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The implementation of energy sharing using a system of systems approach

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THE IMPLEMENTATION OF ENERGY SHARING USING A SYSTEM OF SYSTEMS APPROACH

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ABSTRACT

There is an increasing demand for renewable energy and consumers need more procurement options to meet their needs. Energy sharing provides a peer-to-peer (P2P) marketplace where prosumer electricity is redistributed to fellow energy-sharing community participants. This redistribution of prosumer electricity provides consumers with additional electricity suppliers, while also decreasing the load on the utility company. Though significant progress has been made regarding research and implementation of energy sharing, there is still room for growth when evaluating energy-sharing communities and defining appropriate community coordination based on end-user needs. The first contribution in this work identified nine characteristics of energy-sharing communities as a decentralized complex adaptive system of systems (DCASoS). Considering each characteristic before determining community coordination is vital to ensure ample participation within the energy-sharing community. The second contribution was the exploration of a two-stage stochastic programming model as an alternative to the classic energy distribution business model. The third contribution compares three behavioral theories to identify the best fitting model to predict interest in participating in an energy-sharing community. This research provides companies with foundational knowledge to develop an energy-sharing community that both fulfills end-user satisfaction and increases robustness of electricity distribution business models.

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1. INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

Companies are adapting decentralized business models to provide consumers with an alternative marketplace that is conducted in a peer-to-peer manner. A decentralized coordination in the energy sector gives end-users the ability to transfer electricity between energy-sharing participants, including the utility company. The traditional electricity distribution infrastructures use a hierarchical coordination, which practices a top-down distribution method. Decentralized coordination increases connectivity between energy-sharing participants. This increased connectivity provides energy-sharing participants with additional electricity suppliers. Expanding connectivity to include networks between end-users allows for higher autonomy and creates the opportunity for alternative coordination methods. A sharing economy depends on the exchange of goods and services between individuals and organizations being more efficient and effective than traditional business models . Through energy sharing, excess electricity will be redistributed within the energy-sharing community, which decreases direct expenses incurred by the utility company (Botsman & Rogers, 2011).

End-users that have chosen to invest in a distributed generation unit (DGU) are referred to as prosumers. Prosumers have the ability to both consume and produce electricity. The increase in prosumer population encourages utility companies to reevaluate the current electricity distribution processes and pricing models. Decentralized electricity distribution processes and pricing models account for the additional suppliers of electricity, which directly impact the amount of electricity purchased by utility companies from outside sources. Sharing energy provides an additional option for prosumers and utility companies to combat overgeneration in addition to storage, selling back to the grid, or curtailment (Fleischhacker, 2019; Wiser, 2005; Bird, 2014) . These additional transactions address the demand for renewable energy while providing prosumers with an additional source of income.

A transactive energy system yields a transactive energy management system, and the ability to redistribute excess DGU electricity within the sharing neighborhood or between connected neighborhoods. Transactive energy systems rely on DGU predictions to accurately estimate electricity quantity necessary to purchase from large-scale electricity providers. Transactive energy management systems predict prosumer production and do not accept excess DGU electricity that exceeds the predicted values (Brown, 2017). This limits the management systems' abilities to adapt in the face of DGU production uncertainty. Utility companies can purchase electricity from large-scale electricity producers at either retail or wholesale price. Accurately predicting the amount of DGU electricity allows the utility company to purchase more of the necessary electricity supply at wholesale price.

Before selecting the large-scale electricity source to purchase, a list of community pre-approved suppliers were evaluated by a group of community representatives. The group of representatives consists of residents within the cooperative sharing community, and they must choose the large-scale electricity supplier that most closely follows the community's values. For example, a cooperative community may value environmental friendliness, which would encourage the community representatives to choose the large-scale renewable energy generation as the electricity source. In this scenario, the utility company is an intermediary because utility infrastructure is used to distribute electricity to end-users.

The decision to incorporate a management system is made based on the unique needs of the energy-sharing community. However, many end-users within a decentralized system incorporate home energy management systems to regulate supply, demand, and, in certain cases, controllable and uncontrollable loads. Sharing would be available to all end-users that choose to participate in the energy-sharing community. Some end-users may not choose to participate in energy sharing because the benefits may not outweigh the cost.

1.2. RESEARCH OBJECTIVES AND CONTRIBUTION

This dissertation aimed to identify aspects of consideration from a systems engineering perspective to successfully implement energy sharing in the current energy distribution infrastructure. To successfully integrate energy sharing into the current energy infrastructure, characteristics, optimization, and behavioral theories were applied.

Publication 1: Nine characteristics of energy-sharing communities were identified and used to describe the community as a decentralized complex adaptive system of systems. The initial five characteristics, developed by Boardman and Sauser (2006), autonomy, belonging, connectivity, diversity, and emergence, provided the foundational knowledge of system of systems. This research provided the basic terms used to qualitatively analyze energy-sharing communities as system of systems.

Publication 2: Coordination of independent energy-sharing communities was decentralized. However, energy-sharing communities can be classified as either non-cooperative or cooperative. Using two-stage stochastic programming considering uncertainty, electricity distribution can be optimized. Cooperative energy-sharing communities consider additional variables because of the connectivity options between communities that help maintain consumer electricity demands. This approach is beneficial to future optimization of energy-sharing communities because of the acknowledgment of intermittence for renewable energy resources.

Publication 3: A literature and current existing project review was conducted by identifying subsections directly related to energy sharing. The conducted literature review defined five main categories: (1) decentralized coordination, (2) energy management systems, (3) energy management optimization, (4) energy storage systems, and (5) microgrid. To further understand and better explain the individual concepts of the subsections, each was further segmented into more detailed sections. The review of existing energy-sharing projects revealed that there are energy-sharing pilot projects world-wide. Though there is a wide geographic range of energy-sharing communities, every project was meant to decrease the energy burden on the residential users. This research provided foundational knowledge for better understanding necessary for the development of energy sharing.

Publication 4: Value-belief-norm, diffusion of innovation, and theory of planned behavior were compared as potential behavioral theories to predict consumer adoption of energy sharing. Understanding what factors are likely to influence consumer adoption can inform the design and marketing of energy-sharing communities to increase the robustness of electricity distribution business models. From a systems perspective, the behavior of the system is heavily influenced by consumer engagement and behavior, so it is valuable to characterize the key features of the human side of the system as well as the technical side of the system.

Using a system of systems approach, necessary agents and interfaces between agents are identified to ensure successful implementation of energy sharing. Characteristics used to understand qualitative aspects of energy-sharing communities are identified and used to explain energy-sharing community coordinations. A thorough literature review and existing energy sharing project review provides the foundational knowledge to understand how energy sharing has previously been studied and implemented. However, this analysis also revealed the research gap explaining consumer participation in energy sharing. By understanding consumer actions, an energy-sharing facilitator can market energy sharing to encourage participation in an energy-sharing community.

PAPER

I. ENERGY SHARING COMMUNITY AS A DECENTRALIZED COMPLEX ADAPTIVE SYSTEM OF SYSTEMS

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ABSTRACT

Electricity generated from renewable energy sources (RESs) such as wind and solar is in growing demand as a result of promoting sustainability. Yet RESs are intermittent and volatile, raising new challenges to the cost-effective, reliable operation of widely installed renewable energy systems owned by various entities. These systems include distributed renewable generation units and storage devices, as well as centralized renewable energy plants and storage systems. Forming energy sharing communities locally and coordinating the participants in each community properly will improve their performance. This paper analyzes energy sharing communities from the perspective of systems engineering and identifies nine characteristics of them. Therefore, each community can be seen as a decentralized complex adaptive system of systems (DCASoS). The paper thus proposes two methods for coordinating individual communities. One is the hierarchical coordination requiring a top management at the community level to coordinate participants; the other is the peer coordination replying on the collaboration among participants. They both capture the DCASoS characteristics of energy sharing communities. The choice of one method

over the other for a specific community needs to consider multiple aspects of it, such as the community size, the architecture and bandwidth of its communication network, and the reliability requirement.

1. INTRODUCTION

Sharing economy has impacted multiple industries such as transportation (e.g., Uber) and hospitality (e.g., Airbnb). Now it is spreading to the energy industry. Utility companies are no longer the only electricity service provider. Many consumers are actively choosing to consume electricity generated from renewable energy sources (RESs). As a result, distributed renewable generation units are widely installed. The energy industry has started establishing utility-scale renewable energy plants that have the sole purpose of producing electricity from RESs. Meanwhile, the development and maturity of energy storage technologies have promoted the rapid deployment of both distributed and centralized storage systems [1]. Yet RESs are intermittent and volatile. The rapid deployment of renewable energy generators and energy storage systems, which are in various sizes and owned by different entities, has been raising new challenges to the energy industry.

Forming energy sharing communities locally is a possible solution to the above-mentioned issue. An energy sharing community allows its participants to achieve a greater outcome than they would individually. Participants who generate excess electricity are able to share their generation with participants of their choosing. They are also able to take advantage of shared energy storage systems in the community to improve operational reliability and economy [1]. Participants who consume energy, similarly, can purchase electricity from generators of their choosing. This gives consumers a flexibility in managing their consumption.

Sharing economy in the energy industry has different features than that in other industries for many reasons. The complexity of power systems engineering and unique characteristics of RESs are predominant ones. Therefore, the knowledge of sharing economy gained from other industries cannot be directly transferred to the energy industry. An energy sharing community has many similarities with a microgrid (MG), a way of integrating distributed generation units, energy storage systems, and local loads to effectively utilize RESs [2]. Yet differences between them are present. The sustainable development of energy sharing communities requires a scientific understanding of them. Similar to MGs, an energy sharing community is an integration of many systems. Analyzing energy sharing communities from a perspective of systems engineering would provide insights into the development, operation, and management of them. This need motivates the study of the paper. The remainder of the paper is organized in the following way. Section 2 studies the system of systems (SoS) characteristics of energy sharing community, followed by an analysis of the complex adaptive system characteristics of it in Section 3. Accordingly, methods for coordinating individual communities are proposed. The paper summarizes the findings and future work at the end, in Section 4.

2. ENERGY SHARING COMMUNITY: A SYSTEM OF SYSTEMS

An energy sharing community is a SoS that possesses the characteristics of autonomy, belonging, connectivity, diversity (i.e., heterogeneity), and emergence [3].

2.1. HETEROGENOUS AUTONOMOUS PARTICIPANTS

An energy sharing community has various participants, as Figure 1 shows.

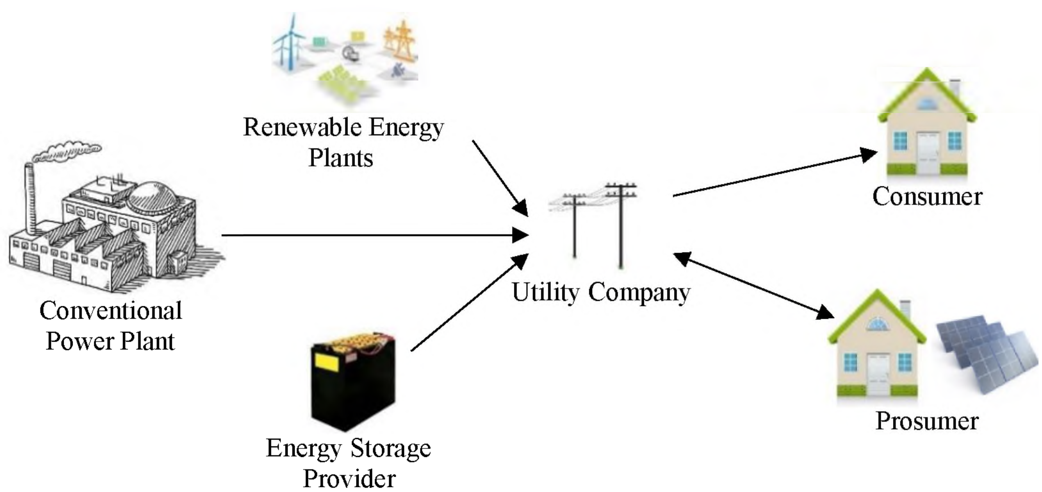

Figure 1. An energy sharing community

A *utility* company serves electricity end-users. It owns a distribution system, and may own the generation and transmission systems. The utility seeks profit by providing economical, reliable electricity service to its customers. Nowadays the utility is no longer the only electricity provider to end-users [4]. Distributed generation units installed at residential and commercial sites, utility-scale renewable energy plants, and large-scale energy storage systems can also provide electricity to end-users. According to the net metering law widely implemented in the United States [5], the utility is required to allow customers to connect their renewable systems to the grid. The utility now purchases electricity from not only conventional power plants, but centralized renewable energy plants and distributed renewable generation units. These changes create both opportunities and challenges for the utility.

A *consumer* does not have a renewable energy system and purchases electricity from service providers such as a utility. A consumer, after installing or leasing a renewable energy system, becomes a *prosumer*. Prosumers both produce electricity with RESs and purchase electricity generated from non-renewable sources [4]. Prosumers facing the uncertainty in RESs aim to maximize returns on their investment in renewable energy systems, which include cost savings, carbon emission reduction, government subsidies, and so on.

Utility-scale *renewable energy plants*, which generate reliable, clean electricity from RESs, have started to be established by the energy industry [6]. Renewable energy plants usually are centralized large-scale systems. Due to the scale of economy and the professional capability of energy management, the cost and quality of renewable generation at renewable energy plants are more competitive than those of distributed generation units. Like conventional power plants, renewable energy plants mainly sell the electricity to utilities, not to end-users. But renewable energy plants face intermittent, volatile generation. Their owners want to maximize the expected return on the asset investment subject to the operation constraints and the uncertainty in RESs.

Large-scale energy storage systems have been built in the energy industry and they may be managed by independent providers [7]. Unlike distributed storage systems, these centralized storage systems serve renewable energy plants, utilities, and, sometimes, end-users. Owners of these systems also confront the uncertainty issue of RESs and would like to best utilize the systems to maximize the expected return on their investment.

The discussion above indicates that all the participants are *autonomous* systems. A participant of a sharing community, indexed by i ($2\ I$, the index set of participants), has its own goal or purpose (G_i), functions (A_i), and management ability (F_i) to seek the goal given its operating condition (X_i). The outcome (O_i) is the result of the system's management compounded by some uncertainty element, e_i; that is,

$$O_i=F_i(A_i;X_i;G_i)+\varepsilon_i: \quad (1)$$

The achieved outcome of any system i overlaps with its goal in certain degree; that is, $O_i \subseteq G_i$. The *diversity* (i.e., heterogeneity) of participants is also captured by at least one difference in their functions, management ability, operating conditions, or the underlying uncertainty elements.

2.2. THE COHESION FOUNDATION FOR SHARING: BELONGING

Each of the participants mentioned in Section 2.1 possesses some functions that is necessary for the proper functions of the sharing community (A); that is,

$$A_i \subset A \subseteq \cup_{i\in I} A \ (2)$$

For example, prosumers can generate electricity from RESs to serve users of the sharing community. Meanwhile, the nature of sharing may create unique operating condition (X) and uncertainty element (e) for the community. For example, the energy storage provided by large-scale storage systems to all users (not only renewable energy plants and the utility, but end-users) help further mitigate the demand pressure the community put on the grid during peak hours and the risk of over generation from RESs. As a result, the electricity service for the community is more reliable and economical. The sharing community utilizes its management ability (F) to produce the outcome (O) in seeking its goal (G) given the obtained functions, operating condition, and uncertainty element:

$$O = F(A;X;G) + \varepsilon \quad (3)$$

The sharing community must possess opportunities for the participants to achieve greater outcome, resulting in a reduction of unachieved goal, $\bar{O}_i \cap G_i$, for any participant i, and/or reductions in uncertainty measurements of ε_i. The opportunities are in the form of one, or a set, of the following representative changes the sharing community brings to its participants.

- *Additional functions*: For example, prosumers and renewable energy plants, who do not have their own energy storage devices, obtain the function of energy storage through participating in the energy sharing community. Specifically, this additional function is acquired either directly from the shared storage systems or equivalently from the shared demands. Denote $\tilde{A}_i$ as the functions that participant i possesses after joining the sharing community, and $A_i \subseteq \tilde{A}_i$. $\tilde{A}_i \cap \bar{A}_i$ represents the additional functions the participant *i* obtains through sharing.
- *Better operating condition*: (1) A flexible operating condition is better, such as one with multiple, diverse sources rather than a single source. For example, consumers are also able to consume renewable energy, an additional source of electricity generated from RESs, through participating in the sharing community. Through sharing, larges-scale energy storage systems serve not only contracted users (e.g., renewable energy plants and utilities), but non-contract users (e.g., prosumers). (2) Less constrained operating condition is also favorable. For

example, prosumers and renewable energy plants that own or lease energy storage devices can expand their storage capacity, either directly or equivalently, in the sharing community. (3) Less uncertain operating condition or more predictable management ability is another case. For example, the utility faces a large number of uncertainties brought to the grid by prosumers. After a sharing community is established, these uncertainties are substantially lowered. Denote $\tilde{X}_i$ as the operating condition for participant i in the sharing community, and $\tilde{\varepsilon}_i$ as the uncertainty element. Then, $\tilde{X}_i \succ X_i$, $\tilde{\varepsilon}_i \succ \varepsilon_i$, or both.

Provided additional functions or better operating conditions, energy infrastructure owners can achieve higher, and less uncertain, utilization of their assets, and so for the return on investments. Infrastructure users and energy consumers are more capable of harmoniously achieving operating reliability, cost savings, and sustainability.

2.3. A CONNECTED NETWORK

An energy sharing community must be a connected network, as Figure 1 illustrates. A line that allows unidirectional flow of power from one participant to another without passing through other participants is a directed linkage between the two participants. A binary variable $l_{i,j}$, when taking the value of 1, indicates the existence of a directed linkage starting from i and ending at j. $l_{i,j} = l_{j,i} = 1$ if an undirected linkage between participants i and j exists, allowing for bidirectional power flow. Denote L as the matrix of directed linkages for the sharing community, whose elements are $l_{i,j}$ ’s. Two participants are certainly connected if there is a linkage between them, regardless of it is a directed or undirected one. Two participants may be connected through other participants although there is no linkage directly connecting them (e.g., a consumer and a prosumer). In other words, a chain of linkages exists, which allow the power to flow from one participant to the other, or vice versa. A binary variable $c_{i,j}$, when taking the value of 1, indicates the existence of a directed connection starting at *i* and ending at *j*. Denote C as the connection matrix of the sharing community, whose elements are $c_{i,j}$'s. The connection matrix C is a function of the directed linkage matrix L. The utility in a sharing community plays a critical role if no additional infrastructure is specifically built for the community. The utility has a linkage (either directed or undirected) with each of the rest participants; that is,

$$\{l_{utility;j}\} \cup \{l_{j;utility}\} = \{1\};\ \forall j \in I, \text{ and } j \neq \text{utility} \quad (4)$$

Therefore, the utility provides connections to participants who are not directly connected by linkages, making sharing possible.

2.4. EMERGENCE FOR SHARING

Emergence is the most important characteristic of any energy sharing community. It is the appearance of new features of the community emerging from the interaction of its participants. Emergence has both good and bad effects. Therefore, coordinating participants, or defining a mechanism to let them collaborate properly, is necessary for enlarging the impact of good effects and reducing that of bad effects [8].

Participants of a well-coordinated sharing community are able to achieve more attractive performance than in the pre-emergent stage; that is,

$$O_i(\tilde{A}_i; \tilde{X}_i; \tilde{\varepsilon}_i; G_i) \cap G_i \succ O_i(A_i; X_i; \varepsilon_i; G_i) \cap G_i \quad (5)$$

Meanwhile, the achievement of the sharing community is more attractive than the aggregate achievement of the participants in the pre-emergent stage; that is,

$$O(A;X;\varepsilon;G) \cap G \;\; \sum_{i\epsilon I} O_i(A_i;X_i;\varepsilon_i;G_i) \cap G_i \quad (6)$$

Therefore, features of the energy sharing community cannot be fully predicted from thoroughly knowing the participants in the pre-emergent stage. Instead, they are understood and measured through analyzing the operations and management of the community.

