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CATALYZING COMMUNITY-LED SOLAR DEVELOPMENT: ESCAPING THE PRISONER'S DILEMMA BY ENABLING COOPERATIVE BEHAVIOR

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ABSTRACT

This work presents an empirically tested method to initiate community solar development by enabling cooperative behavior. Shared solar represents only a fraction of distributed photovoltaic generation despite advantages over other distributed solar models. There is an absence of research investigating how agents decide between the various solar models (e.g. residential; community), and a development framework that addresses the unique characteristics of community solar is needed to increase development. In this work, a non-cooperative game modeled stakeholders' codependent decision between models of solar development. The non-cooperative game served as the uncatalyzed control experiment where there is not facilitated communication. An experimental "catalyst" for onboarding community solar was evaluated to analyze the influence of facilitated cooperation on project development. In the experiment, stakeholders were engaged through demonstrated practices that effectively lead to high-utility cooperative behavior. A cooperative game model was constructed to quantitatively measure the influence of the catalyst. The control non-cooperative game revealed a rational agent preferred a low-utility independent solar strategy to a higher utility cooperative solar strategy (20% difference in normalized welfare). This result emphasized the need for an intra-active force (such as the proposed catalyst) to reach the most economically efficient outcomes, and it established a mechanism that partially explained the broad absence of shared solar. The efforts to facilitate cooperative behavior successfully catalyzed two community-led solar projects in a locale previously void of shared solar. The experimental catalyst was the dominant player for onboarding community solar: it was responsible for 53% of the effective onboarding in the region, and the catalyzed community-led solar projects experienced an increase in onboarding effectiveness by a factor of 2.4 and 2.8. The community solar catalyst can be applied in other locales to overcome barriers inhibiting shared solar development.

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Chapter 1

Introduction

Community solar represents a small fraction of existing photovoltaic distributed generation despite advantages over other distributed solar models [1][2]. The relative shortage of community solar projects is due to an inadequate systems understanding of community solar and economic burdens caused by policy constraints (e.g. lack of virtual net-metering) [1][3][4]. New perspectives and methods of project development are necessary to surmount inhibiting factors and increase the capacity of community solar. This work presents a framework to describe the codependent mechanism of stakeholders deciding between models of solar development, and it offers an evidence-based approach to effectively onboard (i.e. initiate development) community-led solar projects. The conclusions of this research demonstrate that visualizing community solar as a common pool resource and facilitating cooperative behavior (i.e. collective action) through finite repeated games can catalyze project development.

Community-led solar (*or shared solar*) describes a solar array that is funded by multiple, otherwise independent, stakeholders, and the same group of stakeholders receive the solar goods/services from the system. These projects have the potential to significantly increase solar installations by providing solar electricity to a more diverse and inclusive portfolio of stakeholders [1][5][6]. Community-led solar is a fundamentally different product than residential, commercial, or utility solar models. Each model of solar development has a unique stakeholder, design, and value proposition. Stakeholders do not only compare solar PV against other forms of electricity generation when seeking electricity alternatives; they must choose *between* the different options of solar PV (e.g. residential, community, utility, etc.). There is an absence of research analyzing the codependent circumstances that lead a consumer to choose one solar model over another in a locale (confluence of solar resource, economy, markets, policy, and culture in a geographic area [7]). Game theory models were used to bridge this research gap: the models emphasized shared versus independent solar options. Further, the differences in the products necessitate a distinct development process for each model of solar development. The relative absence of community solar implies that current methods of community solar development are insufficient. The proposed development method specifically addresses unique characteristics of a shared solar array (e.g. multi-agent stakeholders, common pool resource, cultural heuristics of solar, etc.). This community solar "catalyst" can increase the total installed solar capacity by providing an appropriate method for inclusive project models (i.e. community-led solar) to develop.

1.1 Community Solar

Community solar is a socially inclusive project model. It is a centralized array, and the benefits are distributed across multiple stakeholders. It was estimated that about 75% of root-top area in the United States is unsuitable for PV [8], and nearly 50% of households are unable to support PV (after excluding renters, multi-unit households, and area shaded in urban environments) [1]. The centralized nature of community solar allows participation from stakeholders barred from rooftop solar due to living in high-rise or rented buildings, and it mitigates issues of microclimate (e.g. shading over a house) [1][5][6]. Due to significant economies of scale, community solar projects are more affordable than residential models, and the projects can include low to middle income families [1][5][6]. Lazard consultants estimated that in 2017, a shared solar array cost 39-59% less than a rooftop solar array (per unit of electricity produced on an unsubsidized basis) [9]. Despite these advantages over rooftop solar, community solar only comprised 1.2% of total solar PV in the United States as of 2018 [2][10]. *Community-led solar* is used in this paper to describe the various solar models that involve a single array purchased by multiple stakeholders and the benefits remain locally distributed among the same stakeholders. This may include some municipal or community-distributed systems in addition to traditional shared solar systems with VNM.

1.2 Common Pool Resource Management

Nobel laureate Elinor Ostrom established the classic framework of a common pool resource as a good which is non-excludable yet rivalrous (i.e. subtractable) in nature (**Figure 1-1**) [11]. In a non-excludable system, a barrier to entry does not exist, and any agent can freely consume the resource. A rivalrous system implies that the resource is subtractable: for each unit of the resource consumed, there is one less unit for another agent to consume. Examples of common pools include fisheries and irrigation systems. Prior analysis has demonstrated that community solar projects can be viewed as common pool resources: community solar projects have few barriers for participation (non-excludable), but participation is limited by the array's installed capacity (rivalrous) [12]. Ostrom demonstrated that non-cooperative game solutions are grossly inefficient means to manage common pool resources [13][14][15]. Common pools often resemble the "prisoner's dilemma:" a game where rational agents settle on a low-utility outcome instead of working together to achieve a high-utility outcome [13][14].

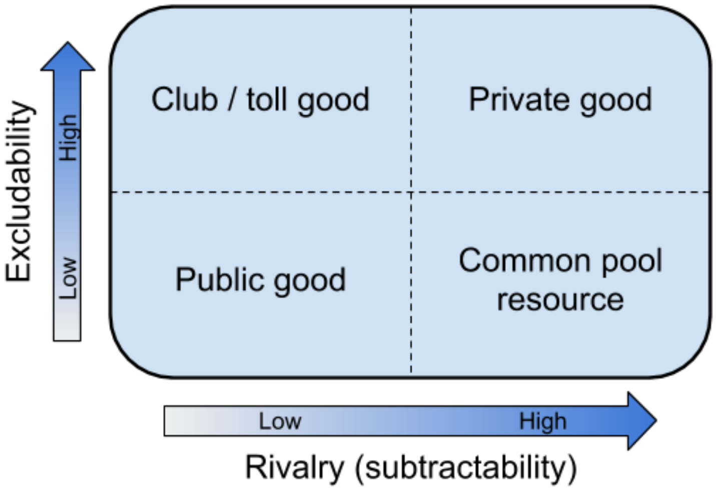


Figure 1-1. Ostrom's classification of goods as a function of rivalry and excludability. Consumption from a common pool is rivalrous, and it is difficult to exclude members from consuming the resource [11].

Issues with efficiently managing the common pool could be the result of an appropriation (i.e. extracting from the resource) or provisioning problem (i.e. establishing the shared resource) [13]. The relative absence of community solar is evidence of a provisioning problem in the system: stakeholders are unable to generate sufficient collective action to initiate the development of a shared resource (i.e. onboard). *Collective action* is when a group of individuals work together to achieve a mutually beneficial goal. Collective action is inherent to provisioning a successful shared solar array because community-led solar requires that independent agents must contribute (e.g. funding, organization, etc.) to a singular project. Unfortunately, collective action is not straightforward in practice. The most recognized literature suggests a mutually beneficial goal is often insufficient to generate collective action [13][17]. Struggles to reach efficient outcomes in common pool resources derive from the difficulties of achieving collective action: individuals' inability to work together to achieve a mutually beneficial outcome leads to low-utility payoffs. Sustained collective action is a common characteristic across all types of community-led solar, and the difficulty in reaching this point is a primary inhibitor to development. An auxiliary force is needed to generate collective action and escape the prisoner's dilemma [13].

Building on the idea of community-led solar as a common pool resource, this paper approached community-led solar development with strategies known to successfully manage commons and avoid inefficient outcomes. Through extensive empirical work, Ostrom outlined a system for efficiency managing and designing common pool resources: *repeated games with facilitated communication and graduated sanctioning* (**Figure 1-2)** [14][15][16]. The repeated games framework enables cooperation by facilitating communication, and it has been demonstrated on a diverse variety of common pool resources [13][14][15]. Central to the idea of finite repeated games are the concepts of communication and sanctioning [14][15][16]. Communication is the process in which agreements are made, and sanctioning (i.e. disapprobation for deviating from the agreement / praise for abiding) provides the incentive to follow through with the established agreement. Sanctioning (up or down) is graduated so that deviating agents are not discouraged from participating in future games. In Ostrom's research, a third-party "facilitator" was a consistent feature of successfully managed commons [13][14][16]. The "games" (i.e. meetings) provide a non-naturally occurring environment for stakeholders of a shared resource to communicate and discuss how to distribute the pool, and repeated meetings allow for trial and flexibility with resource allocation. The external facilitator monitors the pool between games and sanctions players that deviated from the agreements. After a variably finite number of games, welfare optimizing cooperative strategies are established that efficiently manage the common pool.

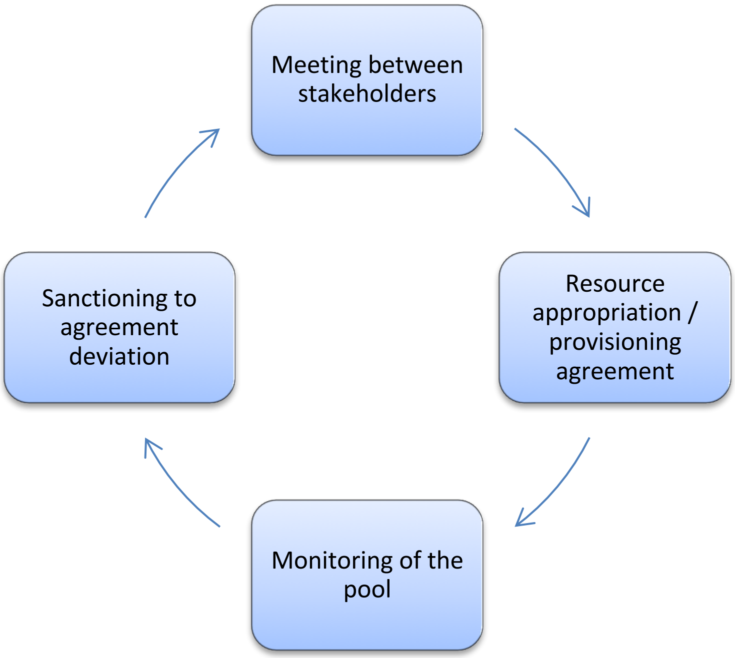


Figure 1-2. Ostrom's framework of *Repeated games with facilitated communication and graduated sanctioning.* This process includes a third-party facilitator to host the meetings, monitor the pool, and apply sanctioning as necessary. It has been empirically demonstrated to yield cooperative strategies [13][14][15].

