Developing a Secure, Smart Microgrid Energy Market using Distributed Ledger Technologies

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***Abstract*—The ability for the smart microgrid to allow for the independent generation and distribution of electrical energy makes it an attractive solution towards enabling universal access to electricity within developing economies. Distributed Ledger Technologies (DLTs) are being considered as an enabling technology for the secure energy trade market however the high processing, energy and data exchange requirements may make them unsuitable for the Industrial Internet of Things technologies used in the implementation of the microgrid and the limited connectivity infrastructure in developing technologies. This work serves to assess the suitability of DLTs for IIoT edge node operation and as a solution for the microgrid energy market by considering node transaction times, operating temperature, power consumption, processor and memory useage, in addition to mining effort and end user costs.**

***Index Terms*—Blockchain, Distributed Ledger Technology, Industry 4.0, Industrial Internet of Things, Performance Testing, Raspberry Pi, Smart Microgrid, Smart Contracts, Security.**

I. INTRODUCTION

The current iterations of the power grid are experiencing an increasing number of problems. An ageing infrastructure, the rising costs of fossil fuels, construction materials, general day-to-day operations and continuous load growth means that the reliability of electrical energy supply from the grid is decreasing [1]. This results in more frequent rolling blackouts and load shedding incidents, losses owing to distribution/delivery processes and illegal connections, slower response times and poor situational visibility of the real time grid state [2], [3]. Within developing countries, the growing cost of electrical energy, an increasingly unstable grid and unreliable energy supply leads to growing cases of energy poverty. Energy poverty is defined as cases where households spend over 10% of their net income on energy costs or where the supplied electrical energy is insufficient for the household needs such as cooking, space heating, or lighting [4]. In rural areas, non-electrified communities resort to other means of energy— coal-based or paraffin-based cooking and/or space heating and candles, battery-based or gas-based lighting sources [4]. The dangers of these alternative methods of energy are made apparent in the growing number of devastating fires, and carbon monoxide-based deaths observed annually in poorer communities.

To aid in meeting the increasing demand for electrical resources, include more renewable sources as part of generation activities, and grow the number of fully electrified communities, smart microgrid solutions— which incorporate disruptive technologies such Industrial Internet of Things (IIoT) edge processing, artificial intelligence, industrial big data, and machine learning— are emerging [5]. In addition to self-actuation and self-healing activities that are based on real time, grid state information; the smart microgrid encourages consumer participation through self-regulating load management [2], [6], the provision of bidirectional communication infrastructure and a secure, distributed energy market in which excess energy, from privately-owned generation loads, may be sold to neighbouring participants [1].

As a fundamental part of the smart microgrid system, the transactive, energy market will require a stored state for each microgrid load, will have multiple, known writers that aren't necessarily trusted, will remove a central, trusted third party in favour of distributed generation, supply and management, will require currency-based transactions and micro-transactions and will require publicly visible verifiability of the grid state and energy exchange transactions between microgrid nodes for the purposes of real time pricing and demand forecasting operations [7]. Distributed Ledger Technologies (DLTs) are proposed to provide such operations owing to the immutable, distributed nature of the ledger, the inclusion of cryptographic operations on transactions, consensus-based trust on transaction authenticity, and a global, traceable ledger history. The problem with implementing DLTs as a full solution in the microgrid space is the possible performance of these technologies when running in environments with high availability requirements, irregular connectivity resources and constrained

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processing devices.

This work forms part of a larger body of research which serves to consider the feasibility of DLTs as a solution in the secure, transactive energy context by first presenting a model of a smart microgrid market as it would be implemented in a developing community. Within this context, the performance of popular, native-state DLT implementations shall be tested on an IIoT edge processing device, in the role of a microgrid controller node, and analysed in the context of standard smart microgrid network availability requirements.

II. BACKGROUND

The provision of electrical energy to residential households is an ongoing challenge in developing economies such as South Africa. A survey conducted by the Department of Energy (DoE) in 2017 determined that 13.5 million of 15.6 million households had been electrified since 1994, with approximately 2.2 million households still remaining without access to electricity. The majority of these households are within rural communities or informal settlements [8]. Despite the increase in electrified households, and in spite of the government aiming to have universal access to electricity by 2025, electrification efforts have been hampered by the speed of household growth within the country [4].

