A Transdisciplinary Blueprint for Energy Markets Modelled after Mycorrhizal Networks

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Received 26 March, 2023; Revised 13 April, 2023; Accepted 13 April, 2023
Available online 13 April, 2023 at www.atlas-tjes.org, doi: 10.22545/2023/00226

Abstract:*The resource distribution strategies of trees and plants in the forest are applied here as inspiration for the development of a blueprint for transactive, hybrid solar and storage microgrids. We used the Biomimicry Institute's Biomimicry Spiral and their toolbox as a design methodology to inform the structural and functional characteristics of this peer-to-peer microgrid energy market and propose its utility in addressing some of the challenges associated with grid integration of distributed energy resources (DERs). We reviewed literature from the ecological domain on mycorrhizal networks and biological market theory to extract key insights into the possible structure and function of a transdisciplinary energy market modeled after the mutualism between trees and mycorrhizae. Our process revealed insights into how overlapping, virtual energy markets might grow, contract, adapt, and evolve through a dynamic network-based protocol to compete and survive in rapidly changing environments. We conclude with a discussion of the promise and limitations involved in translating the derived conceptual blueprints into a cyber-physical system and its potential for deployment in the real world as a novel energy market infrastructure.*

Keywords:Mycorrhizal Networks; Transactive Energy Networks; Bio-inspired Design; Ecological Modeling; Wholesale Energy Markets; Distributed Energy Resources; Distributed Ledgers.

1 Introduction

The distribution of energy generation through increased solar and storage installations presents utilities with the unique challenge of balancing an influx of less predictable power from a variety of locations on the grid. The U.S. government's Energy Information Agency, which oversees domestic energy-related information and statistics, forecasts over 100 gigawatts of residential solar distributed generation capacity in the U.S. alone by 2050 (Energy Information Agency, 2021). Industrial and commercial energy assets will only compound the challenge of managing this new production of energy at the edge of a distribution grid originally designed only to deliver energy generated from a distant centralized source. The Federal Energy Regulatory Commission (FERC) that regulates most of the electrical grid in the U.S. issued Order 2222 in September 2020 to mandate the inclusion of distributed energy resource (DER) aggregations of 100kW or more in wholesale energy markets (Cano, 2020). Various strategies for DER wholesale energy market integration have been proposed by the scientific community to improve cost and interoperability (Lezama et al., 2021), transparency and security (Khoshjahan et al., 2021), and market pricing and settlement (Wang et al., 2015), but residual challenges in reliability, telemetry and governance have delayed FERC Order 2222 compliance for several independent system operators (Trivedi et al., 2023).

Fortunately, nature has already optimized the management of DERs through hundreds of millions of years of evolution. In particular, trees and other plants in forest ecosystems have evolved to form mutualisms with mycorrhizal fungi and create vast networks capable of distributing resources in the form of energy, water, and other nutrients (Simard et al., 2012). According to a recent study, sixty percent of trees in global forests form these mutualistic relationships with ectomycorrhizal fungi that forage for limited nutrients in exchange for energy in the form of photosynthetic carbon (Steidinger et al., 2019). These forest energy networks have developed adaptive feedback and network building mechanisms that support small, vulnerable plants in the network while also building resilience to network disruption. For example, different organisms of different species of mycorrhizal networks can connect to a single tree, each specializing in a niche with respect to nutrient allocation and other characteristics (Sheldrake et al., 2018). This specialized redundancy translates well to the wholesale power systems domain where a given energy asset has an opportunity to participate in both real-time spot markets and capacity markets simultaneously. Furthermore, the generalist nature of some mycorrhizal species allows diversification of communities in response to seasonal changes in the environment (Davison et al., 2011) suggesting that virtual DER aggregations may also benefit from the ability to dynamically adapt to change by shifting energy allocations to various partners over time.

Recent breakthroughs in ecological science have begun to reveal essential structure and function of mycorrhizal networks through analytical and experimental methods. Groundbreaking research by Simard and colleagues has experimentally documented the exchange of radioactive carbon isotypes between trees connected by mycorrhizae (Simard et al., 1997). The network structure of this “wood-wide web” was first sampled experimentally, mapped, and modeled by Beiler et al. through genotype analysis of root cores from a douglas-fir forest. They identified a highly interconnected, small-world typology in which any node could be reached from any other node with relative ease (Beiler et al., 2009). The nested structure of these mycorrhizal connections with specialist fungi overlapping on the roots of the same tree as generalist fungi was further revealed using mathematical graphs and ecological network theory (Montesinos-Navarro et al., 2012). Though some mycorrhizal species such as Rhizopogon vesiculosus are obligate to only one tree species (douglas-fir), others form mutualisms with vast arrays of different plants and trees (Massicotte et al., 1994). Researchers have mathematically modeled fungal growth patterns based on biomass recycling for mycelia in general and mycorrhizal fungi specifically (Schnepf et al. 2008). Lessons from these studies have already informed other explorations in wireless communication (Hao et al,. 2009) and P2P overlays (Snyder et al., 2009).

Previous work in transdisciplinarity has attempted to better understand the complexities of large interconnected systems by drawing expertise from similar systems in different domains. Biomimicry has been presented as an opportunity to address complex problems through the integration of diverse biological perspectives and knowledge bases and recommended the same bio-inspired design process utilized here (McGregor, 2013). Another transdisciplinary effort utilized community participatory methods to better inform complex energy models when introducing decentralized renewable energy generators into indigenous lands in Canada (Codrington et al., 2022). A transdisciplinary lens applied to urban mega-projects revealed that governance models, not digital tools themselves, will ultimately dictate the success of sustainable smart cities and that the complexity of urban centers cannot be understood in traditional hierarchies (Santamaría, 2020). Similar lessons apply to the current work, where digital tools such as distributed ledgers can automate decentralized governance of DER aggregators that allows easier accounting of energy transactions between buildings regardless of their size and location within a distribution network.

