The Mycorrho-grid: A Blockchain-based Mycorrhizal Model for Smart Solar Microgrids

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ABSTRACT

The Mycorrho-grid is a blockchain-based microgrid inspired by the way trees collect and distribute resources through mycorrhizal networks in the forest. It was first developed in conjunction with Virginia Tech's grand-prize winning TreeHAUS entry in the 2019 Solar Decathlon Design Challenge and is expanded upon here with a focus on further potential for biologically inspired functionality. The baseline case as simulated in the competition is a 12-unit multi-family microgrid with a shared 50kW rooftop solar array and fixed price return from the grid. A framework derived from literature in mycorrhizal networks and the mathematical modeling of mycelial growth is developed to help transition the Mycorrho-grid from phyto-centric operation, where resources are exchanged based on the needs of the trees (energy producing and consuming households), to myco-centric operation, where resources are exchanged based on the needs of the fungal energy storage and distribution mechanism (local battery and centralized grid) with a larger environmental awareness. This transition helps introduce an element of altruism into the larger grid network that the authors believe could improve overall reliability in response to regular outages and resilience in response to major outages. Degrees of decentralization and their implications for the security and fault tolerance of critical infrastructure are discussed along with strategies for simulating the efficacy of a mycorrhizal dynamic pricing algorithm moving forward.

INTRODUCTION

With the proliferation of distributed energy resources (DERs), it is becoming critical to manage many different energy generators with intermittent power production on a connected network. This distributed generation not only allows for the integration of more sustainable power production through wind and solar, it also encourages energy self-sufficiency and awareness instead of dependence on centralized power from an unknown source. The simultaneous decentralization of computational architectures with distributed ledger technologies like blockchain presents an opportunity to assemble groups of prosumers (producers and consumers of electricity) into dynamic, self-sufficient networks. Implicit in this arrangement is an improved sense of autonomy on the local level, where communities can generate and control their own energy on smaller scales (Morstyn et al. 2018). In an increasingly connected world, it is also critical that the security of such networks is robust enough to stand up to bad actors attempting to hack critical infrastructure. The novelty and appeal of blockchain as it was initially conceived in the Bitcoin white paper (Nakamoto 2008) was in reaching consensus in a truly decentralized manner. Thus, blockchain protects against attacks on central hubs where taking out one node on the network could cripple an entire community's access to infrastructure, whether it be energy, water, or food. Many recent innovations and proposals have focused on semi-centralized approaches that hybridize the blockchain approach, privatize it, and impose a centralized hub or traditional database onto the platform (Wu et al. 2017). Volareo, a brand of smart speakers, has created a private blockchain-based alternative to products like Google Home and Amazon Alexa, but it still serves as a middleman in controlling devices in the Internet of Things (IoT). While this has its merits for practical implementation and economic gain, it threatens many of the benefits of the truly distributed information architecture initially proposed by Satoshi Nakamoto in 2008 (Lin et al. 2017).

Through millions of years of evolution, nature has already developed solutions to manage distributed energy generation and distribution. Trees and plants in the forest can be seen as the forest's equivalent of DERs, but they do not operate in isolation. Fungal mycorrhizal networks connect these biological DERs and facilitate the distribution of energy, water, and nutrients amongst themselves (Beiler et al. 2009). Some of the largest known organisms in the world, these networks connect autotrophic organisms such as trees and other photosynthetic plants in a forest and enable widespread resource exchange (Simard et al. 2012). The flow of energy resources through natural ecosystems have been studied and quantified by scientists such as Howard Odum since the middle of the 20th century. In his systems ecology framework, Odum defined information, not electricity, as the purest form of naturally occurring energy (Odum 2007). The proposed work seeks to integrate energy and information systems by applying a mycorrhizal model to inform the flow of electricity through decentralized collections of solar powered homes. Evolution solved this particular distributed energy problem through many iterations over time and through the introduction of symbiotic organisms acting as a fungal distribution grid. The authors believe that a learning algorithm with proper feedback parameters will allow microgrid smart contracts to derive an optimized solution to this same problem, but in the domain of electrical infrastructure.

