable to suggest that if such a discussion were to be facilitated without all stakeholders having some base line understanding of the proposed system the value of the discussion would be diminished. It is at this point where this study’s business process model would be able to aid in facilitating this multi-stakeholder discussion. As, Gruhn and Laue (2006, p.1) note:

> *"One of the main purposes for developing business process models (BPM) is to support the communication between stakeholders…"*

Similarly, Smirnov et al., (2012, p.1) note:

> *"… process models are first and foremost required to be intuitive and easily understandable, especially in* ***IS project*** *phases that are concerned with* ***requirements*** *documentation and* ***communication****.*[35]*"*

As to the specific question of whether this study's BEES requires off-chain storage solutions for regulatory compliance remains an open question for future research.

8.2.2 Functional requirement 1: The system must assist in the microgrid configuration process

The feedback received for this functional requirement was minimal. It seems that the reason for this is two-fold. First, the primary business processes of the model focus on the cyber-layer of the system (i.e., the smart contract implementations). Perhaps participants did not feel the need to go into detail about the inner workings of the physical layer as they felt it was ancillary when compared to the rest of the model. If there were major issues with the functional requirement feedback was to be expected, yet 71% of the participants believed that the BEES did satisfy the functional requirement (see Figure 14).

A possible second reason for the lack of feedback relates to the complex nature of the system implementation at the physical layer. The physical layer is intimately tied up with the electrical engineering discipline, and as such, the business process model (oriented around the cyber-layer and built from an Information Systems interpretivist lens) was only able to capture the basic functions of the physical layer. Participant 5, the only expert holding a Masters' degree in electrical engineering would, technically speaking, be the most suitably qualified individual to address this question.

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[35] Emphasis mine

Participant 5 noted that he/she:

> *"… would need a bit more information about what the Microgrid configuration process entails. Is there going to be a physical MC [i.e., microgrid controller) module sitting in each participant's premises as part of the network?"*

Participant 5's comment confirms the interpretation about the model on capturing the basic functions of the physical layer. Participant 5 felt that at an implementation level the model did not convey enough information about what the microgrid configuration process entails. However, this is not a critique of the model itself. It is rather indicative of the fact that more than one business process model may be needed to fully understand the complex business processes involved in the BEES. As previously mentioned (see section 8.1.2), it is often the case that multiple business process models are required to capture all dimensions of the modelled reality (Smirnov et al., 2012). Future research could involve expanding the physical layer of the model into its own separate business process model. The goal of the physical layer in this study's BPM was simply to convey the cyber-physical nature of the system and show the information exchanges between the two layers at a base level.

The second part of participant 5's comment poses the question of whether there would be a physical "microgrid controller module" sitting in each participant's premises as part of the network. Presumably, the participant means a module which can be used by the main microgrid controller (MC) to control the prosumers and consumers energy systems. This question moves well beyond the medium-abstraction level at which this study operated at. It is near impossible to capture all detail in a business process model, and as such, capturing details such as whether microgrid modules will be placed at all participant's premises is sacrificed for model clarity and intuitiveness (Smirnov et al., 2012). This study will not address the question posed by participant 5 as it does not have an impact on the model of the study, nor whether the system satisfies functional requirement 1. The business process model emphasises that there must be a physical layer present in the system with smart meters and a microgrid controller overseeing the primary microgrid configuration processes. It is up to system implementors, based on their specific system environments and expertise, to decide how they wish to implement the processes modelled in the *BEES BPM*.

Participant 6, did not have a question about the physical layer as such, but rather noted that:

> *“You can simulate this [i.e., the configuration of the microgrid] without a blockchain and use blockchain to manage clearing and settlement.”*

It is not entirely clear what participant 6 meant by ‘simulate’ the configuration of the microgrid. The configuration of the microgrid is a process that *has* to take place if the system was to be implemented. However, it seems more plausible that what the participant meant by the word ‘simulate’ is rather something similar to ‘to carry out’ or ‘actualise’.

If this is the case, the larger sentiment expressed in participant 6’s comment seems to be rooted in a misunderstanding of the functional requirement. The participant notes that the configuration of the microgrid can be ‘simulated’ (i.e., carried out) without a blockchain, where the blockchain would be responsible for managing the clearing and settlement of financial transactions. This is how the BEES is presented in the business process model. The blockchain, per se, is not responsible for configuring the microgrid. The microgrid controller, a physical actor, configures the microgrid, with assistance of the data housed on the digital ledger. Smart contracts are responsible for managing the financial settlement processes, amongst other processes, in the BEES.

This misunderstanding does not necessarily highlight a mistake made by participant 6. It could simply point to one of the challenges of using questionnaires as a data collection instrument. Questionnaires, by nature, have no room for follow up questions where real-time clarification can be provided. Suppose this comment took place in an interview setting, it would only have served to highlight the agreement between the study’s business process model and the way participant 6 suggests the processes be modelled. Thus, conversely, this comment, can be taken as confirmation of the design of the business process model rather than as a vote against it.

8.2.3 Functional requirement 2: The system must provide secure access control

Functional requirement 2 was one of the simpler processes modelled in the business process model. Overall, 71% of the participants believed that the BEES satisfied functional requirement 2 (see Figure 15).

Participant 6, neutral about the BEES’s ability to satisfy the functional requirement noted that:

> *“Yes [i.e., yes it does satisfy FRQ2], but should be decentralised to benefit from blockchain value. E.g., EWF Switchboard.”*

It can be noted from the above comment that participant 6 did in fact believe that the BEES satisfies functional requirement 2. However, when answering the Likert scale-based question about the system’s ability to satisfy the functional requirement, the participant remained neutral. It seems that the reason for this neutrality does not stem from the BEES’s approach to addressing the functional requirement, but rather from participant 6’s *preference* for a specific approach.

Participant 6 emphasised that the access control mechanism should be decentralised by making use of a tool such as EWF Switchboard. EWF Switchboard is one iteration of a self-sovereign identity (SSI) service offered by the Energy Web Foundation. In the above comment, participant 6 is highlighting the fact that by utilising a SSI ecosystem all processes related to access control stand to benefit from the possibilities offered by SSI ecosystems. For example, the EWF Switchboard does not only provides SSI services, but also provides decentralised asset identifiers and verifiable claims (Energy Web Foundation, 2021). As the Energy Web Foundation (2021) explain, utilising a tool such as EWF Switchboard means that:

> *“For users, Switchboard enables them to manage their core identity and associated VCs, their assets (such as solar panels, thermostats, electric vehicles, and batteries), and their enrolment in various applications and digital services (such as messaging and storage).”*

For this study, it was assumed that users already went through an initial onboarding / registration process through a SSI service (as discussed in Chapter 6). As such, the only access control processes modelled in the business process model related to verifying whether system users were allowed to participate in a given energy exchange window. From a design perspective, this access control mechanism could be implemented through a SSI service, or alternatively, it could simply make use of blockchain’s native functionalities (as it was done in the process model). However, if a system adopts one specific approach, it does not necessarily follow that the system does not satisfy the functional requirement, as suggested by participant 6’s final answer. At most it could suggest that the system does not satisfy the functional requirement *as efficiently* as it possibly could. Whether SSI access control is better than more traditional approaches is a question that remains open for further investigation. It also ultimately is a question of what does one value more as the system implementor. A simple access control process, such as the one found in this system, does not necessarily need to make use of an SSI to manage user identities. However, for systems where user identities need to be presented to multi-stakeholder groups, the strengths behind the adoption of an SSI identity management system becomes clearer. In summary, participant 6's feedback highlights the need for system architects and implementors to be aware of the tools that already exist within the blockchain eco-system, and based on the system environments, decide which implementation will best fit to the systems needs and purposes.

Participant 3 raised a concern about reputation data and the BEES's permission to access this data. This is valuable feedback. In this study it was assumed that all users of the system had already granted permission for their energy consumption/production data to be used to calculate reputation points. Based on the comment above, future system implementors should take the question seriously of how to utilise cryptography inherent to the blockchain to obfuscate and safeguard users' personal consumption data, whilst still making it available to the smart contract functionality of the BEES.