3. COORDINATION FOR ATTAINING DESIRED EMERGENT FEATURES

An energy sharing community usually has a management provider who offers energy transfer technologies to the participants [4]. The technologies are composed of a coordination method, decision-making algorithms, and a communication network [9]. The management provider may be contracted by the utility or it is directly contracted by participants. It charges a service fee to some or all of its subscribers to make a profit. The management provider, when designing a coordination method for functionalizing an energy sharing community, must consider the full spectrum of its system characteristics, which are discussed below.

3.1. SYSTEM CHARACTERISTICS IMPACTING THE DESIGN OF A COORDINATION METHOD

The design of a coordination method for functionalizing a sharing community must take into account the SoS characteristics, as well as other system characteristics [10], to enlarge the impact of good features and reduce that of bad ones. The SoS characteristics of energy sharing community have been discussed in Section 2. Other system characteristics of it are the following:

• Complexity: The energy sharing community is a complex system, which can be seen from two perspectives. On one hand, individual participants have their own complex behavior. For example, end-users all respond to the time-varying pricing strategy of the utility. Consumers and prosumers are two groups of end-users. Both between-group and within-group variations in their consumption behavior are present, which are difficult to predict. One the other hand, simultaneous interactions among participants, and those between the management provider and participants, result in complexity.

• Adaptability: Participants of an energy sharing community can adjust, or change, themselves to respond to environment changes. For example, renewable generators (both renewable energy plants and distributed generation units) can adjust the energy curtailment, the output power, and the injection of energy to storage, to maximize the overall reward. Another example is the switch of a consumer to prosumer. A consumer, when observing sustainable growth of renewable energy benefits, may decide to install or lease a renewable generation unit and, thus, become a prosumer.

• Self-organization: An energy sharing community has the ability to develop new system architectures by itself. For example, an energy storage system with excess capability provides the capacity to two users whose needs as a whole best utilize the excess capacity. If one of the two users substantially changes its operation, the energy storage system may find it is beneficial to stop serving one or both, and seek other users who need storage. The system architecture of the sharing community will be changed accordingly.

• Feedback Loops: An energy sharing community has two types of feedback loops. Internal loops connect participants of the community because the decision and information that a participant shares with the management provider or other participants are inputs to their decisions. Internal loops are necessary for the community to derive an optimal solution of coordination during a time period and quickly converge to it. External loops are present because the sharing community responses and adapts to changes in the environment.

The complexity and autonomy characteristics of participants determine that centralized coordination of the sharing community is not realistic. Instead, decentralized coordination is more applicable. Different participants of a sharing community need their own decision models to capture the characteristics of belonging, heterogeneity, complexity, and adaptability. The interdependence between participants, and that between the management provider and participants, must be formulated in their decision models to capture the characteristics of connectivity, self-organization, and feedback loops. The decision model for coordinating the sharing community must explicitly capture the way in which participants contribute to the sharing community (e.g., increase in the social welfare) and value-added opportunities the sharing community provides to its participants.

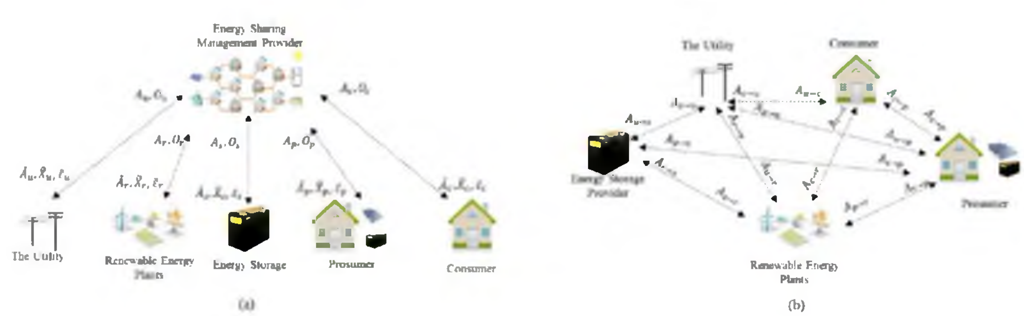

Figure 2. Coordination methods for sharing communities: (a) hierarchical coordination; (b) peer coordination

3.2. PROPOSED COORDINATION METHODS

We thus propose two coordination methods: hierarchical coordination and peer coordination, which are illustrated in Figure 2 and discussed in the following.

• Hierarchical Coordination: Participants independently govern their management and operations. But a top management (e.g., the management provider) is present at the community level, which coordinates the participants and determines an optimal way of sharing. Under the hierarchical coordination, participants do not directly communicate with each other. Instead, they interact with the top management of the community. A bi-level optimization model is suitable for this type of decentralized coordination. The model is composed of a master problem (for the management provider) and multiple slave problems (for participants), which are interdependent. All the decision problems explicitly consider the impact of their environment [11].

• Peer Coordination: A top management is not present at the community level. Instead, participants collaborate with each other, more or less voluntarily, to reach an optimal solution of sharing. Under the peer coordination, participants directly interact with each other. Peer coordination can be modeled as a game [8]. To assure that the participants effectively collaborate in their community to produce desired sharing results, the management provider needs to design an algorithm or an incentive mechanism to facilitate their collaboration.

The choice of one coordination method over another should be based on the community size, the autonomy degree of participants, the architecture and bandwidth of the communication network, the requirement on reliability, and so on.

4. CONCLUSION

This paper analyzes energy sharing communities from a systems engineering perspective and identifies nine important characteristics of them: autonomy, belonging, connectivity, diversity, emergence, complexity, adaptability, self-organization, and feedback loops. Therefore, an energy sharing community can be seen as a decentralized complex adaptive system of systems (DCASoS). Based on the identified DCASoS characteristics, the paper proposes two methods for coordinating individual sharing communities. The choice of one coordination method over another for a sharing community requires evaluating the community from multiple aspects, which will be an immediate extension of this paper. Findings from the study of this paper have built a foundation for modeling the operational decisions of participants and developing solution algorithms for achieving desired outcomes from sharing.

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II. MODELING AND UNDERSTANDING ENERGY SHARING COMMUNITIES: A SYSTEM OF SYSTEMS APPROACH

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ABSTRACT

The renewable energy technology has recently advanced dramatically, accelerating the society's pace of transitioning to a sustainable living environment. Distributed renewable energy generators and energy storage devices are widely installed, which are owned and operated by various entities. Facing intermittent and volatile renewable generations, they have recognized the need for collaborative energy management. As more and more distributed renewable generators are being connected to distribution networks, owners of the networks are under the pressure of changing their business model to adapt to the new trend. Forming sharing communities locally is a potential solution which allows the participants to share excess generations and unmet demands within their community. Forming energy sharing communities also benefits distributed networks from multiple aspects. This paper aims to develop a thorough understanding of this new business model and, meanwhile, explores an approach to the management of energy sharing communities. Through analyzing the participants of energy sharing communities, the paper first identifies nine characteristics of the communities. Accordingly, the paper justifies that cooperative sharing communities can form a decentralized complex adaptive system of systems (DCASoS). The paper further classifies the nine characteristics into two types: underlying

characteristics and the derivative characteristics. The goal of managing energy sharing communities is to enhance the good effects and reduce the bad effects of the derivative characteristics given its underlying characteristics. Based on this fact, the paper develops a system of systems (SoS) approach to describing, modeling, and analyzing sharing communities, which builds a foundation for engineering the corresponding DCASoS.

1. INTRODUCTION

Sharing economy has had a positive impact on many industries including the energy industry. A sharing economy is an innovative solution to the influx of consumer demand while conventional forms of electricity supply are diminishing. Distributed renewable energy generators and storage devices are widely installed along with the decrease of the investment cost required for traditional consumers to evolve into prosumers who have capability to privately generate electricity (Kargarian et al., 2014). The distributed generation can be initially used to fulfill the owner's demand while any excess electricity can be shared with their neighbors who need more. Sharing energy provides an additional option for prosumers to deal with overgeneration besides storage, selling back to the grid, or curtailment.

Current net metering laws require utility companies to financially compensate prosumers who put excess electricity back into the grid (Rossi, 2016). Utility companies are now presented with various challenges. They are not only facing additional stochastic electricity supplies (Stoutenborough & Beverlin, 2008) but financially compensating prosumers for their supply (Rossi, 2016). A potential solution to these issues is to cluster local end-users of utility into individual energy sharing communities and coordinate the energy shared within individual communities and between communities. The similar concept has been successfully applied to the management of multiple microgrids (Zhao et al., 2018). Allowing for locally generated supply to be maximally disbursed by local consumers would reduce the impact of stochastic supplies on the utility company (Liu et al., 2017). The utility is also able to minimize the cost by distributing prosumer generated electricity locally.

This paper aims to develop a thorough understanding of the new business model for utility companies while exploring an approach to the energy management of sharing communities. By taking into consideration current net metering laws, an appropriate energy sharing model is proposed. The effectiveness of energy share is analyzed using

the proposed model and defined characteristics identified within decentralized complex adaptive system of systems (DCASoS). The end the paper summarizes findings of this study and future work. proposed. The paper summarizes the findings and future work at the end, in Section 4.

2. ENERGY SHARING COMMUNITIES

An energy sharing community is a SoS that possesses the characteristics of autonomy, belonging, connectivity, diversity (i.e., heterogeneity), and emergence [3].

2.1. A SHARING COMMUNITY

A sharing community includes both consumers and prosumers; both consumers and prosumers are end-users of electricity. Consumers only use electricity, whereas prosumers both consume and produce electricity using the distributed renewable energy generators (REGs) they own or lease. The demand of consumers, D, is nonnegative. We

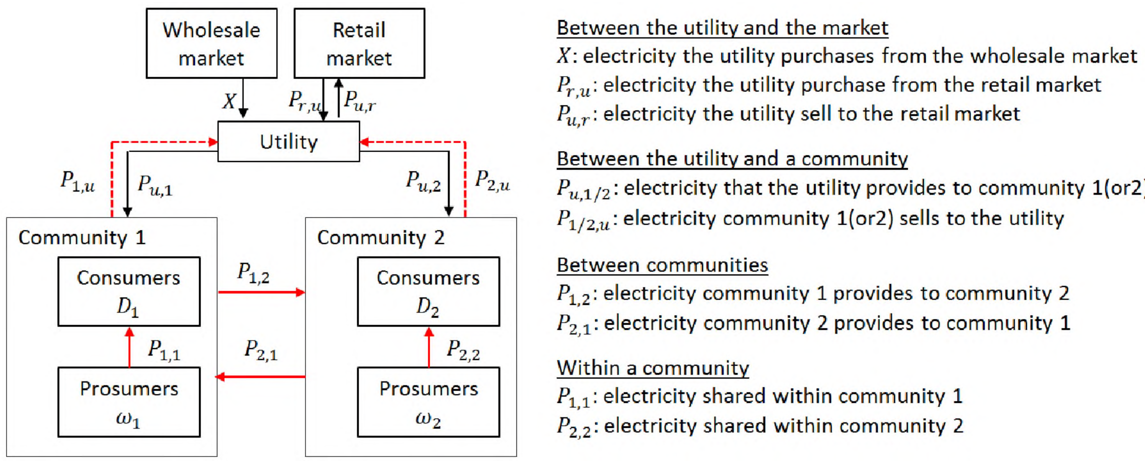

Figure 1. Grid-connected cooperative communities

define the net demand of prosumers, ω, as the difference between their demand and the supply produced from their REGs. ω taking a positive value means that prosumers do not generate enough electricity from their REGs to meet their own demand, otherwise they generate excess electricity. Considering that renewable generations are intermittent and volatile, $\omega$is represented by a random variable in this modeling approach.

Within a sharing community, prosumers with extra generations can share their supply with consumers within the same community. The coordination of the community will try to meet the demand of the community using the renewable energy generation of the community as much as possible. If the supply is not equal to the demand within the community, the deviation will be adjusted by either purchasing electricity from, or selling to, the utility and/or other connected communities. The coordination within any individual community can be performed by either the utility or an independent management company, which must ensure the benefit of community participants.

2.2. COOPERATIVE COMMUNITIES

Connected Communities can share demand and generation between one another. As Exhibit 1 shows, community 1 can provide electricity to community 2 if the former generates excess electricity whereas the latter is still short of electricity after it internally balances the supply and demand, and vice versa. If a community, after sharing its electricity with other communities, still has extra electricity, it can sell the extra electricity back to the utility; otherwise, it can purchase electricity from the utility. Therefore, the utility needs to coordinate the energy sharing between communities.

2.3. THE UTILITY

The utility can supply electricity to communities to respond to their demand (Pu,1 and Pu,2 in Exhibit 1). It will have to take electricity that the communities send to it ($P1$,u and $P2$,u in Exhibit 1). Due to the uncertainties in load and renewable generation, the realized net demand of sharing communities may deviate away from the electricity the utility purchases from the wholesale market, X. Therefore, the utility can address the deviation through buying electricity Pr,u from, or selling Pu,r to, the retail market.

3. DECENTRALIZED COMPLEX ADAPTIVE SYSTEM OF SYSTEMS

Cooperative energy sharing communities can be seen as a DCASoS. An individual energy sharing community is either a system of systems (SoS) (Morgan et al., 2018) or a system. In this paper, individual communities are systems, and a group of cooperative sharing communities coordinated by the utility is a SoS. They possess the characteristics of DCASoS, which should be taken into account by the coordination of participants. Characteristics of DCASoS can be divided into two types: underlying characteristics and derivative characteristics, which are briefly discussed below.

3.1. UNDERLYING CHARACTERISTICS

Forming a SoS requires multiple systems that have the following four underlying characteristics: autonomy, belonging, connectivity, and diversity (Morgan et al, 2018).

- Autonomy. A SoS is not a simple system. Its components, named constituent systems, are autonomous systems. The autonomy of individual communities is reflected by the fact that each constituent system has its own purpose of existence, functions, and independent management ability to seek the goal given its operating condition. The independence of each community is not temporary but can be maintained on the long run.
- Belonging. Belonging signifies that the constituent systems of a SoS bring positive aspects to the SoS and, meanwhile, the SoS also possesses opportunities for the constituent systems to achieve greater outcomes. The belonging characteristic of energy sharing communities is related to the following fact.

Through energy sharing, some communities provide additional supply to satisfy the unmet demand of others or they contribute additional demand to absorb the excess demand.

• Connectivity. Connectivity describes the linkages, and directional flow of linkages, between constituent systems. Given that sharing communities are connected to the distribution network of the utility, the connectivity between any two sharing communities must exist at the physical layer. Connectivity at the information layer is also important, which needs to be built to accommodate the selected approach to the coordination of sharing communities. Connectivity is dynamic in that linkages between communities can be closed or opened, which is affected by the willingness of the communities to participate, as well as the operating condition of the networks (e.g., congestions, failures).

• Diversity. Diversity or heterogeneity states the fact that constituent systems of a SoS are widely distributed on one or multiple dimensions such as functions, resources, capacities, working environment, and so on. Diversity provides rich choices for SoS architecting and, thus, a better foundation for functionality expansion and performance improvement. Sharing communities are heterogenous. RESs and end-users in one community may differ than those in another. The diversity of sharing communities helps mitigate the impact of load and source uncertainties and improve the cost-effectiveness of energy system.

3.2. DERIVATIVE CHARACTERISTICS

Systems with the above four underlying characteristics, after forming a SoS, may promote the generation of emergence and other derivative characteristics.

The emergence characteristic of sharing communities is the appearance of new features emerging from the interaction of the communities. When forming sharing communities and connecting them as a SoS, emergence can be deliberately and intentionally designed (Boardman & Sauser, 2006). A SoS with high emergence should have high functioning autonomous systems. Enabling constituent systems to have high autonomy allows for unknown positive benefits of an overall system to become visible.

3.3. DERIVATIVE & UNDERLYING CHARACTERISTICS

Some characteristics of DCASoS are both underlying and derivative characteristics because they are presented at both the level of constituent systems and the SoS level.

• Complexity. Each individual community is a complex system, which is seen from multiple aspects. Participants of each community have their own complex behavior, which cannot be fully predicted. Moreover, interactions among the participants produce a new level of complexity at the community level (i.e., system level). The interaction of the cooperative communities further creates the complexity at the SoS level.

• Adaptability. Participants within a community adjust or change themselves to adapt to the environmental changes. For example, consumers and prosumers within each community would adjust their consumption behavior to adapt to the change in renewable generation and price. Communities also adjust it management to adapt to any environmental changes.

• Self-organization. A community has the ability to adjust the existing architecture or develop new system architectures by itself. Cooperative communities also have this ability. Self-organization is realized either through the collaborative interaction of participants, or facilitated by the top management of cooperative participants.

• Feedback Loop. Internal loops are present, both within individual communities and between communities. With the internal loops, a participant (e.g., an end-user of a community, or a community) and the top management (if it exists) can receive decisions and information of other participants and use these as the inputs of its decision. External loops are those that participants receive information from the environment. Internal loops are the prerequisite for self-organization and external loops are for adaptability.

4. COORDINATION

SoS architecting and the coordination of constituent systems of the SoS are two important tasks. The former is focused on the optimal design, and the latter deals with the optimal operation, of the SoS. In this paper, we dedicate our discussion to the coordination of cooperative communities by the utility as in the example shown in Exhibit 1. Creating an objective function with stage one decision variables and stage two decision variables enables the uncertainties to be considered in a way that minimizes their negative impact.

To highlight the emergence characteristics of SoS, we consider three cases of coordination:

- Coordination of all end-users: In this case no energy sharing communities are formed, and, therefore, energy share between end-users does not exist. This is equivalent to the conventional approach to managing multiple distribution networks (DNs).
- Coordination of uncooperative communities. In this case energy sharing communities are formed and, yet they do not collaborate with each other. That is, energy share occurs within communities, but not between communities.
- Coordination of cooperative communities. In this case energy sharing communities exist, and they operate cooperatively through sharing.

The utility purchases the amount of electricity, X, from the wholesale market ahead at the wholesale price, cw, to serve its end-users and charge them at the service price ps. Due to the uncertainties in RESs and loads, $\boldsymbol{\xi}$ =[$D1$, $D2$, $\omega 1$, $\omega 2$]T, the realized total demand $D1 + D2 + \omega 1 + \omega 2$ may deviate away from the available supply X. To fulfill the service commitment, the utility will either purchase the amount of electricity Pr,u from the retail market at the price cr, or sell Pu,r at the price pr, to fill the gap between the supply and demand. Decision variables of coordinating the participants (communities or end-users) will be specified later in individual cases. It should be noticed that the cost and revenue coefficients have the following relationship: $cw < cr$ and $cw \leq ps$. Considering that arbitrage opportunities do not exist between the two markets, we can assume that $pr \leq cw$. Service price, ps, is not dependent to either retail cost, cr, or wholesale cost, cw.

Instead, the cost incurred by the end-user is the sum of utility service cost and market cost paid by the utility company multiplied by the amount of units of electricity demanded by the end-user. Typically, utility companies pay prosumers wholesale cost for excess electricity. However, because this price point is not currently strictly regulated, utility companies have the ability to alter this value to mimic the daily electricity cost fluctuation (Brown & Sappington, 2017). For simplification, ps is used to represent the price for purchasing electricity from communities.

We formulate the cases of coordination discussed above as three different two-stage stochastic programs (SPs), indexed by i. The first stage decision variable is X, which must be made before the uncertainty, $\boldsymbol{\xi}$, is disclosed. It is important to specify that X is a non-negative variable because the initial amount of electricity purchased by the utility company will always be positive. Any discrepancies between the forecasted X value and actual X is accounted for using Pr,u or Pu,r. The second stage decisions are the adjustments, $\boldsymbol{Y}$, the utility makes after $\boldsymbol{\xi}$ is disclosed.

The objective of the utility is to minimize the expected total cost, including the cost of purchasing electricity from the wholesale market in the first stage and the expected cost of adjustments in the second stage:

$$\text{Min } X\geq 0\ c\ wX + E\boldsymbol{\xi}\ [\ \boldsymbol{Y}\epsilon\text{min } \Omega i(X,\boldsymbol{\xi})\ psP1,u + psP2,u + crPr,u - prPu,r] \quad (1)$$

where $\Omega i(X, \boldsymbol{\xi})$ is the feasible set for the second stage decision variables $\boldsymbol{Y}$ in problem i, i = 1, 2, 3. Denoted by $Qi(X)$, the expected minimal cost from the second stage at a given value of first stage decision X, then the two-stage SP in (1) becomes

$$\text{min } X\geq 0\ cwX + Qi(X) \quad (2)$$

In the following we describe the three different feasible sets.