BACKGROUND

The Brooklyn Microgrid (BMG) is one of the most well-known examples of blockchain applied to peer to peer (P2P) energy exchange in a microgrid (Mengelkamp 2018). LO3, the company behind BMG was one of the first groups to implement a transactive energy grid, where participant prosumers can actively sell energy amongst themselves (LO3 Energy 2017). Other projects in the blockchain-based energy domain include Austin, TX based Grid+ that recently released a hardware wallet with physical cards containing private keys that enable users to automate their energy purchasing decisions on a distributed ledger (Grid Plus, Inc. 2018). Both companies have faced extensive hurdles in tackling policy issues pertaining to legal interaction with their respective local utilities.

The main contribution of this paper is the application of a biological model to the distribution of power in a blockchain-based microgrid. This will enable the introduction of altruism to market-based mechanisms where individual agents may sacrifice their optimal performance for the long-term reliability and resilience of the network as a whole. Though many attempts have been made to apply lessons from nature to critical infrastructure such as wireless networks, none to the authors knowledge have taken inspiration directly from the formation of mycorrhizal networks, and none have dealt specifically with electrical microgrids. Mobile ad-hoc wireless networks have drawn upon trends in biomimicry to apply swarm theory in creating dynamic routing algorithms that minimize the number of nodes traveled in relaying messages and increasing the reliability of transportation and other network-based infrastructures (Harrabi et al. 2018). A basic principle in these networks is that any given node is only aware of its neighboring nodes (within feasible communication range) and not the entire system state which can span much larger distances. The more complex behavior and capabilities of the larger network is made up of relatively simple, repeated actions on the scale of individual nodes. This type of thinking has inspired wireless routing algorithms that derive function from termite swarm intelligence (Roth and Wicker 2003), beehive behavior (Çelik and Zengen 2018), ant colony pheromone exchange (Chandana and Thakur 2016), and fungal mycelial growth patterns (Hao et al. 2009).

Hao et al.'s FUNNet is of particular interest here and used as a starting point because the hyphae in fungal mycorrhizae also display similar patterns of growth. Also of direct interest is an example in the transportation domain, where researchers in Japan retraced optimally efficient transportation networks by letting a slime mold grow between bits of food placed on the map at locations of major Japanese cities (Tero et al. 2010). This work resulted in general guidelines for adaptive, bio-inspired networks including algorithms that allow for the reallocation of resources to areas of higher energy input. In general constructal theory and other biologically-inspired frameworks help determine form by optimizing the flow of some resource through space and time, whether it is cars through highway corridors, packets of information through wireless networks, blood through the veins and arteries of our bodies, or energy through distributed electrical networks (Bejan and Lorente 2008).

Mycorrhizal networks have been studied and modelled in various ways, both analytically and experimentally. The measurement of mycorrhizal transfer of carbon between different tree species using tracer ions was featured in Nature in 1997 (Simard et al. 1997). Beiler et al. made one of the most comprehensive attempts at identifying the network structure of mycorrhizal networks by tracing genotypes of fungi at different trees in a forested plot. They determined that mycorrhizal networks follow a highly interconnected small-world typology meaning that most nodes can be reached in a relatively small number of hops (Beiler et al. 2009). Other researchers have also used graph theory to define mycorrhizal network structure (Montesinos-Navarro et al. 2012). Further attempts have been made to model the growth patterns of mycelia in general (Falconer et al. 2005) and mycorrhizae specifically (Schnepf at el. 2008). Falconer et al.'s mycelial model directly inspired the work of FUNNet and will be examined further in this paper to inform environmentally-aware dynamic pricing algorithms in the Mycorrho-grid.