Research has shown that the management of a common pool resource is a first-order problem, and a second-order problem exists as a public good that the stakeholders must pay so that communication can be established and the non-cooperative outcome of the prisoner's dilemma can be avoided [14]. The repeated games serve as the second-order public good problem that leads to the effective management of the common pool resource (first-order problem) when solved. Extensive theoretical and empirical work with common pool resources demonstrated that with the described methodology, players were most likely to adopt cooperative strategies and optimize the group's payoff from the common pool resource [14][15][16].

Aligning stakeholders around their shared identity with a common goal at facilitated repeated games was proposed to enable collective action and generate high-utility cooperative strategies. This process is especially fit for the effective development of community-led solar. In this paper, using this method **(Figure 1-2)** to onboard shared solar is referred to as "catalyzing" community-led solar.

1.3 Game Theory

Game theory is the mathematical study of decision making, and it is relevant in the practice of economics, politics, social science, and natural sciences [18]. A game is a series of strategies that can be elected by each player [18]. The selection of a strategy yields a payoff that can be valued and compared to the payoffs of the other players. Players can be individuals, businesses, or nations. Strategies may include binary decisions (e.g. buy or don't buy) or the optimal quantity of a product to sell. Payoffs represent the value that is gained or lost by a player from the strategy selection, and it does not necessarily need to be measured in standard currency (e.g. USD). The crucial component of game theory is that a player's payoff is dependent on the strategy selection of the other players. Therefore, game theory can quantitatively determine an optimal strategy by modeling co-dependent interactions. Game theory is broadly divided into two types of problems: non-cooperative and cooperative games [18].

1.3.1 Non-cooperative Games

In a non-cooperative game, rational players make decisions to optimize their payoffs without communication to the other players. A two-player nonzero sum game is commonly applied in economics and policy due to the flexibility of outcomes provided by players being able to win and lose simultaneously (i.e. nonzero sum) and the practical simplicity of modeling only two players [18]. This type of non-cooperative game reflects the methodology used in literature to describe classical problems such as “Tragedy of the Commons” and the “Prisoner’s Dilemma” as well as the inefficient outcomes expected from in situ common pool resources [13][14][15].

The game is solved for each player by finding the strategy that optimizes their payoff under the uncertainty of what the other player will choose. A *Nash equilibrium* is a payoff where neither player has an incentive to change their decision, and a purely dominant strategy Nash equilibrium is the solution if there is only one Nash equilibrium for the game [18]. In this case, each player has a dominant strategy in all scenarios. In the event of multiple Nash equilibrium, mixed-strategy solutions guide strategy selection based on payoff-optimizing probabilities [18]. Common pool resource management problems and the Prisoner’s Dilemma both result in a dominant strategy Nash equilibrium with low global utility [13][14].

1.3.2 Cooperative Games

Cooperative game theory is a branch of economics concerned with the value of an individual within a coalition [18]. The Shapley value represents the relative contribution of a single player to a group outcome [19][20]. The value is a measure of how essential an agent was to a product. The Shapley equation (**Equation 1**) is the formulaic materialization of four axioms that assure mathematical fairness [20], and the model requires a game (i.e. an objective), players, and a metric to value the product of the coalitions.

$$\emptyset_i(v) = \sum\nolimits_{S \subset N} \frac{(s-1)!\,(n-s)!}{n!}[v(S) - v(S-i)]$$

Equation 1. Mathematical definition of the Shapley value: a measurement of a player's marginal contribution to a coalition.
Source: Ref. [19][20].

The Shapley value ($\emptyset_i$) is the solution to the formula, and it represents the marginal contribution of a player (*i*) to the value of the game (*v*). The marginal contribution of a player (*i*) to a coalition (*S*) of players in the game (N) is the value achieved by that coalition of players (*v(S)*) with the value of that coalition excluding player i subtracted (*v(S-i)*). This partial marginal contribution is repeated for all possible orderings of players into coalitions (*n!*), and the Shapley value ($\emptyset_i$) is the average of player's marginal contribution to each possible coalition ordering in the game. Shapley's axioms are symmetry, efficiency, dummy player, and additivity [20]. Symmetry requires that players receive the same value if they impact the game's product identically. The efficiency axiom sets the sum of the players' Shapley values to the value achieved by all players working cooperatively (i.e. the final coalition). Players that do not contribute to any coalitions (i.e. "dummy players") must receive a value of zero. Additivity provides that the sum of two cooperative games played separately must be equal to a game comprising of both games simultaneously.

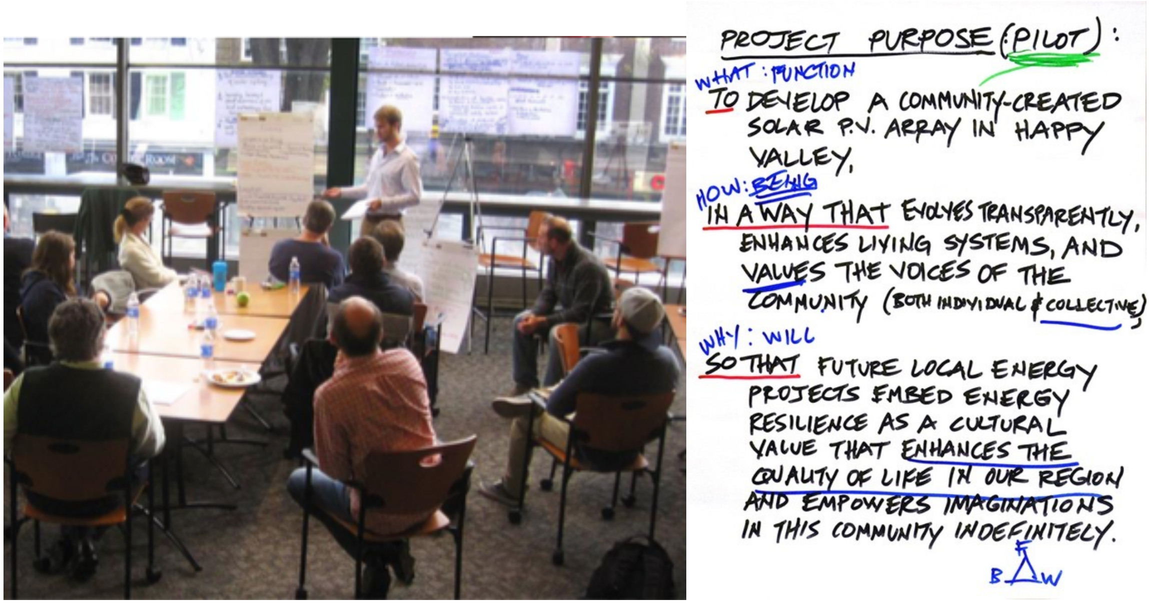
A characteristic equation for the game must be derived to compute the Shapley value. The characteristic equation is a breakdown of the value each combination of players produces acting in coalitions. For example, a three-player game would have seven coalitions in the characteristic equation: three coalitions as individuals, three coalitions as pairs, and one coalition as a complete group.

1.4 Community Solar on State

Community Solar on State (CSOS) was created as a set of repeated games that used techniques of *integrative design* to align stakeholders around their shared identity and narrative of solar ecology ("study of the paired systems of society-environment and technology" [7]) [21] [22]. The objective of CSOS was to have various community stakeholders collectively design the most fitting community solar project for the locale. The effort was theorized to reconcile opposing views and result in the successful implementation of a project.

Four events took place in Centre County, Pennsylvania between August 2014 and March 2015 [21]. The workshops were open to the public and specifically invited a diverse group of stakeholders (e.g. school board members, business leaders, etc.), and the process was deliberately included iterative stakeholder-engaging activities [21]. Representatives of the Pennsylvania State University and 7group acted as the facilitators of the repeated games [21]. The facilitator was a third-party that hosted the workshops, opened communication between participants, and possessed limited sanctioning power. This locale did not have policy enabling shared solar infrastructure (i.e. virtual net-metering), and prior to the catalyst, it did not have MW-scale solar electricity systems [4].

Over fifty individuals attended the first event of CSOS; participants included township board members, university students, local businesses, public school officials, and other local entities (left side of **Figure 1-3)** [21]. Each workshop built on the output of the previous events, and the participants evolved a "purpose statement" through an identical process at each workshop. The produced purpose statement represented an implicit agreement to cooperatively pursue community-led solar and the functional provisioning of such a project **(**right side of **Figure 1-3)**. Participation and contribution to CSOS's mission were mild public commitments to community-led solar by the attendants. These low-stake commitments offered a means of disapprobation for deviation from the agreement without severe consequences.



PROJECT PURPOSE (PILOT):

WHAT : FUNCTION
TO DEVELOP A COMMUNITY-CREATED SOLAR P.V. ARRAY IN HAPPY VALLEY,

HOW: BEING
IN A WAY THAT EVOLVES TRANSPARENTLY, ENHANCES LIVING SYSTEMS, AND VALUES THE VOICES OF THE COMMUNITY (BOTH INDIVIDUAL & COLLECTIVE)

WHY : WILL
SO THAT FUTURE LOCAL ENERGY PROJECTS EMBED ENERGY RESILIENCE AS A CULTURAL VALUE THAT ENHANCES THE QUALITY OF LIFE IN OUR REGION AND EMPOWERS IMAGINATIONS IN THIS COMMUNITY INDEFINITELY.

Figure 1-3. Discussion activities between stakeholders at Community Solar on State: an experimental workshop series to onboard community-led solar in a locale (left). The project purpose statement iteratively derived by stakeholders at Community Solar on State (right). The statement represents the preference for solar goods/services of the represented community acting cooperatively.
Source: Community Solar on State [21].

It is important to note that CSOS did not directly and independently develop a community solar project. Instead, a diffuse impact network from the workshops permeated through the region via participants in the workshops. The short-term impact of CSOS is evident in local community-led solar infrastructure affiliated with the workshops. This relationship suggests the strength of the workshops was not acting as an organized multi-agent client for solar development. The strength of the workshops was fostering communication between stakeholders through repeated games: a practice more likely to lead to utility-maximizing cooperative strategies. In other words, the CSOS campaign was most effective acting as a catalyst for effective management of the solar common pool resource.