4.1. NO SHARING COMMUNITIES

The SP for the direct coordination of end-users is named SP-1. The feasible set for the second stage decisions $\boldsymbol{Y}$ is

$$\Omega_1(X, \boldsymbol{\xi}) = \{\eta P_{u,1} - P_{1,u}/\eta = \omega_1 \tag{3}$$

$$\eta P_{u,2} - P_{2,u}/\eta = \omega_2 \tag{4}$$

$$X + P_{r,u} - P_{u,r} = D_1/\eta + D_2/\eta + P_{u,1} - P_{1,u} + P_{u,2} - P_{2,u} \tag{5}$$

$$\boldsymbol{Y} = [P_{r,u}, P_{u,r}, P_{u,1}, P_{1,u}, P_{2,u}, P_{u,2}]^T \geq \mathbf{0} \tag{6}$$

$P_{1,u}$ and $P_{u,1}$ are the electricity the utility receives from, and provides to, the prosumers in zone 1, respectively. $P_{2,u}$ and $P_{u,2}$ are similarly defined. η is the transmission efficiency of DNs. The second stage adjustments that the utility may make include the trading with the retail market and the power exchanges between the utility and prosumers, which must be nonnegative as (6) defines. The power exchanges between the utility and prosumers in different zones are defined in (3) and (4). Equation (5) is the demand and supply balance that the utility achieves through the purchase in the wholesale market and the adjustments.

4.2. MULTIPLE UNCOOPERATIVE COMMUNITIES

The SP for the coordination of uncooperative sharing communities is named SP-2. The feasible set for the second stage decisions $\boldsymbol{Y}$ is

$$\Omega_2(X, \boldsymbol{\xi}) = \{\eta P_{u,1} - P_{1,u}/\eta = \omega_1 + D_1 \tag{7}$$

$$\eta P_{u,2} - P_{2,u}/\eta = \omega_2 + D_2 \tag{8}$$

$$X + P_{r,u} - P_{u,r} = P_{u,1} - P_{1,u} + P_{u,2} - P_{2,u} \tag{9}$$

$$\boldsymbol{Y} = [P_{r,u}, P_{u,r}, P_{u,1}, P_{1,u}, P_{2,u}, P_{u,2}]^T \geq \mathbf{0} \tag{10}$$

$P_{1,u}$ and $P_{u,1}$ in $\Omega_2(X, \boldsymbol{\xi})$ are the electricity the utility receives from, and provides to, community 1, respectively. $P_{2,u}$ and $P_{u,2}$ are similarly defined. Therefore, The second stage adjustments that the utility may make consists of the trading with the retail market and the power exchanges between the utility and each of the two communities. In this study we assume the transmission loss within each community can be ignored.

4.3. MULTIPLE COOPERATIVE ENERGY SHARING COMMUNITIES (SoS)

The SP for the coordination of cooperative communities is named SP-3. The feasible set for the second stage decisions $\boldsymbol{Y}$ is

$$\Omega_3(X, \boldsymbol{\xi}) = \{\rho P_{2,1} - P_{1,2}/\rho + \eta P_{u,1} - P_{1,u}/\eta = \omega_1 + D_1 \tag{11}$$

$$\rho P_{1,2} - \rho P_{2,1} + \eta P_{u,2} - P_{2,u}/\eta = \omega_2 + D_2 \tag{12}$$

$$X + P_{r,u} - P_{u,r} = P_{u,1} - P_{1,u} + P_{u,2} - P_{2,u} \tag{13}$$

$$\boldsymbol{Y} = [P_{r,u}, P_{u,r}, P_{u,1}, P_{1,u}, P_{2,u}, P_{u,2}, P_{1,2}, P_{2,1}]^T \geq \mathbf{0} \tag{14}$$

$P_{1,2}$ in $\Omega_3(X, \boldsymbol{\xi})$ is the electricity community 1 provides to community 2, and $P_{2,1}$ is the reverse. ρ is the transmission efficiency between communities. We assume $\rho > \eta$; that is, the transmission loss between local communities is smaller than the loss between a local community and the utility.

4.4. EMERGENCE FROM SHARING

It can be easily justified that the feasible set $\Omega_i(X, \boldsymbol{\xi})$ for $i = 1, 2, 3$ is nonempty given any feasible solution to the first stage. A rational second-stage strategy for coordinating energy sharing communities is found from the study of SP-3. If prosumers in a community generate more electricity than needed, the excess electricity will first be shared with the consumers within the same community. If a community has extra electricity, it should share with other communities whose own generations are not enough to meet all demands in the community. Following the same idea, a community that does not have enough generations will first receive electricity from those with extra. After these adjustments, any unsatisfied demands of communities will be fulfilled by purchasing electricity from the retail market, and any success generations will be sold to the retail market.

Both the theoretical analysis and Monte Carlo simulation show that $Q3(X) \leq Q2(X) \leq Q1(X)$, indicating cooperative communities are more capable of lowering the expected cost of adjustments at any given value of first stage decision X. Essentially, the same two-stage stochastic programming approach is applied to the scenario of no sharing communities, multiple uncooperative sharing communities, and multiple cooperative sharing communities represented by $Q1$,$Q2$, and $Q3$, respectively. Monte Carlo simulation was applied to the uncertain values of supply and demand using upper and lower limits to represent extreme values. Values generated during Monte Carlo simulation and theoretical analysis justify the statement that multiple cooperative sharing communities lowers the expected cost of adjustments than multiple uncooperative sharing communities and no sharing communities. By appropriately choosing X, we can minimize the expected total cost for cooperative energy sharing communities. As a result of energy sharing, some communities may have no electricity exchange with the utility and others have more stable exchanges. This effectively eases the energy management of the utility. Reasoning for multiple cooperative sharing between communities being the most successful coordination stems from energy consumers having additional energy suppliers; additional supplies of energy allows the utility to alter the energy distribution patterns to optimize the objective function that is to be minimized. When locally generated energy is sold at retail price, not having a price difference between DN and utility energy provides no financial loss endured by the utility when prosumer energy is distributed between communities.

5. CONCLUSION

This paper discussed the DCASoS characteristics that cooperative energy sharing communities and accordingly modeled the coordination of the communities as SPs. The SPs are used to evaluate the emergence of cooperative sharing communities. The study showed that cooperative energy sharing communities, with coordination, can effectively lower the expected total cost, reduce the effective number of communities that the utility needs to coordinate, and improve the stability of power flows. The paper is also an initial exploration of the DCASoS approach to characterizing, modeling, understanding, and managing sharing communities. Maintaining stability and ensuring a minimized negative effect from uncertainty is a limitation considered throughout development and execution of the model. Results from the study have suggested important extensions, including a simulation-based approach to obtain a thorough understanding of derivative characteristics and the collaborative sharing approach based on stochastic games.

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III. ENERGY SHARING: A LITERATURE AND CURRENT PROJECT REVIEW

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ABSTRACT

Energy sharing is the implementation of a sharing economy in the energy sector and provides a solution to the increase of electricity demand and diminishing finite resources. Four benefits of energy sharing have been identified: (1) economic value added, (2) environmental sustainability, (3) resilience, and (4) social welfare. How each of these uniquely associates with a sharing community is analyzed. These four benefits can be used to describe existing energy-sharing projects. Along with existing projects, a review of current literature is performed. The literature review and existing projects are beneficial for identifying gaps in current research and how they apply to policymaking criteria.

1. INTRODUCTION

Sharing economy has been incorporated into many industries including hospitality and transportation (e.g. AirBnB, Uber) [1]. Recently, the sharing economy has been integrated into the energy industry through energy sharing, community energy, and transactive energy systems. The increase of distributed generation units among end-users has encouraged a re-evaluation of electricity distribution methodology. Utility companies are traditionally the supplier of electricity to all end-users. However, the growing distributed generation units powered by renewable generation resources, in conjunction with the growing demand, disrupts the traditional function of the utility. In recent decades, renewable energy sources (RESs) have become a more significant source for electricity [2]. Through energy sharing, transactive energy sharing, or cooperative sharing, sharing economy can be incorporated into the energy industry, as seen in Figure 1.

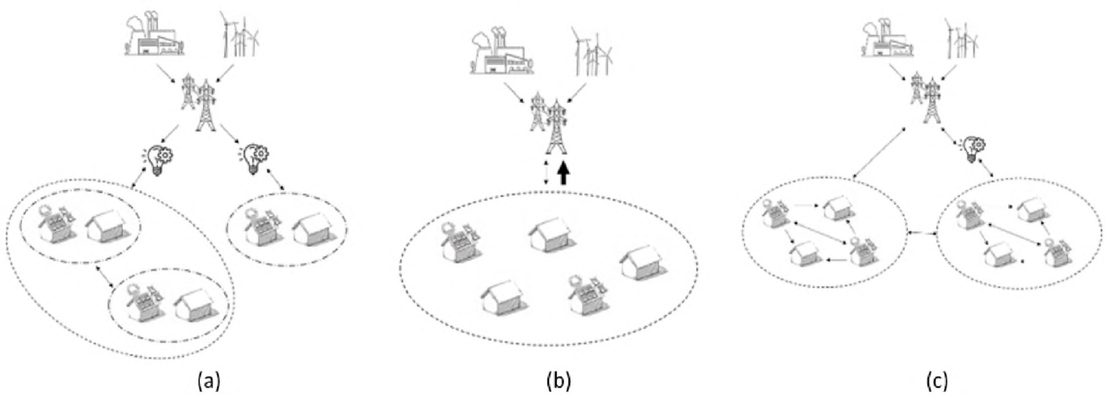

Figure 1. Coordinations of electricity participants that consider sharing economy; (a) transactive energy systems, (b) cooperative energy sharing, and (c) decentralized energy sharing

A transactive energy system can be implemented in either a centralized or decentralized coordination [4]. A centralized representation of a transactive energy system is represented by (a) in Figure 1. The transactive energy system relies on a management system to maintain electricity supply and demand balance. In a transactive energy system prosumers lose a significant amount of autonomy, heavily relying on the management system. Therefore, prosumers lack accurate prediction of renewable energy source (RES) electricity [5]. A cooperative sharing community is represented by (b) in Figure 1. Cooperative sharing incentivizes end-user participation by offering a grid-connected management that increases electricity distribution flexibility [6]. However, cooperative sharing relies heavily on a third-party management to balance community demand, internal supply, and utility supply. The cooperative sharing community gets to choose what source to purchase electricity supply from. This decision, represented by the bold arrow, is made by the community and told to the third-party management. An energy-sharing community is represented by Figure 1 (c). This decentralized configuration allows end-users to directly interact with each other while also providing the opportunity for sharing communities to interact with other sharing communities. The shown decentralized energy sharing has two types of energy-sharing communities represented. The community on the left is a decentralized system of systems. This type of energy-sharing community does not rely on a central controller to manage electricity distribution and keep supply and demand balanced.

Energy sharing is a new energy distribution mode that is ecofriendly, fiscally conservative, and scalable. Yet reasons underlying the benefits are not systematically examined. It is noticed that the research literature on energy sharing, as well as pilot projects, are growing. To escalate the development and maturity of energy sharing in the era of distributed renewable generations, this paper performs a systematic analysis of this emerging topic to help build a deeper understanding of the state-of-the-art. By doing such, the study of this paper will be able to envision the future of energy sharing.

The remainder of this paper is organized as follows: Section 2 identifies the benefits of energy sharing, Section 3 is a literature review of energy sharing from its specified aspects, Section 4 is a summary of energy sharing projects already in existence, and Section 5 is a concluding summary in conjunction with a discussion of future research in relation to energy sharing.

2. BENEFITS OF ENERGY SHARING

Sharing economy allows resources to be divided among more participants so that the people have access to more of what would otherwise be limited [7]. To encourage the participation in and the growth of energy-sharing communities, benefits of energy sharing are identified at both the participant level and the community level. Figure 2 uses a causal model to illustrate various changes due to the incorporation of energy sharing. This causal model uses an "input-throughput-output" format to display the changes in practice linked to the integration of energy sharing [8]. Using the causal modeling, this study can assess outcome variables based on "organizational strategies" [9].

Figure 2 illustrates that energy sharing acts as a moderator for achieving four benefits which are economic value added, environmental sustainability, resilience, and social welfare. Impacts of energy sharing are illustrated using a solid and a dashed line. The solid line indicates an increase of the defined aspect. For example, by implementing energy sharing, accessibility to DGUs reliant on RES increases which, consequently, increases the economic values. However, the implementation of energy sharing causes a decrease of infrastructure demand overload which, consequently, causes a decrease of economic values.

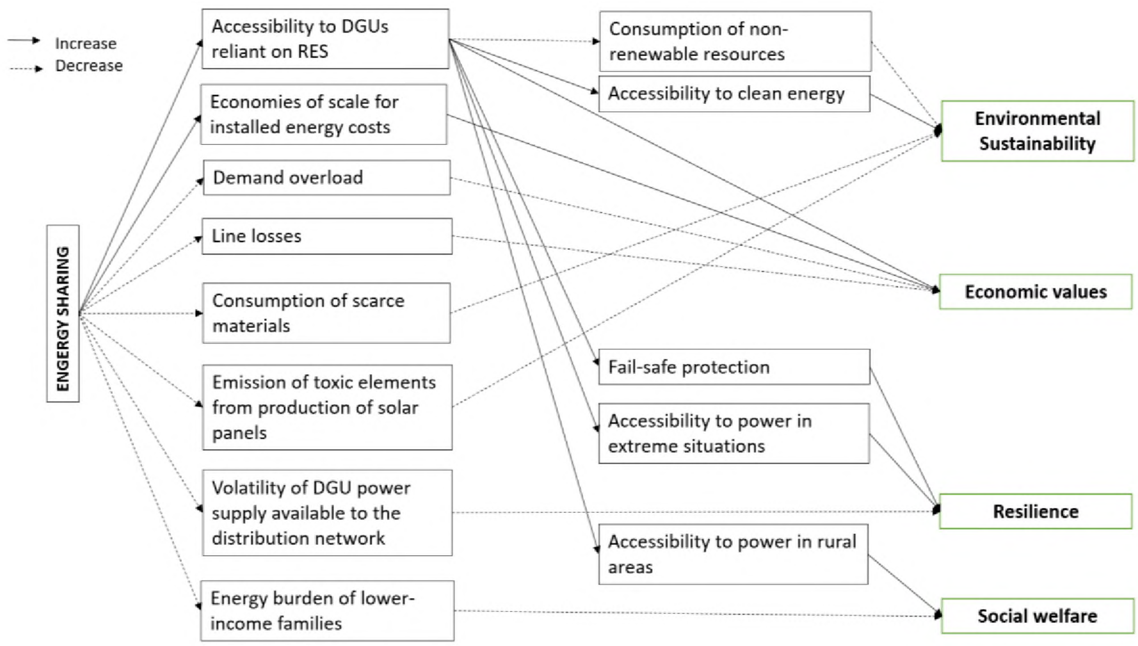

Figure 2. Causal model illustrating the aspects of sharing communities that result in the defined benefits of energy sharing

2.1. ECONOMIC VALUE ADDED

Additional economic value can be generated through energy sharing from multiple sources. The ownership of a distributed generation unit (DGU) generates value only when the generated electricity is accessible and utilized by users [10],[11]. The users can be consumers other than owners themselves. Energy sharing helps owners, particularly those using renewable resources, generate more value from their DGUs, due to increased accessibility to the DGUs by other users.

The financial compensation that DGU owners receive from selling their excessive generation back to the grid is limited by some restrictions. Certain states have indicated that credits for generating excess electricity do not rollover indefinitely or can expire [12]. Some utility companies have strict rules regarding the amount of electricity that a prosumer can sell back to the grid and the compensation they can receive. Energy sharing mitigates the impact of those restrictions and effectively helps owners of DGUs to leverage the return from their investment by selling excess electricity to neighbors as well. Feed-in-tariffs (FITs) are used as a subsidy system to encourage the installation of DGUs. [13] Using the feed-in-tariff system, those with DGU will be financially compensated for the amount of RES electricity generated and an additional amount depending on how much excess electricity is sent back to the grid. The FITs provide a compensation structure while DEGs are also used as a tax incentive. Incorporating FITs increases the drive for RES systems and are used to create and develop global renewable energy policy [14]. Energy sharing addresses the limitations of FITs by allowing multiple distribution outlets for a single DEG which increases the maximum amount of RES electricity sold by the prosumer.

Some energy infrastructures require a large initial investment but provide a higher rate of cost savings from the investment. That is, these infrastructures have a high operating leverage. The economic benefit of high operating leverage is usually justified by a large volume of demand, whereas a smaller volume of demand favors those with low operating leverage. Energy sharing can pool small local demands into a larger demand for an energy infrastructure in high operating leverage, helping it increase its total economic value [15].

Installation costs of wind energy exhibit economies of scales, particularly when moving from small- to medium-sized projects. In 2018, the sampled capacity-weighted average project cost for projects of 5 MW or less was over $4,000/kW, whereas the cost for projects in the range of 20-50 MW was less than $2,000/kW. Energy sharing is an approach to benefit from investing in medium-sized distributed renewable projects that exhibit evident economics of scale in installed costs [16].

The change from a centralized electricity supply chain to a decentralized electricity supply network also effectively reduces the line losses. In the United States, electricity loss during transmission and distribution is estimated to be about 5% of total electricity transmitted and distributed [17]. The reduced line loss greatly reduces the cost, particularly for the distribution network.

2.2. ENVIRONMENTAL SUSTAINABILITY

Environmental sustainability refers to a more efficient use of otherwise limited goods and reduced emission of harmful elements into the natural environment [18]. Energy sharing improves sustainability by increasing the utilization of the existing capacity of generation with renewable resources. The waste of electricity generated from renewable resources in the form of curtailment is reduced through energy sharing because the excess generation from some prosumers can be used to meet a portion, or all, of the electricity demand of nearby consumers [19]. Consequently, the utilization of the existing capacity of RES generation is increased or maximized.

The increased utilization of generation from renewable resources largely contributes to environmental sustainability. Given the same amount of demand, a proportion of electricity supply is shifted from the generation of nonrenewable resources to that from renewable resources. This effectively reduces the consumption of nonrenewable resources such as coal, petroleum, and natural gas, thereby reducing the harmful emissions (e.g., CO_2) associated with their consumption.

The maximized utilization of generating capacity from renewable resources would also help reduce the negative environmental impacts produced during the entire production life cycle of renewable-resourced generators. For example, the materials necessary to build these generators are limited, and some materials are scarce, such as In, Te, and Ga. Meanwhile, the production of solar panels also has toxic emissions such as Cd that are potentially harmful to the environment [20].

2.3. RESILIENCE

A resilient power-supply system is defined by its ability to maintain a minimum level of supply even under extreme conditions and the ability to quickly recover from a sudden loss of a significant portion of the power supply before irreversible damage occurs [21]. Traditional linear electricity supply chains have a centralized large-scale generation location far from demand centers, which relies on utilities to distribute the bulk power from the transmission system to end-users. Energy sharing effectively changes the vulnerable centralized linear supply chain to a more resilient supply network wherein each end-user has access to multiple local suppliers such as nearby prosumers. In extreme situations like electricity grid blackout, the proportion of end-users in an energy sharing community who have access to power supply is higher than that in a non-sharing community because prosumers can share their generations with consumers in the sharing community. Therefore, extreme situations have less impact on energy sharing communities as they are more capable of maintaining essential functions [22],[23]. Moreover, sharing allows the generation from distributed renewable resources to be absorbed locally, which effectively reduces the impact of a large amount of successive generation from renewable resources to the grid.

Additionally, energy sharing creates a more resilient utility-owned infrastructure that is less vulnerable to large-scale outages and decreases recovery time. Not only are there financial losses associated with energy surges and outages, but the majority of the associated costs are incurred by the consumers [24]. As a result of the increasing frequency of electrical grid interruptions, many government agencies and end-user participants have invested in meeting "infrastructure improvements and operational changes" in the United States [25]. Current energy distribution infrastructures lack an energy management system with the capability to mitigate damage caused by energy outages or surges. Energy management associated with energy sharing initially addresses infrastructure damage mitigation, which improves the overall system resilience.