The current transdisciplinary approach combines the benefits of biomimicry with the complexity of modeling large-scale energy systems to define a path toward distributed, decarbonized energy markets in the era of climate change and decentralized computing. This work draws from diverse methods in the disciplines of design, ecology, and electrical and computer engineering: a bio-inspired design process is employed to convert scientific findings from the ecological literature into insights for improved electrical distribution in future evolutions of the smart grid. The authors believe this article is significant because it translates functional and structural lessons from highly evolved ecological systems into a language compatible with the energy domain. Specifically, the blueprint proposed here facilitates constant rebalancing of energy assets within a community through a novel transactive network architecture informed by the structure of mycorrhizal networks in forest ecosystems.

2 Methodology

This research followed the Biomimicry Spiral Method. There were six essential stages in this method, with a seventh fundamental stage for repetition towards improvement. The seven stages were Define, Biologize, Discover, Abstract, Emulate, Evaluate, and Iterate. The Define stage defined the problem set and the scope of the problem. In the Biologize stage the problem was translated into biological terms. The Discover stage required the investigator to identify similar problems and their respective solutions in nature. The Abstract stage breaks down biological and ecological strategies into more generalizable functions and structures. The Emulate stage applies these general functions and structures back to the problem using design and engineering practices. The Evaluate stage used the Nature's Unifying Patterns checklist from the Biomimicry Institute as criteria for the evaluation of the solution's ecological effectiveness. Lastly, the Iterate stage allowed the team to respond to shortcomings of initial ideas and improve the process through repetition until the solution adequately met the needs of all stakeholders in the project.

3 Results

Outcomes of each stage of the Biomimicry Spiral Method are presented below followed by a breakdown of the structural and functional blueprints inspired by the design process.

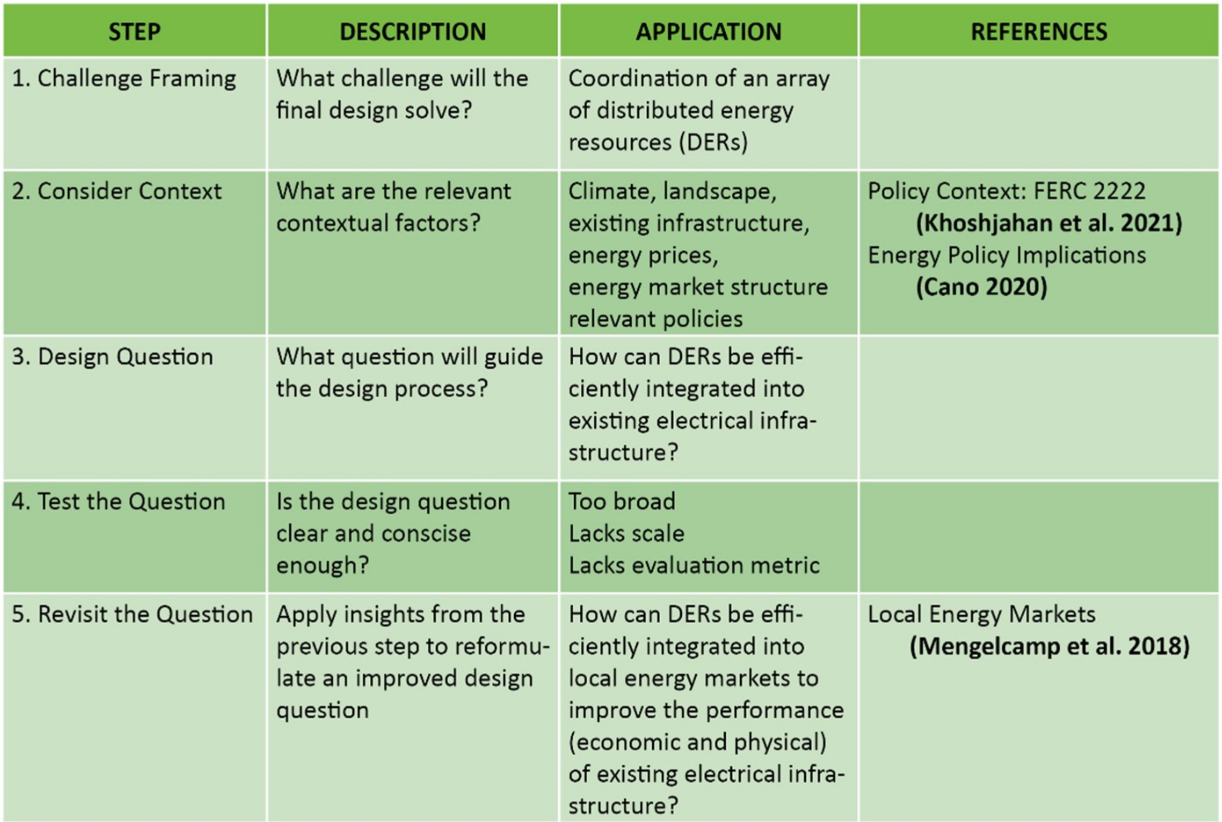
3.1 Design Process Outcomes

3.1.1 Define

The *Define* stage included framing the challenge by considering the context, designing the question as a hypothesis, and then testing the question for scope and scale. This initial phase encouraged iteration - especially in specifying and re-defining the design question, which went on to direct the remainder of the design process. The steps of the Define stage process are displayed in further detail in Figure 1.

3.1.2 Biologize

The *Biologize* stage included identifying biologically relevant functions corresponding to the Define stage question, and then identifying relevant contextual factors to place the design challenge in context. The Biologize stage was the first step in mapping the problem from an engineering space to an ecological space. The relevant biological functions were derived using terms from the biomimicry taxonomy (Biomimicry Institute, 2008b) as shown in Figure 2.



STEP	DESCRIPTION	APPLICATION	REFERENCES
1. Challenge Framing	What challenge will the final design solve?	Coordination of an array of distributed energy resources (DERs)	
2. Consider Context	What are the relevant contextual factors?	Climate, landscape, existing infrastructure, energy prices, energy market structure relevant policies	Policy Context: FERC 2222 **(Khoshjahan et al. 2021)** Energy Policy Implications **(Cano 2020)**
3. Design Question	What question will guide the design process?	How can DERs be efficiently integrated into existing electrical infrastructure?	
4. Test the Question	Is the design question clear and consise enough?	Too broad Lacks scale Lacks evaluation metric	
5. Revisit the Question	Apply insights from the previous step to reformulate an improved design question	How can DERs be efficiently integrated into local energy markets to improve the performance (economic and physical) of existing electrical infrastructure?	Local Energy Markets **(Mengelcamp et al. 2018)**

Figure 1: *Define stage process.*

The five steps of the Define stage are listed with descriptions of what each step elicited from the design team. Applications of each step demonstrate the authors' attempt to apply the step to challenges in distributed energy coordination. References particularly relevant to steps two and five are included at the right.