Participant 3 also raised a question about *how* access control was presented in the questionnaire itself. Participant 3 asked:

> *"However, I am not sure I understand what you mean that each consumer is coupled with their own smart contract instance. Do you not have 1 Electricity Procurement Smart Contract that maintains state for each user based on their address (i.e., public key)? This state can include the quantities consumed in previous energy exchange windows (perhaps tracked via a struct and a mapping of an address to the previous energy exchange window struct – assuming a Solidity Smart Contract."*

To provide context to this comment, participant 3 is an expert in blockchain development, with experience working with Solidity, Algorand and Stellar. As such, it is not surprising to see a question raised about the logic of how the smart contracts' functionality was presented in the questionnaire questions. When explaining the business process model in the questionnaire to the research participants, it was noted that each system user is coupled with their *own* smart contract instance. For example: there would be a smart contract on the blockchain managing access control for user A. Similarly, there would be *another* smart contract managing access control for user B. In the comment above, participant 3 pointed out that this is inefficient way to implement the system, as one smart contract can simply manage state for multiple users. This comment does not have any implication for the business process model as such, as the smart contract swim lanes can be viewed from the perspective of being linked to one system user only, or multiple users. However, participant 3's comment is valuable in that it shows that it makes sense to view the smart contract lanes as carrying out the business processes for multiple users.

8.2.4 Functional requirement 3: The system must facilitate energy exchange

Functional requirement 3 was the requirement with the most detailed business processes, and as such, was broken down into three sub-questions during the evaluation (see section 7.2.5). Feedback from sub-question two (i.e., evaluating the decentralised application) is not addressed in this discussion. This is because most participants (86%) believed the decentralised application performed its role well, with no novel insights emerging from the open-ended feedback. Feedback received was mainly in the form of comments affirming the system's approach to the implementation of the decentralised application.

8.2.4.1 A discussion related to sub-question one

As a reminder, sub-question one evaluated whether any key processes were missing from the energy procurement process. Most participants (72%) agreed that the procurement process did not neglect any core aspects (see Figure 16). Participant 5 (the expert with an electrical engineering background) did pose an especially pertinent question given the South African context. Participant 5 asks:

> *"What if the producer does not have sufficient capacity to provide energy to last the consumer to the next exchange window?"*

Participant 5's question hints towards what the balancing process in the business process model (i.e., sub-question three of the questionnaire) is attempting to solve. Recall from Chapter 6 that energy procurement unfolds in two-phases in the model: first, energy is procured within the microgrid. If there is an energy deficit, energy must either be procured from the public grid operator (i.e., Eskom in South Africa), or alternatively, the community battery must be dispatched. See Chapter 6 Section 6.3.5 for a detailed discussion on how this balancing mechanism works.

To answer participant 5's question, in an ideal world, if energy prosumers within the microgrid do not have sufficient capacity to satisfy the current demand within the microgrid, the energy would have to be procured from outside the microgrid. As previously mentioned, in blockchain-based energy exchange systems, it is often the case that the public grid operator is modelled as an unlimited supplier and consumer (Kirpes et al., 2019). In other words, if the microgrid has to exports surplus energy, the public grid can *always* accept the surplus energy. Similarly, if there is a deficit within the microgrid, the public grid can *always* compensate for this energy deficit.

The complexities undergirding this balancing process was abstracted away in the BPM by modelling the balancing process as a 'sub-process.' Modelling the public grid as an unlimited supplier and consumer might be valid for an efficient and well-established energy sector. However, it is obvious that this assumption is not valid for the South African context. Considering load shedding aside as well as the unreliability of the South African grid system in general means that the public grid (i.e., Eskom) cannot function as an unlimited consumer and supplier (ZAR Department of Energy, 2019). More realistic, given the network's current status, is that the South African grid could function as a limited supplier, and unlimited consumer. Unlimited consumer due to the fact that the grid is frequently trying to procure electricity from new sources (Smit, 2021).

The question posed by participant 5 carries a certain poignancy to it when placed in the context of South Africa. It is reasonable to assume that Eskom will continue to fail the meet the country's electricity demand in the short to medium term (Smit, 2021; Creamer, 2021). As such, this study's BEES has two practical implications for the shortage of electricity. First, the BEES provides a potential hedge against load shedding and energy shortages. For those users of the system connected to the microgrid, energy can be procured from prosumers instead of being captive consumers to Eskom. Given the fact that the public grid will only be able to function as a limited supplier, systems developed and implemented in South Africa may need to put additional emphasis on utilising community battery storage systems. By introducing community battery storage systems, external sources of supply are available if consumer demand cannot be satisfied from within the microgrid by prosumer-injected energy.

Second, it is also possible that the BEES may assist in alleviating the electricity shortfall faced by Eskom if it is producing a surplus of electricity more often than a deficit. Surplus electricity may then be routed to the public grid at a given rate. Granted this is only a small quantity of electricity. However, if a network of microgrids were to be established, the quantities injected into the public grid would accumulate. There is already research available about how microgrids can intra-connect and exchange energy in decentralised fashion with one another, as well as the public grid (Li et al., 2019; Sabounchi and Wei, 2017). A study conducted by Green and Newman (2017) showed that up to 75% of prosumer energy had to be stored in either communal batteries or exported back to the main grid.

8.2.4.2 A discussion related to sub-question three

Sub-question three evaluated whether any key aspects were neglected in the balancing sub-process. As a reminder 71% of the participants felt that no key aspects were neglected in the microgrid balancing process (see Figure 18). Participant 2 noted that the activity of the balancing markets seems to be missing from the BEES. The reason for this is because the intricacies of the microgrid balancing process were abstracted away by modelling the microgrid balancing process as a sub-process in the model. The reason for this was to avoid over complicating the model and instead focus on the core processes in the model. For a discussion of what this microgrid balancing process entails see Chapter 6 section 6.3.5.

Participant 4 wanted to know where the microgrid controller is getting the grid status from (i.e., is the microgrid in a balance or surplus). To answer this query, the decentralised application passes the final allocations to the microgrid controller once they have been prepared. Participant 4 did assume that this is how the business process unfolds but wanted to verify whether he understood the model correctly.

Participant 3 wanted to know if the balancing is batched, with time windows, and whether any priority coding has been factored in. This is ultimately a query aimed at system design and implementation rather than analysis. It is outside the scope of this study to specify these specific details. This study’s BPM emphasises that a microgrid-balancing process needs to be present in the BEES as part of its functional requirements. The fundamentals of the balancing process were modelled. It is up to future system implementors to decide whether they want to batch electricity bundles when balancing the microgrid. Priority coding is also a design consideration left to the system implementors.

Participant 5 wanted to know whether the BEES allows for consumers to purchase electricity from multiple prosumers. The answer to this question is yes. However, consumers do not purchase electricity directly from one prosumer, rather the BEES places an electricity bid for the energy currently in circulation in the microgrid (which would have come from multiple sources). See Chapter 6 for a walk-through of the entire system's operation.

8.2.4.3 A discussion on energy exchange in relation to market-driven trade

The last finding to be discussed for functional requirement 3 relates to participant 6's comment that trade should be market driven. As a reminder, participant 6 commented that:

> *"Trade should be market driven and not have predetermined price and matching; moreover, blockchain enables more preferences, not just price and hence this would be a very limited use of blockchain."*

See Chapter 7 section 7.2.5 (question 4.3) for a detailed presentation of participant 6's comments which relate to the one quoted above. For participant 6, it is important that energy trade be market driven. Market driven trade emphasises the idea that price should be variable and be determined by the current supply and demand within the local energy market. However, this is one option out of a host of other available market mechanisms. More specifically, the idea that trade should be market driven is an idea that aligns itself with one specific branch of economic thought which emphasises the benefits of a laissez-faire approach to the market. As such, whether a market is most efficient when regulated or not is a contentious topic. From a technical point of view (i.e., does the system facilitate energy exchange), the participant does indeed admit that the system does successfully do so. However, just in a:

> *"… very limited use of [the] blockchain."*

As such, participant 6's comment does not directly affect whether the functional requirement is satisfied, but rather *how* it is satisfied. However, it is a point worth discussing as it touches on some of the fundamentals of the blockchain eco-system. As noted above, whether trade should be market driven or rely on predetermined pricing and matching is a topic with no clear-cut answers. Within the context of this study, it was noted that this study situates itself within a common-influenced paradigm, where profit is not the primary operating motive of the system (see Chapter 6 section 6.3.1 for a more thorough discussion on a commons-rule based approach to system conceptualisation). The primary motive of the BEES was to enable residents in a neighbourhood community to be a part of an energy community which promises energy security. It may be easy to think that by adopting a fixed pricing structure is ultimately recreating a scenario like the one currently faced by energy consumers in South Africa. In other words, by adopting a fixed pricing structure in the BEES, system users are ultimately once again captive consumers unable to influence the price paid, or received, for electricity. However, this is not necessarily so. There are two main reasons why this is the case:

1. First, in South Africa, a captive consumer has no influence over the price paid for energy, nor the feed-in-tariff received. In this study's community-based BEES, all community members have a vote on the governing protocol of the system.
2. Second, captive consumers in South Africa fall prey to tariff hikes. As noted in Chapter 3 section 3.3.3, Eskom has already announced a 15.06% tariff hike for 2022 (Comins, 2021). This is the quintessential example of what is experienced by a captive consumer. The captive consumer must continue paying for electricity (as it is the only source available), at an inflated price, with no way to influence the price. In a community-governed protocol the price cannot be inflated without fair justification. In other words, community members would always expect that if they inject 100 watts of energy into the microgrid, that 1 energy token would represent those 100 watts.