2.4. SOCIAL WELFARE

Energy sharing improves social welfare as it facilitates the flow of affordable, clean energy to communities where the affordable, clean energy produces greater social welfare than in the origin communities. Energy sharing makes the electricity generated from distributed renewable resources accessible to consumers who otherwise would not have access to the clean energy.

Energy sharing creates a new way of giving and connectivity. Energy burden is defined as the amount of annual household income spent on the annual energy bill [26]. Sharing excessive generation of electricity with households in low-income communities at a reduced price or no cost will help decrease the amount of income they must devote to energy bills and increase the amount of household income available for other purposes such as food, education, healthcare, and transportation.

The overall quality of life of these communities can be improved from receiving electricity that other communities share with them. Energy sharing lowers the impact of outages and blackouts, thus reducing the damages or losses from these extreme conditions. Currently, net metering laws require utilities to compensate prosumers for any excess electricity put back into the grid. Incorporating sharing creates a solution for utilities because locally generated electricity can be re-distributed locally to meet demand instead of purchasing electricity from the market at wholesale or retail price.

Rural areas, or areas with limited access to electricity, benefit from energy sharing because the costly infrastructure is less of a financial burden on the construction companies. Without access to electricity, quality of life is severely impacted. The World Bank Group estimates that 89% of the entire world population had access to electricity in 2017 [27]; this statistic indicates that nearly one billion people in the world did not have access to electricity [28]. Access to electricity indicates an improved quality of life because of the ability to use necessities such as lighting, heating, and refrigeration.

Incorporating energy sharing specifically in low-income communities can significantly increase the quality of life of low-income residents by decreasing the household energy burden. Energy burden is the amount of annual income a household spends on annual energy bills [26]. Households with a lower annual household income spend a larger portion on utility bills [29]. Creating an electricity source by installing a DGU relieves some of the energy burden for end-users. Furthermore, energy sharing allows low-income residents to purchase DGU electricity from neighbors at reduced or not cost thus increasing the amount of annual household income usable for items other than electricity bills.

3. RESEARCH LITERATURE REVIEW

Energy sharing has received attention by academic researchers as evidenced by the growing publications on energy sharing research. This paper summarizes the literature of energy sharing research. Identifying the state-of-the-art of energy sharing research is needed for shaping the future research to broaden the impact of energy sharing to the society.

Table 1. A list of references based on topic explanation

Approaches	References
Decentralized Coordination	
Individual End-Users	1,3,10,13,15,18,20,22,24,25,31,35,37,40,43,57,58,59,62,65,85,92,100
Uncooperative Communities	2,4,6,15,18,29,30,32,34,39,42,43,52,53,54,66,82,84,88,99,114
Cooperative Communities	2,11,63,64,83,84,86,87,114
Microgrid Classification	3,37,38,41,44,48,49,51,52,53,56,58,60,61,62,63,64, 65, 69,76,81,82,83,84,85,86,88,90,91,94,95,96,97,98,100
Energy Management Systems	
Demand Side Management	30,33,34,38,44,45,46,47,48,57,58,59,61,62,72,75,76,81,97,99
Local Controller	32,63,84,98
Central Controller	50,51,84,88
Home Energy Management System	1,5,31,32,36,45,46,47,57,59,61,69,94
Energy Management Optimization	
Optimization Considering Uncertainty	23,24,31,33,41,42,51,57,60,61,72,74,89,92
Cost Optimization	2,4,19,23,30,31,32,34,35,37,38,41,42,45,46,49,56,57,58,59,60,62,63,65,66,70,71,72,88,95,96,99
Profit Optimization	6,33,35,37,38,43,44,75,88,100
Energy Storage Systems	
Battery Energy Storage System	33,35,40,41,49,50,55,63,65,66,70,76,77,78,79,80,81,82,83,89,94,95,98,99
Electric Vehicle Storage	36,68,71,97

An initial literature research indicates the energy sharing research is divided by five paths: decentralized coordination, energy management systems, optimization methods for energy sharing, and energy storage systems, and microgrid. Then, the study searched the literature on each research path by restricting those with “energy sharing” and the key word of that path either in the publication title or in the abstract. For example, ‘decentralized coordination' and 'energy sharing' were searched and restricted to either publication title or abstract.

3.1. DECENTRALIZED COORDINATION

Traditional energy end-users are coordinated in a hierarchical manner. Peer-to-peer networks are an example that requires decentralized coordination. Decentralizing a community creates the ability for participants to act autonomously while increasing the connectivity between end-users. An energy sharing community has many autonomous end-users. The decentralized coordination of the community allows for individual participants to act in their own self-interest while benefiting the community as a whole. Decentralized coordination references have been classified into three classes of decentralized coordination: individual end-users, uncooperative communities, and cooperative communities. This further classification identifies the degree of coordination within the community and with other communities.

Purely decentralized coordination allows for individual end-users to make independent decisions, as described in [3] and [31], which introduces increased autonomy to the network [10], [15], [18], [20], [31], [35], and [40] explain that greater end-user independence allows energy-sharing participants to embrace economic, environmental, and social benefits. Decentralized coordination implemented in an energy-sharing community allows for emerging attributes to be thoroughly defined and elaborated on an individual energy-sharing participant basis. The lack of defined participant community, lack of common management system, and increase of peer-to-peer connectivity is used to describe a purely decentralized coordination of individual end-users. Individual end-users do not require a control system when the coordination of the sharing community is purely decentralized. When there is no control system, the system behavior is determined by autonomous end-users in the system.

An uncooperative energy-sharing community is a defined group of end-users with energy-sharing participants who do not share electricity with the outside of the community. By trading within a local community, P2P energy sharing with a coordination can generate a win-win outcome [32]. The win-win outcome is achieved because prosumers sell excess electricity to participants with demand. Coordination is accomplished through pricing, forecasting, scheduling, and tariffs. Consumers have the opportunity to purchase locally sourced electricity at a reduced rate in comparison to the retail price [2], [6], [15], [18], [29], and [114]. Through the day-ahead pricing, a reasonable solution to distribution management and flexible demand response is found by balancing the internal electricity supply with the internal end-user demand. Forecasting and scheduling are commonly used solutions to balancing local excess supply in conjunction with local electricity demand [3], [4], [15], [29], [42], and [82]. Scheduling takes into consideration consumer electricity needs and schedules these electricity demands to be fulfilled at a time that is convenient while maintaining minimal cost. In addition to scheduling, feed-in-tariffs can be imposed on end-users as an incentive for prosumers to make charging and discharging decisions that benefit the overall sharing community [35] and [36]. Feed-in-tariff is a policy designed to benefit prosumers by guaranteeing a higher price refunded for excess electricity generated and sent to the electricity distributor. By allowing the prosumer to make charging and discharging decisions, the prosumer will usually choose to maximize excess electricity to send to the electricity distributor because this logic entails the highest reward. [35]

described how a time-of-use tariff in conjunction with P2P coordination is beneficial to residential and commercial consumers because power flow and storage utilization are optimized. Time-of-use tariff is meant to encourage energy consumption at off-peak hours. Implementing a time-of-use tariff is beneficial to the balancing of supply and demand during high usage hours because more participants choose to shift consumption to a time of day when rates are lower. This load shifting is also beneficial to the electricity providers and distributors because necessary grid maintenance is less often due to the more distributed consumption within the grid. Different tariff structures have been considered when assessing benefits of energy sharing [37]. Feed-in tariffs encourage local consumption and DEG. [38] described how energy sharing could be more advantageous to prosumers than the feed-in tariff approach while [39] encouraged a diverse range of incentives to offer in exchange for end-user participation in energy sharing. [40] developed a fair benefit allocation mechanism based on participant contributions. A comparison between tariffs and energy sharing has not yet been done. Additionally, the application of tariffs on residential consumers could be different than the application on business consumers; comparing and contrasting research of the effects of tariffs on end-users has not yet been done.

A cooperative community is a defined energy-sharing community that has a priority of locally supplying electricity demand while maintaining the ability to share excess electricity with another cooperative energy-sharing community. The necessities of a distribution line a decentralized system with multiple production and consumption points can be identified and defined using a figure [114]. Traditional electricity distribution is structured as a single distribution line which can be made more efficient by increasing connectivity between end-users [11], [63], [64], [83], [84], [86], [87]. This clustering of energy consumers also provides the defined community the ability to effectively implement any tariffs that could benefit energy-sharing participants. Cooperative communities allow for separate communities to coordinate as they wish while allowing the connectivity between communities to be increased. The decentralized coordination of collaborative communities allows for participating energy-sharing communities to operate autonomously. The collaborative coordination of cooperative communities mimics a large-scale version of the decentralized coordination of energy-sharing communities.

3.2. ENERGY MANAGEMENT SYSTEMS

A conventional energy management system is offered as a solution to maintain a balance between demands and supplies for consumers, prosumers, and the utility. Though an energy management system can be a third-party organization, the purpose is to maintain a sustainable system at the minimal cost. Energy management systems serve as a efficiency operator between energy suppliers and energy consumers. A prosumer agent can switch between consumer and producer based on electricity status. By integrating a local or central controller, the supply-demand balance of prosumer participants is managed [32], [50]. However, demand side management, supply management, and home energy management together create a more customized balance for individual end-users [1], [5], [30]. Demand side management values energy-sharing participants comfort over the distribution process created by the energy management system. Supply management values the efficiency, feasibility, and reliability of energy producers and distributors. Home energy management values end-user standards in terms of comfort and financial standards.

The demand side management for energy-sharing communities ensures participating residents maintain comfort while uncertainties and instabilities of an energy-sharing community are accounted for [38], [44], [45], [46], [47], [48]. Though demand side management can act as a mediator for supply and demand, demand side management does not serve the purpose of maintaining optimal system function [57], [58], [59]. Instead, demand side management takes a scheduling approach to ensure the end-users maintain personal comfort within their residence [30], [33], [34]. The scheduling approach is often also seen in home energy management systems. Supply management is closely related to both demand side management and HEMS; like demand side management, supply management is used to ensure the necessary supply to fulfill residential demand at minimal cost and maximum efficiency. Similar to HEMS, supply management takes into consideration excess DGU electricity. However, supply management is not a versatile approach to best encompass various needs of energy-sharing participants.

Home energy management systems (HEMSs) are a technology used to autonomously track and schedule electricity usage [45], [57], [59], [61]. For strictly consumers, HEMS use load shifting that takes into consideration controllable loads such as washing machines and dishwashers to minimize electricity cost. However, prosumers can use HEMS as a tool to both minimize electricity cost and maximize profit from excess electricity while taking into consideration consumer experience throughout the energy-sharing process. The collaboration of HEMS with the Internet of Things (IoT) creates a home energy and comfort management system that effectively reduces energy consumption [50]. Incorporating IoT with energy management allows to maximize energy efficiency using collected data [48], [49]. The further application of IoT includes increasing real-time information to improve the gathering and processing of pertinent data to better serve the energy-sharing participants. Three functions of incorporating IoT with HEMS include: (1) prediction of energy demand, (2) balance and applications of energy policies, and (3) allocation of RES depending on intermittence [57]. Advances of RES and DEG promote IoT which encourages technological and methodological evolvement within Internet-of-Energy (IoE), which benefits further research within the energy field.

Local control (LC) is used as a response system to local electricity demand while the home energy management system is unique to every end-user [32]. LC is used as a management system for a small community of energy-sharing agents. Central controller is used for a larger community composed of multiple small communities. In comparison to LCs, central controllers (CC) must account for many more points of common coupling [84], [88], [98]. Both LC and CC act as an intercessor between large-scale electricity distribution and residential end-users.

Blockchain technology applied to an energy-sharing community provides security as well as additional identified, field-proven, benefits [54]. Integrating the blockchain technology with either a LC or CC provides a secure process that contains encrypted energy-sharing exchange data [50], [53], [54]. By creating a cyber secure platform for energy sharing, blockchain technology incentivizes participation through cost-sharing. Additionally, because blockchain is so often used as an exchange system for cryptocurrency, efficiency and reliability aspects of the system have been refined. Incentivizing participation in energy sharing can be done using a cost-sharing mechanism, such as a blockchain, which increases both energy distribution efficiency and social efficiency. Though using blockchain technology presents a solution to ensuring energy sharing safety, energy sharing in conjunction with both blockchain technology and personalized sharing management systems, like phone applications and HEMS, is currently a research gap. Additionally, third-party management may be less secure and/or more expensive than the HEMS option. A thorough comparison of the management systems should be done.

Integration of energy sharing within a defined community that supplies local electricity demand with local supply or utility grid supply with the option of operating in island mode becomes a smart microgrid. Incorporating energy sharing within the defined community creates new connections between participants and establishes a peer-to-peer network that allows for direct interaction between participating residents. Resilience and reliability are two characteristics that are essential to energy-sharing communities when they are classified as a microgrid. However, the ability for the community to act as a separate entity apart from the main grid is what allows the energy-sharing community to be classified as a microgrid. Microgrids have the ability to maintain end-user consumption while islanded from the utility or any large-scale electricity supplier. A microgrid is an engineering system designed to be able to operate independently with distributed generators, storages, and users [83]. Although not common, incorporating energy sharing into a community creates the option for decentralized coordination because the participating entities are coordinated into a decentralized manner to decrease burden on the grid [84]. Because of the concentrated location of electricity loads being in a close vicinity to the local suppliers efficiency of the distribution system is increased [85].

Management of DGUs can become overwhelming for a single microgrid system; a re-grouping of consumers into smaller clusters allows the individual microgrids to collaborate [86], [87]. This collaboration between microgrids is intended to optimize use of DGU production. Some microgrids maintain the ability to switch between island mode and grid-connected mode. Other microgrids rely solely on the utility to exchange electricity and maintain stability, this is called peer-to-grid trading [88]. Maintaining microgrid function by using the island mode is said to increase resiliency of the distribution network [89]. By allowing the utility grid and microgrid to function in parallel, system reliability and reduction of redundancy is improved [90]. Though ESSs are not a requirement for an islanded microgrid to function, the reference supply is necessary to provide continuous supply to consumers [91].

A cost-benefit analysis can be performed on the electricity distribution within a microgrid to determine the financial benefits of using an energy-sharing framework [93, [95]. In order to justify the effectiveness of a hierarchical framework of a MG, an EMS and ESS are often coordinated [94]. Though uncommon, a MG structured with an EMS or optimization system that has bidding and pricing capabilities will create an efficient MG system [96]. By combining a mathematical optimization approach with Pareto optimality, consequences of participating in an energy-sharing community are analyzed to ensure no one type of participants is affected more than other participants [97]. Collaboration of a MG and an energy sharing provider (ESP) can provide framework to the overall business plan and optimize the system framework [98].

3.3. ENERGY MANAGEMENT OPTIMIZATION

Optimization can be used to formulate energy management as a mathematical model that explicitly states the management objective as a function of management decisions. Meanwhile, optimization uses solution algorithms to search the most favorable energy management solution within given constraints. The objective function of each participant is unique in optimization, which creates a breadth of research variety depending on the decision maker's point-of-view. Therefore, there is no one-size-fits-all optimization model for energy-sharing communities because of the high autonomous level of energy-sharing participants. Energy management optimization can use a range of deterministic mathematical optimization approaches such as linear programming [55], [56], [76], integer linear programming [67], mixed integer linear programming, nonlinear programming, genetic algorithm [73], [74], and particle swarm optimization [30], [44]. Another optimization approach is optimization under uncertainty such as stochastic programming [2], [57], and robust optimization [71], [72, [92]].

Cost optimization of an energy management system takes into considering all necessary costs for a specified energy-sharing participant [23], [24]. Cost optimization can be performed from many perspectives such as the utility, a consumer, or an energy community. Because sharing energy may require additional infrastructure, the cost optimization function of any participant should take into consideration any increased cost the utility will offset through participation fees for end-users [30], [31], [34]. Cost optimization from a utility perspective should take into consideration energy purchases from large-scale electricity suppliers at both wholesale and retail prices, necessary infrastructure maintenance, and lost revenue due to DEGs by end-users themselves [32]. Cost optimization from an energy management perspective should have defined priorities. Though not necessary, energy management system may incorporate home energy management system to solve decision and scheduling problems because HEMS is a single-user EMS customized to the end-user [38], [41], [45], [46], [58].

Profit optimization is often used from a prosumer perspective in order to maximize the revenue from DGU investment [6], [33], [37], [38], [44]. The community size has a significant impact on implementation of profit optimization [61], [75], [100]. A more efficient approach to profit optimization is the incorporation of the profit optimization model with individual HEMS [57], [58]. The compilation of individual prosumer profit indicates the proficiency of re-distribution of locally generated electricity. By individually assessing the profit optimization using HEMS, prosumers have the potential to adjust this profit using price negotiation. Using HEMS, prosumers have the ability to sell DGU electricity at a price set by said prosumer. This set pricing adjusted by the prosumer allows for profit optimization to be calculated accurately using customized values.

Not all optimization methods require the consideration of uncertainties. Uncertainties in energy-sharing communities can consist of, but are not limited to, RES generation, energy storage system supply, excess electricity consumption, and necessary energy storage recharge [33], [35], [41], [51], [75], [84]. Considering uncertainties when optimizing energy-sharing management creates a more reliable system when it comes to end-users making buying and selling decisions [31], [34], [89]. In addition to buying and selling decisions, energy-sharing systems that consider uncertainty are able to provide more details necessary to better schedule end-user consumption and generation including energy storage systems [33], [41], [51]. Energy management optimization also considers variable constraints. Variable constraints can include maximum energy storage capacity, maximum DGU generation, and minimum end-user consumption. These variable constraints can be used as lower and upper bounds when using robust optimization [60]. Variable boundaries can also be helpful when performing profit optimization A benefit from considering uncertainties when optimizing energy management decisions includes less wasted locally generated RES electricity [23], [24]. However, solving optimization under uncertainty may be computationally complex, thus raising an issue for some energy management decisions that should be made in near real-time [57], [60], [61], [72], [74]. Therefore, optimization considering uncertainty should be carefully justified by evaluating the tradeoff between its advantages and limitations.

3.4. INCORPORATION OF ENERGY STORAGE SYSTEMS

Energy storage systems (ESSs) are not a necessity to energy-sharing; however, ESSs do increase the resilience and reliability of energy-sharing communities [77], [78]. ESS are important to incorporate because they are helpful to energy sharing communities but cannot substitute the function of sharing [79]. Battery energy storage system (BESS) and electric vehicle storage (EV) are the two types of ESS specified in energy-sharing research. BESS is a static ESS that can be owned by either a residential end-user or a large-scale energy distributor such as a utility company. However, an EV used as an ESS that can be transported as the owner needs. Energy storage systems are important to energy-sharing communities because the RES is not consistent enough to continuously fulfill all consumer demand., an ESS creates an additional source of electricity supply when power disturbances occur. An ESS can be seen as an electricity consumer or supplier. The power inflow to the ESS represents an electricity demand for the community, and the outflow from the ESS represents a power supply to the community. The ESS can be used by consumers in the sharing community to better control the electricity expenses. Consumers with an ESS can store extra electricity when the electricity price is low and consume or share the stored electricity when the price is high. Ahmad et al. illustrated three scenarios to show the integration of RES and ESS results in reducing the consumer electricity bill and peak-to-average ratio (PAR) [76].

State-of-charge (SOC) is important to consider when investigating system reliability because it is varying with time due to charging and discharging [80]. The optimal charge/discharge of an ESS is achieved through properly controlling the SOC of the ESS [80], [81]. ESS act as an additional energy provider with limited supply within an energy-sharing community. However, because ESS do not require the consideration of end-user comfort, once the power supply is depleted the ESS can be re-charged at an off-peak time to minimize system interruption and cost. SOC directly effects RES electricity supply available to disperse within a community. Discharging and charging of the SOC is a sort of maintenance that to the system that keeps the ESS functional. Coordination of load power using SOC ensures system stability [82].

