energies

Article

A Mycorrhizal Model for Transactive Solar Energy Markets with Battery Storage

Zachary Michael Isaac Gould [1,*], Vikram Mohanty [2], Georg Reichard [1], Walid Saad [3], Tripp Shealy [4] and Susan Day [5]

1 Department of Building Construction, Virginia Polytechnic and State University, Blacksburg, VA 24061, USA
2 Department of Computer Science, Virginia Polytechnic and State University, Arlington, VA 22203, USA
3 Department of Electrical and Computer Engineering, Virginia Polytechnic and State University, Arlington, VA 22203, USA
4 Department of Civil and Environmental Engineering, Virginia Polytechnic and State University, Blacksburg, VA 24061, USA
5 Department of Forest Resources Management, The University of British Columbia, Vancouver, BC V6T 1Z4, Canada
* Correspondence: gould@vt.edu

Abstract: Distributed market structures for local, transactive energy trading can be modeled with ecological systems, such as mycorrhizal networks, which have evolved to facilitate interplant carbon exchange in forest ecosystems. However, the complexity of these ecological systems can make it challenging to understand the effect that adopting these models could have on distributed energy systems and the magnitude of associated performance parameters. We therefore simplified and implemented a previously developed blueprint for mycorrhizal energy market models to isolate the effect of the mycorrhizal intervention in allowing buildings to redistribute portions of energy assets on competing local, decentralized marketplaces. Results indicate that the applied mycorrhizal intervention only minimally affects market and building performance indicators—increasing market self-consumption, decreasing market self-sufficiency, and decreasing building weekly savings across all seasonal (winter, fall, summer) and typological (residential, mixed-use) cases when compared to a fixed, retail feed-in-tariff market structure. The work concludes with a discussion of opportunities for further expansion of the proposed mycorrhizal market framework through reinforcement learning as well as limitations and policy recommendations considering emerging aggregated distributed energy resource (DER) access to wholesale energy markets.

Keywords: transactive energy; wholesale energy markets; distributed energy resources; distributed ledgers; blockchain; bio-inspired computing; bio-inspired design; ecological modeling; multi-agent systems; mycorrhizal networks

check for updates

Citation: Gould, Z.M.I.; Mohanty, V.; Reichard, G.; Saad, W.; Shealy, T.; Day, S. A Mycorrhizal Model for Transactive Solar Energy Markets with Battery Storage. *Energies* **2023**, *16*, 4081. https://doi.org/10.3390/en16104081

Academic Editor: Young Gyu Jin

Received: 14 April 2023
Revised: 29 April 2023
Accepted: 5 May 2023
Published: 13 May 2023

1. Introduction

The global market for microgrids is projected to rise to over USD 33 billion by 2027 from just USD 6 billion in 2020, fueled primarily by the need to manage a rapidly increasing penetration of distributed energy resources (DERs) such as solar, storage, wind, and other forms of renewable energy [1]. According to conservative predictions, U.S. solar photovoltaic (PV) projects with linked energy storage systems are projected to increase at least tenfold between 2021 and 2050 [2]. If battery costs continue to decrease and government incentives for energy backups remain high, U.S. capacity is expected to grow to over 16 gigawatts by 2050 [2]. Furthermore, standalone grid-scale energy storage capacity in the U.S. is projected to increase fivefold by 2050 [3]. Still, the ability to manage this proliferation of solar and storage resources on local distribution and larger transmission grids remains a primary concern for future grid reliability globally [4].

In the United States, the approval of Order 2222 on 17 September 2020 by the Federal Energy Regulation Commission (FERC) mandated that grid operators must provide DER aggregators (DERAs) of 100 kW or more access to wholesale electricity markets [5]. There are numerous challenges associated with implementing the complicated auction, pricing, and security protocols required for aggregated DER wholesale market participation, however, as evidenced by independent reports and delayed compliance requests from the independent system operators (ISOs) that manage regional transmission grids in the U.S. [6,7]. Because mycorrhizal networks have evolved over billions of years, in part to help balance carbon surpluses in groups of distributed photosynthetic plants that transitioned to land [8], the authors looked to mycorrhizal fungi and trees to gain insights into possible strategies for the efficient integration of DERs into balanced electricity markets.

Insights from forest ecosystems can help address the distributed energy generation dilemma via the transdisciplinary extension of an intricate network of mycorrhizae that links trees and plants (many distributed photosynthetic generators of chemical energy) through their root systems. In the current work, each tree is modeled as a load, a solar panel array, and a battery. Specifically, a novel, biologically inspired model for transactive energy markets is derived from how trees and plants trade photosynthetically derived carbon through fungal mycorrhizal networks. The proposed energy market structure is modeled directly after the documentation of an ectomycorrhizal network in a Douglas-fir grove in the northwestern United States [9] and other insights gleaned from a review of the ecological literature on mycorrhizal networks. The key insights gleaned from this ecological inspiration include the introduction of multiple competing virtual DER aggregators with energy storage on the distribution scale and the ability of each DER to dynamically subdivide and redistribute its energy assets on these competing marketplaces during each timestep. Furthermore, the decentralized, small-world nature of mycorrhizal networks with competing fungal species connected to individual trees presents a pathway toward modular wholesale market structures where different local energy markets address real-time, capacity, and ancillary service niches on the distribution scale.

Much work has already been produced to demonstrate the role of mycorrhizal fungi in creating ecologically robust plant communities capable of withstanding considerable disruptions to the local environment [10]. In various plants connected by mycorrhizae, studies have demonstrated that seasonal shifts in source–sink gradients also shifted the direction of net nutrient transfer [11,12] and net carbon transfer [13]. Other studies have shown the ability of mycorrhizal fungi to serve as chemical signaling pathways for trees to warn neighbors (even from other tree species) against the attack of pests causing defoliation [14]. Mycorrhizae fill different niches that serve different roles in forest resilience, such as breaking down soil [15], transporting water [16], facilitating phosphorus uptake during drought [17], and improving carbon storage in response to mycorrhizal competition between plants [18]. Some mycorrhizal species, such as Rhizopogon, are specialists and only associate with one type of tree. In contrast, others are generalists and can form mutualisms across different types of plants to form more biodiverse forest communities that are more ecologically robust in response to forest disturbances [19].

The proposed mycorrhizal energy market design is novel in the transactive energy domain while building on previous translations of ecological principles into engineering and critical infrastructure domains. The closest precedent in the power systems literature [20] draws on ecological network theory and applies a food web analogy to increase the robustness of power grids. Other fungal frameworks that are not mycorrhizae specific, have been applied to different domains including transportation infrastructure [21], wireless communication [22], and P2P network overlays [23]. In the current work, prosumer- and community-level energy storage reflect the energy storage capacity of all living things, including both Douglas-fir trees (prosumers) and fungi (DERAs). The market structure of the proposed framework was further inspired by the diversity of mycorrhizal mutualisms in nature where several fungal species often exchange carbon with a single tree.

Several studies and reviews have recently addressed challenges and opportunities specific to the integration of DERAs into existing energy market structures. Whereas previous approaches have addressed DERA market optimization based on traditional market hierarchies [24,25], the current approach transcends market hierarchy using by cloning prosumer buildings on competing virtual marketplaces using a digital twin strategy. Hu et al. model DERA flexibility as a single virtual storage device and include the state of charge (SoC) calculation in their receding horizon optimization model of spot and balancing market participation [26]. They further develop a novel, two-way, iterative, distribution locational marginal price (iDLMP) signal that prevents excessive power consumption or injection to satisfy distribution network constraints [27]. Several studies also address day-ahead and frequency reserve markets [28–30]. Iria et al. preserve privacy in day-ahead and reserve markets through an alternating direction method of multipliers while addressing uncertainty [29]. Iria and Soares present a novel, centroid-based clustering method to efficiently coordinate bids from large numbers of DERs in day-ahead and real-time markets [30].

Furthermore, challenges in efficient allocation of profits [31] and adequate accommodation of user preferences [32] given rapidly changing network configurations are addressed in the proposed approach by automated staking on a blockchain-based architecture. In a recent review on DERA integration into electricity markets, Stekli et al. [33] urge the importance of continued improvements in communication technologies such as distributed ledger technologies. Obi et al. [34] conclude a review of the DERA energy market integration literature by echoing the need for improved, distributed communication approaches and calling for increased control options within asset aggregations to provide a wider range of grid services.

Specific gaps identified in reviewing the literature related to energy market integration of DER aggregations include the following:

- No transactive energy frameworks for DERA integration to energy markets proposed utilizing inspiration from mycorrhizal networks or carbon trading in forest ecosystems.
- No studies reviewed proposed the subdivision of *portions* of building energy assets simultaneously onto competing DERAs at different levels of grid hierarchy by evaluating SoC and revenue at each aggregator's market-level battery.