This paper is a further development of Virginia Tech's grand-prize winning TreeHAUS entry in the U.S. Department of Energy's 2019 Solar Decathlon Design Challenge. TreeHAUS as presented in the competition was a multi-family residential building consisting of three repeating clusters of four units. Each cluster included a diverse array of one-, two-, three-, and four-bedroom modular, prefabricated apartments that were designed to be joined on-site. The projected building location of the twelve collective units is in Blacksburg, Virginia, located in ASHRAE's mixed-humid Climate Zone 4A. The biologically inspired framework for energy exchange presented here would allow for the Mycorrho-grid to evolve to better reflect its initial mycorrhizal inspiration. Within this paper the authors demonstrate how a 'fungi-first', myco-centric perspective could create electrical symbiosis with integrated dynamic pricing that protects local battery life and encourages mitigation of peak demand events on the central grid. A presentation of various states of decentralization and the proposed value of reflecting the network structure of mycorrhizal networks in the energy domain is then discussed in further detail.

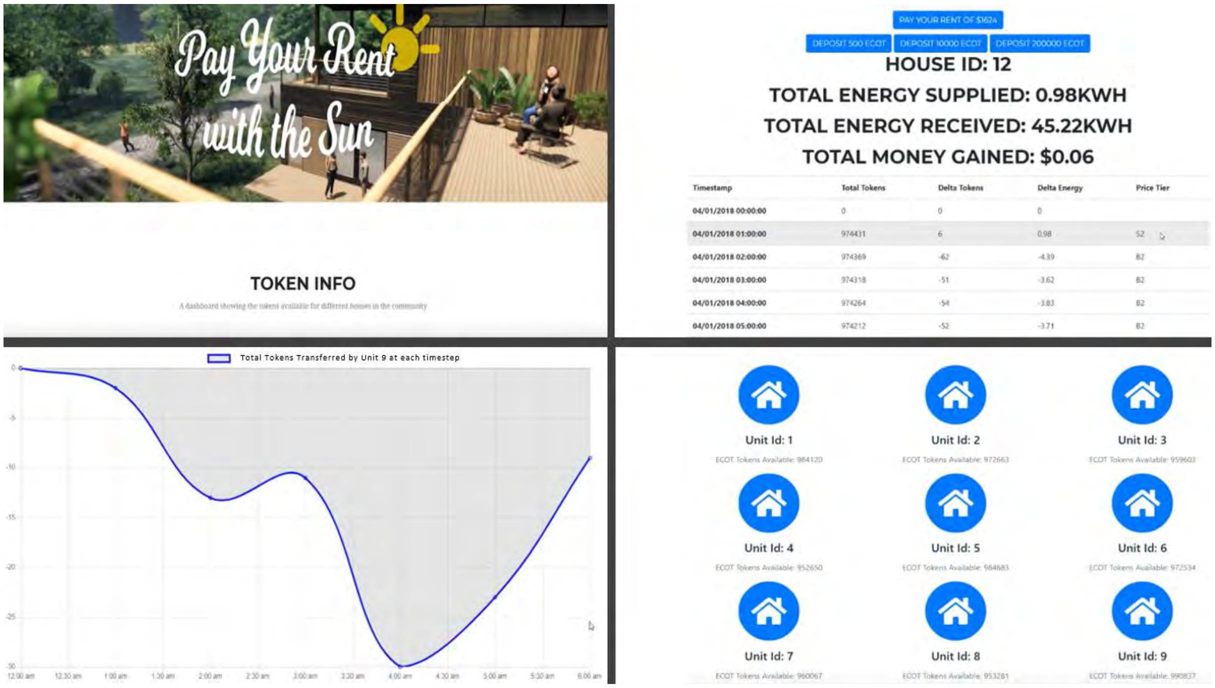
BASELINE MYCORRHO-GRID

Each of the twelve TreeHAUS units from the baseline case participate in sharing the power generated from a 50kW rooftop array. The energy is distributed amongst the units based on normalized heating and cooling loads. For example, the four-bedroom unit with more floor area and more exterior wall area will receive a higher percentage of generated energy compared to the two-bedroom unit with lower passive energy consumption to maintain standard temperature and humidity levels. At each timestep, starting with hourly intervals, a given unit's energy consumption is subtracted from their fair proportion of the solar energy produced by the rooftop array to arrive at a delta factor. This factor is distributed or charged as credit to each of the TreeHAUS tenants depending on whether they were net-producers or net-consumers during the previous hour. The credit or charge is recorded on a blockchain at each timestep and distributed as USD fiat-stable tokens (fixed one to one value with USD) worth the equivalent price of the electricity consumed or produced at that time.