4. ENERGY-SHARING PROJECTS

Few energy-sharing communities are currently functioning in the world. The projects currently in use are limited in size and do not have other functioning sharing communities nearby to perform inter-community energy sharing. Though the five identified existing energy sharing communities elaborated in Table 2 have similar technology uses, drivers and community size differ based on local need.

Western Power, a Western Australian state government-owned utility company, is launching an energy-sharing community in Western Australia. In collaboration with Curtin University, consumers with excess solar generation receive compensation for sharing. Traditional models provide no financial compensations to DGUs that put excess electricity back into the grid. The integration of peer-to-peer coordination in conjunction with blockchain technology allows for end-users to provide electricity supply with other sharing participants while receiving monetary compensation for excess electricity generation. Because Australia does not traditionally monetize excess electricity generation, financial incentive is a significant driver for energy sharing in Western Australia. Additionally, Western Power explicitly states that that they as a company intend to stay relevant in the future by learning, adapting, and developing energy solutions for their community [101]. The energy-sharing community operated by Western Power is not the only energy-sharing community located in Australia. Power Ledger, a startup technology company, has partnered with other companies to create an energy-sharing community based on blockchain-enabled peer-to-peer technology in Western Australia [102].

Brooklyn Microgrid is a peer-to-peer energy sharing grid created and maintained by LO3 Energy and Siemens. Exergy, which is an innovation of LO3 Energy, has created a marketplace for energy-sharing participants to “transact energy autonomously in near-real time with consumers on the platform in their local marketplace” [103]. Sharing participants within Brooklyn Microgrid are connected using blockchain technology that allows prosumer agents to sell RES electricity to other sharing participants within the grid. Brooklyn is a large city in the state of New York, USA whose residents have a large range of annual income. By integrating energy sharing into the Brooklyn area, the local economy is supported because of the financial incentives and resiliency of the electricity distribution system is improved by technological advances. Though Brooklyn itself is a large city, the size of the existing sharing community is limited to 50 participants, but is a mixture of residents and businesses. However, Brooklyn Microgrid is set up with the potential to share with other nearby sharing communities once they are established.

Unlike Western Australia or the UK, the Philippines is classified as a developing country. Because of the difference in classification, drivers to integrate energy sharing are heavily motivated by social and economic welfare. Energo Labs is a China-based company that works to create decentralized energy distribution systems combined with blockchain technology for safety and privacy reasons. However, Energo Labs chooses to incorporate smart meters as opposed to a third-party management system. Smart meters are an efficient and effective option for the sharing community in the Philippines because the end-user population participating in sharing is small. Additionally, Energo Labs have created a phone app to help sharing participants easily manage electricity consumption and production sources [104].

Recently, Thailand has become classified as an upper-income country as opposed to a low-income country due to social and economic development [105]. Because of the improvement of social and economic status, drivers for implementation of energy sharing in Thailand are related to environmental impacts and maintaining positive economic impacts on Thai citizens. Power Leger, the previously mentioned Australian company, has partnered with BCPG to create peer-to-peer energy sharing in a small neighborhood within Bangkok. The existing sharing community is limited to a mall, a school, a dental hospital, and an apartment complex. Looking to the future, the Bangkok Metropolitan Electricity

Authority expects energy sharing to become an extremely relevant form of power supply for businesses and residents. In conjunction with blockchain technology, energy sharing will be an efficient and safe form of energy distribution.

The California Community Choice Association advocates for end-users' ability to choose electricity supplier. While California Community Choice Association (CalCCA) does not provide a sharing platform for end-users, it does support the legislative and regulatory development that benefits communities and the environment [106]. CalCCA creates the opportunity for communities to collectively choose their primary electricity supplier. Because prosumers do not generate enough electricity to fully supply the demand of a community, the primary electricity supplier is often a small-scale, local, RES electricity generator. Though not considered a classic energy sharing community, CalCCA was included in the analysis of current energy sharing projects to show an exhaustive list of energy-sharing practices. Piclo Flex, though not a traditional energy sharing community but rather an energy marketplace for sharing, was launched in June 2018. Located in the UK, Piclo has partnered with other companies to fund a peer-to-peer trading trial and will eventually launch the trading service. As a company, Piclo identifies as a leader in energy technology and smart energy systems. The energy-sharing system launched by Piclo was based on the importance of renewable energy in addition to maintaining a sustainable structure for efficiency and reliable electricity distribution [107]. Distribution Network Operators (DNOs) manage the local grid to support the "growth of renewables without impacting the reliability of the grid or increasing customer bills but also to accommodate a range of new devices and other fast-emerging technologies" [107]. Because Piclo uses DNOs to maintain system balance and security, blockchain technology is not incorporated

Table 2. Description of energy-sharing projects

White Gum Valley Energy Sharing Location: White Gum Valley, Western Australia Partnership/funding: Western Power, Curtin University, Power Ledger Purposes: a test of the Western Power network for sharing energy between households. Participants: 80 dwellings including units and townhouses form an energy sharing community Method of sharing: Peer to Peer (P2P) sharing of electricity among neighbors in the community Technologies: (i) a grid-connected solar power (150kW) microgrid with battery storage (300kWh), (ii) the block-chain enabled P2P sharing is realized using the Power Ledger platform Benefits: Residents can balance their energy uses between the local grid and the main network
Brooklyn Microgrid Location: Brooklyn, United States Partnership/funding: LO3Energy, Siemens, Brooklyn Microgrid Purposes: pilot a microgrid with P2P transaction Participants: 50 local prosumers, consumers, and business owners form an energy sharing community Methods of sharing: Peer to Peer (P2P) sharing of electricity among neighbors in the community Technologies: (i) a microgrid of on-the-roof solar panels; (ii) block-chain enabled P2P sharing realized using the visual marketplace by LO3Energy, (iii) mobile app that participants can participate in the visual energy marketplace; (iv) smart meter system that gathers and records energy data for use within the community. Benefits: (i) consumers can choose sources of energy; (ii) prosumers can control where their excess solar energy to go; (iii) through energy sharing, the community better supports local economy and better controls the greenhouse emissions and air pollution; (iv) through sharing, the community is more resilient in conditions such as outrages.

Table 2. Description of energy-sharing projects (cont.)

DLSU-D Microgrid Project Location: De La Salle University – Dasmariñas, Philippines Partnership/funding: Energo Foundation, Qtum Foundation, First Gen Purposes: demonstrative project allowing solar panel-equipped communities to locally produce and directly exchange clean energy Participants: buildings on campus Methods of sharing: Peer to Peer (P2P) sharing of electricity among buildings Technologies: (i) microgrid of solar energy; (ii) the block-chain enabled P2P sharing; (iii) smart meters; (iv) mobile app Benefits: (i) autonomy of sharing community; (ii) cost-efficiency; (iii) energy access particularly in local and non-grid-connected areas by providing consistent, local source of electricity
T77 Precinct Location: T77 Precinct, Bangkok, Thailand Partnership/Funding: BCPG, Power Ledger, Metropolitan Electricity Authority, Purposes: a trail of P2P energy sharing in a sharing community to demonstrate how best to optimize the use of distribution network to accelerate the change to decentralized clean energy system Participants: a shopping center, a school, an apartment building, and a dental hospital. Solar panels installed on every building of the school. Cover 20% of the community's overall needs. Methods of sharing: Peer to Peer (P2P) sharing of electricity among buildings Technologies: (i) grid connected 635kW solar PVs and battery storage; (ii) the block-chain enabled P2P sharing; (iii) smart meters Benefits: (i) monetize excess renewable energy generated by selling it to local peers to receive higher return than selling to the retailer for the feed-in tariff or not being able to selling; (ii) maximize the utilization of renewable energy (iii) real-time data empower consumer decision making

Table 2. Description of energy-sharing projects (cont.)

The California Community Choice Association Location: California, USA Partnership/funding: Investor Owned Utility (IOU) and the California Public Utilities Commission (CPUC) Purposes: allow end-user communities to choose the provider for electricity needs, decrease energy burden for consumers, invest in clean energy suppliers Participants: established local communities, electricity suppliers, investor owned utility Method of sharing: existing infrastructure Technology: bidirectional metering Benefits: support the local economy, investment in clean energy has a positive environmental impact, creation of local jobs, increased competition among electricity providers
Energy on Trial Location: United Kingdom Partnership/funding: Piclo and Department of Business, Energy, and Industrial Strategies (BEIS) Energy Entrepreneurs Fund (EEF) Purposes: pilot a flexibility marketplace for upgrade the existing centralized energy system to decentralized, decarbonized system Participants: flexible buyers (six distribution network operators) and flexible providers (demand-response aggregators, electricity suppliers, generators, battery operators, industrial and commercial customers, local authorities, community groups and electric vehicle charging operators) Method of sharing: a marketplace Technology: open digit platform for trading flexibility with temporal, spatial, and technical requirements. Benefits: It removes the obstacle for small-scale assets seeking to trade flexibility and thus expand the participation of the growing number of flexible providers. It provides a platform for procurement of flexibility nationwide easily, regardless of the size needed. It helps scale up the low-carbon technology at a lower cost to consumers.

with the peer-to-peer energy trading system. However, the six DSO locations have allowed energy sharing to be more widely available to end-users throughout the UK.

4.1. COUNTRY DEVELOPMENT

When installing sharing communities in developed countries research tends to focus more on technological advances and policy impact on social and economic incentives [108]. Three collaborative consumption communities exist in developed countries. These projects are in White Gum Valley, Western Australia; Brooklyn, New York, United States; and Silicon Valley, California, United States. Increasing energy distribution efficiency and lowering existing electricity bills are large influencers for the adoption of energy sharing in these developed countries. Because many neighborhoods are already established and electricity distribution infrastructure is existent, the evolution of hierarchical utility-lead electricity distribution into a decentralized sharing economy approach is a more gradual process.

Underdeveloped countries have less urban infrastructure and housing. Due to the lack of structure, commercial business energy sharing has become a more viable project. Existing projects that are commercial business centered are seen more in the developing or underdeveloped countries. There is an energy sharing community in Dasmarinas, Philippines, and a sharing community in Bangkok, Thailand, that have been identified and researched for this article. In underdeveloped/developing countries, research motives are more centralized on everyday behaviors and factors that directly impact the action outcomes [108]. Though low-income citizens are not directly impacted by the positive aspects of energy sharing, the improvement in access to electricity has an indirect impact on lifestyle.

4.2. PARTICIPANT POPULATION

Because residential locations use less total electricity in comparison to businesses, the amount of electricity demand for a single end-user is more easily supplied by RES. Typically, residents are either in urban or rural locations. Urban locations allow end-users to have more readily available access to electricity. Urban end-users will either have solar panels on top of their home or shared apartment building. Rural end-users have the option to install DEG either on the roof of the building or on nearby land. The White Gum Valley Energy Sharing project in Australia is comprised of 80 dwellings, including units and townhouses. Wester power and Curtin University, the partners creating this project, are expecting 70% of the community energy demand to be supplied by RES [101]. Though more residential demand may be supplied by RES, energy storage systems may not always be available to residential users as a backup supply. Energy storage systems such as batteries require high investment cost and significant maintenance to ensure safety and efficiency. Because of the limited access to ESS, electricity demand not supplied by RES is more likely to be supplied by utility.

Three of the five energy-sharing projects specified in this paper include business consumers; Brooklyn Microgrid is a hybrid community of 50 residents and businesses, the DLSU-D MG project is restricted to a university campus, and the T77 Precinct includes businesses such as a shopping center, a school, an apartment building, and a dental hospital. The T77 Precinct has specified that about 20% of the electricity demand has been supplied by RES [102]. The motivations for businesses to incorporate RES electricity into their power supply are largely influenced by demonstrating the company commitment to sustainable practices and decreasing negative environmental impact.

4.3. TECHNOLOGIES SECURITY

Blockchain technology is widely used to ensure secure transactions. Four of the five energy-sharing projects discussed in this paper utilize blockchain technology. Blockchain is a data management system initially developed for Bitcoin cryptocurrency transactions [109]. Data management is traditionally a service provided by a third-party company. Blockchain technology provides an encrypted data management service that allows users to access records of previous transactions they made [80]. Because blockchain is a data encryption technology, contracting a third-party company is unnecessary and therefore a financial saving [110]. The cost efficiency and data security is important to all sharing economy systems, which explains the universal implementation of blockchain technology in a range of project scopes.

System amenities such as smart meters and mobile apps are not common in energy-sharing communities, but existent in some energy-sharing projects specified in this paper. The DLSU-D MG project utilizes both smart meters and mobile apps. Because the DLSU-D MG project is restricted to one university campus, the range of consumers with access to sharing data is limited. This decreases the variability in load placed on app utilization which, in the case of overloading, could cause a system crash. Smart meters are an efficient, yet costly, way to accurately measure bi-directional electricity values. The T77 Precinct

Table 3. Summary of energy-sharing projects

Project Name		White Gum Valley Energy Sharing	Brooklyn Microgrid	DLSU-D Microgrid Project	T77 Precinct	Community Choice Aggregation (CCA)	Energy on Trial
Location		White Gum Valley, Western Australia	Brooklyn, United States	Dasmarinas, Philippines	Bangkok, Thailand	California, United States	United Kingdom
Partnership/Funding		Western Power, Curtin University, Power Ledger	LO3 Energy, Siemens, Brooklyn Microgrid	Energy Foundation, Qtum Foundation, First Gen	BCPG, Power Ledger, Metropolitan Electricity Authority	State of California	Piclo, BEIS, EEF
P2P Coordination		✓	✓	✓	✓		
Motivations	Economic Value	✓	✓	✓	✓	✓	✓
	Environmental Sustainability	✓	✓			✓	
	Resilience		✓			✓	✓
	Social Welfare		✓		✓	✓	✓
Technologies	Blockchain	✓	✓	✓	✓		
	Smart Meters			✓	✓		
	Mobile App		✓	✓			
Benefits	Clean Energy Source	✓	✓		✓	✓	✓
	Autonomy	✓		✓	✓		
	Cost Efficient		✓	✓	✓	✓	✓
	Increase Energy Access			✓		✓	✓
	Local Economy		✓			✓	✓

utilizes smart meters to measure electricity supply and demand. This project in Thailand is important to both business and residential consumers, which will have drastically different demand values. Ensuring ease of use and a high-quality interface encourages consumers to utilize and participate in the energy sharing community.

5. SUMMARY AND FUTURE RESEARCH

5.1. SUMMARY

As the total demand of electricity is increasing, the reliance on non-renewable energy can be offset by the creation of electricity from RESs. Because the accessibility to DGUs, many end-users will choose to invest in installation of RES reliant DGU. An effective, ecofriendly solution to the disruption of the classic distribution process is the incorporation of energy-sharing capabilities within a defined community [114]. There are many benefits to energy sharing including environmental sustainability, economic values, resilience, and social welfare, as defined in section 2. Based on the academic literature review and energy-sharing projects review, energy sharing is an efficient way to technologically upgrade the electricity distribution system for the utility to remain relevant as a necessary business. The research necessary in the future includes a quantitative approach to optimizing the energy sharing abilities of a defined community.

By continuing research of energy-sharing communities, further understanding of the strengths, weaknesses, and opportunities of incorporating energy sharing technology can be used to the benefit of community participants. Specifically, researching optimized business structures has the potential to benefit several participant point-of-views.

Additional simulation research allows for a quantitative perspective of energy-sharing communities to be analyzed. After implementation of energy sharing within a community, emergent features can be identified and elaborated on as is often done in the mature stages of concept development. Creating a safe and secure platform for energy sharing will be a constant consideration and may be developed throughout the research and implementation process of energy-sharing communities.

5.2. FUTURE RESEARCH

In order to continue developing understanding of energy sharing and the unintended impacts, further research should be performed. A range of research is beneficial to thoroughly understand quantitative and qualitative aspects of energy sharing. The future of energy sharing relies on providing RES electricity to end-users in an efficient, cost-effective manner. Though some energy-sharing communities may be newly constructed, it is possible for energy-sharing communities to be constructed using existing electricity distribution infrastructure. Using this paper as a reference, the future of energy sharing would involve autonomous smart-participants that consider both individual and collective system objectives. Systems should interact on a secure network that has the capacity to store necessary data without security concern. Installation of energy-sharing systems should be available to a large range of end-user demographic because of the significant improvement of reliability as well as potential consequential improvement of quality of life.

5.2.1. Utility Involvement. Energy sharing is changing the role of utilities. Current utility business models acknowledge end-user and company ownership of DGUs. The incorporation of energy sharing causes the need for utilities to evolve into less of a middle-man between end-users and large-scale generators and more of a distribution platform provider for all community end-users. This platform will acknowledge the versatility of prosumer end-users to be identified as both small-scale energy providers or consumers. Therefore, utilities need to change its business model to adapt to this change and capture new opportunities of revenue. Price re-evaluation is a potential solution to the loss of sales caused by the increase of DGU.

There is a research gap between energy sharing research and energy sharing implementation by utility companies [111]. Current research indicates that a central controller that optimizes utility electricity transactions is beneficial to the energy-sharing community as a whole. However, a significant amount of DGU installation is being done on an individual end-user basis. Creating a simulation that acts autonomously for independent end-users will provide a more realistic research foundation. A simulation model can be created to predict DGU investment by considering factors such as neighbor decision to invest in DGU, household income, and amount of people in the household. This simulation will provide a visual representation of end-user conversion from consumer to prosumer and potentially provide a general timeline as to how quickly community technologies should be upgraded.

5.2.2. Optimization. Energy sharing optimization requires the recognition of several participating entities and uncertainty in order to provide an accurate and reliable result. Using tools such as Monte Carlo simulation or multi-objective robust optimization takes into consideration the uncertainty associated with RES and human behavior while quantifying aspects such as profit or energy sharing incorporation. Quantified aspects can range significantly using optimization techniques. Using Monte Carlo simulation rate of consumers evolving into prosumers can be understood and used by the utility company to plan future investment opportunities to keep their business relevant [112,113].

Robust optimization that considers uncertainty provides end-users a more realistic insight when using HEMS. Using multi-objective robust optimization not only can the utility company use this tool to minimize cost, but variations of the optimization function could allow prosumer agents to maximize profits. Prosumer maximization of profits has a domino effect with regards to end-user lifestyles.

5.2.3. Emergent Aspects. State-of-the-art energy-sharing technologies are more available to higher income end-users because of the high investment cost. By identifying the fundamental necessities that energy sharing provides an improvement to, justification for implementing energy sharing throughout a diverse range of consumer demographics. Using a systems engineering approach, the qualitative impacts of communities engaging in energy sharing can be reviewed. Because qualitative impacts are sometimes emergent features, certain aspects may not be identified until after energy sharing has been integrated into communities.

Another benefit to qualitative research is specifying the impact on specific demographics. The causal model presented in this paper, Figure 2, represents the general impacts of incorporating energy sharing within a community. Future research of each of the defined aspects and their relation to the beneficial outcome can be done in either a quantitative or qualitative manner. Figure 2 provides the general conceptual framework linking energy sharing with the defined benefits. However, further research will provide a depth of information across the breadth of causal model linkages.

5.2.4. Security. Security of an energy-sharing community should be efficient, effective, and reliable. The purpose of a security system being incorporated with energy sharing is to minimize threats from outside entities. Recently, the adoption of blockchain in the energy industry has become an effective tool to not only create a safe sharing platform, but also keep data stored securely.

Also, there are concerns about systems with blockchain technology requiring as much energy as the energy-sharing DGUs produce. This large energy sink causes a lack of DGU produced electricity to supply to the energy-sharing community participants. From a systems engineering approach the optimal system architecture can be found and customized to the specific needs of the defined community.

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IV. COMPARING BEHAVIORAL THEORIES TO PREDICT CONSUMER INTEREST TO PARTICIPATE IN ENERGY SHARING

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ABSTRACT

Consumer investment in distributed energy resources (DERs) is increasing the amount of usable renewable energy sourced electricity. Some DERs produce more electricity than necessary, and this excess electricity is traditionally sold back to the utility (e.g., net metering). Implementing energy sharing allows an electricity distribution facilitator to redistribute DGU electricity to fellow community members. However, little is known about consumer interest in participating in this type of arrangement. Research on solar adoption suggests that innovative consumers with high novelty seeking and moral obligation to environmental sustainability express the most interest in residential photovoltaics (RPV) [18]. This study compares three behavioral theories, Value-Belief-Norm, Diffusion of Innovations, and Theory of Planned Behavior to predict consumer interest in participating in energy sharing. Using structural equation modeling, we evaluate survey data from 200 participants to determine which theory better fits the data. The results suggest that value-belief-norm is the better fit. This study has implications for effectively

marketing new products and services, such as energy sharing, to increase participation of end-users.