The current work addresses these gaps by developing an ecologically inspired framework for the dynamic, flexible reconfiguration of multiple DER aggregators on competing, virtual marketplaces. Specific contributions include:

- Establishing a novel, blockchain-compatible, mycorrhizal framework capable of reallocating portions of building energy assets on competing DERAs at different levels of market hierarchy via the scaled cloning of digital twins.
- Developing novel mechanisms for partial asset subdivision (action metric) and reallocation (assignment policy) based on market-level DERA battery SoC and revenue-based feedback from each connected prosumer building.

2. Materials and Methods

A simulated, comparative case study methodology was employed to determine the effect of the proposed mycorrhizal energy market intervention on economic and ecological performance. The approach applied simulation methods to generate six unique cases across seasonal (summer, fall, winter) and typological (residential, mixed-use) variations. Each case was simulated over seven days in static baselines (fixed energy asset distribution on connected markets) and dynamic mycorrhizal (variable energy asset distribution on connected markets) configurations. Baseline and mycorrhizal market performance were compared using the key performance indicators (KPIs) of self-sufficiency (self-consumed energy/total energy demanded) and self-consumption (self-consumed energy/total energy produced) based on the concept of ecological robustness, an ecosystem's ability to recover from large disruptions efficiently. In addition, baseline and mycorrhizal building performance were compared using the KPI of weekly savings (net costs with local energy trading minus net costs with a traditional retail feed-in-tariff model). An analysis of the overall effectiveness and primary drivers of the mycorrhizal intervention based on these KPIs is included in a discussion to put the obtained results in context, especially concerning relevant policy implications.

2.1. Structural Model Definition

The structure of the proposed mycorrhizal energy market model, as displayed in Figure 1, was simplified from the structural blueprint presented in Gould et al. 2023 [35]. The current work was simulated using Grid Singularity Engine (GSyE), a transactive energy modeling platform formerly known as D3A (decentralized autonomous area agents) and developed by the Grid Singularity company based in Berlin, Germany. The full mathematical model employed in D3A is defined in Gazafroudi et al. 2021 [36]. GSyE was selected as the simulation platform for the current work due to its specific focus on transactive energy markets, its design for blockchain interoperability, and its built-in multi-agent architecture [37,38]. The initial assumptions that governed structural simulation development are listed below:

- Each building has a solar panel array representing leaves and a load (energy consumption profile) representing metabolic respiration;
- All markets and building participants have their energy storage capacity in the form of a battery, as each organism can store energy;
- A tree (building) can simultaneously connect to multiple mycorrhizal networks (markets);
- Each building belongs to a specific cohort that determines the size of initial power production, power consumption, storage capacity, and maximum number of linkages;
- The number of linkages determines relative volumes of energy traded by each energy asset on a connected market as it governs carbon exchange capacity in mycorrhizal networks;
- The last remaining linkage between a tree (building) and a mycorrhiza (market) cannot be removed (minimum number of linkages equals one) to maintain a consistent prosumer constituency for comparative analysis. Of course, this assumes that mycorrhizal mutualism cannot be abandoned (not always the case in nature).

2.1.1. Digital Twins for Energy Asset Subdivision

There was a necessary translation between the non-hierarchical nature of the mycorrhizal networks and the hierarchical structure of the GSyE platform. Buildings were modeled in GSyE as markets where internal building assets traded energy with one another before trading with other buildings in the community, region, and so on. Each building was replicated on all connected markets to address this difference as a digital twin. These sets of subdivided energy assets were cloned and scaled by the number of linkages, as depicted in Figure 1. This enabled the simultaneous trading of portions of a building's energy assets on multiple connected marketplaces without having to trade through hierarchical levels.

2.1.2. Cohort-Based Sizing

Cohorts, as used in Beiler et al. 2009 for clustering similarly aged and sized trees into groups, determined all sizing parameters for energy assets in the proposed model. Table 1 displays the parameters and other characteristics of the proposed work organized by cohort. Only three out of four cohorts from Beiler et al.'s original 2009 study were represented. They were relabeled as cohort one, two, and three in ascending order. The solar profiles for all of the cohorts were based on a GSyE default profile for a sunny day with arrays consisting of different numbers of 250 W panels. The winter reduction factor of 54% for each cohort was based on the average percent reduction in solar array energy production between July and January during a typical meteorological year in Blacksburg, VA, according to the PVWatts tool [39] from the National Renewable Energy Lab (NREL) in Golden, CO, USA.

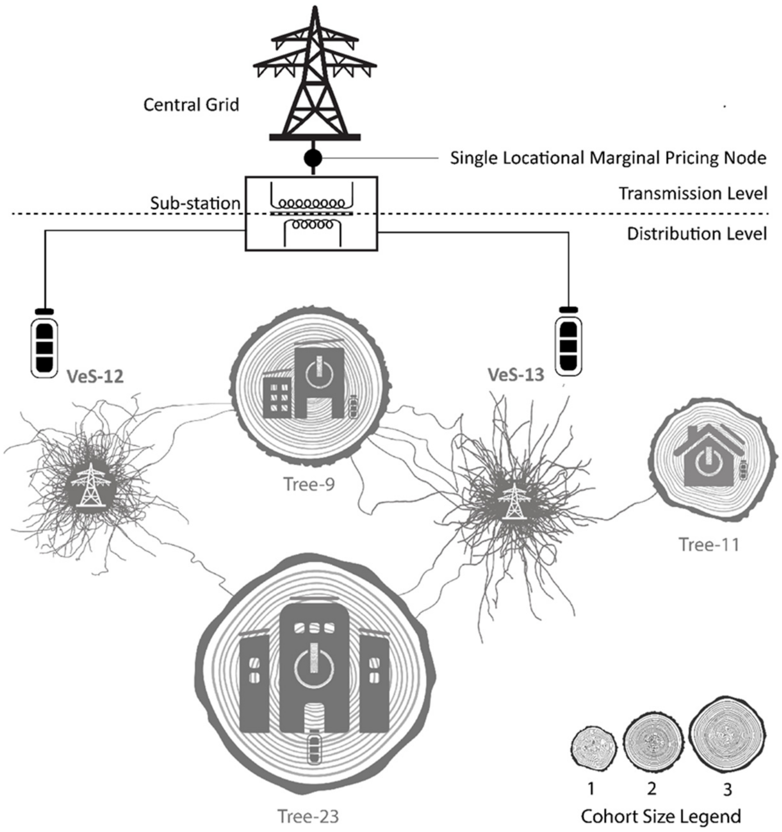

Figure 1. Simplified Simulation Structure. Buildings such as Tree-09 and Tree-23, which were connected to multiple markets, have digital twins with subdivisions of their energy assets allocated on each connected marketplace according to the number of linkages (shown as thin black lines between buildings (trees) and markets (mycorrhizal fungi).

Table 1. Cohort-based Characteristics of Building Participants.

Characteristics	Cohort 1	Cohort 2	Cohort 3
Tree analog	Young sapling	Established tree	Mother tree
Daily energy balance	Deficit	Neutral	Surplus
PV panels	6	28	78
PV power	1.5 kW	7 kW	19.5 kW
Winter PV reduction	46%	46%	46%
Fall PV reduction	20%	20%	20%
Enphase battery basis	EnCharge 3	EnCharge 10	EnCharge 20
Storage capacity	3 kWh	10 kWh	20 kWh
Battery power delivery	1.9 kW	5.7 kW	11.4 kW
Load profile database	OpenEI	OpenEI	OpenEI
Load location basis	Blacksburg, VA	Blacksburg, VA	Blacksburg, VA
Load TMY3 basis	724,113	724,113	724,113
Residential load profile	Residential low	Residential base	Residential high
Mixed-use load profile	Residential low	Comm sml office bldg	Commercial small hotel
Winter MU norm factor	NA	18.6%	3.4%

Table 1. *Cont.*

Characteristics	Cohort 1	Cohort 2	Cohort 3
Fall MU norm factor	NA	12.8%	2.7%
Sum MU norm factor	NA	13.5%	3.1%

Abbreviations: NA: not applicable, Comm: commercial, sml: small, bldg: building.

The three cohorts were employed in both the residential and mixed-use cases using different load profiles from the Open Energy Data Initiative's OpenEI database [40], also developed by NREL. In the residential case, the low, base, and high residential OpenEI profiles corresponded to the load profiles of cohorts one, two, and three, respectively. In the mixed-use case, cohort one remained unchanged, while cohorts two and three were substituted with the commercial OpenEI profiles for small office buildings and hotels, respectively. These larger commercial profiles were normalized to reduce the total daily energy demand to a range consistent with their corresponding residential cohorts for a more consistent comparison between cases. Mixed-use normalization factors (MU norm factors) are shown by season in Table 1 as percentages of larger commercial loads that equal the total daily load of their residential cohort two and cohort three counterparts. Load and PV profile distributions for cohort two are shown in Figure 2.