The following contextual factors were derived by combining the biological functions identified in Figure 23 into biological phenomena relevant to the operational context of the target energy market design. These include 1.) fluctuations of resource availability (i.e., sun, water, and nutrients), 2.) diminishing instances of (bio)diversity within communities, and 3.) variation in the (in)ability of certain plants to photosynthesize their own energy supply (i.e., autotropism vs mycotropism). Relevant biological functions and contextual factors were then synthesized to form the following 'biologized' question: *How does nature distribute resources across communities?*

3.1.3 Discover

The *Discover* stage revealed biological phenomena relevant to the biologized question derived above. The Biomimicry Institute's AskNature database was used to keyword search through more than 1700 distinct profiles of biological strategies that are known to address specific challenges in nature (Biomimicry Institute, 2008a). The database results also included precedent pages of innovations that have already applied nature-based solutions to challenges in human industries. The biologized question above was input into the AskNature database and the top three biological strategies search results were recorded and investigated as shown in the leftmost column of Figure 3.

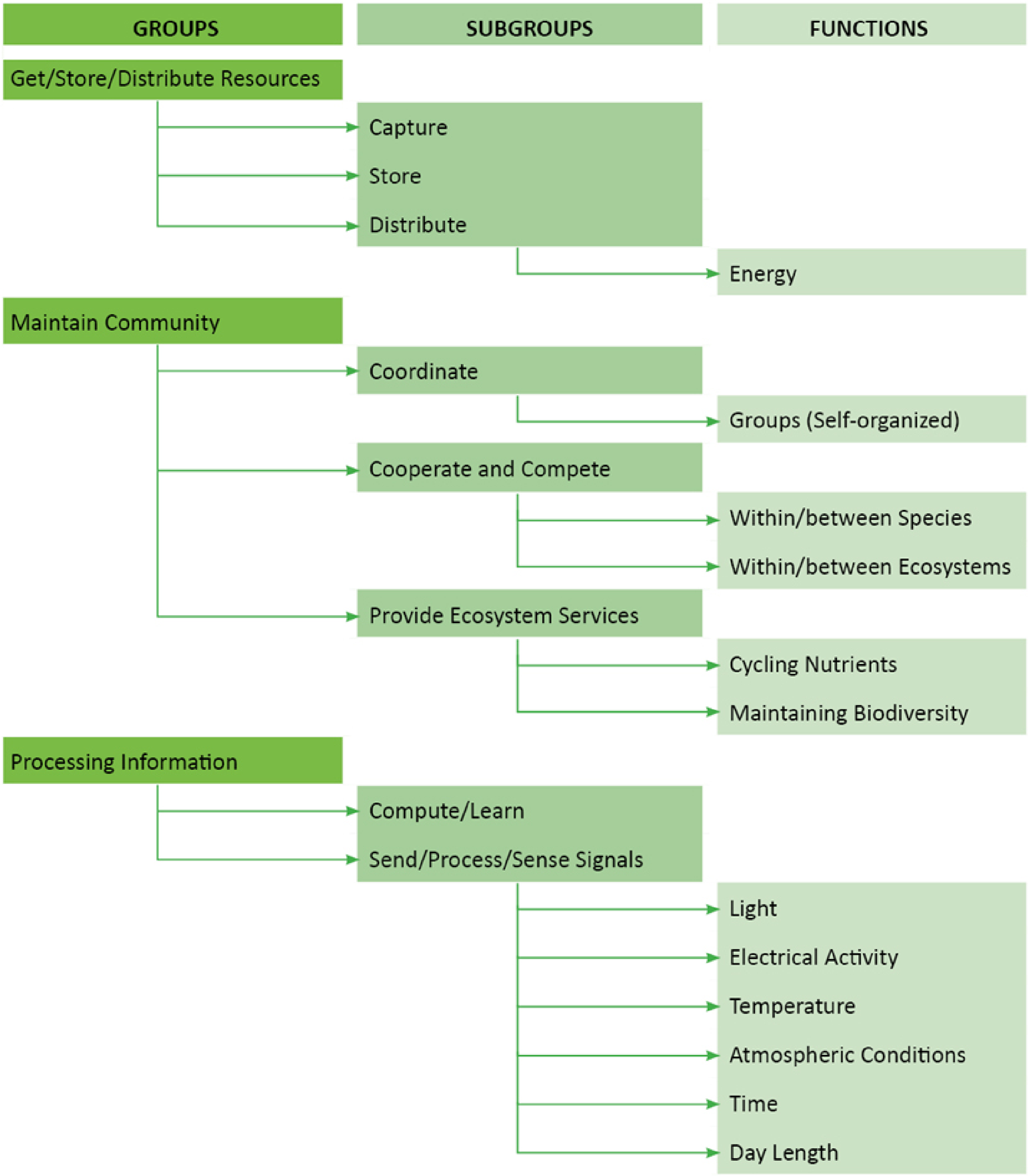


Figure 2: *Biologize function derivation.*

The Biomimicry Taxonomy from the Biomimicry Institute's Toolbox (toolbox.biomimicry.org) identifies biological elements for the Biologize stage where the design question is converted into biological terms.