Perhaps it is the case that system users would be better off within the local energy market if the trade was entirely market driven. However, such a question can only be addressed once pilot projects have been run. It is also a matter that is largely dependent on the goals of the community. For example, a neighbourhood may very well not be interested in buying electricity at a variable rate, but only wish to be guaranteed that if they inject 100 watts into the microgrid, they are allowed to withdraw 100 watts at a later stage based on the energy token received. This was ultimately the approach put forward by the study by this study.

Participant 6 did also note that:

> *"… blockchain enables more preferences, and not just price and hence this would be a very limited use of blockchain."*

This is an important point raised by participant 6. Participant 6 is raising the point that by relying on blockchain’s consensus mechanism one can accommodate a host of different *types* of transactions. For example, some system users may wish to gift family members in their neighbourhood energy, or alternatively, to only purchase solar energy instead of wind generated energy. In that sense, participant 6 is right that this study’s BEES is a limited use of blockchain in that it *currently only* puts forward a fixed price and matching market mechanism. However, at the cost of overcomplicating the study this was a conscious decision made. The ‘fixed price fixed matching’ approach aligned well with the commons-oriented approach to managing a community resource and was satisfactory to explicate the fundamentals of a blockchain-based energy exchange system. Future research may involve expanding the model, where more trading and purchasing options are made available to users of the BEES. Future researchers may also wish to adapt the model so that trade is market-driven as opposed to serving the purpose of providing energy security to a particular community.

Deciding how a blockchain-based energy exchange system should be governed should be a discussion which involves both the community as well as system developers. A commercially driven project will most likely favour a market-driven approach as there is a profit-making opportunity. It can be imagined that a community purely interested in energy sustainability might favour a commons-oriented approach.

8.2.5 Functional requirement 4 and 5: The system must conduct state estimation and financial settlement

Both the functional requirements for state estimation and financial settlement received positive feedback from the participants. For both state estimation and financial settlement, 86% of the participants felt that the BEES satisfied functional requirement 4 and 5.

For functional requirement 4 (i.e., state estimation) two core insights emerged from the data collected:

1. First, participant 2 commented that the system does provide state estimation, but that the success of the state estimation processes ultimately depends on the calculation method utilised. The calculation method adopted by the state estimation process falls outside the scope of this study. In fact, modelling the intricacies of the state estimation process would constitute another

business process model in its entirety. Future research may wish to explore which calculation methods to use when performing state estimation in blockchain-based energy exchange systems.

2. Second, participant 4 (the blockchain development expert), after studying the business process model, raised the point that by performing pre and post state estimation multiple transactions are sent to the digital ledger which incurs fees. This is a valid point, and once again points to the strength of a business process model in facilitating multi-stakeholder analysis. However, the way the system was modelled is that the final allocations for each consumer (i.e., pre-state estimation) are not written to the digital ledger, they are only passed as an input to the state estimation process. Thus, there are no unnecessary fees incurred to the digital ledger. Participant 4's comment, however, does still raise important implications for the state estimation process as it touches on the overall efficiency of the process. State estimation lies at the heart of the BEES, and as such, future researchers may wish to explore the most efficient way to carry out state estimation.

As noted above, for functional requirement 5 (i.e., the financial settlement process) most participants were satisfied with how the BEES addressed the functional requirement. Participant 3 noted that the system should include alerts to warn customers about when their token balance is running low. This is an important insight and could constitute a further functional requirement for the BEES. Participant 6 queried why there was no mention of grid fees in the financial settlement process. In Chapter 6 section 6.3.1 the following community rule was highlighted when the commons-influenced protocol for the system was introduced:

> *As a community rule, 10% of the revenue generated from electricity sold to the public grid goes to a community fund for the maintenance and upgrading of the physical microgrid.*

Once again (as noted in section 8.2.4 above), because the *BEES BPM* is a medium-abstraction level process model it does not make it obvious where grid-fees are charged. Future amendments and updates to the model can expand the microgrid balancing sub-process in the process model to indicate that it is at this point where grid fees are introduced into the model (see swim lane 5 in the BPM). In fact, the entire microgrid balancing sub-process would be best explicated by its own business process model due to the intricate nature of the process.

8.3 Summary

The aim of this chapter was to provide a discussion on this study’s findings that emerged from the primary data analysis process. Practical implications of the research findings were noted throughout the chapter and contextualised to South Africa where appropriate.

The following chapter provides a retro-active overview of the entire study. The research questions posed in Chapter 2 are revisited, and some final reflections are provided.

Chapter 9: Conclusion

This chapter concludes this study by revisiting some of the most important aspects of this study. First, the problem statement of the study is retroactively addressed. Second, the research questions of the study are answered. Next, the limitations and methodological approach of the study are commented on. This chapter ends by discussing areas of future research as well as providing some final reflections.

9.1 Problem statement revisited

In Chapter One section 1.2, it was noted that this study formulated the following problem statement:

South Africa's energy system is still largely based on the traditional centralised energy supply model which sees Eskom satisfying 90% of the country's electricity supply. As such, captive consumers have no option but to rely on Eskom for the provision of electricity. Consumers are left with increasing tariffs and poor service delivery. Furthermore, such a supply model excludes other valuable energy resources (e.g., consumer owned DERs) from contributing towards the supply base. As South Africa starts moving down the path of decentralisation the increasing integration of volatile DERs with the main grid will pose significant challenges.

As highlighted in the problem statement above, South Africa finds itself in a position where Eskom is supplying over 90% of the country's electricity (Winning, 2019). Today, in 2021, the sole provider of electricity in the country is plagued by operational challenges. For example, Eskom has accumulated a R401 billion debt, where load shedding has cost the country as much as R1.4 trillion over the past decade (Lawrence, 2020; Omarjee, 2021). Not only is this troublesome when considering the general health of the economy, but it also impacts upon the everyday lives of ordinary South Africans. As noted throughout this study, tariff hikes have once again been proposed by Eskom for 2022 to restore balance to the company's financial position (Comins, 2021). South African citizens have no choice but to accept the tariff hikes (unwillingly) and pay higher rates for the same level of service delivery (Lovins and Eberhard, 2018). This reduces each electricity consumer's disposable income.

This 'captive consumer predicament' is not a secret in South Africa, with the South African Department of Public Enterprises (2019, p.14) itself admitting that:

> *"Eskom's operating business model is* ***outdated*** *and based on the era of excess electricity supply and* ***captive customers****."*

It was also shown how globally (and locally in South Africa) decentralisation, decarbonisation and digitisation is putting increasing pressure on energy sectors to undergo structural reform. The rise in consumer-owned distributed energy resources (DERs) is increasingly requiring of legacy grid systems to accommodate bi-directional electricity flows.

This study proposed that by utilising blockchain technology and a microgrid, one could create a community-based microgrid energy exchange system. Such a system would firstly, free consumers from being captive consumers. Secondly, the system would provide legacy grid systems with a more effective way to integrate DERs into the larger energy eco-system. Thirdly, the system would provide a hedge against the load shedding crisis in South Africa and provide energy security to the systems' users more generally.

9.2 Research questions revisited

The main research question posed by this study was as follows:

> *How can blockchain and microgrid technology be integrated to facilitate peer-to-peer energy trading in South Africa?*

The main research question was posed to understand *how* blockchain technology and microgrids could be used to create a community-based microgrid energy exchange system. The business process model presented in Chapter 6 (Appendix B) is *itself* an answer to the main research question posed by this study. In other words, the business process model shows exactly *how* blockchain and microgrid technology can be integrated to facilitate peer-to-peer energy trading in South Africa.

For this study to answer the main research question, the following sub-questions were posed:

- **Question one**: *Why is blockchain technology suited to facilitating decentralised energy trading with a microgrid?* This question was largely addressed in Chapter 5 of the literature review. It was specifically noted how blockchain technology is particularly well suited to decentralised (i.e., peer-to-peer) energy trading as it provides the ability to facilitate the settlement of financial transactions without the intervention of a middleman. It was pointed out how cryptography, which is inherent to the blockchain, provides a host of solutions to safeguarding sensitive energy data. Smart contracts, as a part of the blockchain-eco system, provide a unique way in which to provide operational intelligence to the blockchain-based energy exchange system.