1.5 Thesis Novelty

In this study, A non-cooperative game demonstrated that agents choosing between solar models (e.g. residential, community-led, utility-owned) functioned similar to a prisoner's dilemma in the test locale: a collection of rational agents preferred a low-utility solar option over a higher utility community-led system (20% difference in normalized welfare). The uncatalyzed non-cooperative game confirmed that intervention was necessary to reach high-payoff solar options. This game also provided one decision-based mechanism that partially explained the relative absence of shared solar. Approaching community solar development with facilitated communication demonstrated the potential to "catalyze" community solar onboarding (i.e. initiate larger projects in less time). Theories of common pool resource management were used to define a community solar development catalyst. The catalyst was experimentally modelled by Community Solar on State (CSOS): a series of public workshops oriented toward integrating solar into a community. An analysis of the workshop impact network revealed that the experimental catalyst led to two cooperative solar strategies (i.e. community solar projects). The onboarding process for the solar projects derivative of the experiment were used as qualitative and quantitative data points to determine the relative influence of the catalyst. In a cooperative game model, the catalyst was the primary driver for installed shared solar capacity: it was responsible for 53% of the onboarding effectiveness in the region. The two groups that developed community-led solar experienced an increase in onboarding effectiveness (i.e. initiated larger projects in less time) by affiliating with the catalyst. Onboarding effectiveness improved by a factor of 2.4 and 2.8 for the participating groups. The community-led solar outcomes in the test locale would not have been obtained without the catalyst.

The methods section defines the construction of the uncatalyzed non-cooperative game, the experimental catalyst, data collection from the experiment, and the cooperative game model used to analyze the impact of the catalyst. The results section presents the solution to the uncatalyzed control game, the community-led solar outcomes from the experimental catalyst, and the results of the cooperative game analysis. This section reveals the influence of the catalyst on the region and investigates the improved onboarding effectiveness experienced by the catalyzed community-led solar projects in the tested locale.

Chapter 2

Methods

The impact of facilitated cooperation on community-led solar development was evaluated using both non-cooperative and cooperative game theory. The setup of the non-cooperative game is described in section 2.1. The non-cooperative game is the control experiment with unfacilitated communication. In section 2.2, the experimental community solar catalyst that facilitated communication in the test locale is described. Data collection methods to analyze the effectiveness of the catalyst were also outlined in this section. In section 2.3, a cooperative game was established that quantitatively described the effectiveness of the experimental catalyst and the benefits observed by catalyzed community-led solar projects. The cooperative game was constructed using both the qualitative and quantitative results from the data collection (section 2.2). Qualitative data dictated assumptions for setting up the cooperative game model, and the quantitative data served as the model inputs.

2.1 Non-cooperative Game as the Uncatalyzed Control

A non-cooperative game represented the uncatalyzed interaction between the agents in the test locale. It served as the control experiment to analyze how cooperation influences models of solar project development. In a non-cooperative game, rational players make decisions to optimize their payoffs without communication to the other players. This framework is representative of the uncatalyzed control case because it is the default scenario observed: there is not a third-party facilitating communication, and it is non-repeated. A two-player nonzero sum game modeled the option of cooperation between two groups of agents in a locale. This type of non-cooperative game reflects the methodology used in literature to describe the inefficient outcomes expected from common pool resources [13][14]. Additionally, the non-cooperative game exemplified how codependent decisions between agents can result in the development of different solar project models.

The control game needed clearly defined players, decisions, and payoffs. Each component of the game was designed to resemble the test locale. The two players were the major groups agents pursuing solar options in the test locale prior to the catalyst: a general authority and the civil society. General authorities own and operate shared public infrastructure, and the civil society is the aggregation of private citizens. It is an assumption that both group agents have already decided to pursue solar PV, and they have not chosen a model of solar development. It is also assumed that non-financial benefits (e.g. satisfaction from offsetting carbon dioxide emissions) were constant between each payoff because the total amount of solar installed will remain the same (i.e. one 2 MW_p array in lieu of four-hundred 5 kW_p systems). The objective of the game was to optimize the payoff from a decision to pursue solar through a cooperative strategy or independently.

The payoffs were models of project development that correspond to both players' decisions. The civil society opting to independently pursue solar was interpreted as a residential model with net-metering (5 kW_p). The general authority pursuing solar independently did not correspond to a model of solar development based on an assumption of the player: general authorities only own assets that distribute benefits throughout the locale, and any solar installation would be shared among the community. Therefore, the general authority choosing to develop solar independently was modeled as remaining exclusively on grid-supplied electricity (0 kW_p). A kW-scale MUSH (Municipalities, Universities, Schools, Hospitals) solar system was the payoff for a general authority choosing to cooperate when the civil society chose independent solar models (5 kW_p). It was assumed that without the cooperation of the civil society, the general authority would install a PV system net-metered to a small asset (e.g. an office building) as opposed to a large shared asset. The alternative that the civil society opted for cooperative solar when the general authority chose independent solar was modeled as a distributed generation (DG) MW-scale solar array (2.6 MW_p). A traditional “shared solar” array was not a viable option because the game takes place in a locale that does not offer virtual net-metering (VNM). The civil society was represented as a shared investor in this model, and they sell the generated electricity to an off-taker for an agreed PPA. The final alternative was when both players decide to cooperate. It was modeled as a community-led system net-metered to a large load (MW-scale) owned by the general authority and distributed benefits the civil society (e.g. waste water treatment plant) (2.6 MW_p). The game is summarized graphically by the bimatrix in **Figure 2-1**.

		Civil Society	
General Authority		**Cooperative solar**	**Independent solar**
	Cooperative solar	**Community-led solar**	kW-scale MUSH solar / Residential solar
	Independent solar	No solar installations / Investor in DG solar	No solar installations / Residential solar

Figure 2-1. Non-cooperative game bimatrix used as a control experiment. Two players (locale general authority and the civil society in the locale) decide to pursue solar development cooperatively or independently. Payoffs are the solar project models that correspond co-dependently to the decisions of the players (general authority project payoffs are labelled on top, and civil society payoffs are labeled on the bottom).

The value attached to each payoff is the sum of the net present value (NPV) and the applicable externality cost for the project model. Projects were simulated in the System Advisor Model (SAM) based on conditions in the test locale (Centre county, Pennsylvania) at the time of the catalyst experiment (2016). A Monte Carlo simulation controlled for uncertainty in retail electricity rates from transmission or other cost increases. The Monte Carlo analysis was fed a distribution generated using EIA historical data of Pennsylvania's average annual electricity rate (1990-2017). The project NPVs were calculated using after-tax costs and system performance data from the SAM simulations and the electricity price scenarios generated from the Monte Carlo analysis.

Equation 2 presents the equation used to value the solar PV projects: savings for distributed generation are equated to the value of the grid electricity offset by the PV system. Externalities were the cost of retail electricity rate increases (**Equation 3**) and subsequent utility rate increases from the general authority (**Equation 4**). Retail rate externality costs were applied to the portion of load not offset by solar PV for each payoff. Utility rate externality costs were proportional to electricity rate increase, and they were applied to civil society payoffs for scenarios that the general authority did not have solar PV powering a major shared asset. The payoff for the solar decision strategy is the sum of the PV system value, the externality of the electricity meter, and the externality of the utilities (**Equation 5**). A net-present value is taken for this sum; (i) is the discount rate (i = 0.0814) and (n) is the year considered out of the total years in the analysis (n = 25).

Using the sum of the resulting project model's NPV and subsequent externality costs as the payoff for each decision combination, the Nash equilibriums and dominant strategy for solar development were solved for both modelled players in the locale.

$$\boldsymbol{NPV_n} = \left(r_n \times E_{PV_n}\right) - C_{PV_n}$$

Equation 2. The value of the solar PV system in year (n). NPV was a function of the retail electricity rate (*r*), the solar electricity generated (E_{PV}), and the after-cost cost of the system (C_{PV}).

$$\boldsymbol{\delta_{electricity_n}} = \left(D_{electricity} - E_{PV_n}\right) \times \Delta r_{n-0}$$

Equation 3. Externality cost of metered electricity in year (n). $\delta_{\text{electricity}}$ was a function of electricity demanded ($D_{electricity}$), the solar electricity generated (E_{PV}), and the change of the retail electricity rate between year (n) and year 0 (Δr_{n-0}).

$$\boldsymbol{\delta_{utility_n}} = \left(P_{utility} \times \frac{r_n}{r_0}\right) - P_{utility}$$

Equation 4. Externality cost from the utilities cost associated with the general authority. δ_{utility} was a function of the price of utilities charged by the general authority ($P_{utility}$), the retail electricity rate (*r*) in year (n) and in year 0.

$$\boldsymbol{Payoff} = \sum_{n=0}^{n=25} \left({}^{P}\!/_{F_{i,n}} \times \left(NPV_n + \delta_{electricity_n} + \delta_{utility_n}\right)\right)$$

Equation 5. The total payoff associated with a solar decision strategy. The Payoff is a function of the value of the solar PV system (*NPV*), the externality cost of metered electricity ($\delta_{\text{electricity}}$), and the externality cost from utilities associated with the general authority (δ_{utility}). P/F is the present value factor for discounting, (i) is the discount rate, and (n) is the year being considered.

2.2 Modelling the Community Solar Catalyst and Collecting Data

The community solar catalyst was modeled by the experimental series of workshops called Community Solar on State (CSOS) (described in section 1.4). The objective of CSOS was to have various community stakeholders collectively design and provision the most fitting community-led solar project for the locale. Four events took place in Centre County, Pennsylvania between August 2014 and March 2015 [21]. This locale did not have policy enabling shared solar infrastructure (i.e.

virtual net-metering), and prior to the catalyst, it did not have MW-scale solar electricity systems. The workshops were open to the public, and the hosts specifically invited a diverse group of stakeholders (e.g. school board members, business leaders, etc.). The process deliberately included iterative stakeholder-engaging activities. The facilitator was a third-party that hosted the workshops, opened communication between participants, and possessed limited sanctioning power.

The general practice of CSOS followed themes evident in successful efforts of asset-based community development found in literature. Methods that rely on community participation, exercise outside support (e.g. third-party facilitator or aid) with caution, and focus on assets have been demonstrated to generate sustained collective action in the form of community infrastructure [15][16][23][24].

CSOS was used a case study in compliance with methodological guidelines for behavioral studies outlined by renowned empirical economists Marco Janssen and Elinor Ostrom. In accordance with Janssen and Ostrom’s system, the case study was used to “examine the internal logic posited by theorists” and “to understand the interactions between the different components of the system” [25]. The analysis refrained from identifying specific causal factors that may not represent the broader picture, and the study avoided testing a theory reliant on variation in social behavior [25]. Conforming to the standards of agent-based modeling supports the validity of this study on empirical behavior. CSOS was appropriately applied as a case study to meaningfully analyze the relationship between repeated games and shared solar in the locale.

The outcomes from CSOS were investigated to analyze the impact of the community solar catalyst. The goal of the investigation was to locate all community solar projects in the locale (i.e. Centre region, PA), and then determine if and how these projects were influenced by the experimental catalyst (i.e. CSOS). Project leads of the system offtakers were interviewed. The project leads were given an identical set of questions prior to the interview, and the interviews were recorded live so that the responses could be reviewed.

Interview questions centered around the following details: when did the group/community become interested in solar as an electricity alternative, what were the motives for solar, and to what extent (if at all) was the group/community affiliated with CSOS. The first portion of the interview investigated the reach of the catalyst impact network and the penetration of the catalyst for each project. Additional questions were asked regarding the technical specifications, financial set up, and impact on stakeholders (short and long-term). These additional questions served as data for the relative onboarding efficiency of the community solar projects.