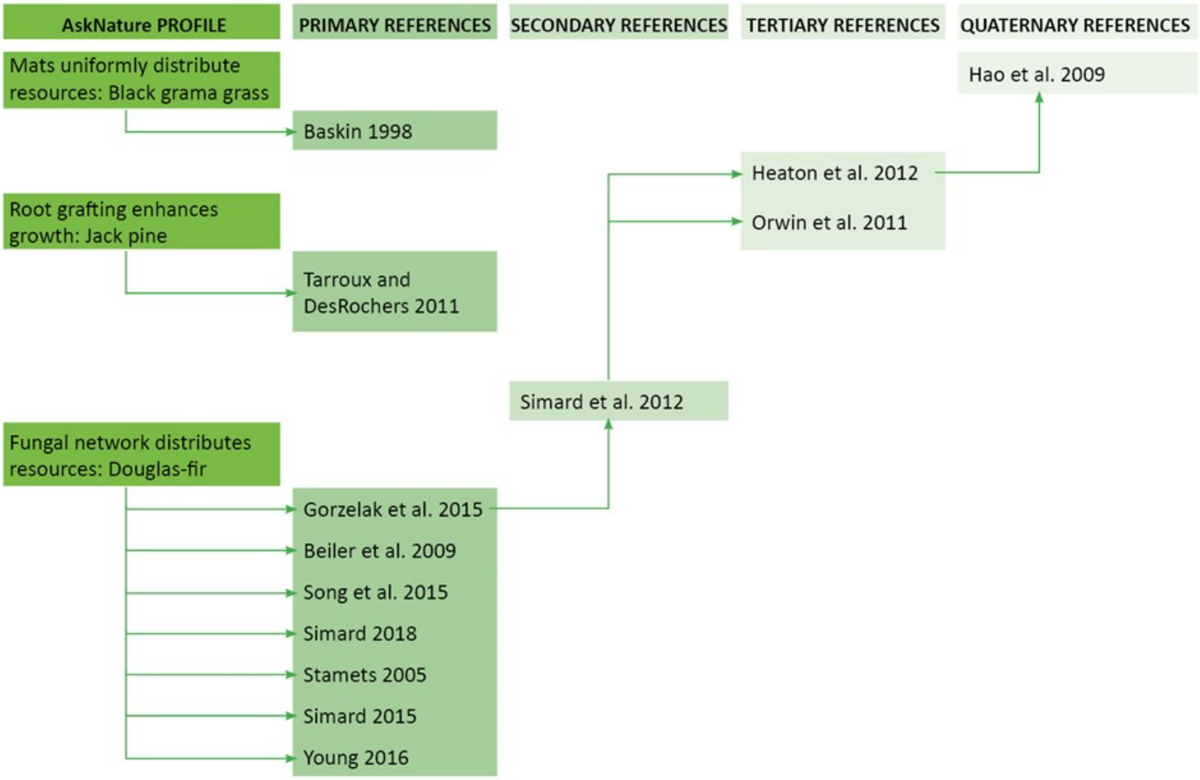


Figure 3: *Discover phase literature cascade.*

Preliminary links from AskNature along with referenced literature from the articles and additional articles relevant to the design process discovered through citation mining.

The wealth of strategies, potential applications, and resource citations associated with the AskNature profile for fungal mycorrhizal networks in forest ecosystems was an indicator to focus on this biological strategy for the remainder of the Bio-inspired design process. Grass rhizome matting and pine grafting behaviors, while relevant as supplemental strategies to inform the design solution, did not closely match our biologized question with respect to distinct, distributed generators and thus were not selected as the primary focus for the remainder of the biomimicry design process.

3.1.4 Abstract

The Abstract stage entailed high level abstraction of the identified biological strategies and their placement in a larger systems context. The foundational abstraction was the identification of the trees or plants as distributed generators of energy on an electrical grid. The larger context encompassed the dynamics of the surrounding forest ecosystem and especially in the transaction of energy between autotrophic organisms through shared roots, direct grafting, or fungal mycorrhizal networks. The authors employed the Systems Explorer worksheet, a tool provided by the Biomimicry Institute, to help develop the context for these initial abstractions and identify design leverage points for the proposed engineering solution as shown in Figure 4.

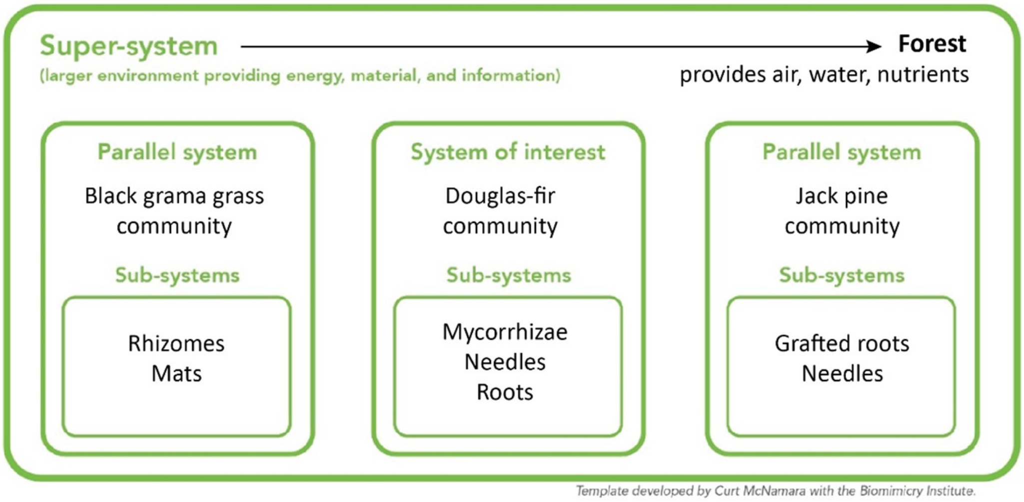


Figure 4: *Systems explorer worksheet – forest overview.*

Mapping possible solutions defines the interaction of elements at various scales (super system and parallel systems) with the goal of identifying and focusing on the most relevant, specific sub-systems.

After breaking down the forest super-system into smaller scales, the parallel systems in Figure 4 emerged to represent different building typologies. When a root is grafted to another root it forms a connection between two trees similar to the way individual buildings are connected by a utility service. A utility hook-up allows the exchange of energy between buildings physically through hard-wired connections such as electrical conduit. When grass or other rhizomatic species distribute energy as a single organism it is analogous to multi-family tenants sharing the power generated by a shared rooftop solar array. When mycorrhizal fungi act as an intermediary for resource exchange, it is analogous to the virtual management of transactions between households on a shared distribution bus without the need for direct connections (and the investment of capital in distribution lines) between every household.

Figure 5 documents the continuation of the Systems Explorer process by zooming in on the hyphal linkages between members of the Douglas-fir community and their connected mycorrhizal organisms as a critical sub-system of interest. This shift in focus revealed the mycorrhizal network as an important intermediary between fungal and tree communities.