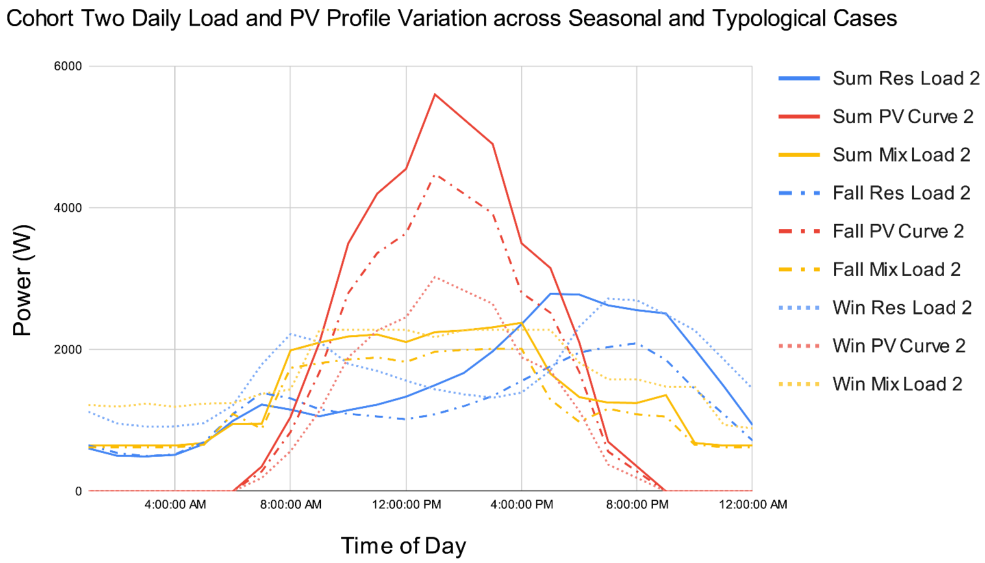

Figure 2. Cohort Two Daily Load and PV Profile Variation. PV profiles are red with different dashed or dotted patterns showing reductions in PV production from summer to winter. Winter loads are shown in dotted blue and yellow lines, and summer loads are shown in solid blue and yellow lines. The suffix 2 after each entry on the legend represents cohort two.

2.2. *Functional Model Definition*

The functional basis of the proposed mycorrhizal energy market was initially blueprinted by Gould et al. in 2023 [35]. The primary function of the proposed model employed redundant linkages to vary the strength of a connection between a building and a market as well as the corresponding trading volumes and rewards for participation. The main objective was to develop a strategy for updating the linkage distributions between buildings and markets periodically based on performance metrics and then updating the corresponding parameters for grid operation. In this case, variations of battery state of charge (SoC) were used as the action metric (determining if a link must be added, removed, or replaced). Variations of trade volume from the previous market slot were used as the assignment metric (determining which links are added, removed, or replaced from which participating buildings). Financial constraints such as grid fees, bidding strategies, and market maker rates also played a fundamental role in model functionality. Below are the preliminary functional assumptions of the proposed model, followed by more details on the linkage-based evolution of the mycorrhizal energy market.

- Mycorrhizal linkage ratios dictate the proportion of energy from each asset a given building can trade on a given market;
- Linkages are added or removed based on market performance metrics;
- Linkages are added to buildings with the highest revenues when net energy storage levels are high;
- Linkages are removed from buildings with the lowest revenues when net energy storage levels are low;
- The maximum number of linkages is governed by cohort size, as in Table 1;
- No new buildings are added, and no existing buildings are removed during the simulation.

The extension of the mycorrhizal linkages analogy to the energy domain was fundamental to the functionality of the proposed simulation. A given building on the network was not just connected or disconnected to the network but rather connected with a certain strength, as represented by a weighted graph with the edge weights equal to the number of linkages. The weight of these connections determined the portion of each energy asset's capacity in a building that could be traded on a given mycorrhizal energy market. This not only diversified the exchanges on which a building can buy and sell energy, but also generated a way of accounting for the subdivision of assets onto multiple markets.

In this context, one essential function of distributed ledgers was to avoid the double spending phenomena where a market participant could sell the same energy product more than once. A consensus protocol such as proof-of-stake for approving blocks almost eliminates the possibility of double spending [41]. This subdivision of asset capacity was also crucial if aggregations of DERs hoped to participate in wholesale capacity markets and be compensated to reserve a certain amount of energy for the grid when needed. The number of linkages in the proposed model also dictated the stake a given building has in any potential profits made by the mycorrhizal market and how much weight its vote carried in determining market behavior. The current work compared a static distribution of linkages with a dynamic distribution of linkages driven by action metrics and assignment policy, as described below.

2.2.1. Baseline Static Linkages

In the baseline static case, the linkages were fixed at their initial weights as inspired by the fungal network structure indicated in Beiler et al. 2009's incidence matrix. Seven one-day-long simulations were run in sequence, and the states of charge of the batteries were updated so that the final state of charge on the first day equaled the initial state of charge on the second day, and so on. This strategy improved the continuity of this discreetly executed, transient model. The baseline case approximated a transactive neighborhood where each building releases all bids and offers onto a single marketplace. Then the markets can balance any surpluses or deficits with other markets afterward. Buildings in the baseline static case did not update the number of linkages they have to each market; the number of linkages remained constant throughout all seven days of the simulation. This baseline assumed that each scaled clone is a fixed, smaller building on the market rather than a shifting, subdivided part of a larger collection of energy assets.

The baseline case described here can be considered a benchmark for a multi-level, hierarchical local energy market utilizing a two-sided pay-as-clear clearing mechanism, comparable to the multi-level case run on the same simulation engine in Okwuibe et al. 2022 [25]. The mycorrhizal case, described in more detail below, differs from this baseline in that daily asset redistribution on competing local energy markets transcends the market hierarchy by allowing portions of building energy assets to be redistributed directly on any aggregators currently active in the distribution region.

2.2.2. Mycorrhizal Dynamic Linkages

In the dynamic mycorrhizal case, the number of linkages was updated after each day based on feedback from that day's trading revenues and battery state of charge dynamics. This linkage updating shuffled two main performance elements of the model as compared to the baseline: (1) the scale of each of that building's clones was updated corresponding to the new linkage ratio, and (2) the weight that the mean state of charge (mSoC) of the battery of each building had in determining whether linkages were added or subtracted on the next day. After determining if a given market will gain or lose a linkage, trading metrics for each building on that market and general constraints (such as a building not being able to lose its last link) determined which building gained or lost that linkage.

The dynamic mycorrhizal market mechanism enabled mycorrhizal markets to 'crawl' the existing energy landscape and 'forage' for additional energy capacities with the goal of improving its overall performance as defined by the user preferences (in this case, economic performance to maximize revenue) of participating buildings. In the ecological analogy, this dynamic structure equated to mycorrhizae growing when energy reserves are high and shrinking when energy reserves are low to help meet its metabolic needs and increase its probability of survival. The strategies governing the dynamic case presented here were just a first attempt at defining possible processes; they are not optimized or tuned. The optimization of these strategies with respect to power flow and distributed energy systems is reserved for future work.

2.2.3. Action Metric

The action metric for the proposed model determined when and where a linkage was added or removed in the network. For this initial simulated case study, the action metric was an average weighted collective state of charge (awcSoC). The weight, w, was determined by the linkage ratio defined as the number of linkages a given building has to a given market divided by the total number of linkages on that market. In the case of the semi-centralized, market-level battery, the weighting factor was always equal to one. Because all the weights of connected buildings added up to one as well, dividing by the total weight in the denominator to obtain a weighted average was the same as dividing by 2, as shown in Equation (1). The mean state of charge (mSoC) was defined as the mean state of charge (measured by percentage) of a given battery throughout each simulated day. The metric awcSoC was calculated for each mycorrhizal market m after a full day of operation, as shown in Equation (1):

$$\mathrm{awcSoC_m} = \frac{\mathrm{mSoC_m} + \sum_1^n \left(\mathrm{w_n} \times \mathrm{mSoC_n}\right)}{2} \tag{1}$$

where n is the number of buildings connected to a given market m, $\mathrm{mSoC_m}$ is the mean state of charge of market m's market-level battery for one simulated day, and $\mathrm{mSoC_n}$ is the mean state of charge of building n's personal battery. The weighting factor $\mathrm{w_n}$ is equal to the linkage ratio as shown in Equation (2), where $\mathrm{l_n}$ is the number of linkages building n has to market m and $\mathrm{l_m}$ is the total number of linkages on market m:

$$\mathrm{w_n} = \frac{\mathrm{l_n}}{\mathrm{l_m}} \tag{2}$$

After awcSoC was calculated for each mycorrhizal market in the network, it was compared to a pre-defined threshold to determine if a linkage was to be added or removed after a simulation day. The metric action threshold was set at 55% state of charge, halfway between the minimum allowable state of charge at 10% and the maximum state of charge of 100% for all connected batteries. A market awcSoC above 55% triggered linkage addition on that market, whereas an awcSoC below 55% triggered linkage removal. The minimum number of linkages across all cohorts was one (a building could not disconnect completely from a market), and the maximum number of linkages varied according to cohort (five for cohort one, ten for cohort two, and 15 for cohort three).