The interview data was used to analyze the influence of the catalyst: qualitative data set assumptions for the economic models, and quantitative data was used as inputs into these models. The qualitative data included the relationship between the stakeholder and the catalyst, and the stakeholders' ability to develop community solar independently of the catalyst. The observed quantitative data was the installation capacity and the amount of time dedicated to the project development phase.

2.3 Quantifying the Value of the Catalyst with Cooperative Game Theory

Cooperative game theory modeled the CSOS case study to quantitatively demonstrate the impact of the catalyst (i.e. enabled cooperative behavior by facilitated communication at repeated games). The objective was to find the relative contribution of the experimental catalyst to community-led solar in the locale. The Shapley equation (**Equation 1**) described in section 1.3.2 was used to solve the cooperative game. The value is a measure of how essential an agent was to a group product [19][20]. The model required a game objective, players, and a valuation metric.

The "game" was defined as effective onboarding of community-led solar in the Centre region within three and a half years of the catalyst. The game boundaries were defined as the impact radius of the catalyst and the gestation period of any catalyzed projects to complete onboarding (i.e. reach the development phase). Players were the groups associated with utility-scale community-led solar developed in this region. Each player was subject to the same solar locale: solar resource, alternative electricity prices, local culture, policy, etc. These constants were necessary for playing a “fair” game, and they provided a unique opportunity to host this cooperative analysis.

The model still required a metric to measure the performance of each coalition. Measurable parameters vital to the game (i.e. “effective onboarding”) formed the model’s metric: (1) installed capacity of the solar array and (2) duration of the development process. An effective community solar onboarding event translates to a larger installed capacity because the community stakeholders were willing to increase the magnitude of the investment. In photovoltaic design, larger does not necessarily mean better. However, in a shared system, the shared load can be many times larger than the shared installed capacity. In these cases, there is little concern of oversizing the system, and larger installed capacity can be interpreted as greater interest among stakeholders. A shorter development process reflects successful community solar onboarding because less time (and opportunity cost) was required for the group agents to agree on a mutually-desired project. Players’ in the game were assessed by their ability to onboard community-led solar according to **Equation 6**: onboarding effectiveness was defined as the ratio of installed capacity (kW_p) to development time (t_{dev}) in units of kW per month, and a greater onboarding effectiveness was advantageous in the game.

$$v(S) = \frac{kW_p}{t_{development}}$$

Equation 6. Onboarding effectiveness: an efficiency measurement of the development process where kW_p is the installed capacity of the system in (kW), and t_{dev} is the time from project conception to signed agreement in (months). The onboarding effectiveness for each combination of players served as the inputs for the cooperative game model.

The game’s characteristic equation must be derived to compute the Shapley value. The characteristic equation includes the onboarding ability of each combination of players acting in coalitions. Single player coalition and paired coalition values in the characteristic equation corresponded to the observed onboarding effectiveness of the community-led solar array developed synergistically by the specific players in the coalition. If an overlap or synergy between all the players in a coalition did not result in the development of a community-led solar system, then the onboarding effectiveness of the coalition had no value (0.0 kW_p / month) because 0 kW were developed over an indefinite amount of time.

The final coalition was intentionally selected to represent the entire region for two reasons. First, a regional game considered the effect of the catalyst with respect to the total amount of community-led solar installed in the locale. This revealed the diffusion of the catalyst with respect to its potential impact radius. Second, it normalized the Shapley values of players to the locale. The normalization was especially valuable because it facilitated a relative comparison between players as opposed to a direct reliance on the numerical result. Relative comparisons were preferred because the significance of the numerical result will vary with locale: an impressive value in one locale may be disappointing in another. Also, focusing on the numerical result was less useful since the onboarding effectiveness value was original and literature comparisons did not exist.

Data derived from section 2.2 (i.e. analysis of community-led solar in the locale) was used for the Shapley analysis. Qualitative data formed assumptions for the relationships between players forming coalitions and initial conditions for coalitions not directly observable. The quantitative data (i.e. installation capacity and development time) were the model inputs for each coalition representing an existing project.

Chapter 3

Results and Discussions

Section 3.1 describes the results from the non-cooperative game that modelled the low-welfare outcome in the locale prior to the catalyst. In section 3.2, the connection between the catalyst and local community solar projects is shown. Section 3.3 presents the effectiveness of the community solar catalyst with cooperative game theory.

3.1 Uncatalyzed Solar Development: Non-cooperative Game Results

The modeled solar options for the general authority and the civil society (on a per member basis) are presented in **Table 3-1**. Payoff values are the total present value and externality costs of each solar option. Due to the differing scale of the general authority and the civil society on a per member basis, the payoffs (i.e. total change in costs through the project lifetime) were normalized to a control baseline cost where solar PV was not purchased in any form by either party. The total change in each payoff was negative: this was because electricity and utility rate increases over the 25-year analysis forced costs upward. The solar projects shielded consumers from the inevitable net-increase in costs of electricity and/or utilities. The distributed-generation investor option resulted in lowest mitigation of costs for the civil society member. In this payoff, the civil society member bore the entire rate increase from both electricity and utilities while recovering modest gains from the distributed-generation investment (10.2% decrease in expenses when normalized to controlled baseline conditions with no solar). The cooperative community-led option shielded the civil society from utility rate increases, and the independent residential option shielded the civil society from metered-electricity rate increases. The SAM-Monte Carlo simulation model revealed that the total change in expenses was similar for these options. The residential payoff (30.3% cost decrease) slightly out-performed the cooperative community-led payoff (26.4% cost decrease) for the civil society. Results will vary with locale, but this comparison demonstrated that a PV-system powering a shared resource can yield benefits to a consumer comparable to a residential system that exclusively services the same consumer.

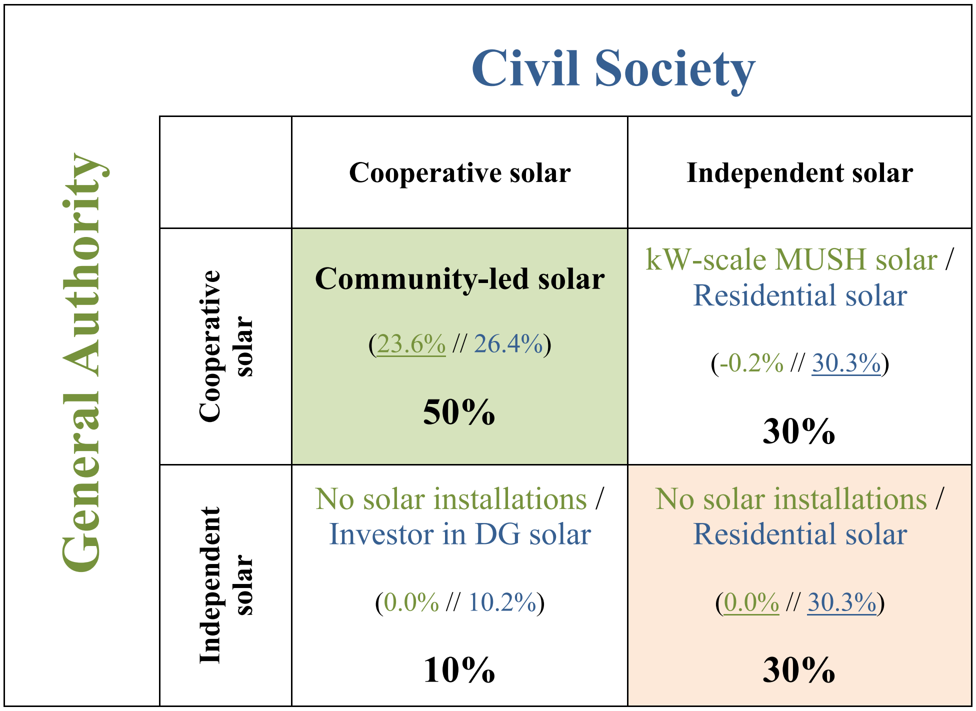
Table 3-1. Value and welfare for each modeled solar option: net present value (NPV) of the PV installation, subsequent externality costs through the project lifetime, and the total change in utilities costs normalized to the controlled baseline no solar cost.

	Civil Society			General Authority		
No solar baseline cost increase ($)	-7,624			-4,296,900		
	Residential	DG Investor	Community-led	No Solar	MUSH	Community-led
System Capacity (kW_p)	5	2,600	2,600	0	5	2,600
Load Covered by Solar PV	49%	n/a	0.0%	0.0%	0.0%	24%
Solar Installation NPV ($)	-260	775	0	0	-6,981	43,096
Externality Cost ($)	-5,055	-7,624	-5,610	-4,296,900	-4,296,400	-3,326,400
Total Change in Cost ($)	-5,315	-6,849	-5,610	-4,296,900	-4,303,381	-3,283,304
Total Change (normalized to baseline cost)	30.3%	10.2%	26.4%	0.0%	-0.2%	23.6%

Normalized welfare increase of each modeled payoff

Community-led Solar	MUSH / Residential	No Solar / DG Investor	No Solar / Residential
50%	30%	10%	30%

The cooperative community-led system returned a profit to the general authority (NPV = $43k) in addition to shielding from electricity rate increases. This cooperative payoff mitigated the most cost to the general authority (23.6% cost decrease). The no solar and MUSH (Municipalities, Universities, Schools, Hospitals) options were approximately the same value for the general authority (0.0% and -0.2 cost decrease respectively) because the MUSH system represented a negligible component of the total load (0.04%), but the no solar option presented more value since the MUSH system had a negative NPV. Welfare gain was the sum the players' normalized expected values for each payoff. The dual-cooperative community-led option created the most welfare for the society in this locale (50%); this option is the Pareto optimal solution. The independent and mixed cooperative-independent strategies resulted in less welfare (30%, 10% and 30%).



		Civil Society	
		Cooperative solar	**Independent solar**
General Authority	**Cooperative solar**	**Community-led solar** (23.6% // 26.4%) **50%**	kW-scale MUSH solar / Residential solar (-0.2% // 30.3%) **30%**
	Independent solar	No solar installations / Investor in DG solar (0.0% // 10.2%) **10%**	No solar installations / Residential solar (0.0% // 30.3%) **30%**

Figure 3-1. Non-cooperative game bimatrix with payoffs for a general authority (left) and a civil society (right) deciding between cooperatively and independently pursuing solar development. Payoffs are NPVs of corresponding solar project models with electricity and utility rate increases considered. The underlined values are the preferred payoffs for each decision combination. The green shade signifies the pareto optimum (highest overall welfare), and the pink shade signifies the dominant strategy Nash Equilibrium for the matrix (rational solution strategy).