Energy exchange is facilitated with the automated exchange of these tokens using smart contracts and a ranking algorithm. All tenants in the TreeHAUS are participants in an automated, hourly contest. Energy efficiency is incentivized by giving the highest net-producers the first chance to sell to their consuming neighbors at a rate just below retail, and the lowest net-consumers the first chance to buy this energy at the same lower rate. In the baseline case, the retail rate from the grid and the discounted rate for local energy exchange are fixed at 12 cents and six cents per kWh. respectively. When simulated in this manner using the EOSIO blockchain platform, the annual net energy distributed within the community was projected to be

18,894 kWh plus an additional 3802 kWh sold to the grid corresponding to a financial savings of $2789 (Choudhry et al. 2019). These simulations were completed using simulated data from the National Renewable Energy Lab's PVWatts tool for PV production, and the U.S. Department of Energy's OpenEI database for energy consumption. A mixture of high, low, and baseline energy values for the adjacent weather station at Blacksburg's airport (TMY3-724113) was adjusted for square footage and corrected for the appropriate electrical versus gas appliances to approximate consumption at the proposed TreeHAUS complex.

An important aspect of this design became the user interface. One of the main appeals of using a blockchain platform is to be able to implement smart contracts to automate the trading of ECOT tokens (the Mycorrho-grid's native cryptocurrency). No forecasting is required for a single or double auction process and can thus avoid the cognitive overload and inconvenience of tenants needing to constantly monitor their energy status. Instead, all functionality is integrated into multi-family residential web portals, which are commonly utilized for setting up autopayment of rent and logging of maintenance requests. Through this same interface it is projected that tenants could utilize their earned tokens to directly pay their monthly rent and other utility costs. See Figure 1 for an overview of the proposed Mycorrho-grid user experience. Its functionality includes paying rent directly with credit earned from solar energy, comparing unit by unit energy consumption, and displaying transparent breakdowns of hourly delta values and token distributions for each tenant. The image in Figure 1 was reproduced with permission from Arjun Choudhry et al. 2019, pending publication in the upcoming 2019 Cryptocurrency and Blockchain Technologies (CBT) conference proceedings in Luxembourg.



TOKEN INFO

A dashboard showing the tokens available for different houses in the community

HOUSE ID: 12

TOTAL ENERGY SUPPLIED: 0.98KWH

TOTAL ENERGY RECEIVED: 45.22KWH

TOTAL MONEY GAINED: $0.06

Timestamp	Total Tokens	Delta Tokens	Delta Energy	Price Tier
04/01/2018 00:00:00	0	0	0	
04/01/2018 01:00:00	974431	6	0.98	S2
04/01/2018 02:00:00	974369	-62	-4.39	B2
04/01/2018 03:00:00	974318	-51	-3.62	B2
04/01/2018 04:00:00	974264	-54	-3.83	B2
04/01/2018 05:00:00	974212	-52	-3.71	B2

Unit Id: 1
ECOT Tokens Available: 984120

Unit Id: 2
ECOT Tokens Available: 972663

Unit Id: 3
ECOT Tokens Available: 959603

Unit Id: 4
ECOT Tokens Available: 952650

Unit Id: 5
ECOT Tokens Available: 984683

Unit Id: 6
ECOT Tokens Available: 972534

Unit Id: 7
ECOT Tokens Available: 960067

Unit Id: 8
ECOT Tokens Available: 953261

Unit Id: 9
ECOT Tokens Available: 990837

Figure 1. Web-based User Interface for the Mycorrho-grid designed to integrate into existing multi-family residential housing online portals.

PROPOSED MYCO-CENTRIC FRAMEWORK

Though the proposed baseline operation of the Mycorrho-grid performed quite well in simulations, it remained a static price model that did not encourage awareness of the surrounding environment in incentivizing certain energy behaviors. More specifically, incentives on the blockchain trading platform remain the same if the grid is experiencing a peak demand event, or if it has plenty of surplus energy available during a given time step. Additionally, the local battery reserve that stores on-site energy was not included in initial simulations which can be essential for reliability during outages. Part of the benefit of applying a mycorrhizal approach to the existing platform is to help increase this environmental awareness, as fungal networks actively respond and adapt to their environmental context to distribute energy and resources most efficiently.