- **Question Two:** *What are the existing subsystems and processes involved in blockchain-based microgrid energy exchange systems?* This study identified six core functional requirements of a blockchain-based energy exchange system (BEES). Additionally, two ancillary requirements were identified. The six core functional requirements included that the BEES must:

  1. Assist in the microgrid configuration process,
  2. Provide secure access control,
  3. Facilitate the energy exchange,
  4. Provide state estimation,
  5. Facilitate financial settlement,
  6. Store all operational data.

  The two ancillary requirements included that the BEES must:

  1. Automate as many of its business processes as possible to streamline the operational efficiency of the system,
  2. Be capable of communicating with all nodes via public broadcast messages, as well as communicate with individual nodes where appropriate.

- **Question Three:** *How can a blockchain-based microgrid energy exchange system be embedded into the larger South African network?* The question sought to understand how a community-based microgrid energy exchange system could integrate with the broader South African network. As discussed throughout this study, if there is a surplus of electricity within the microgrid this surplus can be exported to the main grid. If there is a deficit of electricity within the microgrid, the balance can be imported from the public grid. The public grid operator (i.e., Eskom) plays a crucial role in the BPM presented in Chapter 6, and as such, the South African network is intimately tied up with the community-based microgrid energy-exchange system. However, what this study’s system achieves is that it reduces the reliance on the public grid. If there is a deficit within the microgrid, Eskom is not the only source available to rectify the imbalance. The community battery may be utilised to restore energy imbalance as well as requesting of energy prosumers and consumers to reduce their current electricity consumption rates. As such, energy security is inherent to this study's system model.

9.3 Limitations

The first limitations faced by this study includes the number of experts recruited to participate in the evaluation this study's system. Due to the cross-disciplinary nature of the study, it was challenging to recruit experts who have expert-level knowledge in both blockchain technology and energy systems. Although the 'soft' cap for expert review (when evaluating the functional requirements of the BEES) was satisfied with a total of seven research participants, if more participants were recruited it is possible that additional novel findings would have emerged from the evaluation process (see section 7.2.1).

A second limitation faced by the study was the fact that the business process model was constructed by only carrying out a scoping review of the relevant literature available. As such, the study was limited by the number of articles that could be analysed for functional requirements based on the unique nature of blockchain-based energy trading systems. There are limited publications available that cover these types of systems from a holistic perspective.

A third limitation faced by the study was the structured approach adopted with regards to data collection. Although opened ended feedback was collected, it limited additional free-form responses and participant interaction.

A fourth limitation encountered in this study was that not all the functional requirements identified during the scoping review were implemented in the same manner as other researchers have previously done. This largely related to the pricing mechanism of this study's system. For example, instead of adopting a variable pricing mechanism, this study's blockchain-based energy exchange system adopted a fixed-pricing mechanism and situated itself within a commons-oriented paradigm. This was done firstly, to simplify the model. To model all the business processes, present in the model and introduce the additional complexity of variable pricing would have overcomplicated the model. Furthermore, the interaction between community-based blockchain systems and the commons-paradigm provides interesting use cases for consideration. Taking this approach to peer-to-peer energy trading does not come without precedent (Mihaylov et al., 2014). As discussed in Chapter 4 section 4.3, for Hayek (1945) a fundamental part of a decentralised market is the inclusion of a variable pricing structure. Participant 6 seems to have shared Hayek's sentiments. However, as argued in this study, this is one possible implementation and largely depends on the context as ultimate purposes of the system. This study wished to explore how a community could guarantee its own energy security, whilst maintaining a connection to the public grid (i.e., Eskom in the context of the study).

Furthermore, some of the detail underlying some of the functional requirements discussed in Chapter 5 had to be abstracted away to avoid overcomplicating the model. As mentioned previously, this is the nature of process modelling. To fully capture each business process, multiple business process models would have to be produced.

9.4 Methodological approach

This study was conducted within an interpretivist research paradigm, utilising a case study research strategy. Data was collected from energy and blockchain experts (in both academia and the private sector) by way of open-ended questionnaires, and thematically analysed. Each functional requirement constituted a core theme in the study. The syntactic correctness of the model was evaluated by way of a close-ended questionnaire.

In brief, first, a scoping review was carried out to identify the functional requirements of the system. This was followed by the construction of a use case diagram which captured the core functional requirements of a blockchain-based energy trading system. The use case diagram informed the creation of this study's business process model. The functional requirements were subject to expert review, along with the syntactic correctness of the model. Weber's Theory of Evaluation was used to theorise about the quality of the constituent parts of the model.

9.5 Areas of future research

It was noted at various points throughout this study where future research within this domain might lie. In terms of carrying *this specific study* forward, future researchers may wish to take each of the functional requirements modelled in the business process model and turn them into their own business process models. This study only worked at a medium-abstraction level, and as such, certain tasks and activities had to abstracted away from the businesses processes modelled.

Future research may also include the running of simulations for each of the functional requirements modelled, particularly so for state estimation and financial settlement. Researchers may wish to develop a financial settlement and state estimation smart contract by using this study's business process model as a starting point. Various implementations can then be compared against other to see which implementation is most effective in facilitating peer-to-peer energy exchange.

9.6 Summary

This study set out to investigate how blockchain and microgrid technology could be integrated to facilitate peer-to-peer energy trading in South Africa. Chapter 1 provided readers with the necessary background information to understand the development of this research study's problem statement, along with the key research questions of the study. Chapter 2 provided a detailed discussion on the research methodology and strategy adopted by this study. Chapter 3 introduced the readers to the fundamentals of energy systems, discussing the movement from traditional centralised energy systems to decentralised energy systems. Chapter 3 also discussed the current state of the South African energy sector. In Chapter 4, readers were introduced to microgrids as a solution to integrating distributed energy resources with the main grid, and how local energy markets can be utilised to balance the supply and demand for energy within a microgrid. Chapter 5 discussed how blockchain technology can act as the information system for a peer-to-peer energy exchange system. This chapter also introduced the reader to the six core functional requirements of a blockchain-based energy trading system. Chapter 6 presented this study's iteration of a blockchain-based energy trading system in the form of a business process model. It was noted that this study's system was called the Blockchain-based energy exchange system (BEES). Chapter 7 presented this study's research findings. Chapter 8 discussed the research findings.