1. INTRODUCTION

As prices have decreased, interest in renewable energy has increased [1]. However, many consumers still face barriers to renewable procurement. One emerging strategy is energy sharing. End-users that invest in distributed energy resources (DERs), such as solar, are classified as prosumers because they have the ability to both consume and produce electricity [2]. Energy sharing provides a platform for electricity exchange between grid-connected participants in a specific region, such as a neighborhood [3]. However, energy sharing is limited to the community participants that subscribe to the service. To date, little is known about what factors influence interest in participating in energy sharing.

Energy-sharing management systems facilitate interactions between energy-sharing participants to maintain grid stability. Energy-sharing management systems can be incorporated into energy distribution systems as a way to decentralize the traditional hierarchical system [4]. A decentralized energy distribution system requires more connectivity between participants, but also minimizes transmission line loss. Additionally, energy-sharing participants rely on the energy-sharing management system to coordinate transactions between participants while maintaining system balance [5]. Consumers are encouraged to participate in energy-sharing communities because prosumers are able to set their own price to sell excess electricity. This allows consumers to purchase electricity at a reduced cost [6]. By redistributing excess prosumer electricity, prosumers are optimizing their investment by minimizing energy curtailment while also improving utility resource allocation [7, 8]. Energy curtailment occurs when there is more generation (or supply) than demand for electricity, particularly when renewable generation is limited due to concerns about grid stability [9]. Energy curtailment is considered an inefficiency because electricity production is restricted and not all produced electricity is used [10]. Therefore, minimizing electricity curtailment increases the efficiency of the energy system.

In this study, consumer interest in participating in energy sharing is predicted using two behavioral theories, (1) value-belief-norm (VBN), (2) diffusion of innovations (DOI), and Theory of Planned Behavior (TPB). We use structural equation modeling to determine which behavioral theory has the best fit with the data. Structural equation modeling is a statistical technique to measure relationships between observed and latent variables [11].

1.1. PREDICTING ENERGY SHARING PARTICIPATION

Energy-sharing facilitators are interested in predicting end-user interest to participate in energy-sharing communities. Predictions provide the facilitator with information to maximize energy-sharing system connectivity while minimizing loss and electricity curtailment [12]. Participation and community engagement have been examined using business models [13], optimization [14, 15], and demand side experience [16]. However, each of these approaches emphasizes the characteristics of the service provided to the end-user without consideration of end-user decision-making strategies, which tend to not be purely rational processes. To date, little research has investigated the correlations between consumer attitudes, values, and perceptions with interest to participate in an energy-sharing service. Conradie et al. (2021) found that attitudes toward renewable energy is a significant factor when determining consumer intent to participate in a renewable energy community. This is consistent with Wolske et al.'s (2017) finding that favorable attitudes about the technology provide a good representation of interest, because attitude takes into consideration both intrinsic and extrinsic motivations. Better understanding consumer preferences can benefit a potential energy-sharing facilitator by opening up opportunities to customize the service to best suit a community's needs.

To date, most research on energy sharing has focused on technology development. A few studies have used optimization as an approach for predicting interactions between communities, rather than participation in energy sharing. Liu & Guo (2017) predict interactions of integrated direct current-linked microgrids. Using smart systems in the Internet of Things (IoT), an optimization model developed for the energy management system is used to increase the usage of renewable energy [20]. In order to encourage autonomous activity, Islam et al. (2020) developed an optimization-based algorithm to improve grid resilience. However, these studies fail to accurately represent the dynamics of consumer adoption and potential implications for the energy sharing system.

Behavioral theories have been applied to sharing economy topics, such as acceptance of electric vehicle sharing [21], adoption of solar technologies [18], and energy conservation behavior [22, 23]. Using behavioral theories, outcomes of interest can be explained using latent and observable variables [24]. Wolske (2017) develops an integrated behavioral model that consists of influential aspects from two theories: (1) VBN and (2) DOI. Due to the novelty of the technology and business model, little work has focused on energy sharing directly.

2. BEHAVIORAL THEORIES

2.1. VALUE-BELIEF-NORM

VBN uses three factors, values, beliefs, and norms, to explain consumer behaviors [25]. VBN combines value theory, which identifies the importance of attributes, with the norm-activation model, which explains altruistic and environmentally friendly behaviors [26, 27]. VBN was initially created to explain peoples' actions based on personal obligation and self-expectations [28].

In previous studies, VBN is useful for predicting pro-environmental behavior [29], willingness to pay for the reduction of noise pollution [30], and environmental activism [31]. Stern et al. (1999) use VBN to explain support for social movements and finds that an individual will support a movement when their values are threatened, and the individual believes their actions can assist in the restoration of threatened values. Andersson et al. (2013) use VBN to investigate students' attitudes of sustainable development through Education for Sustainable Development.

In the context of energy sharing, VBN can be used to predict consumer interest in participating in sustainable systems. VBN uses environmental values, in conjunction with awareness of consequences to explain the outcome of interest. Environmental values are addressed by providing access to additional renewable energy sourced electricity. Consumer feeling of obligation to act in a way consistent to their morals and values is referred to as internal obligation. Internal obligation is related to constructs used to defined values within the VBN model. If VBN is the best fitting theory, this suggests that values are most important for predicting interest in energy sharing.

2.2. DIFFUSION OF INNOVATION

DOI uses the dissemination of new technologies or ideas to explain consumer reactions [33]. DOI takes into consideration dissemination, implementation, sustainability, improvement activity, and scale-up [34]. These features allow for successful diffusion of designs and inventions. Both perceived innovativeness and the effectiveness of communication channels predict perceptions of the innovation [35].

Previous research has used DOI to predict acceptance of new technologies related to the education system , health care innovation [36], and sustainable systems [37]. Al Othman & Sohaib (2016) use DOI to enhance innovation and sustainability of Saudi firms. By understanding the interactions and interrelationships between organizational innovation and socio-technical factors, the Saudi Arabian government is provided the knowledge to develop a plan for integrated a knowledge-based economy. Encouraging communities to participate in local business models like energy sharing can be emphasized through diffusion of innovation [39]. Previous studies apply DOI to the energy sector, however no studies have used DOI to predict consumer participation in energy-sharing communities.

In the context of energy sharing, DOI can explain consumer interest in participating in a novel approach to energy distribution. Though decentralized systems are a well-known approach, like blockchain or restaurant chains, energy sharing has yet to become a highly commercialized system. Using this research, if DOI is identified as the best-fitting model, companies will be able to justify their implementing energy sharing in a more technologically savvy geographic area because of the positive reception to new innovations.

2.3. THEORY OF PLANNED BEHAVIOR

The Theory of Reasoned Action (TRA) laid a foundation for the TPB to use conditional variables to better predict behavioral intention [40]. Three different TPB models were developed and compared using structural equation modeling. Various fit indices of these structural models were analyzed and used to determine that traditional TRA and TRB models provide consistent results with previous studies [41]. TPB predicts behavior intentions with significant accuracy. However, there is a lack of defined independent relationship correlation between attitude, subjective norm, and perceived behavioral control and intention [42].

Using the financial market as the research field, Shih & Fang (2004) use the TPB to predict customers' intention to adopt internet banking in Taiwan. The results of the TPB model are then compared to the TRA and structural equation modeling is used as an analysis method. Ambrosio-Albala et al. (2020) use TPB to evaluate the acceptance of decentralized energy storage technologies, specifically batteries, at both household and community (neighborhood) levels. There is low familiarity with the topic of storing energy. However, the perceived overall benefits tend to improve consumer opinions. Participants overall had a positive perspective towards energy storage.

In the context of energy sharing, TPB evaluates consumer intention based on attributes unique to each consumer. The three categories used to define TPB (attitude, subjective norm, and perceived behavioral control) provide the researcher with diverse attributes of each individual. This accounts for a diverse range of qualities that could be unique to each energy-sharing participant. This is especially important to energy sharing because it is a decentralized system that relies on the five system characteristics as described by Boardman and Sauser (2006): (1) autonomy, (2) belonging, (3) connectivity, (4) diversity, and (5) emergence.

Table 1. Similarities and differences between the three theories

	Attitude	**External Influences**	**Internal Influences**	**Moral Considerations**	**Change over Time**
Value-Belief-Norm	X	X	X	X	
Diffusion of Innovations			X		X
Theory of Planned Behavior	X	X	X	X	

Across all theories, VBN, DOI, and TPB, all attempt to understand consumer behavior influenced by decision making characteristics. Table 1 shows similarities and differences between the two theories. Attitude refers to acknowledging consumer emotions, beliefs, and behaviors that will influence the decision making [18]. External influences include communication channel factors while internal influences are factors related to culture and values. Moral considerations refer to the sense of obligation to benefit others because one has already received a benefit [18]. Change over time refers to acknowledging the adoption rate of a product or service over a certain period of time [33].

3. METHODS

3.1. PARTICIPANTS

We recruited 200 participants on Prolific for a study on "energy sharing technology" in February 2021. Prolific is an online platform used to recruit participants that meet researchers' expectations for scientific studies [46]. Amazon Mechanical Turk (MTurk) offers similar services to Prolific. However, Prolific provides more diverse participants [47] that better represent the demographics of national samples [48]. This sample size is consistent with the recommended minimum sample size to ensure adequate power [49, 50]. Eligible participants were current residents of the United States and at least 18 years old. All participants were paid $3 for a 15-20 minute survey.

3.2. MEASURES

This survey applies two the same behavioral theories and approach identified in Wolske, Stern & Dietz (2017), for residential solar adoption, to residential energy sharing participation. In general, most scales were measured on a 5-point Likert scale [51], where 1 = strongly disagree and 5 = strongly agree. We also included an "I don't know" option to avoid over-estimation at the neutral point of the scale [52]. This was particularly important, given that energy sharing is a new technology that participants might be unfamiliar with. Responses of "I don't know" were treated as missing values. For each scale, we conducted a confirmatory factor analysis. For convenience, the scales are described in the text and summarized in Tables 3 and 4.

Ultimately, the outcome variable is *interest in energy sharing*. This is estimated by the mean of four questions that measure interest, "I would be happy to participate in energy sharing even if I have to pay for the total cost", "I would switch to energy sharing if I was considering changing my electricity supplier", "I would support having energy sharing in my area", and "I have a positive overall evaluation of energy sharing" (Cronbach's

α=0.81). Since participants would have few opportunities to participate in energy sharing in the real world, we did not include a measure of behavior due to concerns about validity.

As a precursor to interest in energy sharing, we measured *social curiosity*. This is measured by three items to estimate interest in learning about costs and benefits if a friend, family member, or neighbor participated in energy sharing "I would be interested in learning about the cost and benefits of energy sharing if a [friend/family member/neighbor] participated in energy sharing" (Cronbach's α=0.87). Social curiosity is a weaker version of interest that relies on perceptions of the social environment [53].

3.2.1. Value-Belief-Norm. VBN includes estimates of values, which predict beliefs, which predict norms, which predicts social curiosity and interest (see Figure 1a). Values include altruism, self-interest, traditional values, and openness to change. All measures were consistent with the standard items from the literature [54]. *Biospheric and social altruism* is measured by four items evaluated on a 5-point Likert scale where 1 = not important and 5 = extremely important with an additional "opposed to my values" option (coded as -1). Participants report how closely each statement resembles guiding principles in their life. The statements include "Respecting the Earth, harmony with other species", "Protecting the environment, preserving nature", "A world at peace, free of war and conflict", and "Unity with nature, fitting into nature" (Cronbach's α=0.90). Similarly, *self-interest* is measured by three statements including "Wealth, material possessions, money", "Authority, the right to lead or command", and "Influential, having an impact on people and events" (Cronbach's α=0.73). *Traditional values* include three statements, "Honoring parents and elders, showing respect", "Family security, safety for loved ones", and "Self-discipline, self-restraint, resistance to temptation" (Cronbach's α=0.74). *Openness to* *change* is measured by three statements including "Curious, interested in everything, exploring", "A varied life, filled with challenge, novelty, and change", and "An exciting life, stimulating experiences" (Cronbach's α=0.85).

To measure beliefs, *awareness of consequences* is estimated by a single item, "Climate change is a serious problem for society." Wolske, Stern, and Dietz (2017) found that a single item was sufficient due to the existence of strong, polarized views on climate change. Their analysis suggests that using a single item here does not affect the estimation of relationships between other variables. To measure norms, *personal norm* is estimated by 3 items, "I feel a personal obligation to do my part to move the country to a renewable energy future", "I feel a personal obligation to do my part to prevent climate change", and "I feel guilty when I waste energy" (Cronbach's α=0.90).

3.2.2 Diffusion of Innovation. DOI presumes that consumer innovativeness and communication channels influence the perceived characteristics of the innovation, which predict social curiosity and interest (see Figure 1b). Consumer innovativeness is comprised of consumer novelty seeking [55] and consumer independent judgement [56]. *Consumer novelty seeking* is measured by three items that include "I continuously look for new experiences from new products", "I continuously look for new products and brands", and "I like to visit places where I'm exposed to information about new products and brands" (Cronbach's α=0.87). *Consumer independent judgment* is measured by three items that include "Before I buy a new product or service, I often ask acquaintances about their experiences with that product or service", "Before buying a new brand, I usually ask someone who has experience with the brand for advice", "When considering a new product/service, I usually trust the opinions of friends who have used the product/service" (Cronbach's α=0.65).

The perceived characteristics of the innovation include relative advantage, trialability, riskiness, complexity, and observability. *Relative advantage* is measured by six items, "Participating in energy sharing would save me money", "Participating in energy sharing provides a great return on a prosumer's investment", "Participating in energy sharing will help protect my family from rising electricity prices in the future", "Participating in energy sharing would help meet my family's needs", "Participating in energy sharing could protect my family from electricity blackouts", and "Participating in energy sharing would increase my property value" (Cronbach's α=0.78). *Riskiness* is measured by six items [57], "I would worry about participating in energy sharing because it would be an unfamiliar experience", "Participating in energy sharing is a risky thing for a household to do", "Participating in energy sharing could damage my home", "I think energy sharing for residential use is not yet a mature technology", "I don't like the idea of being connected to a server and sharing my energy usage data", "Energy sharing, as described, entails many risks" (Cronbach's α=0.78). *Complexity* is measured by 3 items, "Participating in energy sharing is a hassle", "There is a lot of paperwork involved in participating in energy sharing", "Participating in energy sharing takes a lot of time" (Cronbach's α=0.73). *Trialability* is measured by five items, "Before contacting an energy-sharing facilitator, I would like to see the participation process up close", "Before considering energy sharing, I would like to talk to someone who uses energy sharing", "If an energy-sharing facilitator tells me how much I would save on my electricity bills by installing solar, I would want a second opinion", and "I would be more interested in energy sharing if there were some way for me to try it out before signing a contract" (Cronbach's α=0.81). *Observability* is measured by two items, "I can tell if a community has energy sharing" and "In a community with energy sharing, I can tell who is and is not participating" (Cronbach's α=0.90). We anticipate that observability will be a weak predictor.

Communication channels include measures of real-world experience with energy sharing, marketing exposure, institutional trust, and trust in social network. *Real-world experience with energy sharing* is measured via four items, "A friend or neighbor has recently participated in energy sharing", "I know more than one person that participates in energy sharing", "Several people in my neighborhood participate in energy sharing", "I have talked about energy sharing with someone who has already installed the energy-sharing technology in their house" (Cronbach's α=0.94). *Exposure to energy-sharing marketing* is measured by two items, "In the last six months, I have seen or heard advertisements from companies that facilitate energy sharing" and "My family has recently received advertising or a call from a company that facilitates energy sharing" (Cronbach's α=0.66). All six of these items are measured as a Yes or No answer. We anticipated that few participants would have real-world experience or exposure to marketing for energy sharing. *Industry trust* is measured by three items [58], "I would support having energy sharing in my area regardless of the facilitator", "I would trust any energy-sharing facilitator to make good decisions about energy-sharing technologies", and "I trust any energy-sharing facilitator to keep my best interest in mind" (Cronbach's α=0.85). *Trust in social network* is measured by three items, "I trust my friends", "I trust my family", and "I trust my neighbors" (Cronbach's α=0.60).

3.2.3 Theory of Planned Behavior. In TPB, attitudes, subjective norms, and perceived behavioral control predict social curiosity and interest. Attitudes are predicted by personal and environmental benefits, perceived risks, expense concerns, and waiting for improvements. *Personal benefits* are the same as *Relative Advantage* in the DOI model. The six items used to measure *personal benefits* are , “Participating in energy sharing would save me money”, “Participating in energy sharing provides a great return on a prosumer's investment”, “Participating in energy sharing will help protect my family from rising electricity prices in the future”, “Participating in energy sharing would help meet my family's needs”, “Participating in energy sharing could protect my family from electricity blackouts”, and “Participating in energy sharing would increase my property value” (Cronbach’s α=0.756). *Environmental benefits* are measured by six items [44], “Energy sharing helps slow down climate change”, “If more households participate in energy sharing, environmental quality will improve”, “Participating in energy sharing would be a good way to reduce my environmental impact”, “I think of myself as someone who is very concerned with environmental issues”, “I think of myself as an environmentally-friendly consumer”, and “I would be embarrassed to be seen as having an environmentally-friendly lifestyle” (Cronbach’s α=0.663). *Perceived risks* is the same as riskiness in DOI which is measured by six items [44], “I would worry about participating in energy sharing because it would be an unfamiliar experience”, “Participating in energy sharing is a risky thing for a household to do”, “Participating in energy sharing could damage my home”, “I think energy sharing for residential use is not yet a mature technology”, “I don't like the idea of being connected to a server and sharing my energy usage data”, “Energy sharing, as described, entails many risks” (Cronbach’s α=0.749). *Expense concerns* are measured by three items, “I can't afford to participate in energy sharing on my family budget”, “For prosumers, solar is still very expensive, even with government subsidies”, and “For prosumers, maintaining solar is expensive” (Cronbach’s α=0.506). *Waiting for improvements* is measured by two items, “For prosumers, the price of solar keeps going down, so it is wise to wait before deciding whether to install it” and “The technologies that facilitate an energy-sharing marketplace will only get better, so it doesn't make sense to sign-up now” (Cronbach’s α=0.507).

Subjective norms are predicted by normative beliefs. *Normative beliefs* are measured by one item [43], “Most people who are important to me would support me if I decided to participate in energy sharing”.

Perceived behavioral control is predicted by perceived unsuitability, expectations to move and self-efficacy. *Perceived unsuitability* is measured by five items [44], “It's not sunny enough in my area for prosumers to invest in solar”, “It's too cloudy where I live for prosumers to invest in solar”, “At my home, I can’t be a prosumer because there's no place to put solar”, “I am not convinced of the need for energy sharing where I live”, and “I think the area where I live is not suitable for energy sharing” (Cronbach’s α=0.786). *Expectations to move* is measured by a single item, “I may not be in my home long enough to see the benefits of participating in energy sharing as a prosumer”. *Self-efficacy* is measured by three items [43], “It is important to me to feel comfortable participating in energy sharing”, “I would feel comfortable participating in energy sharing”, and “I have the knowledge to participate in energy sharing” (Cronbach’s α=0.332).

3.3. PROCEDURE

Because this was an observational study, there were no experimental conditions. A fictional energy-sharing facilitator was described to the survey participants, where they could participate as a prosumer or consumer. This fictional facilitator, E-topia, had a defined mission to encourage the generation and consumption of solar energy throughout the neighborhood. We described necessary energy-sharing technologies for participation, which included wi-fi enabled smart meters and a mobile app to set a budget or price depending on the participation type. Participants were asked to answer the survey questions given this E-topia platform information.