3.1.5 Emulate

The *Emulate* stage entailed the detailed mapping of elements from the identified biological system of interest to the target domain, in the current case electrical infrastructure for the management of distributed energy generation. Gaining fluency in this translation between domains can help solve problems in the infrastructural domain by fostering a deeper understanding of the dynamic relationship between elements in the biological domain. The outcome of the Emulation stage was a translation of major components from Beiler et al. 2009 from the biological domain of forest ecology and mycorrhizal networks to the electrical infrastructure domain of distributed energy resources, as shown in Figure 6. Of particular interest to the proposed mycorrhizal energy market design are the biological elements of *Douglas-fir cohorts* which dictate categories of buildings and energy assets to include as part of the distribution network and *Hyphal linkages* which are the site of adaptation for the network where connections between different households and energy markets can change over time.

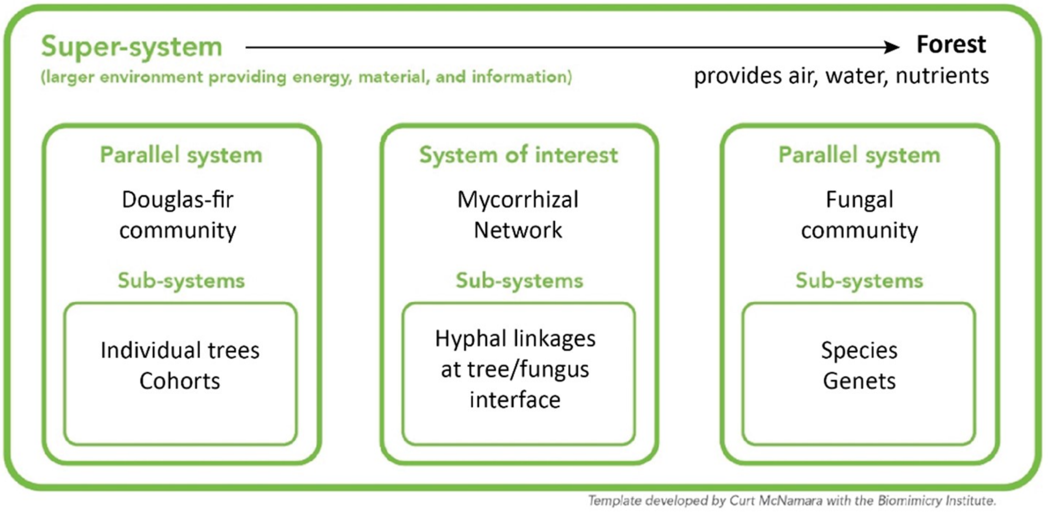
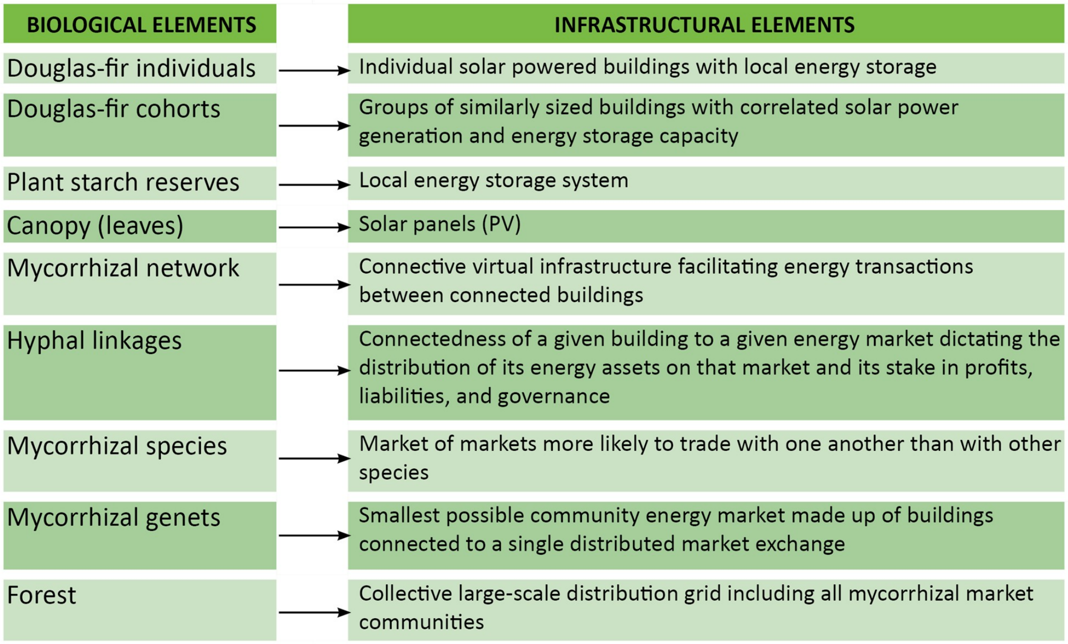


Figure 5: *Systems explorer worksheet – sub-system ID.*

Mapping possible solutions defines the interaction of elements at various scales (super system and parallel systems) with the goal of identifying and focusing on the most relevant, specific sub-systems.



BIOLOGICAL ELEMENTS		INFRASTRUCTURAL ELEMENTS
Douglas-fir individuals	→	Individual solar powered buildings with local energy storage
Douglas-fir cohorts	→	Groups of similarly sized buildings with correlated solar power generation and energy storage capacity
Plant starch reserves	→	Local energy storage system
Canopy (leaves)	→	Solar panels (PV)
Mycorrhizal network	→	Connective virtual infrastructure facilitating energy transactions between connected buildings
Hyphal linkages	→	Connectedness of a given building to a given energy market dictating the distribution of its energy assets on that market and its stake in profits, liabilities, and governance
Mycorrhizal species	→	Market of markets more likely to trade with one another than with other species
Mycorrhizal genets	→	Smallest possible community energy market made up of buildings connected to a single distributed market exchange
Forest	→	Collective large-scale distribution grid including all mycorrhizal market communities

Figure 6: *Mycorrhizal energy mapping across domains.*

Biological elements from mycorrhizal resource distribution in nature are mapped to infrastructural elements related to distributed energy resource coordination.