One of the main divergences in the literature on mycorrhizal networks is the phyto-centric versus myco-centric perspective. In a phyto-centric perspective, autotrophs like trees and plants that produce their own energy and trade it through the fungal network control the flow of energy, nutrients and water in their own self-interest or that of their fellow plants. In a myco-centric perspective, the connected fungal organism is thought to dictate the terms of these resource flows. The baseline Mycorrho-grid model, with energy exchange dictated by energy production (photosynthesis) and consumption of the units (autotrophic metabolism) is decidedly phyto-centric in nature. The well-being of the ‘living’ conduit of fungal connections is not considered. The following is a proposed framework that could be implemented in the context of the Mycorrho-grid to increase contextual awareness of central grid-status and local battery health and to promote a more sustainable and symbiotic operation of the energy system.

Table 1. Network components mapped between fungal and electrical domains.

Fungal Network	**Electrical Network**
Insulated Biomass (Hyphae)	Connection between nodes i.e., wires/conduit
Mycorrhizal network	Entire connective network including central grid, microgrid, TreeHAUS building with PV production and local battery storage.
Non-insulated Biomass (Hyphal Tips)	battery interface with both resource (PV) and network connections (hyphae)
Mobile biomass	Energy in transit
Immobile biomass	Energy stored in batteries
Canopy (leaves)	Solar panels (PV)
Trees/plants (autotrophic organisms)	Households/units
Forest	Whole TreeHAUS multifamily building

To elucidate the biological analogy, different elements of the fungal and electrical networks have been correlated in Table 1. The foundation of these comparisons come from translating the established fungal infrastructure connections in FUNNet from wireless communications to energy domains (Hao et al. 2009). Additional elements come from the specific mycorrhizal growth model (Schnepf et al. 2008) and general terms from mycorrhizal physiology and forest ecology. A fundamental element of Falconer et al.'s fungal growth model is biomass recycling, or the reallocation of biomass from one part of the organism to another based on the surrounding environmental conditions (Falconer et al. 2005). In the presented mycorrhizal correlation, the biomass is energy, either stored locally, or in transit (being transacted). Insulated biomass is sheathed hyphae that serve mainly as conduit, and do not acquire additional nutrients or lose nutrients to the surrounding soil. Uninsulated biomass, on the other hand is correlated to the fungal interface with the autotrophic participants on the network, or the battery charge controller that decides how much energy from the PV gets stored locally (primary storage) versus sent to the larger grid (secondary storage).

Local Battery Life Consideration: In the initial Mycorrho-grid simulation, local battery storage has not been considered. For some of the energy to not be transacted with the local grid, at least one on-site battery would be required to hold energy within the network and meet local loads without triggering net-metering rates from the central grid. This battery's well-being is not considered in the current model, though it is of considerable importance in terms of operational sustainability and maintenance. In the myco-centric perspective, the longevity of the storage mechanism is prioritized over meeting the energy and financial needs of network participants. Battery longevity is often measured by the number of charge and discharge cycles expected before the battery's energy capacity is significantly decreased. The depth of discharge, temperature, and current flow are also important contributing factors to long term battery life and would also need to be included as parameters in the proposed algorithm.

Grid State Consideration: The market dynamics of the grid can be approximated with the wholesale market locational marginal pricing (LMP) model directly obtained from the PJM Interconnection (PJM) regional transmission organization database. These real time market prices reflect the current supply and demand dynamics as well as congestion and cost concerns on the central grid. Though current policies often prevent this type of dynamic pricing from filtering down to the residential level, using wholesale prices as an input parameter to the smart contract algorithm allows for consideration of the central grid's need for extra energy during peak demand events. This factor serves as an environmental indicator of the presence or absence of energy on the larger network, with the likelihood of selling back to the grid being higher when demand is high, and supply is low. The result of these adaptations to the baseline performance of the microgrid is a biologically informed dynamic pricing algorithm with feedback for consideration of local battery health and longevity.