The survey questions were split into three categories, (1) attribute, (2) area, and (3) overall. This structure is an approach to minimize order effects suggested by Schreier et al. (2018). Each category consists of questions that are randomized. At the end of the survey, participants were asked about their perception of three types of energy-sharing facilitators, a third-party non-profit, local utility, and a third-party for-profit. Lastly, participants were asked demographic questions including gender, age, education level, race, employment status, annual income, and electricity supplier.

3.4. ANALYSIS

To estimate and evaluate the fit of each behavioral theory, we used structural equation modeling (SEM). To ensure robustness, we estimated the relationships using the lavaan package in R [60, 61]. The lavaan package explains latent variables using observed variables through a variety of models including confirmatory factor analysis, structural equation modeling, and latent growth curve models. SEM is a modeling technique that uses a combination of complex path models with latent variables [62, 63]. SEM is the preferred approach because complex structures can be understood based on interactions of latent variables [64]. This analysis was preregistered on the Open Science Framework website (https://osf.io/k78vn/). Based on pilot survey results, we modified the wording of the comprehension checks after preregistration.

There are six primary steps in SEM, model (1) specification, (2) identification, (3) data preparation, (4) estimation, (5) evaluation, and (6) modification [65]. Model specification involves identifying predicted relationships between variables (see Figure 1). Once the data are collected, we examine Pearson correlations to understand the relationships between variables. In model identification, we perform a confirmatory factor analysis to ensure all model parameters are identified. The confirmatory factor analysis measures the loading of each indicator variable (or question) on latent variables as described in italics above [66]. In model estimation, we perform SEM.

In model evaluation, we examine the estimated parameters, variances, and fit indices including comparative fit index (CFI), Cronbach's alpha, standard loadings, and correlation. CFI values are always between 0 and 1, where a value closer to 1 indicates a better fit. Cronbach's alpha indicates model consistency. A Cronbach's alpha value greater than 0.7 is considered good. When analyzing standard loadings, a value of 0.7 indicates sufficient variance is explained [67]. Lastly, in model modification, we can conduct post-hoc changes to improve model fit [68].

4. RESULTS AND DISCUSSION

4.1. SAMPLE

A total of 200 participants consented to participate in this research and completed the survey. Of those, 5 participants were removed because of data quality issues. They either reported that we should not use their data because they did not take the survey seriously or provided the same response to all of the Likert questions (N = 195). In the sample, 100 participants identified as male (51%), 91 identified as female (47%), and 3 chose other options. Participants ranged from 18 to 78 years old (*M* = 33, *Med* = 35, *SD* = 12). The majority of the participants were employed full time (120, 62%) while 26 were employed part time (13%), 25 were students (13%), and 35 chose other options (18%). There were a wide range of annual salaries, with most participants earning less than $60,000/year (112, 57%) and 79 participants earning more than $60,000/year (41%). As expected, most participants (131, 67%) had not heard of energy sharing before this study.

4.2. MODEL SPECIFICATION AND IDENTIFICATION

The proposed models for both behavioral theories are summarized in Figure 1. Overall, participants were open to participating in energy sharing as either a consumer or prosumer (see Table 1). Based on the similar pattern of responses for consumer and prosumer participation, it does not appear that participants clearly distinguished between these two modes of participation (e.g., expressing less interest in participation as a prosumer due to barriers associated with installing solar on their home). Confirmatory factor analysis (CFA) is used to evaluate how well measured variables represent defined latent constructs. For this research, measured variables are the questions presented to the survey participants.

Using CFA, we ensure that the latent variables are measured by their associated questions. Across all of the variables, real world experience had the lowest standardized loading values. This may be explained by the novelty of energy sharing, thus few participants had experience with it. The correlations for each model are summarized in Tables 4-6.

Table 2. Participant responses when asked if they would be willing to participate in energy sharing in the future as either a consumer or prosumer

	Strongly Disagree	Somewhat Disagree	Neither Agree Nor Disagree	Somewhat Agree	Strongly Agree	Don't Know
Consumer	9 (4.61%)	18 (9.23%)	24 (12.3%)	68 (34.9%)	68 (34.9%)	8 (4.10%)
Prosumer	5 (2.56%)	16 (8.20%)	25 (12.8%)	64 (32.8%)	73 (37.4%)	12 (6.15%)

4.3. MODEL ESTIMATION

4.3.1. Value-Belief-Norm Model. The model fit for VBN is unacceptable (CFI = 0.87) and below the desired threshold of 0.9 (see Table 4) [69]. Also, the other fit metrics do not meet the desired thresholds, TLI = 0.85 < 0.9 and SRMR = 0.15 > 0.08. As expected, social curiosity, personal norms, and awareness of consequences all positively predicted interest in energy sharing in the path model (see Figure 2). Self-interest has the weakest significance, likely due to weak loading of the first question increasing observed variance (see Table 4). While altruism and self-interest were positively related to awareness of consequences, traditional values were negatively related. Openness to change was not a

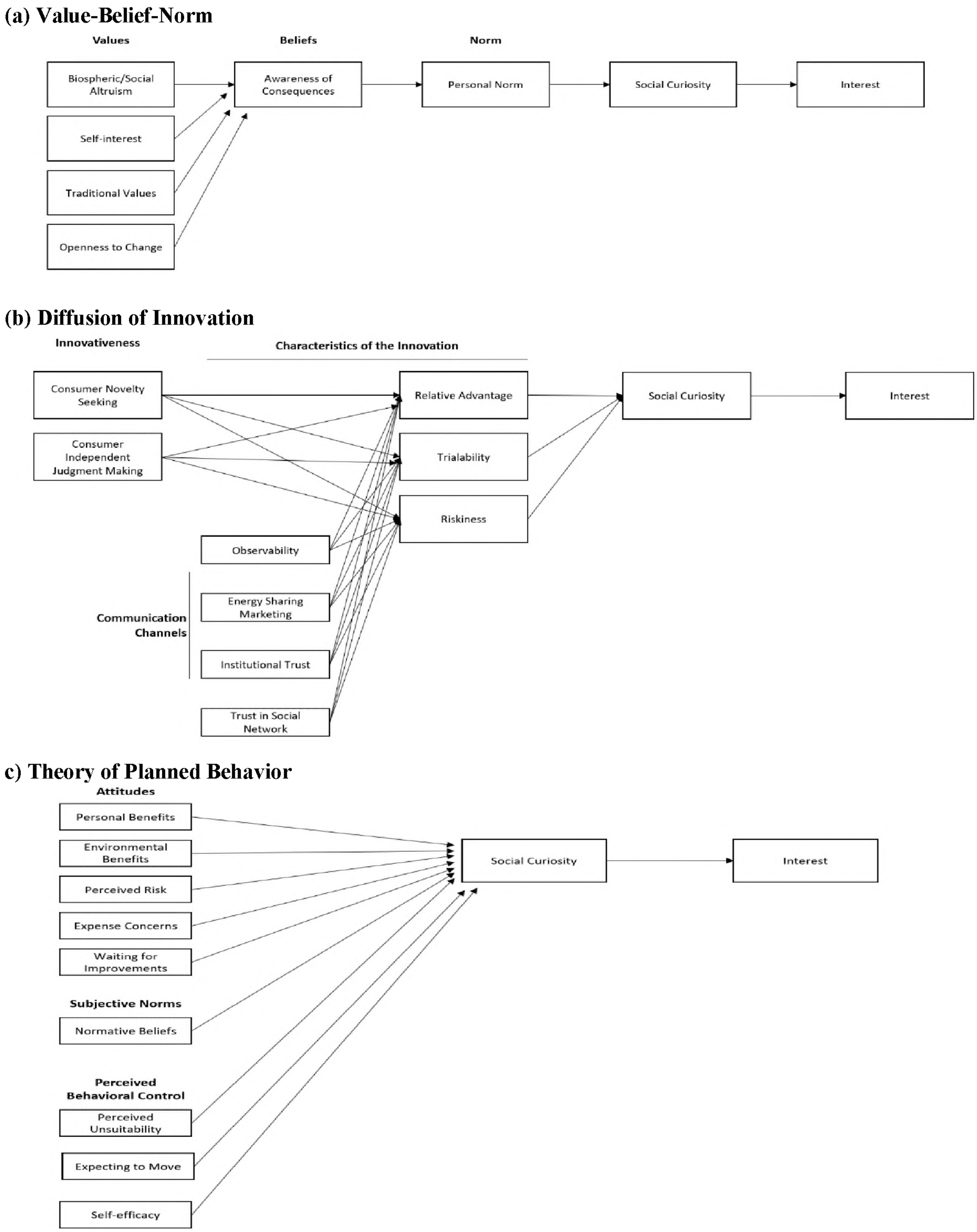

Figure 1. Proposed path models for (a) Value-Belief-Norm, (b) Diffusion of Innovation, and (c) Theory of Planned Behavior

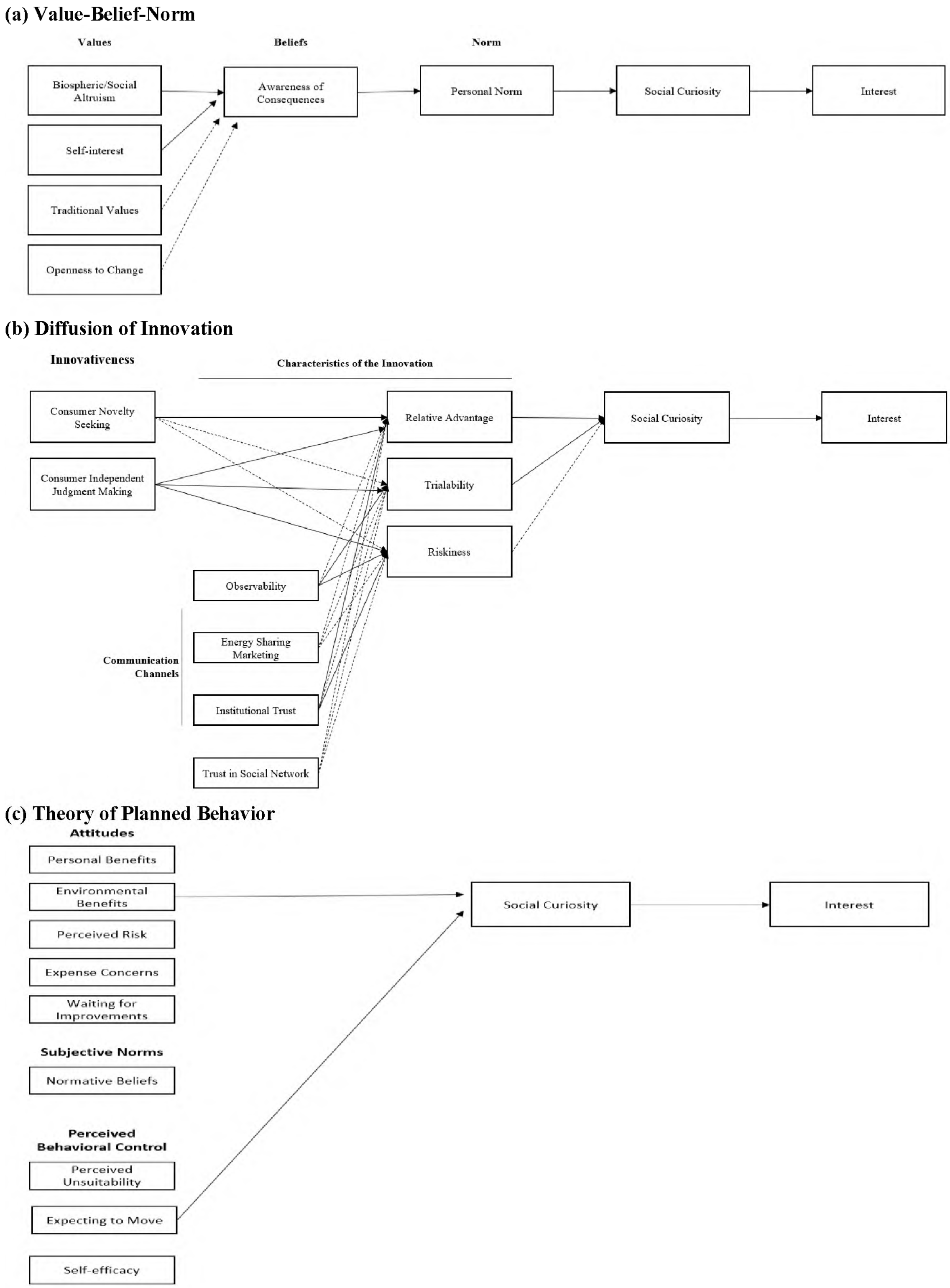

Figure 2. Significant SEM pathways. Significant and positive relationships are indicated by a solid line, while negative relationships are indicated with a dashed line

Table 3. Summary of standardized factor loadings in combined confirmatory factor analysis for outcome variables interest in energy sharing and social curiosity

Outcome Variables	N	*Mean (SD)* Std Ldg
Interest in Energy Sharing (Cronbach's α=0.81)		*3.88 (0.83)*
I would be happy to participate in energy sharing even if I have to pay for the total cost	180	0.47
I would switch to energy sharing if I was considering changing my electricity supplier	183	0.75
I would support having energy sharing in my area	192	0.86
I have a positive overall evaluation of energy sharing	192	0.87
Social Curiosity (Cronbach's α=0.87)		*4.26 (0.81)*
I would be interested in learning about the cost and benefits of energy sharing if a friend participated in energy sharing	194	0.91
I would be interested in learning about the cost and benefits of energy sharing if a family member participated in energy sharing	194	0.86
I would be interested in learning about the cost and benefits of energy sharing if a neighbor participated in energy sharing	194	0.76

Table 4. Summary of standardized factor loadings in combined factor analysis for VBN

Value-Belief-Norm (CFI = 0.903)	N	*Mean (SD)* Std Ldg
Altruism (Cronbach's α=0.90)		*5.06 (0.96)*
Respecting the Earth, harmony with other species	194	0.93
Protecting the environment, preserving nature	195	0.92
A world at peace, free of war and conflict	193	0.64
Unity with nature, fitting into nature	194	0.84
Self-Interest (Cronbach's α=0.73)		*3.35 (1.14)*
Wealth, material possessions, money	194	0.45
Authority, the right to lead or command	193	0.81
Influential, having an impact on people and events	193	0.83
Traditional Values (Cronbach's α=0.74)		*4.75 (0.92)*
Honoring parents and elders, showing respect	195	0.85
Family security, safety for loved ones	194	0.58
Self-discipline, self-restraint, resistance to temptation	194	0.66
Openness to Change (Cronbach's α=0.85)		*4.68 (1.03)*
Curious, interested in everything, exploring	194	0.69
A varied life, filled with challenge, novelty, and change	195	0.83
An exciting life, stimulating experiences	195	0.93
Awareness of Consequences		*4.51 (1.01)*
Climate change is a serious problem for society	193	1.00
Personal Norm (Cronbach's α=0.90)		*4.02 (1.03)*
I feel a personal obligation to do my part to move the country to a renewable energy future	192	0.92
I feel a personal obligation to do my part to prevent climate change	192	0.96
I feel guilty when I waste energy	193	0.73

Table 5. Summary of standardized factor loadings in combined factor analysis for DOI

Diffusion of Innovation (CFI = 0.73)	**N**	***Mean (SD)*** **Std Ldg**
Novelty Seeking (Cronbach's α=0.87)		*3.65 (1.02)*
I continuously look for new experiences from new products	194	0.84
I continuously look for new products and brands	194	0.94
I like to visit places where I'm exposed to information and new products and brands	194	0.74
Independent Judgement (Cronbach's α=0.65)		*4.12 (0.71)*
Before I buy a new product or service, I often ask acquaintances about their experiences with that product or service	195	0.84
Before buying a new brand, I usually ask someone who has experience with the brand for advice	195	0.72
When considering a new product/service, I usually trust the opinions of friends who have used the product/service	194	0.37
Relative Advantage (Cronbach's α=0.78)		*4.20 (0.61)*
Participating in energy sharing would save me money	185	0.57
Participating in energy sharing provides a great return on a family's investment	185	0.68
Participating in energy sharing will help protect my family from rising electricity prices in the future	186	0.85
Participating in energy sharing would help meet my family's needs	190	0.77
Participating in energy sharing could protect my family from electricity blackouts	171	0.38
Participating in energy sharing would increase my sense of community	172	0.53
Riskiness (Cronbach's α=0.78)		*2.69 (0.89)*
I would worry about participating in energy sharing because it would be an unfamiliar experience	191	0.64
Participating in energy sharing is a risky thing for a household to do	185	0.76
Participating in energy sharing could damage my home	177	0.70
I think energy sharing for residential use is not yet a mature system	176	0.38
I don't like the idea of being connected to a server and sharing my energy usage data	183	0.61
Energy sharing, as described, entails many risks	193	0.68
Complexity (Cronbach's α=0.73)		*2.80 (0.96)*
Participating in energy sharing is a hassle	185	0.72
There is a lot of paperwork involved in participating in energy sharing	154	0.68
Participating in energy sharing takes a lot of time	175	0.67
Trialability (Cronbach's α=0.81)		*4.21 (0.69)*
Before contacting an energy sharing facilitator, I would like to see the technology up close in someone else's house	195	0.76
Before considering energy sharing, I would like to talk to someone who has energy sharing in their home	195	0.88
If an energy sharing facilitator tells me how much I would save on my electricity bills by installing solar, I would want a second opinion	193	0.42
I would be more interested in energy sharing if there were some way for me to try it out before installing it	194	0.82
Observability (Cronbach's α=0.90)		*1.84 (0.94)*
I can tell if a community has energy sharing	178	0.96
In a community with energy sharing, I can tell who is participating and who is not	177	0.86
Real World Experience (Cronbach's α=0.94)		*1.72 (1.01)*
A friend or neighbor has recently participated in energy sharing	150	0.91
I know more than one person that participates in energy sharing	178	0.94
Several people in my neighborhood participate in energy sharing	148	0.90
I have talked about energy sharing with someone who has already installed an energy sharing system in their home	192	0.83
Marketing Exposure (Cronbach's α=0.66)		*1.94 (0.21)*
In the last six months, I have seen or heard advertisements from companies that facilitate energy sharing	195	0.93
My family has recently received advertising or a call from a company that facilitates energy sharing	195	0.60
Industry Trust (Cronbach's α=0.85)		*3.13 (1.18)*
Companies that provide or facilitate energy sharing	186	0.84
Energy sharing industry trade organizations	189	0.88
Social Trust (Cronbach's α=0.60)		*4.17 (0.63)*
I trust my friends	193	0.57
I trust my family	193	0.95
I trust my neighbors	194	0.33

Table 6. Summary of standardized factor loadings in combined factor analysis for TPB

Theory of Planned Behavior (CFI = 0.773)	**N**	***Mean (SD)*** **Std Ldg**
Relative Advantage (see DOI)		
Environmental Benefits (Cronbach's α=0.84)		*3.68 (0.61)*
Energy sharing helps slow down climate change	182	0.76
If more households participate in energy sharing, environmental quality will improve	181	0.83
Participating in energy sharing would be a good way to reduce my environmental impact	187	0.83
I think of myself as someone who is very concerned with environmental issues	194	0.68
I think of myself as an environmentally-friendly consumer	193	0.56
I would be embarrassed to be seen as having an environmentally-friendly lifestyle	194	0.48
Riskiness (see DOI)		
Expense Concerns (Cronbach's α=0.59)		*3.17 (0.98)*
I can't afford to participate in energy sharing on my family budget	174	0.75
For prosumers, solar is still very expensive, even with government subsidies	166	0.55
Improvements (Cronbach's α=0.72)		*3.05 (1.00)*
The prices of investing in distributed energy resources keep going down, so it is wise to wait before deciding whether to install it	166	0.88
Distributed energy resource technology will only get better, so it doesn't make sense to get them now	179	0.64
Normative		*4.09 (0.91)*
Most people who are important to me would support me if I decided to participate in energy sharing	184	1.00
Unsuitability (Cronbach's α=0.79)		*0.619 (0.18)*
It's not sunny enough in my area for energy sharing to work well	179	0.54
It's too cloudy where I live for energy sharing to be effective	188	0.37
At my home, there's no place to put an energy sharing system	185	0.41
I am not convinced of the need for energy sharing where I live	185	0.92
I think the area where I live is not suitable for energy sharing	185	0.93
Expect to Move		*2.42 (0.96)*
I may not be in my home long enough to the benefits of participating in energy sharing	188	1.00
Self-Efficacy Cronbach's α=0.45)		*2.93 (1.38)*
It is important to me to feel comfortable participating in energy sharing	190	0.14
I would feel comfortable participating in energy sharing	188	0.88
I have the knowledge to participate in energy sharing	187	0.53