The non-cooperative game of the simulated payoffs for the control experiment are presented in **Figure 3-1**. The game had one Nash equilibrium: independent-independent (no solar / residential). The Nash equilibrium was the solution to the game: it represents the strategy combination that rational agents would play to optimize their individual expected value in a non-cooperative format. The Pareto optimum strategy (i.e. welfare maximized) was cooperate-cooperate (shared community-led system). In this game, rational agents selected a payoff which did not optimize the shared welfare of the co-dependent stakeholders; the Nash equilibrium had 20% lower normalized welfare than the Pareto optimum (i.e. dual-cooperative strategy). Consequently, the rational players produced a sub-efficient economic result. This paradox is characteristic to the "prisoner's dilemma" which plagues common pool resources [13][14].

The uncatalyzed control experiment demonstrated that community-led solar was the highest utility model (i.e. Pareto optimum) for the stakeholders in this locale. This result corroborates previous suggestions that community-led solar systems present financial benefits over individual systems in many locales [1][5][6]. However, community-led solar was not the project outcome based on the Nash equilibrium. Rational agents were most likely to develop exclusively residential systems with lower global-utility in this non-cooperative framework. The Nash equilibrium preference for independent residential solar instead of shared solar projects offers a decision-based mechanism that partially explains the observed absence of community solar compared to residential models [2][10]. Based on this experiment, solar development behaved as an unmanaged common pool resource. The non-cooperative game results confirmed the need for a design process that facilitates communication and enables cooperative behavior. From a catalyzed cooperative process, agents may be able to escape low-efficiency outcomes similar to the prisoner's dilemma and develop high-utility, cooperative solar projects.

3.2 Community-led Solar Projects Derivative of the Catalyst

The investigation of local community-led solar derivative of the catalyst resulted in two projects: one installed by the University Area Joint Authority (UAJA) and another installed by Penn State's Office of the Physical Plant (OPP).

The University Area Joint Authority (UAJA) is a general purpose authority for the Centre region in Centre county, Pennsylvania. The primary responsibility of the UAJA is the operation and maintenance of the Centre region's waste water treatment facility. The UAJA purchased a 2.6 MW_p solar array with battery storage in February 2017; the generated electricity offsets over a quarter of the load required for the region's water treatment [26]. This solar plant is shared by the Centre region community: the solar array is funded through rate payments to the UAJA, and it provides a solar good (i.e. waste water treatment) to all rate payers. OPP maintains and manages the infrastructure for the entire Pennsylvania State University (including all branch campuses). OPP purchased a 2.0 MW_p solar array in January 2018. The PV system is shared by the Penn State community: all students utilize power generated by the system and benefit from the educational opportunities provided, and the array is paid for through student tuition (via OPP's budget). Interview results from the project leads of the UAJA and OPP are summarized in **Table 3-2**.

Both organizations participated in the catalyst and expressed that value was gained from the experience. The UAJA felt a direct impact of reinforced confidence in solar energy, and they felt encouraged to further investigate the connection between energy and water systems. OPP built relationships with solar developers which continued through the construction of their 2.0 MW_p system; enabling the trust in these relationships was noted as a crucial component to the success of the final array. Also, the catalyst prompted additional considerations (e.g. site assessments of available lands) from OPP that were necessary prior to advanced stages of development.

Table 3-2. Highlights of the University Area Joint Authority's and Office of the Physical Plant's community-led solar project and the relationship to the Community Solar on State workshops. The information was provided courtesy of the UAJA and OPP organizations. Interview results yield that the catalyst (represented as CSOS) benefited the development of community solar in the locale. Full interview results are presented in Appendix A.

Question	**Response (UAJA)**	**Response (OPP)**
Attendance at Community Solar on State	Yes (via UAJA representative)	Yes (via senior OPP officials); OPP co-created workshops
Direct impact of Solar on State on the UAJA	Reinforced confidence in solar; need to look deeper into energy-water connection	Useful solar relationships were established with developers; need to become organized in development efforts; community partnerships are complicated.
Conception of interest in solar	Years prior to CSOS	Years prior to CSOS
Hesitations on previous solar project attempts	Lacking mechanism to demonstrate long-term financial benefit	Difficulty to find a financial structure that satisfied objectives; unable to holistically value solar benefits; organization was absent in efforts

Notably, both organizations were interested in solar years prior to CSOS, but neither party were able to successfully develop a community solar project. In previous efforts, the UAJA lacked a financial mechanism to demonstrate long-term benefit to stakeholders. OPP were held up by similar circumstances: finalizing a financial structure that accommodated the project goals. However, the first attempts into solar after the conclusion of the workshop series (i.e. the catalyst) resulted in the community solar projects currently in operation. This contributes to the conclusion that CSOS was not as effective as a project development agent, but as a catalyst that facilitated cooperative strategies.

It is important to note that community solar projects did not exist in this locale prior to the catalyst, and all community-led solar projects that have since developed have had a strong affiliation to the catalyst. However, the workshops were not the originator of community-led solar concepts to the stakeholders. The parties were already interested in solar by the time the workshops occurred, but they were able to find value and benefit from participation in the repeated games process (i.e. catalyst). The gained value enabled the stakeholders to overcome the collective action barrier and onboard solar projects. The catalyzed projects were the first community-led solar systems (and first MW-scale solar systems) to penetrate the locale. This assessment furthers the conclusion that the catalyst was successful as a cooperative platform that diffusely facilitated community-led solar development across the locale.

3.3 Contribution of the Catalyst to Local Community-led Solar

The cooperative game was constructed using the data from the derivative projects of the experimental catalyst. In the Centre region locale, there were three groups simultaneously pursuing community-led solar: CSOS, UAJA, and OPP. The catalyst was represented by CSOS. For this three-player game, the characteristic equation included seven distinct components (**Table 3-3**).

Table 3-3. Coalitions in the characteristic equation for the CSOS case study cooperative game.

Coalition
CSOS
UAJA
OPP
CSOS and UAJA
CSOS and OPP
UAJA and OPP
CSOS, UAJA, and OPP

A value was assigned to each coalition in the game and is summarized in **Table 3-4**. First coalition: CSOS did not onboard solar entirely independent from the other players. In this case, it is known that the CSOS event dissolved prior to the development of an original solar project. Therefore, without another players' intervention, CSOS achieved 0.0 [kW_p/month] of solar development in the Centre region. The investigation discovered that all attempts into solar by the UAJA prior to intervention from CSOS were unsuccessful. Thus, the UAJA acting alone produced

0.0 [kW_p/month]. As an individual agent, OPP resulted in 0 [kW_p/month] because the group agent was unable to produce any solar capacity in the timeframe of the game independent of the catalyst, and there were no major community solar investments prior to the experiment.

The *CSOS and UAJA* coalition was responsible for onboarding the solar project derivative of the catalyst and purchased by the UAJA. After the UAJA participated in CSOS, an overlap existed between the two players. The overlapping CSOS-UAJA coalition was connected through the implicit cooperative agreement established at the experimental catalyst. The 2.6 [MW_p] array was developed over the 31 months after the start of CSOS (August 2014 – February 2017); the *CSOS and UAJA* coalition earned 84 [kW_p/months]. The OPP project derivative of the catalyst was an overlapped effort which corresponded to the *CSOS and OPP* grouping. The 2.0 [MW_p] array developed over 42 [months] after the CSOS event (August 2014 – January 2018); the coalition developed 48 [kW_p/months]. The UAJA and OPP were not collectively involved in a solar project throughout this time period; nor was any portion of existing solar infrastructure associated with this partnership. The *UAJA and OPP* coalition was responsible for 0.0 [kW_p/months] of solar onboarding in the locale.

The final coalition (*CSOS, UAJA, and* OPP) accounted for all of the community-led solar capacity installed in the Centre region throughout the entire time period of the game. Each player contributed to community solar in the locale. Therefore, the final coalition was the aggregate capacity of the existing community-led solar projects (4.6 MW_p) over the entire timeframe (42 months). As expected in a cooperative analysis, the comprehensive coalition resulted in the greatest score: 110 [kW_p/month]. This coalition was particularly important because it represented the total onboarding observed in the region, and results of the game were fractions of this total value. The product values may be evaluated by relative comparison because the regional boundary of the final coalition normalized the Shapley analysis to the locale. A relative comparison was more valuable because the significance of the results would vary with locale (i.e. one value may be impressive in a certain locale but disappointing in another).

Table 3-4. The characteristic function for the cooperative game. Onboarding data for each partnership reflects how each coalition contributed to onboarding community solar in the Centre region. The coalitions' onboarding values served as the inputs for the Shapley value calculation.

Coalition	**Installed Capacity [kW$_p$]**	**Onboarding Duration [months]**	**Onboarding Value [kW$_p$ / month]**
CSOS	0	*n/a*	0
UAJA	0	*n/a*	0
OPP	0	*n/a*	0
CSOS and UAJA	2,600	31	84
CSOS and OPP	2,000	42	48
UAJA and OPP	0	*n/a*	0
CSOS, UAJA, and OPP	4,600	42	110

Using the Shapley value equation in **Equation 1** and the characteristic equation (**Table 3-4**), the matrix of marginal player contributions was derived (**Table 3-5**). The Shapley values are interpreted as the marginal contributions for the effective onboarding of solar into the region. Each player's onboarding contribution observed in the Centre region (CSOS: 59 kW/month, UAJA: 35 kW/month, OPP: 17 kW/month) was greater than their respective individual ability to onboard community solar (0 kW/month). The contributions to the aggregate of community solar onboarding into the region is presented in **Figure 3-2**; this figure demonstrates the influence of each player to the total community-led solar onboarded across the locale. Several significant relationships were quantified by the cooperative game. The catalyst was the dominant onboarding player in the coalition: CSOS contributed 53.3% to the total community-led solar onboarded in the Centre region through the analysis period; 1.7 times more than the UAJA and 3.5 times more than OPP. As the third-party communication facilitator, CSOS did not onboard independently from the other group agents, but the catalyst (CSOS) was the dominant player in the locale because it was involved in both existing solar projects. The other two players (UAJA and OPP) were only involved in their respective projects and were unable to install community solar without some degree of cooperation. Despite being unable to onboard community solar prior to the CSOS-catalyst, the UAJA and OPP had significant shares of onboarding in the region due to their involvement as the only major purchasers of community-led solar in the Centre region.

Table 3-5. Mathematical work and solution to the cooperative game of the Community Solar on State case study. CSOS, representing the catalyst, was the primary driver for community-led solar installed capacity in the Centre region.