Mycorrhizal Structure Consideration: Beyond pricing mechanisms to facilitate altruistic P2P energy exchange and increase grid awareness, the network structure of microgrids and of the larger grids is another opportunity to investigate how the evolution of mycorrhizal networks could possibly inform more reliable Mycorrho-grid operation. The superimposition of mycorrhizal structure from Beiler et al. in 2009 onto a simulated grid of distributed prosumers could test the hypothesis that these network structures have evolved to improve performance parameters over time. The networks are not completely decentralized as the more central 'mother tree' nodes have higher degrees of centrality, but they are small-world networks where every node can be reached in relatively few hops from every other node. Various degrees of decentralization could be tested as displayed in Figure 2, and then compared to the performance of a mycorrhizal network structure subject to the same environmental conditions. Stress testing for fault tolerance may reveal clues as to how to design efficient P2P microgrids with improved reliability (during shorter, regular outages) and resilience (during longer, extreme outages) even when hub nodes are wiped out.

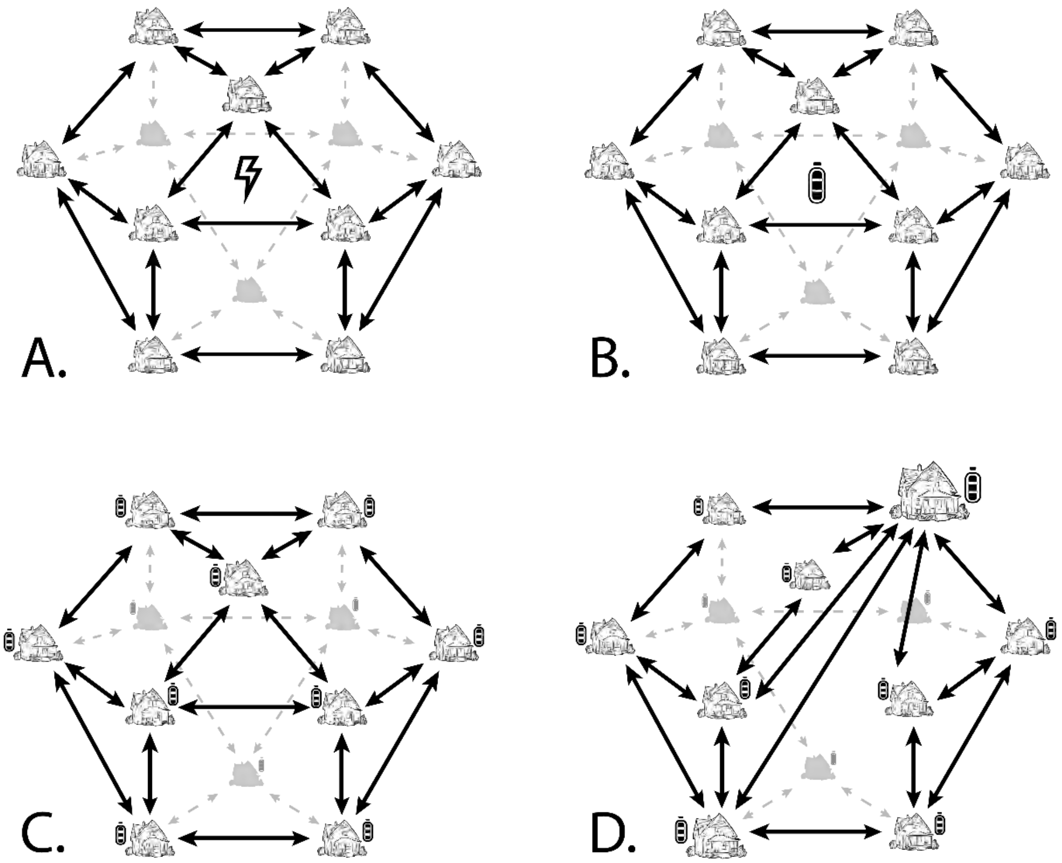


Figure 2. Degrees of decentralization for Mycorrho-grid simulation ranging from A.) Fully Centralized with each unit grid-tied and no local battery storage, B.) Locally Centralized with each unit connected directly to local battery storage, C.) Fully Decentralized with each unit having its own battery storage and an equal degree of centrality, and D.) Mycorrhizally Decentralized where each unit has its own battery storage but larger 'mother tree' hubs have higher degrees of centrality and reflect the small world structure of mycorrhizal networks as described in Beiler et al. 2009.