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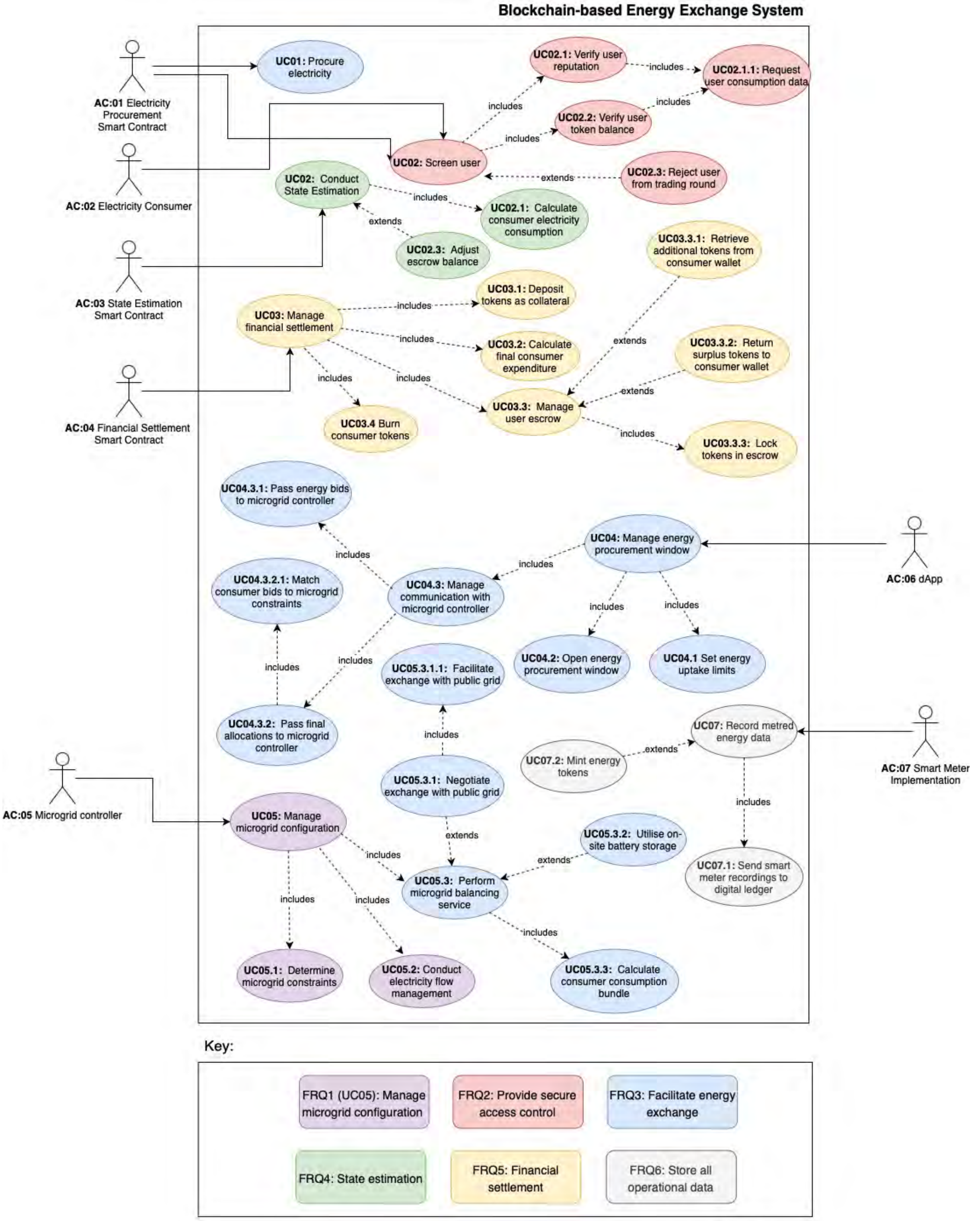
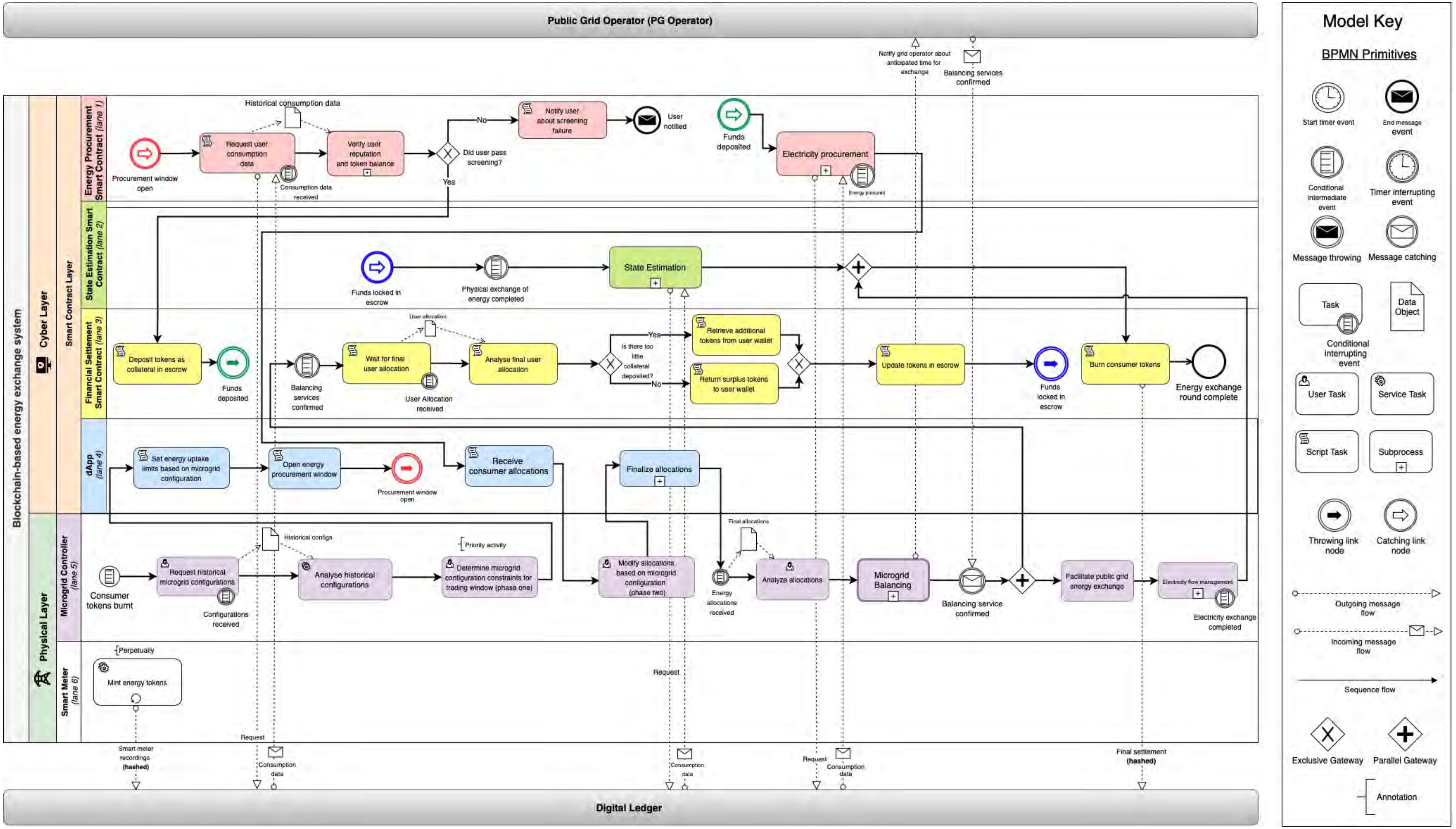
Appendices

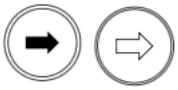
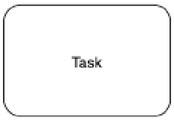
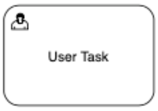
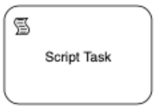
Appendix A: Use case diagram

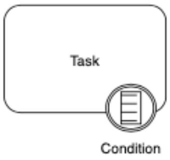
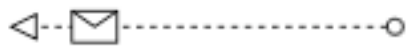
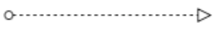


Appendix B: Business process model



Appendix C: Glossary for BPMN 2.0 Notation

Element	Notation	Description
Pool		A graphical representation of the Energy Trading System (ETS).
Collapsed pool		Similar to a pool, except that it denotes an actor whose internal processes are not of direct concern to the BPM. Often used to model third parties.
Swim lane		Used to organize and categorize the business activities that unfold within a pool. Swim lanes are used to represent actors in the system, as well as the cyber and physical layer of the system.
Sequence Flow		Used to indicate the shift from one task to the next.
Throw and catch link nodes		Link nodes are used in BPMN 2.0 to show a continuation in the flow from one task to another without requiring a sequence flow between the two tasks.
Task		A task is a basic activity carried out by the system.
User Task		A task performed by a human with the assistance of an information system.
Service Task		Tasks carried out by software applications. Service tasks are fully automated software applications.
Script Task		Script tasks are used to represent smart contract units in the BPM.
Sub-process		A sub-process indicates that there are other processes going on in the background to bring the current sub-process to completion. A sub-process element is used to indicate that the background processes are not of direct importance to the current abstraction layer of the BPM.

Conditional start event		Signals the start of the business process model once a certain condition is satisfied.
Conditional interrupting event		Interrupts a task once a certain condition is satisfied.
Conditional intermediate event		Intermediate events are conditions that must be satisfied to move from the execution of one task to the next.
Throwing and Catching Message event		Throwing message events indicate the sending of a message from one system actor to another system actor. Catching message events indicates the receiving of a message by a system actor from another system actor.
Incoming message flow		Indicates an incoming message from a third-party busy communicating with the ETS.
Outgoing message flow		Indicates an outgoing message to a third-party communicating with the ETS.
Exclusive Gateway		Indicates a mutually exclusive decision. The activities merge at the closing exclusive gateway.
Parallel Gateway		Indicates the split of activities into two concurrent streams of activities. Both streams of activities must merge at the closing parallel gateway before the task after the closing parallel gateway may begin.
Data Object		Represents important information that flows between process tasks and is utilized by specific process tasks.

Appendix D: Questionnaire

Table 11 below contains the questions from the first questionnaire presented to the research participants. Questionnaire one evaluated the functional requirements of the blockchain-based energy exchange system. Each question was accompanied with a use-case diagram. Figure 23 to Figure 30 below provides each of the use case diagrams presented to research participants. Each use case diagram was associated with a functional requirement and are presented in the question order they appeared in the questionnaire.