The increasing price and decreasing quality of electrical services is also of growing concern. Following various collapses in the national grid, the price of electrical energy increased by 12.7% in 2015/2016, 9.4% in 2016/2017 and 2.2% in 2017/2018 with the consumer tariffs increasing by 5.7%, 6.59% and 6.6% for the respective years [9]. Additional strain on the national grid also lead to instances of power load shedding with 1325 GWh shed over a total 858 hours in 2015, 192 GWh over 127 hours in 2018 and 769 GWh shed over 272 hours in the first quarter of 2019 [10]. [10]

The smart microgrid's ability to function in various modes of operation and the use of distributed, renewable generation sources is ideal in the context of developing economies. Islanded operation modes removes the burden of supplying additional communities from the strained national grid while still allowing for the country to meet the set targets for providing universal access to electrical energy. At times when the microgrid has produced energy exceeding the current demand and storage capacity, rather than losing this energy, surpluses could be sold to neighbouring microgrids or back into the main power grid. This would be aided by the smart microgrid's bidirectional communication infrastructure and would allow for community income generation that would aid towards the maintenance of the microgrid infrastructure [11]. This would also then serve in lowering the consumer tariffs on electrical energy through real time energy market data and demand-based price adjustments.

Authenticity of energy transactions and the prevention of fraudulent sales are some of the security mechanism a secure, energy trading market would need to establish. Such a market would also need to guarantee secure data handling of energy and real time market pricing, contract-based transactions between market participants, automated financial settlement of energy trades, non-repudiation of transactions along with providing a true reflection of transaction history while preserving the privacy of customer payment data [12]. DLT implementations are able to provide cryptographically secure communications and an immutable, viewable ledger history while facilitating transactions between entities that do not necessarily trust each other. Instead of device-to-device trust establishment—which becomes difficult at the scales of typical IIoT network deployments— a consensus is established by network participants; determining the validity of transactions, the true ledger history and the ordering of ledger entries. This builds a community trust instead of a peer-to-peer trust.

Owing to the limited resources available on the IIoT microgrid nodes, common concerns in the use of DLTs are the large processing and high energy requirements for blockchain based technologies in addition to the limited network scalability and increasing transaction approval times as the number of participants in the microgrid grows. In addition, a consistent, high throughput network connection would be required in the DLT-energy market to enable transactions and ledger updates. Unfortunately, high speed connections are not yet widespread in developing countries and the microgrid would need to make allowances for the heavy reliance on mobile network connections such as 2G, 3G and 4G in the majority of areas and would need to minimise the transaction and update times in order to minimise the data bundle cost to end users. 4G coverage in South Africa is limited; with the majority of the country being provided with 2G and 3G connectivity. This is discounting areas in which mobile network coverage is highly limited or not yet present.

Fig. 1 shows the download speeds provided by the four biggest carriers in the country, with the best download speed provided by Vodacom at 6.4Mbps. DLT Nodes in the microgrid would therefore need to minimise the time taken to update the network ledger using the limited download speed provided by the 3G carrier; including providing consensus on transactions that may have occurred during an interruption of the mobile signal. In this regard, it is also important to determine the time taken by mining efforts when processing DLT transactions and updating the ledger to its most recent state.

III. MODELLING A DLT-ENABLED SMART MICROGRID

To adequately determine the practicality of a DLT-based energy trade market in South Africa, a model depicting a small rural community of 50-100 people living in government housing was constructed. This amounts to approximately 25-50 neighbouring households which are to be equipped with a solar water heater, solar panels and batteries for storing generated electrical energy, as depicted in Fig. 2. Each household forms a distinct node in the microgrid; with each having a copy of the microgrid ledger. As part of the percentage of the country which are yet to be connected to the electrical grid, the community would be a completely self-sufficient, islanded