Orderings (S)	**CSOS [kW$_p$/month]**	**UAJA [kW$_p$/month]**	**OPP [kW$_p$/month]**
CSOS,UAJA,OPP	0	84	26
CSOS,OPP,UAJA	0	62	48
UAJA,CSOS,OPP	84	0	26
UAJA,OPP,CSOS	110	0	0
OPP,CSOS,UAJA	48	62	0
OPP,UAJA,CSOS	110	0	0
Shapley (ϕ_i)	**59**	**35**	**17**
% contribution	**53%**	**32%**	**15%**

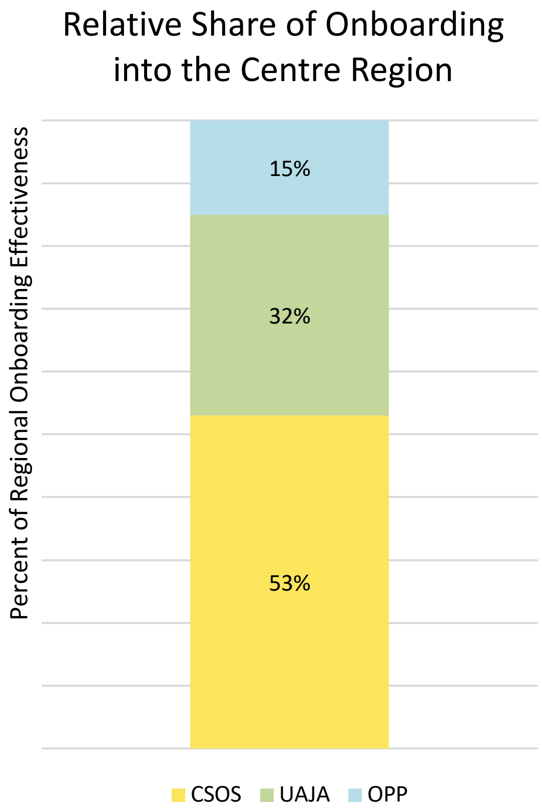


Figure 3-2. A visual representation of the marginal contribution of each player in the cooperative game to onboard community solar into the Centre region. The catalyst (CSOS) contributed half of the overall onboarding value to the region; project owners (UAJA and OPP) contributed the remaining portion.

The gap between CSOS and the other players' onboarding contributions does not take away from their value to community-led solar in the locale. The Shapley values generated represent each group's contribution to the entirety of community-led solar onboarding across the region. All other non-profits, general authorities, businesses, etc., are effectively considered as "dummy players" in this cooperative game (0% marginal contribution to onboarding). From this perspective, each player in the cooperative game yielded a substantial benefit to onboarding in the locale.

The catalyzed solar projects were developed to completion without a reconvening of the CSOS facilitator; this signifies that the project offtakers (UAJA and OPP) were able to reach a stable agreement with their respective communities to provision the shared resource. The catalyst supported the offtakers in domains where they previously experienced setbacks: onboarding (i.e. reaching the development phase). Using Ostrom's *repeated games with facilitated communication* strategy to onboard community-led solar is aptly labeled as a "catalyst:" it did not alter the fundamental reactants (e.g. identity of stakeholders, interest in solar PV), nor did it become integrated with the final product (i.e. a co-owner or developer), but it allowed a stalled "reaction" to proceed (i.e. onboarding).

The observed onboarding values of the respective UAJA and OPP coalitions involving CSOS were significantly greater than the resultant onboarding values for the UAJA and OPP as individuals. The catalyzed UAJA project was 2.4 times larger than the marginal contribution (i.e. Shapley value) of the UAJA, and the catalyzed OPP project was 2.8 times larger than the marginal contribution of OPP. This difference, represented in **Figure 3-3**, implies that both the UAJA and OPP benefited significantly from cooperation. The analysis concluded that without the catalyst, the UAJA and OPP projects would have been smaller in capacity and/or taken longer to develop. The cooperative game results indicated the extent in which the community solar catalyst was essential to onboarding the existing community-led solar in Centre county.

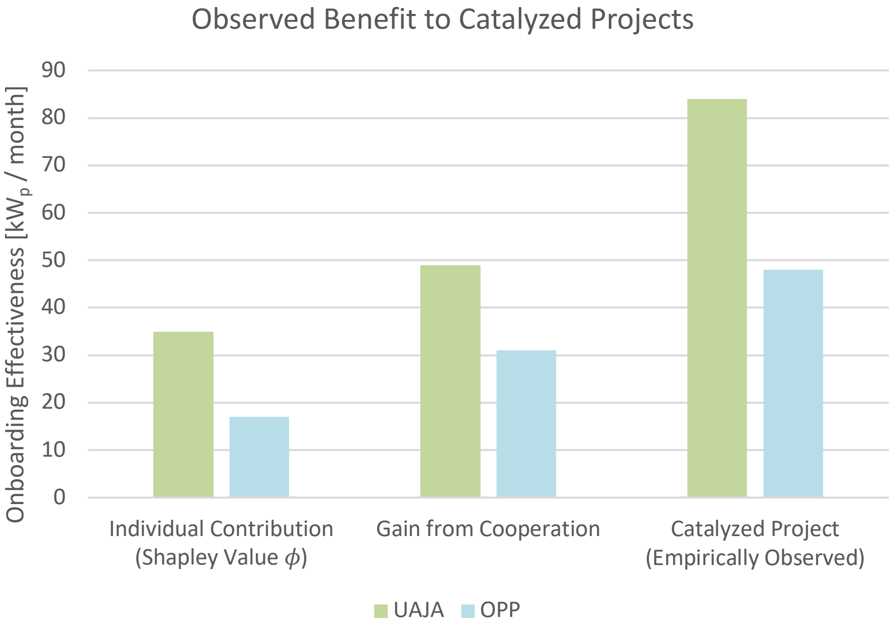


Figure 3-3. Comparing the benefit received from the catalyst by the University Area Joint Authority and the Office of the Physical Plant. The individual contributions are less than half of the contributions of coalitions with the catalyst. As a result, both parties gained significantly from the cooperation.

An interesting conclusion also rises from the solution to the cooperative game: the UAJA was nearly twice as effective at onboarding solar in Centre county than Penn State's OPP. The relative difference in the Shapley values is surprising given the similarities between the organizations shown in **Table 3-6**. This may be a result of how the two agents perceived the stakeholders participating in CSOS: the UAJA viewed the events as meetings within their jurisdiction (i.e. their own community and commons), and OPP treated the workshops as a meeting *between* the Penn State and Centre region communities. The difference in perception may partially explain why OPP felt the process was more difficult (see interview results in section 3.2). The assessment of perception from the interviews is backed up by the workshop documentation: the majority of participants were Centre region representatives; less than a third of attendants identified as the Penn State students (i.e. the largest stakeholder in the Penn State community) [21].

Table 3-6. Summary of OPP and the UAJA as community solar hosts.

	Penn State's Office of the Physical Plant (OPP)	**University Area Joint Authority (UAJA)**
Installed capacity	2.0 MW_p	2.6 MW_p (and battery)
Community stakeholder	Penn State students	Centre region constituents
Affiliation to Community Solar on State (i.e. the catalyst)	Co-created and participated in workshop series	Participated in workshop series
Size of Serviced Community	99,000* [27]	93,000** [28]

* Total number of Penn State students; this includes undergraduate, graduate, branch campus, and online students. Regardless of location, all Penn State students are served by OPP.

** Sum of the populations serviced by the UAJA: Harris Township, Patton Township, College Township, Ferguson Township, and the State College Borough. Note that the UAJA does not serve the entire portion of the State College Borough.

The composition of stakeholders was an intuitive explanation to why the similar agents experienced different results from the catalyst. An agent is less likely to value the cooperative meetings if the repeated games do not adequately represent stakeholders in the agent's commons, and a cooperative strategy to manage that specific commons is less likely develop.

Chapter 4

Conclusions

A collective action catalyst was analyzed to determine the influence of facilitated cooperative behavior on community-led solar development, and a non-cooperative game that modeled group agents in the locale choosing between models of solar development (e.g. residential; community) served as the "uncatalyzed" control experiment. The non-cooperative game between group agents pursuing solar in the same locale demonstrated that solar projects exhibit a phenomenon similar to a prisoner's dilemma. In the test locale, a rational society preferred residential models with low-utility to a cooperative model with higher utility. The dominant strategy Nash equilibrium resulted in 20% less normalized welfare than the dual-cooperative strategy. The non-cooperative game was one of the first demonstrations of stakeholders' codependent decision *between* different models of solar development and the influence of interaction from other stakeholders. This analysis was also the first quantitative corroboration of a qualitative literature assertion that community solar should behave as a common pool resource [12]. The Nash equilibrium from the game provided a decision-based explanation of the observed absence of shared solar relative to residential models [2][10]. The non-cooperative control game confirmed that (in the tested locale) among the different models of solar development, a community-led project offered the greatest utility to the society, and the facilitation of cooperation was needed to reach the high-utility option.

A community solar "catalyst" was created to increase the development of community-led solar by enabling cooperative behavior. The catalyst relied on methods demonstrated to efficiently manage common pool resources (i.e. repeated games with facilitated communication). The catalyst was modelled by a series of workshops called Community Solar on State (CSOS), and the experiment successfully catalyzed the development of the first two community-led solar infrastructures in the locale. A cooperative game model revealed that the community solar "catalyst" was the primary driver for onboarding installed community-led solar capacity in the region, and it contributed 53% of the total onboarding effectiveness of community-led solar in the locale. The Shapley values from the cooperative game showed that the two catalyzed community-led projects experienced an onboarding process that was 2.4 – 2.8 times more effective (i.e. installed additional capacity in less time) than the uncatalyzed potential of the energy offtakers acting independently.

Solar design is extremely dependent on locale, and results from one locale do not necessarily apply to others. Given the broad absence of community-led solar, the insights and proposed techniques from this study are generally applicable. A prediction from this study is that several themes will exist in future catalysts and related community-led solar. The community solar catalyst will be more effective at integrating solar capacity into a community than organizations working non-cooperatively. Derivative projects that align more closely with the stakeholders present will experience notably more success. Most importantly, incorporating a catalyst into pre-project development will enhance the onboarding process. This enhancement may materialize as installing more capacity, a quicker development period, or both.

Enabling cooperative behavior to onboard community-led solar was aptly labeled as a "catalyst" because it allowed a stalled reaction (community solar onboarding) to proceed without altering the fundamental reactants (e.g. identity of stakeholders) or products (i.e. the catalyst did not become a co-owner). For future community solar catalysts, the second-order public good problem would still need to be initially resolved. The second-order problem is the introduction of a trusted third-party facilitator that has appropriate resources to host the repeated games with an objective of integrating community solar into the locale (e.g. the CSOS workshops). The facilitator could be a local government, community non-profit group, or university.

For the stakeholders in the tested locale, community-led solar development behaved as a mismanaged common pool resource, and an intra-active force was necessary to reach high-welfare outcomes. The experimental community solar catalyst incorporated stakeholders and repeated games into the initial stages of shared solar development (i.e. onboarding), and the process resulted in larger installations and required less time to complete. The community solar catalyst can be attempted in other locales to facilitate the development of shared solar infrastructure.

References

[1] D. Feldman, A.M. Brockway, E. Ulrich, R. Margolis, National Renewable Energy Lab, U.S. Department of Energy, Shared Solar: Current Landscape, Market Potential, and the Impact of Federal Securities Regulation, 2015.

[2] National Renewable Energy Lab, NREL Community Solar Project List, 2018. https://data.nrel.gov/files/95/NREL_Community_Solar_Project_List %281%29.xlsx.

[3] Michaud, Community Shared Solar in Virginia: Political and Institutional Barriers and Possibilities, PB&J Polit. Bur. Justice. 5 (2015) 1–15.