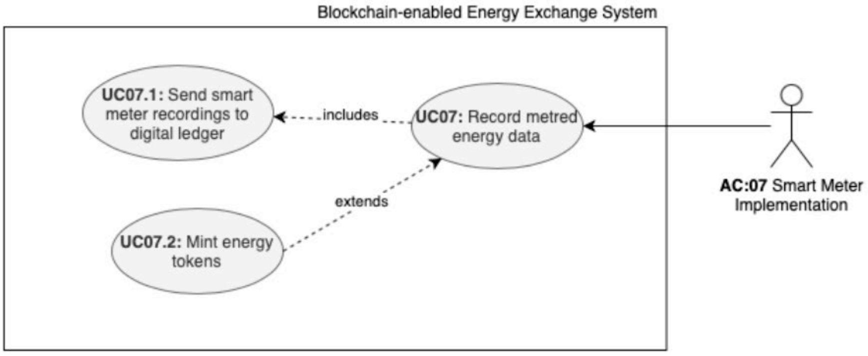


Figure 23: Use case diagram for storing operational data (Question 1 FRQ6)

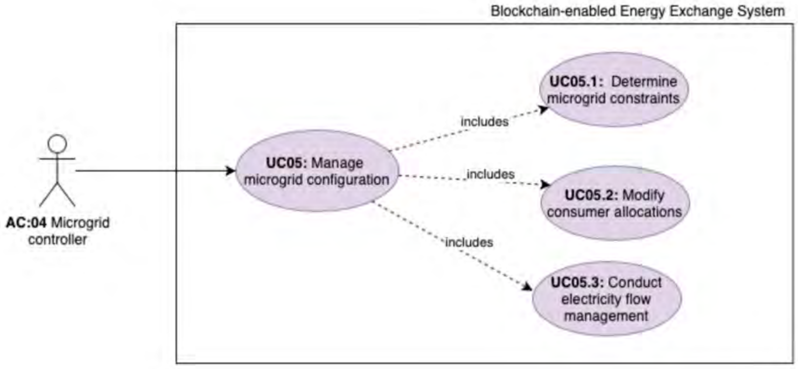


Figure 24: Use case diagram for microgrid configuration (Question 2 FRQ1)

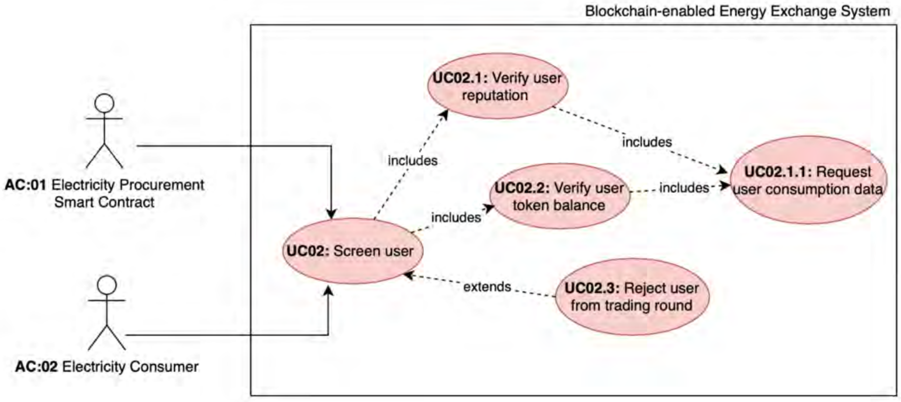


Figure 25: Use case diagram for access control (Question 3 FRQ2)

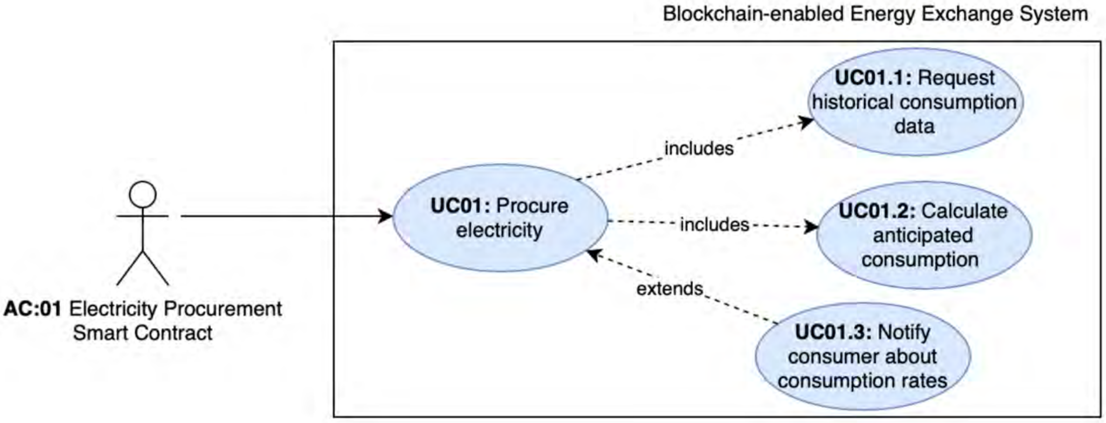


Figure 26: Use case diagram for facilitating energy exchange (Question 4.1 FRQ3)

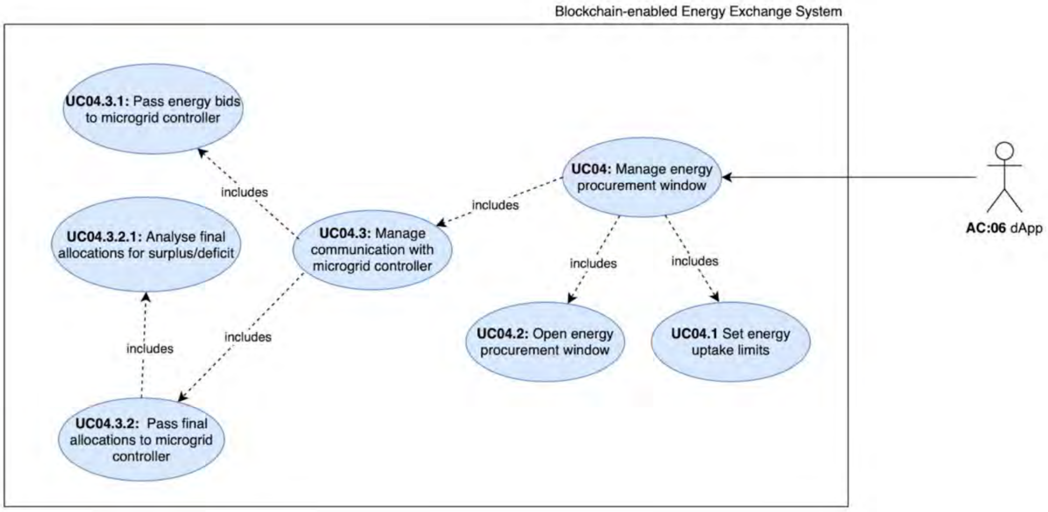


Figure 27: Use case diagram for facilitating energy exchange (Question 4.2 FRQ3)

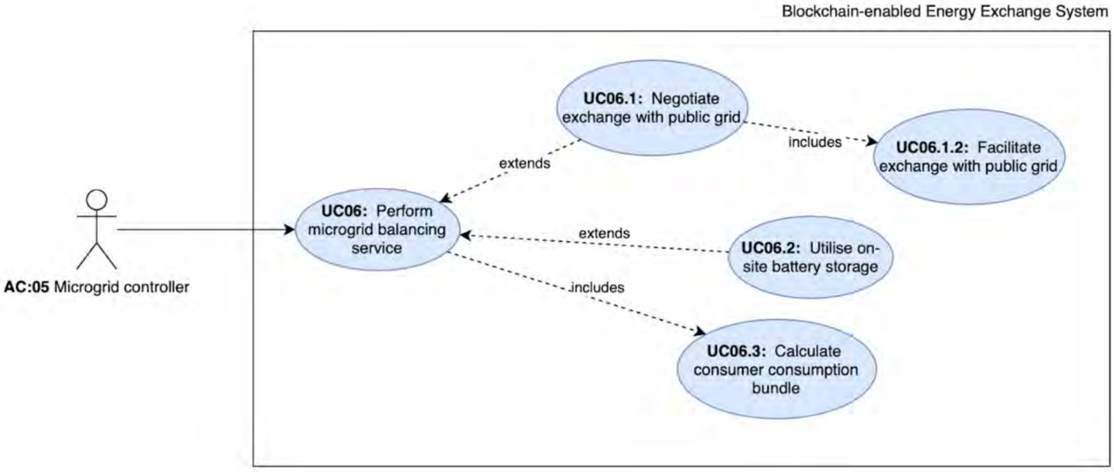


Figure 28: Use case diagram for facilitating energy exchange (Question 4.3 FRQ3)