2.2.4. Assignment Policy

Once an action was determined for a given timestep, the assignment policy determined which links were added or subtracted from which participating buildings. The assignment policy was driven by daily building revenue metrics. After each simulation cycle, every building on a given market was ranked by net revenue in descending order. The buildings at the top with the highest revenues were first in line for the following linkage added, while the buildings at the bottom with the lowest revenues were first in line for the next linkage removed. This revenue-based policy was ultimately selected for its alignment with a capitalistically dominated energy landscape, though several other metrics related to trade volume and market liquidity were also considered.

All considered assignment policies reflected the literature in biological market theory regarding dynamic preferential allocation or soft switching, where an organism gradually transitions between trading partners rather than abruptly cutting off trade entirely [42]. The proposed policy is also consistent with the evolutionarily stable strategy of linear proportional discrimination, where resource allocation is proportional to resource acquisition for a given trading pair [43]. Where mutualism is thriving, and exchange rates for resources are favorable, there is likely to be more metabolic activity and opportunity for hyphal proliferation and reproduction according to the metabolic rate hypothesis [44,45]. Though the model developed here adhered strictly to ecological principles, the authors acknowledge that future iterations of the assignment policy may have to depart from these ecological foundations to better adapt to the needs of energy markets, their regulatory bodies, and power systems control.

2.2.5. Auction Parameters

Auction parameters include market maker settings, asset bidding strategies, and a market clearing strategy detailed in the sections below.

Market Maker Settings

The proposed model's market maker (MM) simulated the financial relationship between buildings and the larger electrical grid. The MM was modeled as an infinite bus with the capacity to buy and sell an infinite amount of energy. The GSyE platform accommodated a retail electricity rate for energy delivered to the local networks along with lower feed-in-tariff (FiT) values for excess energy sold back to the grid. In this simulation, USD 0.11 per kWh was the retail rate in correlation with Appalachian Power Co. (APCo) rates in Blacksburg, VA, USA. The FiT was set to USD 0.03 per kWh—just above APCo's claimed avoided cost—the value per kWh saved by not having to deliver energy that is produced by a photovoltaic system. The MM infinite offers and bids are displayed in Figure 3.

Asset Bidding Strategies

The linear ramp bidding strategies for each asset type are shown in Figure 3. Each market timeslot was 15 min and was broken down into 14 ticks (one every minute) on which trades and offers were matched and executed. PV assets could only make offers for the energy they produced. Load assets could only make bids for the energy they required. Storage assets could make both bids and offers, but their bidding strategies were designed to prevent them from selling energy to themselves by ensuring that the final bid price and final offer price never crossed. The slopes of these linear-ramp bidding strategies ensured that within an individual building, the local PV energy had a chance to meet the local load first, then the local storage had a chance to buy or sell to meet excess supply or demand, and lastly, the market maker could meet any remaining bids and offers within range. This auction strategy left only a modest window in the second part of the trading slot for buildings to trade amongst themselves and with the local market-level energy supply.

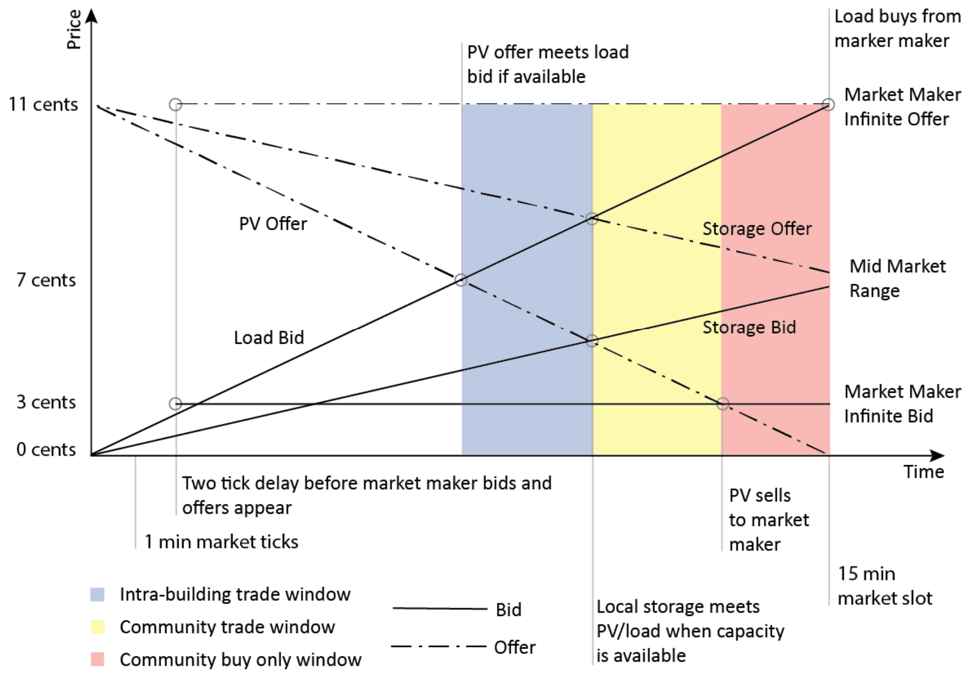

Figure 3. Asset Bidding Strategy and Timeline. The blue range represents trades between a solar array and a local battery or a local load in the same building. The yellow range represents local trading between buildings on the same distribution grid. The red range is buy-only, local trading.

Market Clearing Strategy

The simulated two-sided pay-as-clear market had a merit-order effect clearing mechanism with a settling point at the intersection between the ranked bid and offer depth curves. Bids and offers matched by the linear ramped bidding process shown in Figure 3 were executed three times throughout the trading slot. All accepted bids were ranked and sorted in descending order, while all accepted offers were ranked and sorted in ascending order. The clearing rate was set where the price versus volume bid curve intersected the price versus volume offer curve. Those bids and offers left unmet remained on the market for future matching and clearance until the end of each 15 min market slot.

2.3. Key Performance Indicators

The key performance indicators selected to evaluate the market performance of the simulation were self-sufficiency and self-consumption, while the key performance indicator for building performance was total weekly savings. Both self-sufficiency and self-consumption were selected as indicators related to ecological robustness, a network's ability to sustain itself when a disruption cuts it off from external resources. Total weekly savings was selected as a building performance indicator to capture the dominant economic driver of building owner behavior change when considering participation in new energy programs.

2.3.1. Self-Sufficiency

Self-sufficiency was defined as the total amount of self-consumed energy over the total energy demanded. Self-sufficiency relates to physical robustness and the ability to provide enough energy locally to meet critical demands during a disruption. The self-sufficiency of the baseline and mycorrhizal cases were compared over the seven-day simulation period in each of the seasonal and typological cases. Total self-sufficiency was calculated by adding up all of the daily self-consumed energy from every tree (building) on a given market and dividing it by the total energy demanded by all the trees (buildings) over the course of the same simulated week.

2.3.2. Self-Consumption

Self-consumption was defined as the total amount of self-consumed energy of the total energy produced from PV assets. Self-consumption relates to economic robustness and the ability to sustain demand for generated resources even in the case of disconnection from the central grid. The self-consumption of the baseline and mycorrhizal cases were also compared over the seven-day simulation period. Total self-consumption was calculated by adding up all of the weekly self-consumed energy from each market and dividing it by the total weekly energy produced by the same market throughout the entire simulation period.

2.3.3. Total Weekly Savings

Total weekly savings (TWS) was utilized for evaluating the performance of individual buildings participating in local energy trading compared to currently common retail and feed-in tariff (FiT) models. The total savings metric was selected as an indicator of the tangible financial benefit or detriment a given prosumer building would receive by switching to the proposed market model compared to a standard utility scenario with FiT and retail rates. The equation for calculating TWS is shown in Equation (3):

$$\mathrm{TWS} = \sum_{i=1}^{scn} \sum_{j=1}^{d} \left[\left(S_j \times \mathrm{CR} \right) - \left(D_j \times \mathrm{CR} \right) \right] - \left[\left(D_j \times \mathrm{RR} \right) - \left(S_j \times \mathrm{FiT} \right) \right] \quad (3)$$

where CR is the average daily clearing rate calculated by merit-order effect in a market with a pay-as-clear settling mechanism, S_j is the total daily energy surplus sold in kWh for a given building on a given market, D_j is the total daily energy deficit bought in kWh for a given building on a given market, FiT is the fixed feed-in-tariff rate from the market maker (in the current case \$0.03 per kWh), and RR is the fixed retail rate from the market maker (in the current case \$0.11 per kWh). The index SCN is the number of digital twins needed for a building participating in multiple markets simultaneously (maximum of two in the current work), and the index d is the total number of days in the simulation period (7 days in the current work).