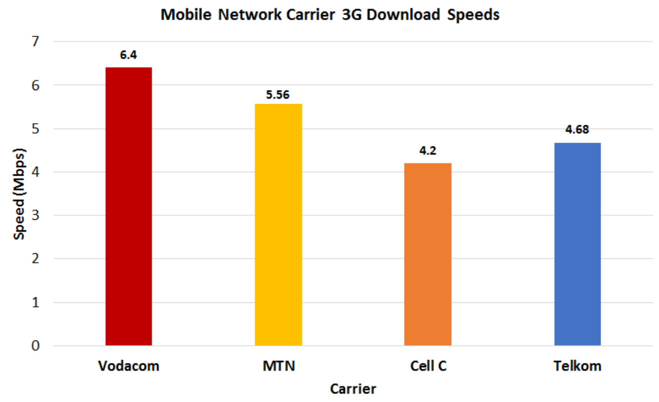

Fig. 1. 3G Network Download Speeds for Mobile Network Carriers [13]

microgrid; independently generating their own energy for space heating, cooking, lighting and entertainment purposes.

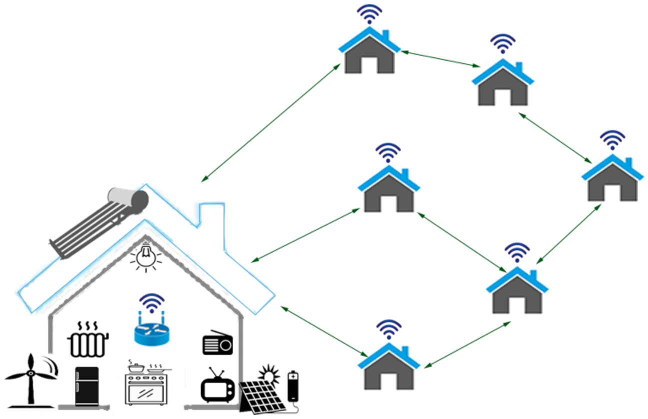

Fig. 2. Islanded smart microgrid community

Given the high data costs, intermittent cellular network connection and slow upload and download speeds, microgrid nodes would typically perform approximately 50 distinct transactions daily which require fast completion rates on purchasing and selling activities. Given that each household acts as its own energy generator within the grid, energy market transactions would occur should a household node need to source additional energy resources from the wider microgrid. Nodes would need to minimize the amount of time spent connected to the cellular network when updating the current state of the ledger, performing the purchasing transactions and updating the energy reserves view presented to the microgrid. This is to preserve and prolong the data bundles available to households for microgrid activities and keep costs at a minimum.

IV. EVALUATING DLTS FOR THE SMART MICROGRID ENERGY MARKET

As one of the more powerful, popular edge device platforms used within IIoT network deployments, the Raspberry Pi 3 was chosen as the microgrid node owing to the architectural compatibility with a large selection of DLTs while a Dell Optiplex 9020 desktop PC was chosen as the mining node. Ethereum was selected as the test DLT implementation owing to its support for the deployment of Smart Contracts in its native state, its support for the creation of private networks independent of the live blockchain and its growing popularity in applications beyond cryptocurrency. Transaction execution time, power consumption, node CPU and memory consumption and node core temperature experiments were conducted in order to determine the suitability of Ethereum in the energy market context.

When considering the performance of the microgrid node, under normal operation conditions, Ethereum transactions were completed by the Raspberry Pi in an average time of 513.40ms with an average power consumption of 25.53mW. Contract execution raised the core temperature of the node 8.35°C from its starting temperature with 32.66% utilization of the CPU resources and 4.24% utilization of the RAM resources observed. With the high cost of data in South Africa and the slow download rates observed on the 3G networks of the two largest network providers, the transaction times for Ethereum would lead to each microgrid transaction requiring 0.415MB at ZAR0.15 per MB on a 1GB data bundle [14]. With 50 distinct transactions per day, this would lead to a daily data bundle consumption of 20.75MB at ZAR3.11 for each household node in the microgrid. To minimize the data bundle cost to the consumer, any DLT solution intended for the energy market would therefore need to be able to complete transactions at a much faster rate than what was observed for Ethereum.