3.1.6 Evaluate

The *Evaluate* stage entails using a checklist of Nature's Unifying Patterns from the Biomimicry Institute's biomimicry toolbox to determine how well the proposed solution mimics the fundamental structure and function of natural systems. The ten unifying patterns are laid out below and a brief discussion of the proposed solution is evaluated using these laws as criteria. A link to the full check sheet that was utilized with breakdowns of applied criteria can be found in the references section (Biomimicry Institute, 2017). There are 48 sub-categories distributed amongst the following patterns that are used in scoring each solution. The best possible score of 48 out of 48 reflects a system fully aligned with nature's unifying patterns, while lower scores reflect solutions less attuned to the fundamental characteristics of biological and ecological systems. There is no minimum score, however, scores lower than 48 represent an opportunity for further iteration. Not all criteria are relevant for every biomimetic design project.

3.1.7 Iterate

The *Iterate* stage involves the repetition of the Biomimicry Spiral processes to center in on an ideal solution for the problem at hand. While the first iteration may bring some important insights and partial solutions, only iteration paired with feedback and testing can determine if the solution adequately addresses the stated challenge. The iterations performed in this research yielded several different functional and structural blueprints for a bio-inspired energy market. The analyses presented above in the *Emulation* stage reflect the elements of the third and final iteration through the biomimicry spiral process. This final concept for a virtual transactive energy market informed by mycorrhizal networks received a score of 45/48. The two other earlier concepts using black grama grass mats and grafted Jack pine roots received scores of 38/48 and 40/48, respectively.

3.2 Structural Blueprint

Structurally, the network derives its organization including the type of participant nodes and their connections to one another directly from Beiler et al 2009's documentation of the network structure of a network of ectomycorrhizal Rhizopogon fungi and their Douglas-fir carbon trading partners. Specifically, cohort size determines the size of each building corresponding to a tree and the size of its associated energy assets. The nature of trees as photosynthesizing, metabolizing autotrophs led to the inclusion of a solar array on each household (tree) and a correlated load profile. Each household and each mycorrhizal energy market has a battery representing the capacity of all trees and fungi to store energy in various forms within their biomass. The energy markets, represented by distinct genets of Rhizopogon mycorrhizae in Beiler et al. 2009, are overlapping and can interact with the same households simultaneously by interacting with digital twins of the household and subdividing resources according to the number of relative linkages between household and market (how connected one household is to a given market compared to another household).

3.2.1 Graph Theoretic Structural Mapping

Starting with the mother tree, the proposed market structure is depicted with weighted, directed graphs as shown in Figure 7. The identified mother tree is displayed in the center (non-bold circle, Tree-23). Weighted graphs with numbered edges demonstrate the number of linkages each tree has to a given mycorrhizal market, and directional graphs can demonstrate if a given tree is autotrophic (with energy generation and the capacity to provide liquidity to the market) or mycotrophic (capable of consumption only with no energy generation capacity). In this case, the constituent buildings participating on the market are assumed to be autotrophic to accurately represent photosynthesizing douglas-firs. The network is bipartite because tree nodes can only be connected directly to fungi nodes, and vice versa. The nodes highlighted in green correspond to those selected as part of the simplified mycorrhizal energy market network displayed in Figure 8.

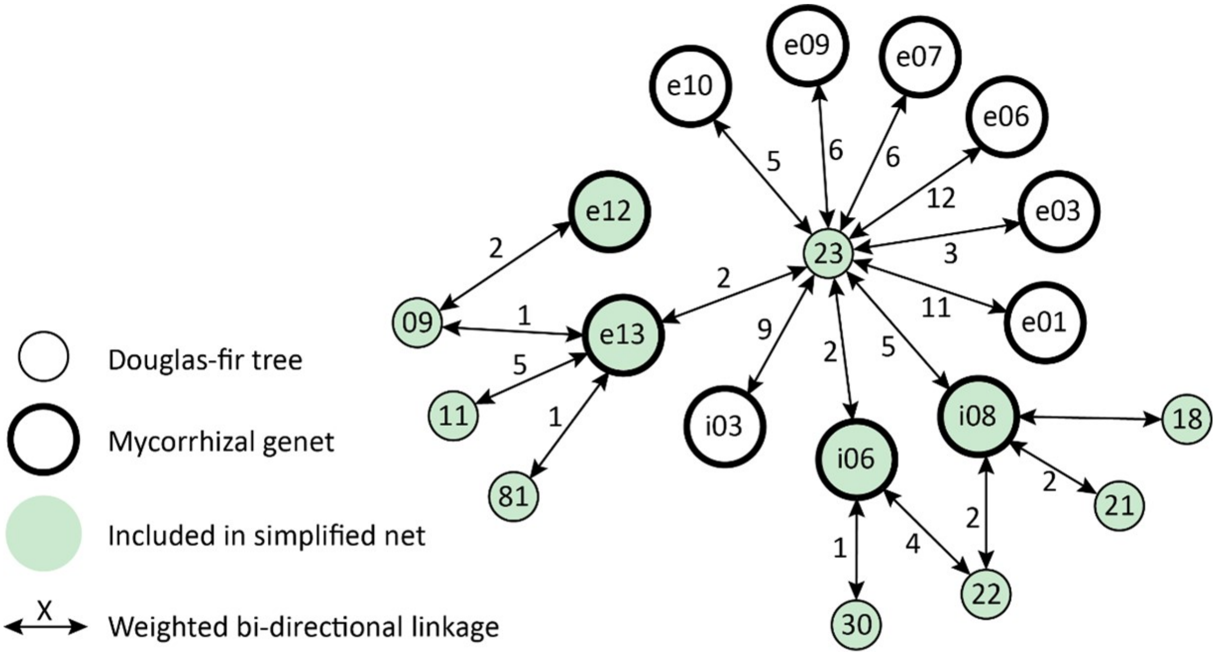


Figure 7: *Graph-theoretic mycorrhizal network structure.*

The weights on each arrow represent the number of linkages between a given tree and a corresponding fungal genet. The letter 'e' represents genets from the Rhizopogon vesiculosis species and the letter 'i' represents genets from the Rhizopogon vinicolor species.