[4] Center for Sustainable Energy, California Solar Energy Industries Association, Interstate Renewable Energy Council, Virtual Net Metering Policy Background and Tariff Summary Report: Solar Market Pathways, 2015.

[5] J. Coughlin, J. Grove, L. Irvine, J.F. Jacobs, S.J. Phillips, L. Moynihan, J. Wiedman, U.S. Department of Energy, Energy Efficiency & Renewable Energy, A Guide to Community Solar: Utility, Private, and Non-Profit Development, 2010. http://www.nrel.gov/docs/fy12osti/54570.pdf.

[6] Interstate Renewable Energy Council, The Vote Solar Initiative, Model Rules for Shared Renewable Energy Programs, 2013. http://www.irecusa.org/wp-content/uploads/2013/06/IREC-Model-Rules-for-Shared-Renewable-Energy-Programs-2013.pdf.

[7] J. R. S. Brownson, Solar Energy Conversion Systems, First, Academic Press, Oxford, 2014. doi:10.1016/B978-0-12-397021-3.00019-3.

[8] P. Denholm, R. Margolis, National Renewable Energy Lab, U.S. Department of Energy, Supply Curves for Rooftop Solar PV-Generated Electricity for the United States, 2008. Technical report: NREL/TP-6A0-44073.

[9] Lazard, *Lazard's Levelized Cost of Energy Analysis: Version 11.0* (2017). Lazard. Retrieved from: https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

[10] SEIA, Solar State by State, Solar Energy Industries Association (2018). https://www.seia.org/states-map

[11] E. Ostrom, Understanding Institutional Diversity, Princeton University Press, Princeton, NJ, 2005.

[12] J. R. S. Brownson, Framing the Sun and Buildings as Commons, Buildings. 3 (2013) 659–673. doi:10.3390/buildings3040659.

[13] E. Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action, Cambridge University Press, United Kingdom, 1990.

[14] E. Ostrom, R. Gardner, J. Walker, Rules, Games, and Common Pool Resources, University of Michigan Press, Ann Arbor, 1994.

[15] E. Ostrom, The value-added of laboratory experiments for the study of institutions and common-pool resources, J. Econ. Behav. Organ. 61 (2006) 149–163. doi:10.1016/j.jebo.2005.02.008.

[16] D. S. Wilson, E. Ostrom, M. E. Cox, Generalizing the core design principles for the efficacy of groups, J. Econ. Behav. Organ. 90 (2013) S21–S32. doi:10.1016/j.jebo.2012.12.010.

[17] M. Olson, The Logic of Collective Action: Public Goods and the Theory of Groups, Harvard University Press, Cambridge, MA, 1965.

[18] E. N. Barron. Game Theory: An Introduction, John Wiley & Sons, Hoboken, NJ, 2008.

[19] L. S. Shapley, A Value of n-Person Games, in: H.W. Kuhn, A.W. Tucker (Eds.), Contrib. to Theory Games. Ann. Math. Stud., Princeton University Press, 1952: pp. 307–317. doi:10.1515/9781400881970-018.

[20] A. E. Roth, The Shapley Value: Essays in Honor of Lloyd S. Shapley, in: A.E. Roth (Ed.), Game Theory Appl., Cambridge University Press, 1988: pp. 1–27. doi:10.1017/CBO9780511528446.

[21] Solar Ecology Program. Community Solar on State: Workshops, CommunitySolar.psu.edu (2016), B. Ferster, J.R.S. Brownson (Eds.), Penn State College of Earth and Mineral Sciences. https://www.communitysolar.psu.edu/workshops

[22] 7group, B. Reed, J. Boecker, S. Horst, T. Keiter, A. Lau, M. Sheffer, B. Toevs, The Integrative Design Guide to Green Building: Redefining the Practice of Sustainability, Wiley & Sons Inc., Hoboken, 2009.

[23] G.P. Green, Community Assets: Building the Capacity for Development, in: G.P. Green, A. Goetting (Eds.), Mobilizing Communities Asset Build. as a Community Dev. Strateg., Temple University Press, Philadelphia, 2010: pp. 1–13.

[24] J. Mulligan, A.L. Tompsett, P.M. Guthrie, An “engineer–client” framework for participation in community-scale infrastructure projects, Proc. Inst. Civ. Eng. - Eng. Sustain. 164 (2011) 35–47. doi:10.1680/ensu.2011.164.1.35.

[25] M.A. Janssen, E. Ostrom, Empirically Based, Agent-based models, Ecol. Soc. 11 (2006). http://www.ecologyandsociety.org/vol11/iss2/art37/

[26] K. Pickerel, 2.6-MW solar project planned for Pennsylvania wastewater treatment plant, Sol. Power World. (2017). https://www.solarpowerworldonline.com/2017/02/2-6-mw-solar-project-planned-pennsylvania-wastewater-treatment-plant/.

[27] Penn State University Budget Office, Undergraduate and Graduate/First Professional Fall Enrollment: 2016 and 2015, (2016). https://budget.psu.edu/factbook/studentdynamic/UGGREnrollSummary.aspx?YearCode=2016Enr&FBPlusIndc=N.

[28] U.S. Census Bureau, U.S. Department of Commerce, Quick Facts: Centre County, Pennsylvania, (2016). https://www.census.gov/quickfacts/fact/map/centrecountypennsylvania/PST045216

[29] Centre Region Council of Governments, Centre Region Comprehensive Plan, 2013. http://www.crcog.net/vertical/sites/%7B6AD7E2DC-ECE4-41CD-B8E1-BAC6A6336348%7D/uploads/2010_Comprehensive_Plan_(Complete_Report_with_Resolutions)_Small_File.pdf

Appendix A

Interview Responses from Local Community-led Solar Owners

Full summary of the University Area Joint Authority's and Office of the Physical Plant's community-led solar project and the relationship to the Community Solar on State workshops. The information was provided courtesy of the UAJA and OPP organizations. Interview results yield that the catalyst (represented as CSOS) benefited the development of community solar in the locale. Prior, non-cooperative, efforts by the organization were unsuccessful. Similarities include: strong affiliation with CSOS, long (yet unfruitful) interest in solar prior to CSOS, and project motives.

Question	Response (UAJA)	Response (OPP)
Attendance at Community Solar on State	Yes (via UAJA representative)	Yes (via senior OPP officials); OPP co-created workshops
Direct impact of Solar on State on the UAJA	Reinforced confidence in solar; need to look deeper into energy-water connection	Useful solar relationships were established with developers; need to become organized in development efforts; community partnerships are complicated.
Conception of interest in solar	Years prior to CSOS	Years prior to CSOS
Hesitations on previous solar project attempts	Lacking mechanism to demonstrate long-term financial benefit	Difficulty to find a financial structure that satisfied objectives; unable to holistically value solar benefits; organization was absent in efforts
Primary project driver	Community goals (from Comprehensive Plan [29])	Balance between financial, environmental, and community relationships
Secondary project drivers	Sustainability, financial, and education	Research / education; university energy goals
Financial gain	Long term gain (13-15 years)	Long term neutral
Internal project support	Unanimous	Very supportive
External project support (local communities)	Very supportive (inferred from Comprehensive Plan)	Zero opposition materialized
Greatest barrier	Understanding the public-private partnership necessary to capitalize on tax incentives	Reaching cost goals and partnerships

Appendix B

System Advisor Model (SAM) PV Design Inputs (Control Experiment)

Design parameters and assumptions put into the System Advisor Model (SAM) to model the electricity production and after-tax costs of each solar photovoltaic option used as the payoffs in the non-cooperative game control experiment.

	Community-led	MUSH	DG Investor	Residential
Resource	Penn State – Surfrad (TMY3)	Penn State – Surfrad (TMY3)	Penn State – Surfrad (TMY3)	Penn State – Surfrad (TMY3)
Load (kWh/yr)	13,650,240	13,650,240	n/a	9,157
Installed Capacity (kW_p)	2,600	5	2,600	5
Battery	Yes	No	No	No
Inverter DC/AC Ratio	1.21	1.06	1.12	1.06
Land Purchase	No	No	Yes	No
Cost ($\$/W_p$)	1.55	2.93	1.39	2.93
Tax Credit	Yes	No	Yes	Yes
Retail Electricity Rate on load - year 0 ($/kWh)	0.065	0.065	n/a	0.1136

Appendix C

Control Experiment Matlab Code (Non-cooperative Game)

***Code 1**: Monte Carlo function to account for the uncertainty in the change of electricity prices.*

Input: Historical electricity prices.
Output: 25-year Monte Carlo simulation of electricity rates.

```
function [RateSimulation] = ElecRateMonteCarlo(rate0,trials)

load('PAannualRate.mat')

lnrate = log(rate);          %natural log of annual elec. prices
dlnrate = diff(lnrate);      % lnrate(t) - lnrate(t-1)
AVEdlnrate = mean(dlnrate);   % average of change in ln(rate)
STDdlnrate = std(dlnrate);    % standard dev. of change in ln(rate)

%fit change in ln(rate prices) to normal dist
ratedist = makedist('Normal','mu',AVEdlnrate,'sigma',STDdlnrate);

% create matrix to hold new simulation
RateSimulation = zeros(26,trials);             %26 rows for 25 years plus year
0
RateSimulation(1,1:trials) = log(rate0);       %set first column to last real
value (2016) cents/kWh
RateSimulation(2,1:trials) = log(rate0);       % set year 1 to last value

% simulate 10 years by month using diff(ln(P))
for i = 3:26         % iterate through rows
    for j = 1:trials    % iterate through columns
        RateSimulation(i,j) = RateSimulation(i-1,j) + random(ratedist);
    end
end

RateSimulation = exp(RateSimulation);  % take the exponential to undo ln
RateSimulation = RateSimulation / 100; %convert to $/kWh

end
```

***Code 2:** Simulate the NPV of various solar projects using Monte Carlo simulations for electricity rate increases.*

Input: PV annual generation (from SAM), system after-tax annual cost (from SAM), rate simulations from code 1
Output: Net present value (NPV)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% SIMULATION OF PROJECT NPVs
%%% with MONTE CARLO ANALYSIS FOR UNCERTAINTY IN ELECTRICITY RATES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%GENERATION OF PV MODELS IN KWH/YEAR
PVpower = zeros(3,26);  % 3 models; 25 years (and year 0)

% Community-led PV electricity generation (kWh)
PVpower(1,:) = [0,3311398,3294841,3278366,3261974,...
    3245665,3229436,3213289,3197223,3181237,3165330,3149504,...
    3133756,3118087,3102497,3086984,3071550,3056192,3040911,...
    3025706, 3010578,2995525,2980547,2965644,2950816,2936062];

% MUSH kW-scale PV elec. generation (kWh)/year
PVpower(2,:) = [0,4997.85,4972.86,4947.99,4923.25,4898.64,...
    4874.15,4849.77,4825.53,4801.4,4777.39,4753.5,4729.74,...
    4706.09,4682.56,4659.14,4635.85,4612.67,4589.61,4566.66,...
    4543.82,4521.11,4498.5,4476.01,4453.63,4431.36];