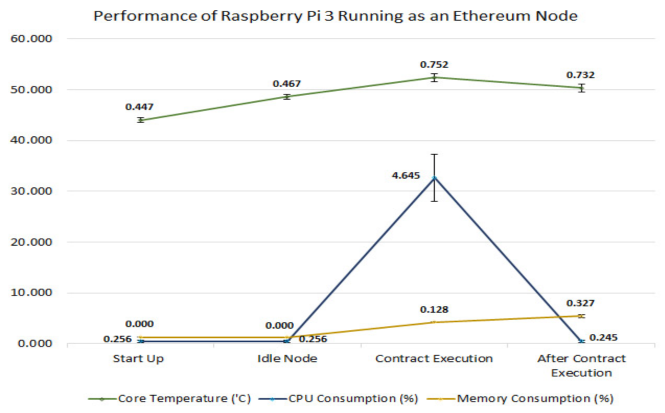

Fig. 3. Performance Evaluation Results of the Raspberry Pi Ethereum Node

Two stress test conditions were also evaluated, in which Ethereum transactions executed concurrently with an additional, work intensive Python program. When simulating normal edge node operations, indicative of off-peak microgrid transaction periods, an average execution time of 0.80s was observed in the Python script execution with the node core rising to a final temperature of 59.38°C. Simulating near-real time operations, indicative of peak microgrid transaction periods, the node observed an 18.04°C increase in core temperature and a 6.03s increase in the Python script execution time, illustrating that significant interference was introduced by the Ethereum operations. This interference would also serve in further driving up the data bundle cost of Ethereum transactions, adding to the effective cost of electrical energy trade in the microgrid.

Considering the performance of the miner node, the fee per transaction was small and remained relatively unchained at US$0.004 or ZAR0.058[1] independent of the number of transactions mined into the block. However, as the microgrid expands to include more household nodes and in conjunction with the data bundle costs seen for Ethereum transactions, the addition of a new cost could hamper the ability for all economic classes to actively participate in the energy market without being priced out. The limited scalability and network slow down of the blockchain structure would also serve to increase the cost to participate in the microgrid network. With approximately 50 distinct transactions per household occurring in the microgrid model, the Ethereum network would grow by around 1 250-2 500 transactions per day or 456 250–912 500 transactions per year. The rapid growth on the live Ethereum network resulted in a slow down in transaction approval rates as a result of the lack of scalability in the blockchain structure. This slow down would also affect the microgrid as the ledger size grew, leading to increasing data bundle costs for end users as transactions approval times increased. As such, a more scalable DLT structure would be required for the energy market solution.

Other ledger structures, such as the directed acyclic graph structure and the block lattice structure, could be explored while incorporating the conditional execution provided by Smart Contracts. One of the main problems identified however is the current lack of compatibility for IIoT edge device applications by the relevant DLT implementations. Work therefore needs to be done towards enabling these technologies for use with devices and real time operating systems typically found within the IIoT.

V. CONCLUSION

With the move towards greener, more efficient generation and distribution systems, the smart microgrid is emerging as the next iteration of the power grid that could aid in enabling universal access to electrical energy in developing countries. DLTs are being proposed in order to provide an adequately secure energy trade market. To determine their suitability for operation within the IIoT-microgrid context; node performance evaluations and stress tests were performed on a Raspberry Pi 3 acting as an Ethereum node. It was seen that while normal edge node operations were not impacted by the Ethereum processes, the node was not suited for near real time operations. It was also observed that the Ethereum node transaction time duration had the potential of adding an additional end user cost in the form of rapid data bundle depletion and that the mining process could disrupt the scalability of the microgrid network. While there are a number of alternate DLTs, their current implementation requirements make them unsuitable for the microgrid's IIoT edge processing activities. For DLTs to be a viable solution in the secure energy market, further work is needed towards conducting a detailed investigation into the full capabilities and limitations of running DLTs on IIoT edge processing devices, improving the efficiencies of Proof of Work or Proof of Stake consensus mechanisms, reducing the implementation requirements for these technologies to improve compatible with IIoT SoC architectures and exploring different ledger and permissibility structures as part of the effort towards improving the scalability and privacy of the network.

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[1] At the time of writing, 1 Ether= US$131.51 and US$1= ZAR14.50