Table 7. Correlation table of scales and constructs for VBN where *p<0.05, ** p<0.01, ***p<0.001

	1	2	3	4	5	6	7
1. Interest							
2. Social Curiosity	0.69***						
3. Altruism	0.41***	0.36***					
4. Self-Interest	0.15*	0.17*	0.12				
5. Traditional Values	0.10	0.05	0.36***	0.35***			
6. Openness to Change	0.30***	0.29***	0.28***	0.21**	0.18**		
7. Awareness of Consequences	0.40***	0.37***	0.36***	0.07	-0.14	0.05	
8. Personal Norm	0.55***	0.44***	0.61***	0.12	0.09	0.19**	0.69***

Table 8. Correlation table of scales and constructs for DOI where *p<0.05, ** p<0.01, ***p<0.001

	1	2	3	4	5	6	7	8	9	10	11	12
1. Interest												
2. Social Curiosity	0.69***											
3. Novelty Seeking	0.38***	0.31***										
4. Independent Judgment	0.27***	0.36***	0.34***									
5. Relative Advantage	0.57***	0.33***	0.38***	0.21**								
6. Riskiness	-0.53***	-0.32***	-0.28***	-0.11	-0.40***							
7. Complexity	-0.36***	-0.24***	-0.15*	-0.11	-0.26***	0.71***						
8. Trialability	-0.08	0.10	0.04	0.27***	0.03	0.21**	0.11					
9. Observability	0.03	-0.01	0.16*	-0.06	0.03	0.17*	0.27***	-0.14*				
10. Real World Experience	0.10	0.03	0.21**	-0.02	0.08	0.15*	0.24**	-0.22**	0.91***			
11. Marketing Exposure	-0.09	-0.12	-0.06	0.07	-0.08	0.03	-0.03	0.00	-0.35***	-0.34***		
12. Industry Trust	0.45***	0.27***	0.33***	0.21**	0.42***	-0.35***	-0.24***	-0.11	0.29***	0.33***	-0.18*	
13. Social Trust	0.07	0.21**	0.17*	0.28***	0.08	-0.05	-0.08	0.07	-0.06	-0.03	-0.13	0.22**

Table 9. Correlation table of scales and constructs for TPB where *$p<0.05$, ** $p<0.01$, ***$p<0.001$

	1	2	3	4	5	6	7	8
1. Interest								
2. Social Curiosity	0.69***							
3. Environmental Benefits	0.56***	0.48***						
4. Expense Concerns	-0.40***	-0.31***	-0.31***					
5. Improvements	-0.22**	-0.14	-0.42***	0.34***				
6. Normative	0.48***	0.40***	0.41***	-0.26***	-0.22**			
7. Unsuitability	-0.48***	-0.34***	-0.45***	0.36***	0.38***	-0.34***		
8. Expect to Move	-0.13	0.01	-0.27***	0.35***	0.23**	-0.06	0.40***	
9. Self-Efficacy	0.45***	0.36***	0.44***	-0.33***	-0.29***	0.24***	-0.31***	-0.17*

Table 10. SEM path coefficients and model fit metrics for VBN where *p<0.05, ** p<0.01, ***p<0.001

Path	**β**	**SE**	***p*-value**
Interest ~ Social Curiosity	0.78	0.11	< 0.001 ***
Social Curiosity ~ Personal Norms	0.49	0.06	< 0.001 ***
Personal Norms ~ Awareness of Consequences	0.74	0.06	< 0.001 ***
Awareness of Consequences ~ Altruism	0.63	0.08	< 0.001 ***
Awareness of Consequences ~ Self-Interest	0.34	0.20	0.004 **
Awareness of Consequences ~ Traditional Values	-0.58	0.11	< 0.001 ***
Awareness of Consequences ~ Openness to Change	-0.15	0.10	0.05
CFI	0.87		
TLI	0.85		
AIC	9,702		
SRMR	0.147		

significant predictor of awareness of consequences. This is largely consistent with the model of solar adoption measured by Wolske et al. (2017). However, in this model, self-interest is a positive predictor of awareness of consequences. In the confirmatory factor analysis, self-interest is largely explained by values related to authority and influence, but not wealth. It is possible that energy sharing aligns with values related to control because the participants are able to set thresholds for how to buy and sell renewable electricity.

4.3.2. Diffusion of Innovation Model. Despite including more variables, the model fit (CFI = 0.71) was lower and below the desired threshold (< 0.9) for the DOI model. As expected, social curiosity positively predicted interest in participating in energy sharing. Although trialability and riskiness predicted social curiosity, relative advantage was not a significant predictor. Trialability was predicted by independent judgement. Riskiness was predicted by observability, novelty seeking, and industry trust. Relative advantage was predicted by industry trust.

Our findings deviated from Wolske et al. (2017) in two key ways. First, in our study social curiosity was positively predicted by trialability and negatively predicted by riskiness. This suggests that participants who perceived more opportunities to try out energy sharing before making a commitment and energy sharing as less risky were more likely to be interested. In Wolske et al. (2017), interest in solar adoption is positively predicted by relative advantage and trialability. This suggests that trialability may be an important feature across energy technologies. More novel technologies, like energy sharing, may be better predicted by riskiness than relative advantage.

Table 11. SEM path coefficients and model fit metrics for DOI where *$p<0.05$, ** $p<0.01$, ***$p<0.001$

Path	**β**	**SE**	***p*-value**
Interest ~ Social Curiosity	0.78	0.17	<0.001***
Social Curiosity ~ Relative Advantage	0.18	0.19	0.16
Social Curiosity ~ Trialability	0.14	0.10	0.25
Social Curiosity ~ Riskiness	-0.27	0.11	0.04*
Riskiness ~ Novelty Seeking	-0.34	0.13	0.02*
Riskiness ~ Independent Judgment	0.11	0.15	0.43
Riskiness ~ Observability	0.57	0.11	< 0.001***
Riskiness ~ Marketing Exposure	0.00	0.45	0.99
Riskiness ~ Industry Trust	-0.45	0.13	0.003**
Riskiness ~ Social Trust	0.03	0.26	0.78
Trialability ~ Novelty Seeking	-0.15	0.12	0.30
Trialability ~ Independent Judgment	0.77	0.20	<0.001***
Trialability ~ Observability	-0.16	0.09	0.22
Trialability ~ Marketing Exposure	-0.43	0.54	0.02*
Trialability ~ Industry Trust	-0.51	0.12	0.001**
Trialability ~ Social Trust	-0.25	0.28	0.06
Relative Advantage ~ Novelty Seeking	0.21	0.07	0.16
Relative Advantage ~ Independent Judgment	0.10	0.09	0.96
Relative Advantage ~ Observability	-0.10	0.05	0.49
Relative Advantage ~ Marketing Exposure	-0.08	0.27	0.58
Relative Advantage ~ Industry Trust	0.34	0.07	0.03*
Relative Advantage ~ Social Trust	0.04	0.15	0.77
CFI	0.71		
TLI	0.67		
AIC	8,894		
SRMR	0.12		

Second, the precursors to relative advantage, trialability, and riskiness differed in our study. In Wolske et al. (2017), relative advantage was positively predicted by novelty seeking, observability, trust in industry, and trust in social network. In contrast, we only found a positive relationship with novelty seeking, independent judgment, trust in industry, and trust in social network. This suggests that relative advantage generally explained less variance for energy sharing than solar adoption. This may be because participants have to purchase electricity anyway, so they perceive a weak advantage to doing so through energy sharing versus the traditional channels. In Wolske et al. (2017), trialability was positively predicted by novelty seeking and trust in social networks as well as negatively predicted by independent judgement and trust in industry. In our study, trialability was positively predicted by independent judgement alone. This suggests that participants recognized that most people do not participate in energy sharing, so it would be difficult to try out in advance. Lastly, in Wolske et al. (2017), riskiness was negatively predicted by observability and trust in industry. In our study, riskiness was negatively predicted by novelty seeking and trust in industry. It is unclear why observability is in the opposite direction. This suggests that participants who perceived energy sharing as more observable also perceived it as riskier. Ultimately, riskiness was a negative predictor for interest. It is possible that observability was perceived as unappealing.

4.3.3. Theory of Planned Behavior Model. Although TPB has a higher amount of initial observable variables, the model fit (CFI = 0.73) was lower and below the desired threshold (< 0.9) for the TPB model. As expected, social curiosity positively predicted interest in participating in energy sharing. However, normative beliefs negatively impacted social curiosity. Normative beliefs may have a negative impact on social curiosity because the overall participants in the survey viewed the people in their lives that are important to them as potentially having a negative perception of energy sharing.

Wolske et al. (2017) found that social curiosity was predicted by relative advantage, environmental benefits, riskiness, and normative beliefs, which is similar to our findings. However, we also found that improvements and expect to move have a statistical significance when predicting social curiosity. In Wolske et al. (2017), interest in solar adoption is positively predicted by social curiosity, relative advantage, normative beliefs, and unsuitability. Expense concerns negatively predicts interest in solar adoption in Wolske et al. (2017). This suggests social curiosity is not a necessary intermediate for TPB to predict the outcome of consumer interest.

Table 12. SEM path coefficients and model fit metrics for TPB where *$p<0.05$, ** $p<0.01$, ***$p<0.001$

Path	**β**	**SE**	***p***
Interest ~ Social Curiosity	0.98	0.34	<0.001***
Social Curiosity ~ Relative Advantage	0.24	0.13	0.06
Social Curiosity ~ Environmental Benefit	0.49	0.08	0.003**
Social Curiosity ~ Riskiness	-0.43	0.16	0.23
Social Curiosity ~ Expense Concerns	-0.16	0.24	0.64
Social Curiosity ~ Improvements	0.31	0.08	0.09
Social Curiosity ~ Normative	-0.02	0.04	0.85
Social Curiosity ~ Unsuitability	0.04	0.07	0.74
Social Curiosity ~ Expect to Move	0.21	0.03	0.03*
Social Curiosity ~ Self-Efficacy	0.13	0.63	0.44
CFI	0.73		
TLI	0.70		
AIC	9,484		
SRMR	0.10		

5. CONCLUSION

This study estimates and compares the model fit of the three behavioral theories, (1) VBN, (2) DOI, and (3) TPB, to determine which is most appropriate for modeling interest in participating in an energy sharing community. Each theory frames participation in energy sharing in a slightly different way, as a way to achieve internal values, as a novel technology, and as a way to achieve concrete benefits.

Based on the results, this study has two primary findings. First, we found that VBN had the best model fit (out of 3) for predicting consumer interest in participating in energy sharing. This suggests that marketing efforts that appeal to consumer values may be most effective. Specifically, participants who were more altruistic, self-interested (in terms of valuing control), and less inclined toward traditional values tended to be more interested in participating in energy sharing. Surprisingly, openness to change was not a significant predictor, despite the fact that energy sharing is a novel technology. From a systems perspective, this suggests that prosumers may be willing to sell electricity for lower prices to align with altruism values and appreciate that they can control the price [12]. Similarly, consumers may be willing to buy electricity via the energy sharing platform even if it is more expensive to align with altruism values and appreciate that they can control price thresholds for when to buy renewable versus grid electricity [12].

Second, the DOI model suggests that independent judgement, novelty seeking, industry trust, and observability may be important factors for driving participation in energy sharing. We observed weak social effects, but this may be primarily related to the lack of awareness and experience with energy sharing (e.g., compared to solar technologies). Instead, independent judgement and novelty seeking emerged as significant predictors. Participants with higher independent judgement perceived energy sharing as more triable, while participant that were seeking novelty perceived energy sharing as less risky. For industry trust, the results suggest that organizations may be more effective energy sharing facilitators if they are perceived as more trustworthy. More trustworthy organizations made energy sharing seem less risky. The results for observability were unintuitive. Participants who perceived energy sharing as more observable also perceived it as riskier. It is possible that observability was perceived as unappealing.

Overall, the VBN model was fairly consistent with results for solar adoption [18], while the DOI model deviated in more significant ways. The DOI model in Wolske et al., (2017) indicates there is an importance of reliable communication channels. Our research suggests that consumer understanding of consequences related to adopting a new technology is imperative when predicting interest. This suggests that VBN may be a more useful model for estimating interest in new energy technologies. However, as the technologies become more well known, other models like DOI may be better. In Wolske et al. (2017), DOI better predicted interest in adoption solar.

This study had three primary limitations. First, we had challenges measuring some of the constructs for energy sharing. The internal consistency of our measures was inconsistent. This is likely because most participants had little experience with energy sharing and, in fact, learned about it for the first time in this study. As a result, they may not have had stable perceptions, which increased the variance of our observed measures. In addition, there were higher rates of missing data (i.e., responses of "don't know") for constructs in DOI than VBN. This suggests personal experience consumers have with technologies directly affects their confidence in responding to the associated questions. In future work, measurement may improve with a larger sample size.

Second, this study did not distinguish between prosumer and consumer participation, which may influence the relevant behavioral theory. Framing the scenario in more concrete terms may improve estimation of constructs in DOI that are more directly related to behavior. VBN tends to capture more abstract interest. Future work should specify, and potentially experimentally manipulate, this feature to determine the antecedents for different types of participation.

Lastly, most participants had not heard of energy sharing before this study. This posed a measurement as well as interpretation problem. Some of the results, particularly for observability, were unintuitive. Future work may benefit from targeting geographic locations where participants are more likely to have real world familiarity with energy sharing. For example, targeting a study around the Brooklyn Microgrid may find participants who have more stable perceptions about energy sharing.

In the context of systems engineering, this study provides insight on how behavioral factors may influence the overall system performance of an energy sharing community. Failing to account for factors such as trust in industry and participant values may lead to the development of business models that struggle with adoption. In addition, optimization for system operation may be able to be improved by using behavioral theories to better account for when and how prosumers and consumers will engage with the system. For example, prosumers who are motivated by altruism may be more willing to decrease prices, or offer electricity for free, in the context of a heat wave where grid electricity is likely to be the least environmental (due to the use of fossil fuel intensive peaker plants). Rational economic theory would predict prices to increase when there is high demand – but energy sharing communities may find more pro-community results.

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SECTION

2. CONCLUSION AND FUTURE WORK

The work in this dissertation focuses on the successfully implementing energy sharing and taking into consideration unique community needs and emergent aspects that will impact participants of an energy-sharing community. Identifying contributing factors that predict end-user participation in energy sharing will provide facilitator organizations with the knowledge to enhance energy-sharing efficiency. Additionally, the research in this dissertation uses stochastic programming considering uncertainty as an approach to optimize prosumer investment in DERs while acknowledging consumer want for electricity at a reduced cost. Successfully implementing energy sharing will be beneficial for the end-user participants of the sharing community and the facilitating entity because the load on the utility will be lessened, consumption of renewable energy sourced electricity will increase, consumers can actively decrease their energy burden, and prosumers will have an additional source of income to offset the DER investment cost.

The first paper in this dissertation uses the five system characteristics, as defined by Boardman and Sauser (2006), to describe energy-sharing communities. These characteristics are then defined using general equations to denote objective function, management ability, function, operating condition, and goal or purpose all while considering uncertainty associated with the specific participant or overall community. Two coordination methods of energy-sharing communities: (a) hierarchical coordination and (b) peer-to-peer coordination are then presented. These communities differ based on level of connectivity. Though the participants are the same in each proposed coordination, the hierarchical coordination has a higher dependency on the energy sharing management provider. Implementation of energy-sharing community coordination should be justified using attributes such as size, autonomy degree of participants, and connectivity feasibility.

Future work can include using simulation to understand and predict both negative and positive emergent aspects. By predicting emergent behavior, the positive aspects can be enhanced while the negative aspects can be avoided. Simulation may be used to actively address uncertainty associated with emergent behavior. Researchers may use energy storage systems, such as batteries or electric vehicles, as a back-up source for mitigating uncertainty.

The second paper in this dissertation identifies energy-sharing communities as a decentralized complex adaptive system of systems. Boardman and Sauser (2006) suggest using the five characteristics of autonomy, belonging, connectivity, diversity, and emergence to describe system of systems. Our research suggests expanding the seven underlying characteristics to include autonomy, belonging, connectivity, complexity adaptability, self-organization, and feedback loops while keeping diversity and emergence as the two derived characteristics. These additional characteristics will provide a wider range of participant information that will be useful when attempting to describe participant interaction and necessary interfaces within the energy-sharing community. Additionally, two-stage stochastic programming is used as an optimization approach to minimize expected total cost including purchasing from the wholesale market in the first stage and minimize expected cost of adjustments in the second stage. The three different feasible sets of (a) no sharing communities, (b) multiple sharing communities, and (c) multiple uncooperative communities are used to describe the three different possible scenarios of energy-sharing community connectivity.

Future work would include using a real-life dataset to run the stochastic programming approach to determine the reliability of the presented models. Seasonal forecasting may be useful for identifying variables associated with DER production. Researchers may choose to compare results from a two-stage robust optimization model with the proposed two-stage stochastic programming model. Characteristics that define an energy-sharing community as a decentralized complex adaptive system of system should also be elaborated. Researchers may determine the optimal population of prosumers and consumers within a community to ensure each autonomous system is likely to meet their goal.

The third paper in this dissertation provides a literature review and review of existing decentralized energy distribution systems. The literature review is segmented into four subsections: (a) decentralized coordination, (b) energy management systems, (c) energy management optimization, and (d) energy storage systems, to provide a more thorough analysis of research related to energy sharing. The review of current existing decentralized energy distribution systems specifically looks at the few energy-sharing communities currently functioning as well as other peer-to-peer communities and a community choice aggregation. Aspects that may have been considered when developing these communities are also elaborated to examine the influential characteristics when integrating the new technology. These aspects include: (a) country development, (b) participant population, and (c) technologies security. The results of the literature and existing project review indicate that though energy-sharing communities are being developed, there is still a significant gap between academic research performed to understand implementation of energy sharing and the existence of true energy-sharing communities. Positive and negative impacts of energy sharing is illustrated using a causal model. A wide range of impacts from the implementation of energy sharing are used to demonstrate how energy sharing will benefit economic value, environmental sustainability, resilience, and social welfare.

Future work can include addressing the gap between academic research and real-world implementation of energy sharing. Identifying factors that hinder energy providers from investing in the development of energy-sharing communities will provide a foundation for addressing commercialization concerns. Additionally, using energy sharing as a solution to the utility death spiral may encourage utility companies to invest in the technology necessary to facilitate energy sharing. Each of the four benefits of energy sharing identified using the causal model can be expanded in future research. By demonstrating the impact energy sharing has on environmental sustainability, economic values, resilience, and social welfare individually, energy providers may be encouraged to advance the accessibility of energy sharing.

The fourth paper in this dissertation compares three behavioral theories to identify the best model to predict consumer interest in participating in an energy-sharing community. The three behavioral theories used are: (a) value-belief-norm (VBN), (b) diffusion of innovations (DOI), and (c) theory of planned behavior (TPB). Statistical analysis and structural equation modeling were used to explain the data obtained from 195 survey participants. The survey participants were given information about a fictional energy-sharing facilitator and the technologies necessary to participate in an energy-sharing community. Each participant was then asked a series of questions that were designed to define constructs within each behavioral model. Confirmatory factor analysis was then used to confirm each question assigned to their respective construct did, indeed, explain the nature of the construct as we intended. Structural equation modeling was then used to analyze relationships between the defined constructs and the output variable of interest in participating in energy sharing. The results of this paper show that VBN is the best fitting model for predicting consumer interest in participating in energy sharing.

Future work can focus on gathering data from consumers that have already invested in DERs and actively show an interest in sustainable development. Restricting survey participants to those that either already own DERs or participate in a renewable energy community may provide results consistent with the population that would likely be early adopters of energy sharing. Additionally, energy-sharing facilitators may be interested in identifying differences between residential and commercial perception of energy sharing to determine whether one group may be more receptive than the other.

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VITA

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