3.2.2 Simplified Structural Overview

A subset of the network mapped by Beiler et al. 2009 was selected for further analysis. As shown in Figure 8, two of the *Rhizopogon vesiculosus* genets and two of the *Rhizopogon vinicolor* genets were included for a total of four mycorrhizal markets. These markets connect to eight different douglas fir trees from three out of four of the cohorts identified in the 2009 study. The most centrally connected tree, number 23, is shown at the center of the figure with different numbers of linkages to each of the four displayed markets. There is a maximum of five linkages shown between Tree-23 and the *Rhizopogon vinicolor* genet number eight (ViN-08). The number of linkages is shown across all the displayed trees and mycorrhizae by fungal black lines intersecting the black outline of tree bark. Cohort size correlates to size of the tree cross-sections depicted in the figure as shown in the key. Each tree represents a household participating in the network that has its own solar array, battery storage, and load profile – all correlated in size to each tree's cohort.

3.3 Functional Blueprint

The main functional innovation is the use of linkages a given house has to a given mycorrhizal market. This is executed through the cloning of houses connected to multiple markets simultaneously and the dynamic addition and removal of hyphal linkages that strengthen a given node's connection (and therefore trading capacity and voting/rewards stake) with respect to the rest of the network. The mycorrhizal analogy brings the lifeless ledger of an energy marketplace to life by incentivizing the connective infrastructure itself to grow and adapt to its environment if there is enough energy reserved in the collective capacity of the network. Nodes that are not helping the mycorrhizal market to thrive can be dropped, and those that produce power at the right times and demonstrate flexibility in their loads can be reinforced and rewarded. Similar to the behavior of organisms in a colony, the constituents of the market can decide to change their

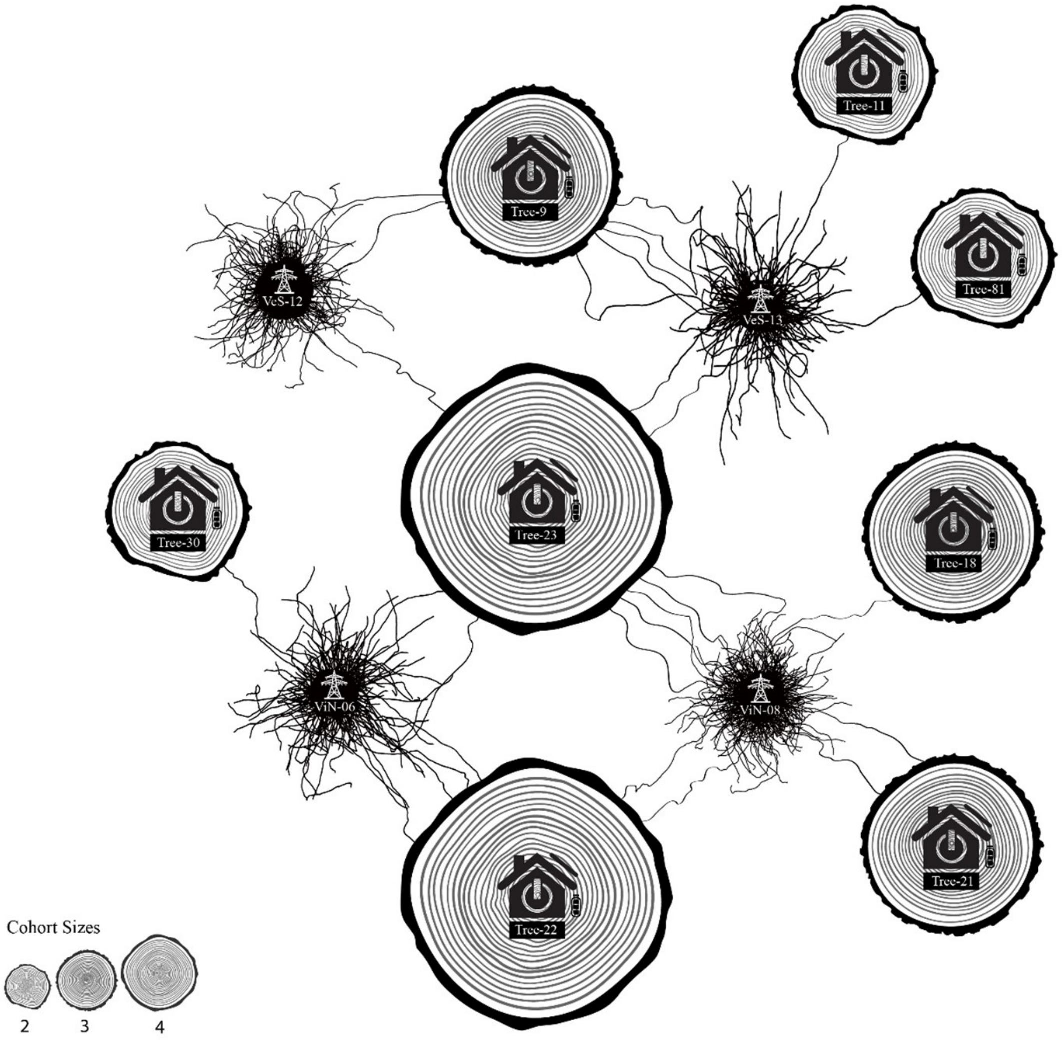


Figure 8: *Mycorrhizal energy market network structure.*

The second, third, and forth cohorts from Beiler et al. 2009's wood-wide web study are depicted by different sized tree round cross-sections shown in the key. Each cohort corresponds to a group of smaller (cohort two), medium (cohort three) and larger (cohort four) buildings with proportionally sized solar panels and load profiles.

strategies in response to certain environmental stimuli (such as extreme weather or malicious attacks) and the behavior of the network as a whole can change and improve over time.

3.3.1 Scaled Digital Twins

To translate the simplified network structure from Figure 8 in a typically hierarchical distribution grid, it is necessary to create scaled digital twins, or virtual clones of each household with a portion of their energy assets allocated to each connected market. In other words, if a household participates in two markets, there are two digital twins of that household, one on each market. The size of the energy assets on each digital twin correspond to the number of linkages connecting the household to a given market and the total number of household linkages. For example, the household represented by Tree 9 in the figure above has two of its seven linkages connected to market VeS-12 and five of its seven linkages connected to market VeS-13. The digital twin of household Tree 9 on VeS-12 would therefore have 2/7 of its PV capacity, 2/7 of its load profile, and 2/7 of its battery storage capacity whereas the digital twin of the same household on market VeS-13 would have 5/7 of the capacities and profiles of the same three energy assets. Initial asset size is determined by cohort- the PV capacity, battery capacity, and load profile of cohort two is smaller than the same assets on cohort three, and so on.