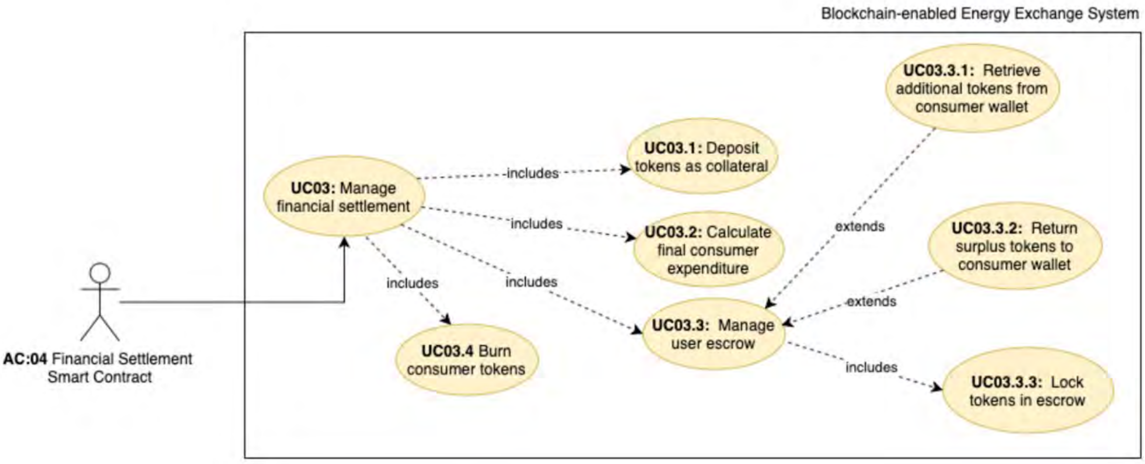


Figure 29: Use case diagram for financial settlement (FRQ5)

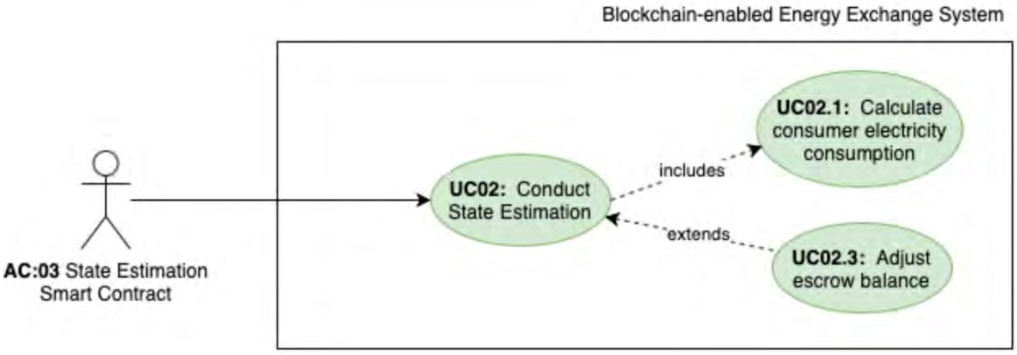


Figure 30: Use case diagram for state estimation (FRQ6)

Table 12: Questionnaire One

Question Number	Question	Response Type	Explanation presented in questionnaire with each question
Background information	Please indicate your age	Multiple choice response with various options listed	N/A
	Please indicate your highest level of education	Multiple choice response with various options listed	N/A
	Briefly describe your background and experience in relation to blockchain and energy systems. If you do not have expertise in this area, please indicate your background and experience in relation to systems development more broadly.	Open ended response	N/A
Question 1	**1.1)** Based on the above use case, the BEES satisfies functional requirement 6 (The system must store all operational data).	**1.1**) Likert based response ranging from strongly agree to strongly disagree	Storing the energy system's operational data is foundational to enabling prosumers and consumers to exchange energy in a decentralized manner. This energy data is used for all other processes in the system. To store the BEES's operational data, smart meter implementations are responsible for recording energy consumption data for consumers. For prosumers, consumption data, as well as the quantity of energy injected into the microgrid, are recorded. These energy readings are sent to the digital ledger where they are securely stored. Smart meter implementations operating in conjunction with the blockchain are involved in minting (i.e., issuing) energy tokens for prosumers once electricity is injected into the microgrid.
	1.2) Please elaborate	**1.2)** Open ended response	

Question 2	**2.1)** Based on the above use case, the BEES satisfies functional requirement 1 (The system must assist in the microgrid configuration process).	**2.1)** Likert based response ranging from strongly agree to strongly disagree	The microgrid controller (MC) is located in the physical layer of the system (see business process model) and is the first actor involved in each energy exchange window. Ultimately, the MC is responsible for managing the configuration of the microgrid. To do this, the MC determines the microgrid's operational constraints, modifies consumer energy allocations to align with operational constraints and conducts electricity flow management.
	2.2) Please elaborate	**2.2)** Open ended response	
Question 3	**3.1)** Based on the above use case, the BEES satisfies functional requirement 2 (The system must provide secure access control).	**3.1)** Likert based response ranging from strongly agree to strongly disagree	
	3.2) Please elaborate	**3.2)** Open ended response	
Question 4.1	**4.1.1)** No key aspects of the energy procurement process have been neglected in the above use case.	**4.1.1)** Likert based response ranging from strongly agree to strongly disagree	Once the consumer has passed the screening process (as discussed in the previous question), the BEES uses the Electricity Procurement Smart Contract to procure electricity on behalf of the consumer. To successfully procure electricity on behalf of the consumer, the smart contract requests the consumer's historical consumption data. Based on past consumption data, the smart contract calculates and procures the consumer's anticipated quantity of energy to be consumed until the next energy exchange window opens.
	4.1.2) Please elaborate	**4.1.2)** Open ended response	

			If the smart contract notes that the consumer does not have enough tokens to last until the next exchange window the consumer is notified to cut back on consumption, as well as to purchase more energy tokens.
Question 4.2	**4.2.1)** The management of the procurement window is well handled by the dApp.	**4.2.1)** Likert based response ranging from strongly agree to strongly disagree	Once energy has been procured for all consumers involved in the energy exchange window, a decentralised application (dApp) is responsible for managing the key interactions between actors in the system, including performing some of its own tasks. Tasks carried out by the dApp includes setting energy uptake limits (as informed by the microgrid controller), opening the energy procurement window as well as managing communication with the microgrid controller. When managing communication with the microgrid controller the dApp passes energy bids to the microgrid controller, as well as informing the microgrid controller about whether there is a surplus or deficit of electricity within the microgrid at the conclusion of the energy procurement process.
	4.2.2) Please elaborate	**4.2.2)** Open ended response	
Question 4.3	**4.3.1)** No key aspects of providing a microgrid balancing service have been neglected in the above use case.	**4.3.1)** Likert based response ranging from strongly agree to strongly disagree	

	4.3.2) Please elaborate	**4.3.2)** Open ended response	
Question 4.4	**4.4.1)** Step 1-3, taken collectively, satisfy functional requirement 3 (The system must facilitate energy exchange).	**4.4.1)** Likert based response ranging from strongly agree to strongly disagree	N/A
Question 5	**5.1)** Based on the above use case, the BEES satisfies functional requirement 5 (The system must provide financial settlement).	**5.1)** Likert based response ranging from strongly agree to strongly disagree	The Financial Settlement Smart Contract is responsible for managing the various financial settlement processes in the BEES. The smart contract performs functions in three distinct phases of the system lifecycle: **Pre-electricity procurement** • If the consumer has passed the screening process previously discussed, the smart contract deposits the consumer's tokens as collateral in escrow for the energy exchange window. **Post-electricity procurement** • Once the microgrid controller has performed the balancing service, and calculated the consumer's consumption bundle, the smart contract calculates the final quantity of tokens to be spent on the energy exchange window. • The smart contract then balances the collateral stored in escrow based on the number of tokens to be spent. **Post-state estimation** • At the conclusion of state estimation (to be discussed next), consumer tokens are burnt by the Financial Settlement Smart Contract. Burning a consumer's tokens is the payment
	5.2) Please elaborate	**5.2)** Open ended response	

			mechanism for the energy consumed in the BEES.
Question 6	**6.1)** Based on the above use case, the BEES satisfies functional requirement 4 (The system must provide state estimation).	**6.1)** Likert based response ranging from strongly agree to strongly disagree	In the previous question, the financial settlement smart contract burnt consumer tokens **post-state estimation**. Before the financial settlement process could burn tokens, the BEES had to determine whether consumers have received the electricity in the quantities that were procured on their behalf by the system. This process is known as **state estimation.** If consumer tokens were burnt without a state estimation process it opens the opportunity for a discrepancy to exist between the energy procured in the cyber layer and the actual energy consumed in the physical layer. The BEES implements state estimation through a State Estimation Smart Contract. The smart contract is responsible for calculating the quantity of energy the consumer consumed. This is achieved by analyzing a consumer's smart meter readings saved on the digital ledger.
	6.2) Please elaborate	**6.2)** Open ended response	