3. Results

The overall effect of the mycorrhizal intervention was minimal, with self-consumption increasing slightly and both self-sufficiency and weekly saving decreasing slightly. The case with the largest overall effect was the summer residential case, where both larger buildings from cohorts two and three shifted their resources significantly from market VeS-13 (larger market with an extra energy deficient household from cohort one) to VeS-12 (smaller market without extra energy demand). Both VeS-12 and VeS-13 are based on the Rhizopogon vesiculosus species of mycorrhizal fungi and derived from Beiler et al. 2009's wood-wide web study. Below are more details on the effect of the mycorrhizal intervention on self-sufficiency, self-consumption, weekly savings, and aggregations of all three for the various seasonal and typological cases.

3.1. Self-Sufficiency

Self-sufficiency stayed about equal or slightly down in both markets with the dynamic mycorrhizal linkage intervention for all seasonal and typological case variations. As expected, the markets steadily gained self-sufficiency as solar energy production increased from winter to summer. Mixed-use cases were consistently less self-sufficient than residential cases. The largest mycorrhizal effect was observed in the summer residential case on market VeS-13 as its main producer of local solar energy, Tree-23, transferred most of its production to market VeS-12. Figure 4 displays the self-sufficiency profiles of the markets VeS-12 and VeS-13. Comparisons of average self-sufficiencies across seasonal, typological, and total cases for the current study are shown in Section 3.4 below.

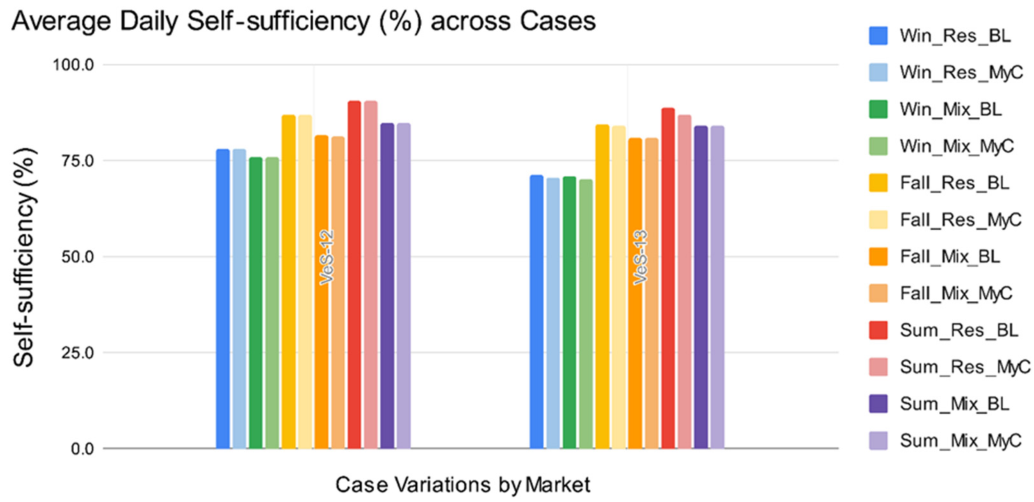

Figure 4. Average Daily Market Self-Sufficiency across Cases. The mycorrhizal interventions are shown in every other bar as lighter shades of the baseline case, as shown in the key. The seasonal variation goes from winter (blue and green) to fall (yellow and orange) to summer (red and purple) for both mycorrhizal energy markets (VeS-12 and VeS-13).

3.2. *Self-Consumption*

Self-consumption increased or stayed the same for all cases on market VeS-13 when the dynamic mycorrhizal linkages were added, as displayed in Figure 5. On market VeS-12, which had one less energy-deficient building, self-consumption rose in the winter cases but decreased in both summer and fall cases with the mycorrhizal intervention as the larger surplus of Tree-23 shifted toward market VeS-12. Market VeS-13 consumes all the energy it produces in both residential and mixed-use cases in the winter. The largest mycorrhizal effect was observed in the summer residential case on market VeS-13 as its main producer of local solar energy, Tree-23, transferred most of its production to market VeS-12, therefore decreasing the total amount of local energy produced and increasing the self-consumption percentage.

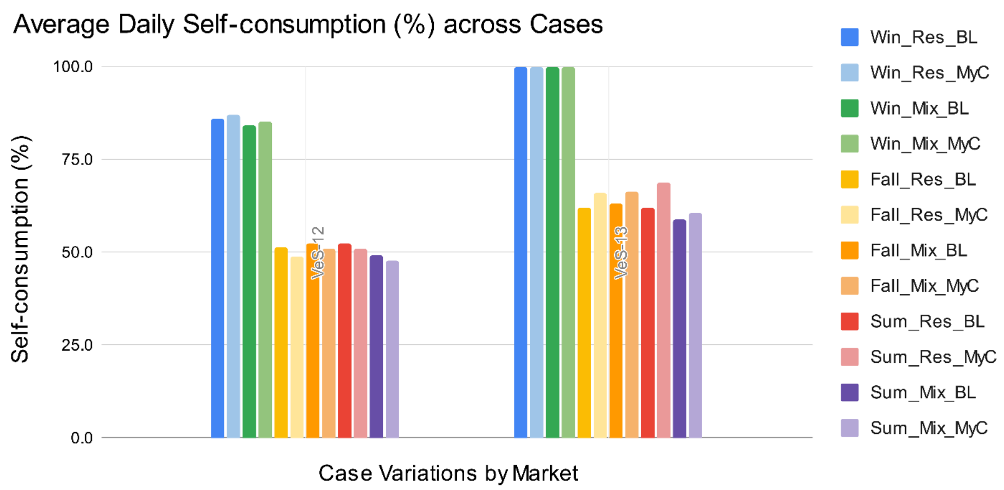

Figure 5. Average Daily Market Self-Consumption Across Cases. The mycorrhizal interventions are shown in every other bar as lighter shades of the baseline case, as shown in the key. The seasonal variation goes from winter (blue and green) to fall (yellow and orange) to summer (red and purple) for both mycorrhizal energy markets (VeS-12 and VeS-13).

3.3. Total Weekly Savings

Figure 6 shows how weekly monetary savings varied with seasonal and typological differences. The biggest changes with the addition of dynamic mycorrhizal linkages were observed in winter mixed-use and summer residential cases on Tree-23 (cohort three). In both scenarios, Tree-23 shifted its resources away from market VeS-13 with an extra mycotrophic consumer and toward market VeS-12 with less demand to meet its excess supply. Since these values were not normalized by cohort size, the mycorrhizal effects on Tree-23 savings would be the largest because, as a member of cohort three, it traded the largest volumes and benefited the most from local transactions.

Figure 6. Weekly Monetary Savings across Case and Cohort Variation. The mycorrhizal interventions are shown in every other bar as lighter shades of the baseline case, as shown in the key. The seasonal variation goes from winter (blue and green) to fall (yellow and orange) to summer (red and purple) for all participating buildings (Tree-11 (cohort one), Tree-9 (cohort two), and Tree-23 (cohort three)).

3.4. Overall Trends

In terms of total performance across seasonal and typological case sets, only self-consumption increased, most significantly in the winter cases. Seasonal case variation was the strongest, as shown in Figures 7 and 8. Summer savings were consistently higher than in other seasons due to excess solar production. Winter self-sufficiency was significantly lower, and winter self-consumption was significantly higher than the comparable fall and summer cases. Typological variation between all residential and mixed-use cohorts had a much smaller effect. As shown in Figure 8, there was a small but consistent decrease in average self-sufficiency for mycorrhizal cases when compared to baseline cases throughout seasonal and typological variation. The total average self-consumption across all cases increased slightly over baseline values with the proposed mycorrhizal market mechanism.