3.3.2 Linkage-based Learning

The following elements of the functional blueprint are initial steps toward the formulation of a reinforcement learning (RL) strategy. Action spaces and exploration/exploitation policies are fundamental parts of the Markov decision processes (MDPs) that drive RL approaches. In the proposed model, the hyphal linkages at the interface between fungus and tree communities are the actuators that carry out steps determined by the linkage action metric (the addition, removal, or replacement of linkages) and the linkage assignment policy (which linkages get added, removed, or replaced). Possible drivers of the action metric include various metrics related to the overall state of charge of all energy storage systems connected to a given mycorrhizal energy market. The assignment policy can be governed by any combination of key performance indicators including environmental (weather, power systems status) or economic (pricing, revenue generation) signals.

4 Discussion

4.1 Design Process

Hyphal linkages that are both redundant and responsive are the essential component that brings this mycorrhizal market model to life, and the bio-inspired design process was essential in identifying and solidifying the role of linkages and cohorts as critical elements of the proposed strategy. The authors found significant value in the Biomimicry Institute's design methodology. Their toolbox forces the user to investigate the biological inspiration deeply to reveal root functions and then provides a wealth of relevant resources to help designers break down these functions and apply them to new domains. In the case of the current work, the AskNature profile for mycorrhizal fungi guided the design team to Beiler et al. 2009's wood-wide web where the graphical structure of a real mycorrhizal network revealed the linkage redundancy inherent in ecological energy systems that directly informed the remainder of the energy market blueprint development.

Though the NUP evaluation process was effective at determining how well aligned a bio-inspired is with fundamental characteristics of nature, it was not necessarily effective at evaluating the accuracy of applying a specific biological or ecological analogy nor determining the functionality of a solution in addressing a physical problem in the engineering domain. In order to improve upon this iterative process, a panel of experts from all relevant domains (i.e., mycorrhizal networks, forest ecology, distributed electrical infrastructure, and wholesale energy market economics in the final design case) is recommended for future studies. This would allow for specific feedback on how well a design element mimics the target mechanism in nature and how well the physical outcome of the design problem would help solve the existing problem in engineering and economic realms. In the case of the proposed design, a quantitative simulation catered to specific performance metrics is an essential element of the evaluation and iteration process when many physical prototypes are not technically or economically feasible.

4.2 Blueprints

There are some limitations in existing market structure that make it extremely challenging to implement the proposed innovations. A functional multi-agent framework must be adopted by not only households but also energy system operators for the mycorrhizal energy marketplace to work. The current hierarchical market model where buildings only trade with buildings, communities only trade with communities, and grids only trade with grids (in increasing orders of magnitude) is not sufficient to implement the proposed strategy at scale. To accurately recreate the overlapping ecological structure of mycorrhizal networks, each building must be able to connect with multiple genet markets simultaneously, something that current grid structures and energy market policies do not facilitate.

To continue serving its members and its purpose in providing a more resilient and reliable distributed electrical infrastructure, the proposed model must learn and continue to evolve in the face of constant changes in regulatory policies and technological trends. Similar to the way in which renewables such as solar have the potential for zero marginal cost in producing their next unit of energy (no fuel and minimal routine maintenance), virtual market redundancy allows for multiple energy trading pathways without the capital cost of additional distribution lines. This inexpensive method for virtual fault tolerance in energy markets lies in accordance with the ecological principal of ecosystem robustness, which measures the ability of an ecosystem to survive in the midst of disturbances and corresponds to the strength of a network (Panyam et al., 2019). There is a window of vitality where robustness remains high despite lower degrees of system order (redundancy in the number of connections between nodes in the network). It is much easier to create networks within this window of vitality when households can effectively trade and balance energy locally without investing in additional physical infrastructure.

5 Conclusion

There are several key characteristics identified here that make the proposed blueprint different than existing solutions in energy markets. First, the proposed mycorrhizal market design infuses the “will to survive” within an electricity market mechanism by updating linkages only when the fungal element has enough collective storage—a major departure from current energy market structures that focus on optimization from pure power systems points of view. Secondly, the dynamic linkages make it possible to gradually shift trading partners over time rather than abruptly starting or stopping trade, a strategy that becomes especially promising when more that one distributed energy resource aggregation is operating within the same distribution network. This gradual shifting reflects more of a fuzzy transition between trading partners that can balance supply and demand locally with more precision and prevent abrupt disruptions in energy flows. Lastly, the cohort-based characteristics reveal a key insight into the necessary coding for the incorporation of many diverse types of prosumers into the future energy grid. Residential and commercial loads can typically complement one another because of coordinated work schedules and business hours. Depending on manufacturing demands and flexibility, industrial loads can be manipulated to ramp up and down in response to grid need as is already common in current demand response pricing policies.

The further study of mycorrhizal networks can provide additional insight to improve future implementation of this mycorrhizal energy market model. New methods for linkage creation and destruction that dictate the more intelligent growth and evolution of the mycorrhizal market structure and function over time could be discovered by applying mycorrhizal structure and function to bio-inspired computing techniques in evolutionary multi-objective optimization and population-based metaheuristics. A better understanding of resource fluxes in mycorrhizal carbon trading and the specific biochemical awareness of participating organisms could help inform manageable reinforcement learning in an improved reinforcement learning policy. Ultimately the robustness of these techniques must be tested through additional comparative case studies including weather events induced by climate change, cyber-attacks, and the radical diversification of DER participants in the network.

Authors Contribution: Zachary Gould was responsible for conceptualization, copy writing, and production of graphics. Susan Day was the main copy editor and introduced critical ecological perspectives into the iterative design process. All other authors contributed scientific expertise to inform the design process and reviewed and edited the manuscript.

Funding: W. Saad was supported by the U.S. National Science Foundation [CNS-2025377].

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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