			The difference between the predicted bundle and the consumed bundle is then used by the State Estimation Smart Contract to adjust the number of tokens held in escrow by the consumer it is bound to. In this manner, the Financial Settlement Smart Contract will be guaranteed to burn the correct quantity of energy tokens.
Question 7	**7.1)** Taking FRQ 1 – 8 into consideration, there are no core functional requirements missing for the blockchain energy exchange system.	**7.1)** Likert based response ranging from strongly agree to strongly disagree	N/A

An explanation accompanied each functional requirement as presented in Table 11 above. Additionally, a *detailed* explanation was provided for the research participants who wanted further detail about the functional requirement under consideration. Table 12 below provides the detailed explanations provided for each question in the questionnaire.

Table 13: Detailed explanations provided to research participants

Question Number	Detailed Explanation
Question 1	• **UC07**: Smart meter implementations record energy flows throughout the lifecycle of the system. ➢ For consumers, the only energy data recorded is consumption data. ➢ For prosumers, consumption data, as well as the quantity of energy injected into the microgrid, is recorded. • **UC07.1**: Smart meter readings are pushed to the digital ledger every interval as specified by a configurable parameter. • **UC07.2**: If prosumers have surplus electricity available at a given point in time, prosumers inject the electricity into the microgrid. This process takes place continuously throughout the lifecycle of the system. ➢ Every 5 minutes, prosumers' smart meter readings are analysed by a smart contract to determine how much electricity each prosumer has injected into the microgrid. ➢ In turn, the smart contract issues the appropriate number of energy tokens to each prosumer's wallet. ➢ This 'minting process' is how energy tokens are created in the BEES. Consumers (who are not also prosumers) obtain tokens off a

	secondary exchange, or directly from prosumers if they wish to have the requisite tokens to purchase electricity in the BEES. ➢ The ‘minting process’ takes place every 5 minutes.
Question 2	• **UC05**: The MC is responsible for managing and configuring the physical microgrid. O **UC05.1**: First, the MC determines the operational constraints of the microgrid prior to the energy exchange window opening. By accessing the historical microgrid configurations stored on the MC’s on-site database, the MC (assisted by machine learning techniques) determines the operational constraints of the microgrid. ➢ For example, an operational constraint that needs determining for a given exchange window includes how best to ensure quality electricity service delivery. O **UC05.2**: At the conclusion of the energy procurement process the MC revaluates the operational constraints of the microgrid determined earlier and modifies consumer allocations to match the operational constraints of the system. O **UC05.3**: Once consumer allocations have been finalised and the electricity circulates throughout the microgrid it is possible that there is an unexpected surplus or decrease of electricity within the microgrid. The MC has to rectify the imbalance by utilising the emergency dispatch community battery to restore the imbalances found within the microgrid.
Question 3	• **UC02**: To determine whether a consumer may participate in an energy exchange window the BEES screens each consumer utilising smart contract implementations. Each consumer is coupled with his/her own smart contract instance. O **UC02.1**: First, the Electricity Procurement Smart Contract verifies whether the consumer’s reputation score is above a pre-defined threshold by analysing whether the consumer has consumed the appropriate quantities of energy as procured by the BEES in previous energy exchange windows. O **UC02.2**: Next, the Electricity Procurement Smart Contract verifies the consumer’s token balance. Here, the mean quantity of energy tokens spent over a specific period (e.g., two weeks) is calculated. If the user’s current energy token balance is above or equal to the calculated mean (i.e., token balance >= mean quantity spent) the user will qualify to partake in the energy exchange window. O **UC02.3**: If the consumer does not pass the two access control checks discussed above, the consumer is rejected from the energy exchange window until the next window opens. Exchange windows are ‘micro-cycles,’ and can last anywhere from seconds to minutes.
Question 4.1	• **UC01**: Once the consumer has passed the access control measures (as discussed in question two) the BEES procures electricity on behalf of the consumer. O **UC01.2**: At this point, the smart contract will consider the consumer’s past consumption patterns and procure the appropriate quantity of energy based on the anticipated quantity of energy to be consumed until the next energy exchange window. **Smart meter implementations in conjunction with other physical infrastructure regulate the quantity of energy a consumer can consume in a given exchange window. So, once an exchange window closes, the consumer will consume the procured energy whilst the next exchange window is ongoing. In other words,**

	the system will procure enough energy for the consumer to last the consumer until the conclusion of the next energy exchange window.
Question 4.2	The dApp's primary responsibility is to manage the energy procurement window that is currently open (UC04). The dApp is responsible for carrying out the following tasks: • **UC04.1**: The dApp receives the operational constraints of the microgrid from the microgrid controller sets the energy uptake limits based on the calculated constraints. • **UC04.2**: Once the energy uptake limits are confirmed, the dApp opens the energy procurement window. This, in turn, allows the system to procure electricity on behalf of the consumer (step 1 above). • **UC04.3**: The dApp is also responsible for managing the communication between the smart contract layer and the microgrid controller. **UC04.3.1**: Once the electricity procurement process has concluded, the dApp collects all the consumer energy allocations and passes the allocations to the microgrid controller. ➢ Once the MC has modified the bids to match the operational constraints of the microgrid, the dApp receives the modified bids. **UC04.3.2.1**: The dApp analyses the final allocations and determines whether there is a surplus or deficit of electricity within the microgrid. **UC04.3.2**: The dApp then passes the final allocations back to the microgrid controller.
Question 4.3	No further detailed was provided here as it was not necessary.
Question 5	**Pre-electricity procurement** • **UC03.1**: If the consumer passed the screening process discussed under FRQ2, the Financial Settlement Smart contract deposits the consumer's tokens as collateral for the energy exchange window. This prevents consumers from procuring electricity without having energy tokens available to pay for the procured electricity. The number of tokens deposited is based on the consumer's mean quantity of tokens spent during an exchange window over the last two weeks. **Post-electricity procurement** • **UC03.2**: Once the microgrid controller has performed the microgrid balancing service and calculated the consumer's consumption bundle, the Financial Settlement Smart Contract calculates the final quantity of tokens to be spent on the electricity exchange for the given window. • **UC03.3**: Once the final quantity of tokens to be spent is calculated the smart contract checks the number of tokens deposited as collateral and either returns surplus tokens to the user wallet or retrieves additional tokens from the consumer wallet. Tokens are then locked in escrow once more. **Post-state estimation** • **UC03.4**: At the conclusion of the state estimation processes discussed above, consumer tokens are burnt by the Financial Settlement Smart Contract. For example, taking a rudimentary example, if the state estimation process determines that the consumer has consumed 5 units of electricity, and costs 5 energy tokens, the tokens currently held in escrow on behalf of the consumer are burnt.
Question 6	No further detailed was provided here as it was not necessary.
Question 7	No further detailed was provided here as it was not necessary.

Table 13 below contains the questions from the second questionnaire presented to the business process modelling expert. Questionnaire two was specifically concerned with evaluating the syntactic correctness of the business process model.

Table 13: Questionnaire Two

Question Number	Question	Possible response
Background information	Please indicate your age	Multiple choice response with various options listed
	Please indicate your highest level of education	Multiple choice response with various options listed
	Briefly describe your background and experience in relation to blockchain and energy systems. If you do not have expertise in this area, please indicate your background and experience in relation to systems development more broadly.	Open ended response
Question 1	**1.1)** Gateways have been correctly used in the business process model. Please elaborate if any mistakes have been identified.	**1.1)** Open ended response
Question 2	**2.1)** Events have been correctly used in the business process model. Please elaborate if any mistakes have been identified.	**2.1)** Open ended response
Question 3	**3.1)** The description of activities is accurate in the business process model. Please elaborate if any mistakes have been identified.	**3.1)** Open ended response
Question 4	**4.1)** Sub-processes have been correctly used in the business process model. Please elaborate if any mistakes have been identified.	**4.1)** Open ended response