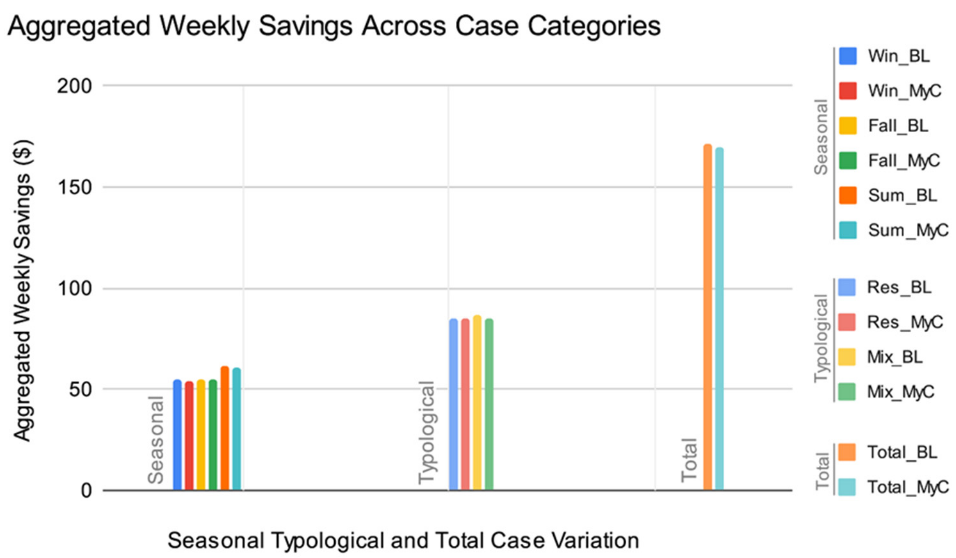

Figure 7. Aggregated Weekly Savings across Case Categories. The mycorrhizal interventions are shown in every other bar after their corresponding baseline case, as detailed in the key. Seasonal, typological, and total aggregated weekly savings are presented in succession from left to right.

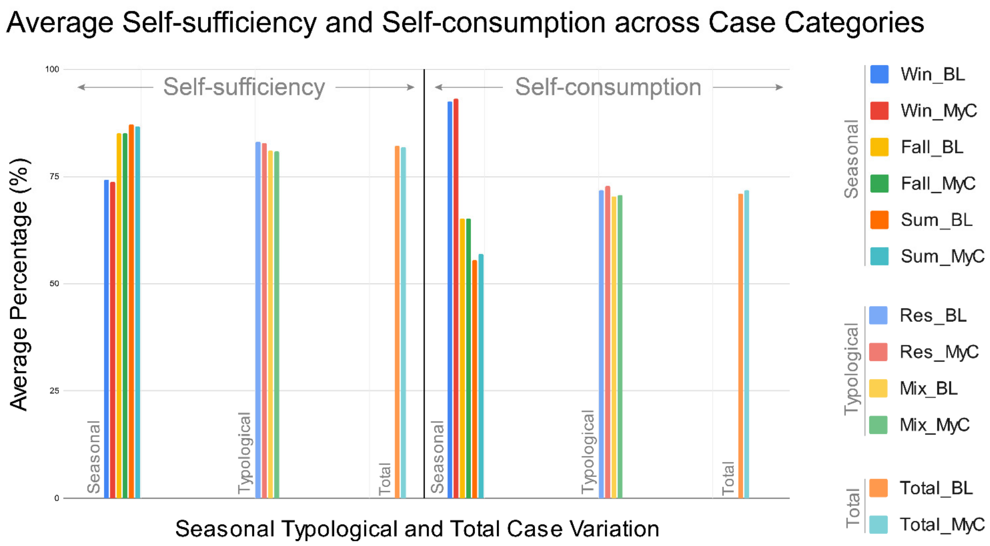

Figure 8. Average Self-Sufficiency and Self-Consumption across Case Categories. The mycorrhizal interventions are shown in every other bar after their corresponding baseline case, as detailed in the key. Seasonal, typological, and total averages are presented in succession for both self-sufficiency (left) and self-consumption (right).

4. Discussion

4.1. Comparative Analysis

The simulation results indicate that the overall effect of dynamic mycorrhizal linkages on the key performance indicators is minimal. When tallies of self-sufficiency and self-consumption were aggregated over the full seven-day trial period and compared between baseline and mycorrhizal cases, the differences in self-sufficiency and self-consumption were only 0.28% (worse) and 0.70% (better), respectively. This self-consumption metric is particularly important for sustaining the benefit of transactive grids in communities at the far extremes of the grid edge, where excess energy may have to travel far distances in a direction opposite to that which the infrastructure was designed for (one-way central production through transmission lines out to smaller distribution networks) to serve more distant loads. The total savings aggregated across all cases went down by USD 1.78 from

USD 171.46 to USD 169.68. Though this nearly negligible shift was not the expected result, it promises that energy assets can be subdivided and redistributed daily without a significant negative effect on the performance of the simulated network overall.

The mycorrhizal market mechanism had its most significant effect during the summer residential case. This amplified effect is likely due to a fixed feed-in-tariff rate and the large shift of resources from market VeS-13, which had an extra energy deficient building from cohort one, to VeS-12, which had no participants from cohort one. The shift was amplified as Tree-23 added linkages on VeS-12 while Tree-9 removed linkages from VeS-13, as shown in the animation in Figure 9. This shift was driven by metric action dynamics where one market (VeS-12) had an action metric consistently above the 55% threshold. In contrast, the other market (VeS-13) had an action metric consistently below the 55% threshold. The opposite directionality of market linkage dynamics during the summer residential case, referred to as summer residential divergence, is detailed in Figure 9.

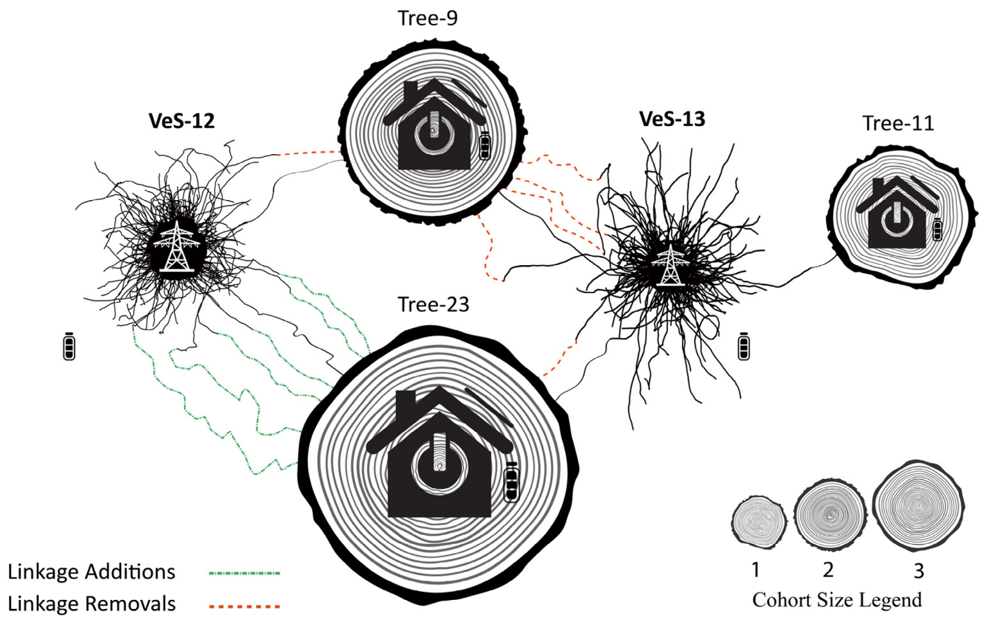

Figure 9. Summer Residential Divergence. Market VeS-12 gained linkages rapidly in the summer residential case, while market VeS-13 lost linkages rapidly. This tendency toward opposite extremes created the largest mycorrhizal effect compared to the baseline static case. Each line represents a linkage between a market and a building, with net linkage changes highlighted in the key.

The result of this summer residential shift was a large excess producer of solar energy (Tree-23) moving over to a market with fewer consumers and fewer loads to absorb (and pay for) its local supply. This diminished demand explains the drop in weekly savings for Tree-23 as it transitioned from VeS-13 to VeS-12. Simultaneously, Tree-9 also transitioned most of its energy assets over to market VeS-12; however, as a more neutral cohort two building, it benefited slightly from the lower pricing due to the influx of extra Tree-23 supply. As expected, self-consumption on market VeS-13 went up as it is left with a demand dominant Tree-11 from cohort one and only fractions of the solar energy supply it started off with. Self-sufficiency on VeS-13 went down according to the same logic.

The lack of significant effect in mixed-use load diversification can largely be attributed to ineffective temporal load shifting, but several promising adaptations could improve future performance. Normalized hotel loads were the largest (cohort three) constituent in the mixed-use case and are not altogether different from residential loads. The office building load profile balances out the typical residential duck curve with a spike during mid-day, but not enough to overcome the reinforcement from a larger hotel load curve. More intelligent grouping of loads with a larger pool of potential loads and supplies to draw from could result in mixed-use communities better equipped to meet their own needs during grid disruptions, similar to the ecological intuition of increased robustness to changes in more biodiverse ecosystems. That being said, the theoretical pros of increased flexibility and competition within a demand side management strategy that employs asset redistribution instead of behavioral or automated change in energy use are balanced by theoretical cons, including more complexity in prevention of double spending and control of energy assets at the building level.