Quantifying the effect that these changes would have on the performance of a given grid are outside of the scope of this paper and will be saved for future work. The focus of this paper is to present the biological correlation as a framework and elucidate how the features of biological and ecological systems may map to electrical infrastructure in the Mycorrho-grid environment.

Discussion of Correlations

There are a couple of critical assumptions being made here related to energy flow in a physical environment. First, in order to implement the wireless routing algorithms of Hao et al. in the electricity domain it must be assumed that energy flows in a manner more like information than it does in actual, physical power systems. A second corollary to this is that batteries would charge much faster and more reliably than the current status quo, without sacrificing longevity. While physical conduit connections are not out of the question in the multi-family arrangement presented here, it becomes more questionable when houses physically further apart want to exchange actual electrons with neighbors in a Mycorrho-grid arrangement. The cost of running separate conduit in this case could outweigh the benefits of keeping transactions behind the meter, if policy in the area even allows implementation of this strategy. The prospect of safe, wireless power transfer at these higher rates and longer distances is not currently feasible but could be assumed in order to proceed with initial simulations.

In terms of testing the various degrees of decentralization presented in Figure 2, the sizes of various loads are not specified. Only the ‘mother tree’ hub and other nodes in the Mycorrhizally Decentralized case (D.) are shown as larger and smaller to reflect how connected they are to other units in the network. Beiler et al. group tree nodes into categories based on their diameter at breast height (DBH) and estimated age (2009). If larger, older trees are assumed to generate more energy, store more energy, and consumer more energy than their smaller, younger counterparts, then the various categories of simulated residential load profiles from the Department of Energy’s OpenEI database (high, low, and baseline) could be mapped to various tree categories and assigned the same place in the network. As long as the larger load profiles also have larger solar panel arrays and larger battery banks, the analogy will hold true and will help to provide a reasonable translation between domains.

The importance of blockchain in allowing the Mycorrho-grid to run in a decentralized manner is critical to transparency and security. The use of blockchain-based distributed ledgers not only provides an immutable, accessible record and accountability for all exchanges of credit, but also prevents bad actors from easily altering systems states to steal money or manipulate critical infrastructure like the grid. Battery charging and discharging commands can be brought under the jurisdiction of the blockchain, requiring a percentage of the nodes to reach consensus before the platform sends any energy to the local battery or to the larger grid. The same can eventually be applied to toggling appliances on and off in an Internet of Things (IoT) controlled environment that could be integrated into demand side management (DSM) scenarios. Though the authors have not addressed the specific mechanisms through which this added security could be implemented in this paper, the data architecture of the Mycorrho-grid provides an important baseline in protecting more connected, critical infrastructures.

From a socio-economic perspective, decentralized solutions like blockchain could help promote energy solidarity in local economies in terms of instilling trust and incentivizing cooperation amongst neighbors (Yu 2018). Electrical utilities remain one of the most powerful and most connected industries in the modern U.S. democracy. Incredible amounts of money can get siphoned off in large government contracts, and the common people see little to no benefit (Nyang'Oro 2017). True energy reliability in many parts of the world is still unheard of, with restrictions in policy sometimes preventing small scale producers from selling excess energy back to a central grid, even when the extra power is desperately needed during peak demand events. Traditional energy distribution systems that rely on regulated utilities governing all aspects of supply and distribution exclude other participants, creating serious obstacles for experimentation in distributed models that could provide society with more energy security. The Brooklyn Microgrid and Grid+ have had to apply to become local utilities themselves just to interface with the existing entities and transact energy locally (Mengelkamp et al. 2018).