4.2. Limitations

The conducted simulation and the associated results' implications are economically limited as related to pricing models and bidding behaviors. The GSyE platform was designed for a fixed, retail feed-in-tariff model rather than wholesale market participation by DER aggregators. The current results do not reflect what might happen if mycorrhizal markets could actively engage in energy arbitrage with awareness of dynamic energy prices and congestion conditions on the transmission level. Furthermore, the fixed grid fees of one cent per transaction implemented in the current work unfairly impact smaller traders, while percentage-based fees and dynamic grid fees are harder to implement and still only act as a deterrent to buying and never as an incentive to sell downstream during times of congestion. The employed simplistic linear ramp bidding strategy for all energy assets cannot react to price changes and does not reflect actual human behavior nor the state-of-the-art dynamics of real-time trading bots.

Temporal, spatial, and physical considerations also limit the proposed mycorrhizal energy market model. The maximum simulation window of seven days on GSyE prevents a complete picture of how mycorrhizal energy market performance varies throughout the year. In addition, the timing constraints of API customization (for custom bidding strategies and custom grid fees) with internal and external communications and their effects on distributed ledger integration are poorly understood. Spatially, the current results only apply to the mixed-humid climate in Blacksburg, VA. A different climate zone with different solar resources and heating/cooling degree days would likely produce vastly different outcomes. Furthermore, the energy models employed only cover a single type of building for each cohort and do not reflect most communities' vastly variable building stock. Lastly, the trades taking place in this simulated community do not consider the physical voltage and frequency limitations of distribution grid equipment and would be subject to further power system constraints in accordance with a distribution network operator (DSO) to ensure safe and reliable operation.

5. Conclusions

The dynamic, mycorrhizal structure of transactive grid components developed here holds significant promise as a pilot case for the further optimization of feedback mechanisms for DER balancing in local energy communities. The fundamentals of network reconfiguration and energy asset distribution through scaled digital twins and the proposed weighted graph structure translate extremely well between ecological and electrical domains, even if the automated functions and feedback loops were not tuned adequately to produce measurable performance improvements. The linkage algorithm would benefit from awareness of local supply/demand dynamics, dynamic (seasonal/weekly/intraday) energy pricing, and individual building owner preferences (revenue-based economic/carbon-based ecological) before deciding where to add or subtract a linkage. Rather than changing linkage numbers one by one, floating percentage redistributions would enhance system versatility and avoid the diminished marginal ratio effect of later linkage additions and subtractions. There is also an opportunity here for compatibility ranking to automate linkage dynamics and network reconfigurations based on relevant metrics, including overall carbon equivalents, rather than coordinating energy redistributions with a single economic metric such as revenue.

As defined by relative energy deficits and surpluses in the cohorts, source and sink gradients intuitively dominated system performance as carbon source and sink relationships dominated early ecological studies into carbon transfer between trees through mycorrhizal networks (Simard et al. 1997). The most likely cause for faulty feedback in the current work is that the effect of adding or subtracting a linkage can change if the market is supply versus demand dominated. For example, removing a linkage from a deficient energy market will restrict the flow of internally self-produced energy out of the system, so this strategy only works in a scenario where overselling has come at the expense of missed local loads. In the current model, however, a low collective energy state would trigger the removal of that linkage from a low revenue-producing source regardless of contextual source–sink gradients on participating markets.

Further adaptations to the model are required to accommodate smaller participants and consumer-only households. For example, because of the intentionally skewed PV profiles of cohorts one, two, and three, the smallest building on the network (Tree-11) could never compete in terms of revenue and was always last in line for linkage additions. A fixed fee per transaction also severely limited the financial viability of smaller energy trades. In future iterations of this mycorrhizal energy market model, transaction fees should scale with transaction size, and all assignment metrics should be normalized based on a common factor, such as square footage or heating and cooling loads. This would place all the participating buildings on a similar footing in terms of competing for new linkages based on relative-to-size performance. Furthermore, households that do not produce any solar power and, therefore, always operate at a severe energy deficit drive important demand with local energy markets and must be accommodated in unbiased algorithms and policy considerations around DER aggregation.

Building on the current work, there are several opportunities for diverse teams of power systems experts, natural scientists, and regulators to refine applied ecological lessons and improve future distributed energy infrastructure. The optimal temporal scale for network reconfiguration may be on the minute scale rather than the daily, seasonal, and annual root and hyphal growth cycles. A mycorrhizal market's ability to shed a connected building entirely, though not practical for analysis in the proposed simulation, is critical in maximizing the collective, symbiotic fitness of the mycorrhizal super-organism that encompasses both fungi and plants. Intelligent temporal load shifting based on reinforcement learning rather than fixed percentage, revenue-based load diversification could also increase the performance of the proposed mycorrhizal energy model over time. Competition between multiple virtual mycorrhizal wholesale energy markets of each type (real-time, capacity, and ancillary services) should improve cost for building owners and performance for grid operators while also creating a holistic module of wholesale energy markets for implementation at the local level. The proposed bio-inspired transactive energy modeling framework developed here, once further optimized with power systems principles, serves as a valuable platform for engineers, academics, and policymakers to improve the robustness of future energy systems through the automated coordination and distribution of renewable resources.

Author Contributions: Conceptualization, Z.M.I.G.; methodology, Z.M.I.G., V.M. and G.R.; software, V.M. and Z.M.I.G.; validation, Z.M.I.G., W.S., T.S., G.R. and S.D.; formal analysis, Z.M.I.G. and V.M.; investigation, Z.M.I.G.; resources, Z.M.I.G. and G.R.; data curation, V.M., Z.M.I.G. and G.R.; writing—original draft preparation, Z.M.I.G.; writing—review and editing, S.D., W.S., T.S. and G.R.; visualization, Z.M.I.G.; supervision, G.R., T.S., W.S. and S.D.; project administration, G.R.; funding acquisition, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: W. Saad was supported in this work by the U.S. National Science Foundation, grant number CNS-2025377.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to pending copywrite applications.

Acknowledgments: The authors acknowledge significant technical support from Christopher Dietrich at Grid Singularity throughout model development.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gupta, A.; Gupta, R. Microgrid Market Share Analysis | Global Statistics 2021–2027. Available online: https://www.gminsights.com/industry-analysis/microgrid-market (accessed on 13 April 2023).
2. Prasanna, A.; McCabe, K.; Sigrin, B.; Blair, N. *Storage Futures Study: Distributed Solar and Storage Outlook: Methodology and Scenarios*; NREL/TP-7A40-79790; National Renewable Energy Laboratory: Golden, CO, USA, 2021.
3. Frazier, A.; Cole, W.; Denholm, P.; Machen, S.; Gates, N.; Blair, N. *Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector*; NREL/TP-6A20-77449; National Renewable Energy Laboratory: Golden, CO, USA, 2021.
4. Wankhede, S.K.; Paliwal, P.; Kirar, M.K. Increasing Penetration of DERs in Smart Grid Framework: A State-of-the-Art Review on Challenges, Mitigation Techniques and Role of Smart Inverters. *J. Circuits Syst. Comput.* **2020**, *29*, 2030014. [CrossRef]
5. Cartwright, E.D. FERC Order 2222 Gives Boost to DERs. *Clim. Energy* **2020**, *37*, 22. [CrossRef]
6. DeVita, T.; Glazer, C. Order No. 2222 Compliance Filing of PJM Interconnection. Available online: https://pjm.com/directory/etariff/FercDockets/6522/20220201-er22-962-000.pdf (accessed on 13 April 2023).
7. Macbeth, H. *Are We There Yet? Getting Distributed Energy Resources to Markets*; Social Science Research Network: Rochester, NY, USA, 2021.
8. Brundrett, M.C. Coevolution of roots and mycorrhizas of land plants. *New Phytol.* **2002**, *154*, 275–304. [CrossRef]
9. Beiler, K.J.; Durall, D.M.; Simard, S.W.; Maxwell, S.A.; Kretzer, A.M. Architecture of the wood-wide web: *Rhizopogon* spp. genets link multiple Douglas-fir cohorts. *New Phytol.* **2009**, *185*, 543–553. [CrossRef]
10. Pickles, B.J.; Simard, S.W. Chapter 18—Mycorrhizal Networks and Forest Resilience to Drought. In *Mycorrhizal Mediation of Soil*; Johnson, N.C., Gehring, C., Jansa, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 319–339. ISBN 978-0-12-804312-7.
11. Frey, B.; Schüepp, H. Transfer of symbiotically fixed nitrogen from berseem (*Trifolium alexandrinum* L.) to maize via vesicular—Arbuscular mycorrhizal hyphae. *New Phytol.* **1992**, *122*, 447–454. [CrossRef] [PubMed]
12. Hamel, C.; Furlan, V.; Smith, D.L. Mycorrhizal Effects on Interspecific Plant Competition and Nitrogen Transfer in Legume-Grass Mixtures. *Crop. Sci.* **1992**, *32*, 991–996. [CrossRef]
13. Simard, S.W.; Perry, D.A.; Jones, M.D.; Myrold, D.D.; Durall, D.M.; Molina, R. Net transfer of carbon between ectomycorrhizal tree species in the field. *Nature* **1997**, *388*, 579–582. [CrossRef]
14. Song, Y.Y.; Simard, S.W.; Carroll, A.; Mohn, W.W.; Zeng, R.S. Defoliation of interior Douglas-fir elicits carbon transfer and stress signalling to ponderosa pine neighbors through ectomycorrhizal networks. *Sci. Rep.* **2015**, *5*, 8495. [CrossRef]
15. Miller, R.M.; Jastrow, J.D. Mycorrhizal Fungi Influence Soil Structure. In *Arbuscular Mycorrhizas: Physiology and Function*; Kapulnik, Y., Douds, D.D., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 3–18. ISBN 978-94-017-0776-3.
16. Marjanović, Ž.; Nehls, U. Ectomycorrhiza and Water Transport. In *Mycorrhiza: State of the Art, Genetics and Molecular Biology, Eco-Function, Biotechnology, Eco-Physiology, Structure and Systematics*; Varma, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 149–159. ISBN 978-3-540-78826-3.
17. Püschel, D.; Bitterlich, M.; Rydlová, J.; Jansa, J. Drought accentuates the role of mycorrhiza in phosphorus uptake. *Soil Biol. Biochem.* **2021**, *157*, 108243. [CrossRef]
18. Averill, C.; Turner, B.L.; Finzi, A.C. Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. *Nature* **2014**, *505*, 543–545. [CrossRef]
19. Tedersoo, L.; Bahram, M.; Zobel, M. How mycorrhizal associations drive plant population and community biology. *Science* **2020**, *367*, eaba1223. [CrossRef]
20. Panyam, V.R.; Huang, H.; Davis, K.; Layton, A. Bio-inspired design for robust power grid networks. *Appl. Energy* **2019**, *251*, 113349. [CrossRef]
21. Tero, A.; Takagi, S.; Saigusa, T.; Ito, K.; Bebber, D.P.; Fricker, M.D.; Yumiki, K.; Kobayashi, R.; Nakagaki, T. Rules for Biologically Inspired Adaptive Network Design. *Science* **2010**, *327*, 439–442. [CrossRef] [PubMed]
22. Hao, X.; Falconer, R.; Bradley, D.; Crawford, J. FUNNet—A Novel Biologically-Inspired Routing Algorithm Based on Fungi: More efficient network management solutions. In Proceedings of the 2009 Second International Conference on Communication Theory, Reliability, and Quality of Service, Colmar, France, 20–25 July 2009; pp. 97–102. [CrossRef]
23. Snyder, P.L.; Greenstadt, R.; Valetto, G. Myconet: A Fungi-Inspired Model for Superpeer-Based Peer-to-Peer Overlay Topologies. In Proceedings of the 2009 Third IEEE International Conference on Self-Adaptive and Self-Organizing Systems, San Francisco, CA, USA, 14–18 September 2009; pp. 40–50.
24. Almassalkhi, M.; Brahma, S.; Nazir, N.; Ossareh, H.; Racherla, P.; Kundu, S.; Nandanoori, S.P.; Ramachandran, T.; Singhal, A.; Gayme, D.; et al. Hierarchical, Grid-Aware, and Economically Optimal Coordination of Distributed Energy Resources in Realistic Distribution Systems. *Energies* **2020**, *13*, 6399. [CrossRef] [PubMed]
25. Okwuibe, G.C.; Gazafroudi, A.S.; Hambridge, S.; Dietrich, C.; Trbovich, A.; Shafie-Khah, M.; Tzscheutschler, P.; Hamacher, T. Evaluation of Hierarchical, Multi-Agent, Community-Based, Local Energy Markets Based on Key Performance Indicators. *Energies* **2022**, *15*, 3575. [CrossRef]

26. Hu, J.; Yang, G.; Ziras, C.; Kok, K. Aggregator Operation in the Balancing Market Through Network-Constrained Transactive Energy. *IEEE Trans. Power Syst.* **2018**, *34*, 4071–4080. [CrossRef]
27. Hu, J.; Wu, J.; Ai, X.; Liu, N. Coordinated Energy Management of Prosumers in a Distribution System Considering Network Congestion. *IEEE Trans. Smart Grid* **2020**, *12*, 468–478. [CrossRef]
28. Guzman, C.P.; Arias, N.B.; Franco, J.F.; Rider, M.J.; Romero, R. Enhanced Coordination Strategy for an Aggregator of Distributed Energy Resources Participating in the Day-Ahead Reserve Market. *Energies* **2020**, *13*, 1965. [CrossRef]
29. Iria, J.; Coelho, A.; Soares, F. Network-secure bidding strategy for aggregators under uncertainty. *Sustain. Energy Grids Netw.* **2022**, *30*, 100666. [CrossRef]
30. Iria, J.; Soares, F. A cluster-based optimization approach to support the participation of an aggregator of a larger number of prosumers in the day-ahead energy market. *Electr. Power Syst. Res.* **2019**, *168*, 324–335. [CrossRef]
31. Ma, L.; Wang, L.; Liu, Z. Multi-level trading community formation and hybrid trading network construction in local energy market. *Appl. Energy* **2021**, *285*, 116399. [CrossRef]
32. Zade, M.; Lumpp, S.D.; Tzscheutschler, P.; Wagner, U. Satisfying user preferences in community-based local energy markets—Auction-based clearing approaches. *Appl. Energy* **2021**, *306*, 118004. [CrossRef]
33. Stekli, J.; Bai, L.; Cali, U.; Halden, U.; Dynge, M.F. Distributed energy resource participation in electricity markets: A review of approaches, modeling, and enabling information and communication technologies. *Energy Strat. Rev.* **2022**, *43*, 100940. [CrossRef]
34. Obi, M.; Slay, T.; Bass, R. Distributed energy resource aggregation using customer-owned equipment: A review of literature and standards. *Energy Rep.* **2020**, *6*, 2358–2369. [CrossRef]
35. Gould, Z.M.; Day, S.; Reichard, G.; Shealy, T.; Saad, W. A Transdisciplinary Blueprint for Energy Markets Modelled after Mycorrhizal Networks. *Transdiscipl. J. Eng. Sci.* **2023**, *14*, 125–140. [CrossRef]
36. Gazafroudi, A.S.; Okwuibe, G.C.; Hambridge, S.; Dietrich, C.; Trbovich, A.; Tzscheutschler, P.; Hamacher, T.; Shafie-khah, M. Mathematical Model for Agent-Based Local Energy Exchange Engine (D3A). In Proceedings of the 2021 International Conference on Smart Energy Systems and Technologies (SEST), Virtual, 6–8 September 2021; pp. 1–6.
37. Grid Singularity Github Grid Singularity. Available online: https://github.com/gridsingularity (accessed on 9 November 2021).
38. Grid Singularity Wiki Grid Singularity Wiki. Available online: https://gridsingularity.github.io/d3a/d3a-documentation/ (accessed on 9 November 2021).
39. Dobos, A.P. *PVWatts Version 5 Manual*; National Renewable Energy Laboratory: Golden, CO, USA, 2014.
40. Wilson, E. Open Energy Data Initiative (OEDI). Available online: https://data.openei.org/ (accessed on 10 November 2021).
41. Karpinski, M.; Kovalchuk, L.; Kochan, R.; Oliynykov, R.; Rodinko, M.; Wieclaw, L. Blockchain Technologies: Probability of Double-Spend Attack on a Proof-of-Stake Consensus. *Sensors* **2021**, *21*, 6408. [CrossRef]
42. Bachelot, B.; Lee, C.T. Dynamic preferential allocation to arbuscular mycorrhizal fungi explains fungal succession and coexistence. *Ecology* **2017**, *99*, 372–384. [CrossRef] [PubMed]
43. Wyatt, G.A.K.; Kiers, E.T.; Gardner, A.; West, S.A. A biological market analysis of the plant-mycorrhizal symbiosis. *Evolution* **2014**, *68*, 2603–2618. [CrossRef]
44. Brown, J.H.; Gillooly, J.F.; Allen, A.P.; Savage, V.M.; West, G.B. Toward a metabolic theory of ecology. *Ecology* **2004**, *85*, 1771–1789. [CrossRef]
45. Noë, R.; Kiers, E.T. Mycorrhizal Markets, Firms, and Co-ops. *Trends Ecol. Evol.* **2018**, *33*, 777–789. [CrossRef]