Conclusion and Future Work

In a myco-centric approach to energy management in a microgrid, the importance of battery life cannot be overlooked. Battery capacity remains a central challenge in many electronics industries, including but not limited to electric vehicles, consumer electronics, and solar energy storage. Shifting from a phyto-centric focus to a myco-centric focus helps to account for this critical limitation in system performance by considering the energy storage and distribution infrastructure as an organism with a will to survive and extend its own lifetime.

The diversification of load profiles is a critical element to the function of the Mycorrho-grid. If all units attached to the network produce and consume energy at the same time, it would be very difficult to foresee any improved performance from P2P energy trading. Just like biodiversity breeds resilience in natural ecosystems, the authors are of the opinion that load diversification in an infrastructural system will also provide for higher levels of resilience, especially in terms of providing access to stored energy during a longer, more extreme power outage. This applies not only to load type and magnitude, but also to the temporal diversity, more akin to Jane Jacobs' definition of schedule diversity from The Death and Life of Great American Cities creating safer communities in urban environments. This type of temporal diversity could be achieved by introducing a mix of industrial and commercial buildings to the initial residential units, or through automated scheduling and incentivization of load shifting coordinated through IoT.

Small-scale autonomous energy grids could pave an elegant, modular path toward full electrification and equity in energy systems, but first policy must catch up and governments must acknowledge that it is time to rethink our centralized approach to power. The next step in proving the value of this myco-centric approach and the fungal metaphor in power system policy is to simulate this adapted smart contract governed by the principals laid out in the preceding framework. The baseline static simulation including a fixed six cent return for selling energy back to the grid was imposed by local co-generation rates in Blacksburg, Virginia. In reality, the incentive is only offered to commercial entities and returns closer to three cents per kWh energy produced. In the next phase of this research, the grid will be assumed to be more progressive in addressing its own needs and incentivizing innovation in distributed generation techniques.

Future work includes testing these same ideas in different contexts and at different scales. Blacksburg, Virginia offers a unique opportunity to understand the dynamics of this type of microgrid and the benefits of a biologically inspired dynamic pricing algorithm in a rural, developed context, but there are many other areas where this model could apply. Highly developed urban areas and extremely rural developing regions are two examples of where the Mycorrho-grid could make the most difference in either providing relief to overloaded urban grids or providing a pathway to electrification of remote villages. Each of these contexts presents different challenges in terms of policies, existing infrastructure, surrounding supply and demand, and resource availability and cost. Ongoing research efforts may reveal what an operation like this could look like in Austin, Texas through the existing Pecan Street program, and in the Arusha region of Tanzania on a microgrid run by the Innovative Technology and Energy Center (iTEC) at the Nelson Mandela African Institution of Science and Technology (NM-AIST). The idea of biomass recycling for backup energy production could also be tested at different scales, from appliances in an IoT environment taking turns in demand side management to the recycling of organic waste streams through anaerobic digestion to generate back-up power.

Moving forward, new techniques and methods that have been developed and published recently present opportunities to expand upon this work, both in simulations and in real biological experiments. The max-flow complex network methodology in power systems to demonstrate security and bad-actor simulations to show the true security benefits of decentralization through distributed ledger platforms (Dwivedi and Yu 2013). Other fault tolerant energy distribution mechanisms could also be tested on the Mycorrho-grid to demonstrate how the system recovers when battery storage at a given node is suddenly wiped out (Prodan et al. 2015). The ultimate validation of this theoretical work lies in experimental measurement of resource flux at the root-mycorrhizae interface. Laser speckle contrast imaging has been utilized to visualize fluid flow in roots (Braga et al. 2009) and agricultural applications (Zdunek et al. 2014). As long as the interface of the root with the mycorrhizal fungi could be exposed, environmental conditions could be varied and corresponding flows at different connected plants could be estimated. The adaptation of mycorrhizal network topologies could be tested and compared to random network topologies, but quantification of the actual flux of carbon or other resources such as water and nutrients would enable a direct bio-inspired approach to the mycorrhizal distribution of energy, water, food, and information in the built environment.

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