% residential PV elec. generation (kWh)/yr
PVpower(3,:) = [0,4997.85,4972.86,4947.99,4923.25,4898.64,...
    4874.15,4849.77,4825.53,4801.4,4777.39,4753.5,4729.74,...
    4706.09,4682.56,4659.14,4635.85,4612.67,4589.61,4566.66,...
    4543.82,4521.11,4498.5,4476.01,4453.63,4431.36];


%COSTS FLOW AFTER TAXES FOR MODELS IN $
systemCost = zeros(3,26);

%Community-led: UAJA
systemCost(1,:) = [0,1.09029e+06,...
    24251,-131321,-225965,-229152,-301232,-373499,-377249,-381212,...
    -385403,-389837,-394530,-399499,-404765,-410347,-416266,-422546,...
    -429213,-436293,-443814,-451808,-460308,-469349,-478969,-489211];

%MUSH kW-scale
systemCost(2,:) = [0,-1061.34,-1066.3,-1071.39,-1076.6,-1081.94,...
    -1087.41,-1093.02,-1098.77,-1104.67,-1110.71,-1116.9,-1123.25,...
    -1129.76,-1136.43,-1143.27,-364.082,-371.265,-378.627,-386.174,...
    -393.909,-401.837,-409.964,-418.294,-426.832,-435.583];

%residential PV
systemCost(3,:) = [0,2332.35,-1220.01,-1235.11,-1250.84,-1267.22,...
    -1284.28,-1302.06,-1320.6,-1339.91,-1360.04,-1381.03,...
    -1402.91,-1425.73,-1449.53,-1474.35,-364.082,-371.265,...
    -378.627,-386.174,-393.909,-401.837,-409.964,-418.294,...
    -426.832,-435.583];



%SINGLE VALUES
demandElec = zeros(3,1); % DEMAND OF ELECTRICITY
```

```
demandElec(1,1) = 13650240; %UAJA
demandElec(2,1) = 13650240; %MUSH kw scale
demandElec(3,1) = 9157;     %residential

taxEffect = .349;           %UAJA, MUSH kw scale, residential

trials = 10000;             %trials for MONTE CARLO simulation



% GRID POWER RATE cents/KWH
gridRate = zeros(3,26,trials);  % projects, years, simulation trials

gridRate(1,:) = 6.5;   %Community-led system
gridRate(2,:) = 6.5;   % MUST kw-scale
gridRate(3,:) = 11.358; %residential

%MONTECARLO ELECTRICITY RATES
for j = 1:3
    ElecRateMC = ElecRateMonteCarlo(gridRate(j,1),trials);
    gridRate(j,:,:) = ElecRateMC;
end

%inflation
r = 0.025;
for j = 1:3
    for i = 2:26
        for t = 1:trials
            % Find future value of grid rate
            gridRate(j,i,t) = gridRate(j,i,t)*(1+r)^(i-2);
        end
    end
end



% REVENUE STREAM
revenue = zeros(3,26,trials);

%%% SolSavings - SolCost
%%% (rate*PVgen)*tax - SolCost

%with tax rate
for j = 1:2
    for t = 1:trials
        revenue(j,:,t) = gridRate(j,:,t).*PVpower(j,:)*(1-taxEffect)...
                         + systemCost(j,:);
    end
end

%without tax rate
for t = 1:trials
    revenue(3,:,t) = gridRate(3,:,t).*PVpower(3,:) + systemCost(3,:);
end


%discount
NPVsims = zeros(3,trials);
NPV     = zeros(1,3);
discRate = 0.0814;

for j = 1:3
```

```
    for t = 1:trials
        NPVsims(j,t) = pvvar(revenue(j,:,t),discRate);
    end
    NPV(1,j) = mean(NPVsims(j,:));
end

NPV
```

Code 3: *Calculate payoffs by summing the project NPV and externality costs.*

Input: NPV from code 2
Output: Total cost of project option (payoff to non-cooperative game)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% EVALUATE TOTAL COST OF SOLAR PV PROJECT
%%% total cost = NPV + externalities
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

elecDemand = zeros(1,3);
elecDemand = [13650240,13650240,9157];

% increase in grid rates from year 0
rateIncrease = zeros(3,26,trials);

for j = 1:3
    for i = 3:26
        rateIncrease(j,i,:) = gridRate(j,i,:) - gridRate(j,1,:);
    end
end



%externality cost associated with utility increases
utility_increase = zeros(1,26,trials);
for i = 3:26
    % $416 is annual UAJA water price to residential customer
    utility_increase(1,i,:) = 416*gridRate(1,i,:)./gridRate(1,1,:) - 416;
end

%calculating externality cost
opp_costMC = zeros(6,26,trials);  % ext cost for each year in each trial
opp_costSims = zeros(6,trials);   %sum/discounted year flow of each trial
opp_cost = zeros(1,6);            %average of trials

%1. GA: community-led system
%%% grid increase (small)
for i = 1:26
    % externality cost = (net-grid demand) * (rate increase delta)
    opp_costMC(1,i,:) = (elecDemand(1) - PVpower(1,i)) * rateIncrease(1,i,:);
end
for t = 1:trials
    opp_costSims(1,t) = pvvar(opp_costMC(1,:,t),discRate);
end
opp_cost(1) = mean(opp_costSims(1,:));

%2. GA: MUSH
%%% grid increase (large)
for i = 1:26
    % Opportunity cost = (net-grid demand) * (rate increase delta)
    opp_costMC(2,i,:) = (elecDemand(1) - PVpower(2,i)) * rateIncrease(2,i,:);
end
for t = 1:trials
    opp_costSims(2,t) = pvvar(opp_costMC(2,:,t),discRate);
end
opp_cost(2) = mean(opp_costSims(2,:));

%3. GA: no solar
%%% grid increase (full)
for i = 1:26
```

```
    % externality cost = (net-grid demand) * (rate increase delta)
    opp_costMC(3,i,:) = (elecDemand(1) - 0) * rateIncrease(1,i,:);
end
for t = 1:trials
    opp_costSims(3,t) = pvvar(opp_costMC(3,:,t),discRate);
end
opp_cost(3) = mean(opp_costSims(3,:));

%4. CS: community-led
%%% grid increase (full)
for i = 1:26
    % externality cost = (net-grid demand) * (rate increase delta)
    opp_costMC(4,i,:) = (elecDemand(3) - 0) * rateIncrease(3,i,:);
end
for t = 1:trials
    opp_costSims(4,t) = pvvar(opp_costMC(4,:,t),discRate);
end
opp_cost(4) = mean(opp_costSims(4,:));

%5. CS: investor DG (club good)
%%% grid increase (full) + utility increase
for i = 1:26
    % externality cost = (net-grid demand) * (rate increase delta)
    opp_costMC(5,i,:) = (elecDemand(3) - 0) * rateIncrease(3,i,:);
    % add on utility rate increase
    opp_costMC(5,i,:) = opp_costMC(5,i,:) + utility_increase(1,i,:);
end
for t = 1:trials
    opp_costSims(5,t) = pvvar(opp_costMC(5,:,t),discRate);
end
opp_cost(5) = mean(opp_costSims(5,:));

%6. CS: residential
%%% grid increase (small) + utility increase
for i = 1:26
    % externality cost = (net-grid demand) * (rate increase delta)
    opp_costMC(6,i,:) = (elecDemand(3) - PVpower(3,i)) * rateIncrease(3,i,:);
    % add on utility rate increase
    opp_costMC(6,i,:) = opp_costMC(6,i,:) + utility_increase(1,i,:);
end
for t = 1:trials
    opp_costSims(6,t) = pvvar(opp_costMC(6,:,t),discRate);
end
opp_cost(6) = mean(opp_costSims(6,:))
```

Appendix D

Shapley Value Python Code (Cooperative Game)

Input: Number of players; values to fill characteristic equation
Output: Shapley values; players' percent contribution to overall coalition

```
"""COOP GAME"""
### COMPUTE SHAPLEY VALUE FOR 3-PLAYER COOPERATIVE GAME
##### code is deliberately elongated to clearly show steps in analysis
##### this modified code only works for 3-player games


#####
#IMPORT AND INITIALIZE
#####
import pandas as pd
import math
import statistics as stat

num_players = int(input('How many players? '))   # set up total number of players

#set up: players names
players = []
i = 1
while i <= num_players:
    given = input('Player ' + str(i) + ': ')
    players.append(given)
    i = 1 + i


#####
# FORMAING COALITIONS
#####

coalitions = []
i = 0
j = 0
h = 0
k = 0

# forming coalitions of individual player
while (i < num_players):
    coalitions.append(players[i])
    i = i + 1
i = 0

# forming coalitions of 2 players
while (i < num_players):
    while(j < num_players):
        if (j == i):
            j = j + 1
        else:
            coalitions.append(players[i] + ", " + players[j])
            j = j + 1
    i = i + 1
    j = i
i = 0
```

```
j = 0

# forming coalitions of 3 players
while (i < num_players):
    while (j < num_players):
        if (j == i):
            j = j + 1
        else:
            j = j
        while (h < num_players):
            if (h == i or h == j):
                h = h + 1
            else:
                coalitions.append(players[i] + ", " + players[j] + ", " + players[h])
                h = h + 1
        j = j + 1
        h = j
    i = i + 1
    j = i
    h = j


#####
#CHARACTERISTIC EQUATION
#####
chareq = pd.DataFrame(index=[0],columns = coalitions)

chareq

#assign values to characteristic equation
i = 0

while (i < len(coalitions)):
    chareq.loc[0][i] = float(input(coalitions[i]+":"))
    i = i + 1

chareq


# set up rows to be in Shapley calculation matrix
rows = []
i = 0
while (i < math.factorial(num_players)):
    rows.append(i)
    i = i + 1

# set up Shapley calculation matrix
matrix = pd.DataFrame(index=[rows],columns = players)


#####
# SUBGAME SOLUTIONS FOR 3-PLAYER ANALYSIS
#####

#a,b,c
matrix.iloc[0][0] = chareq.iloc[0][0]
matrix.iloc[0][1] = chareq.iloc[0][3] - chareq.iloc[0][0]
matrix.iloc[0][2] = chareq.iloc[0][6] - (matrix.iloc[0][0] + matrix.iloc[0][1])

#a,c,b
matrix.iloc[1][0] = chareq.iloc[0][0]
matrix.iloc[1][2] = chareq.iloc[0][4] - chareq.iloc[0][0]
```

```
matrix.iloc[1][1] = chareq.iloc[0][6] - (matrix.iloc[1][0] + matrix.iloc[1][2])

#b,a,c
matrix.iloc[2][1] = chareq.iloc[0][1]
matrix.iloc[2][0] = chareq.iloc[0][3] - chareq.iloc[0][1]
matrix.iloc[2][2] = chareq.iloc[0][6] - (matrix.iloc[2][1] + matrix.iloc[2][(1+2)%3])

#b,c,a
matrix.iloc[3][1] = chareq.iloc[0][1]
matrix.iloc[3][2] = chareq.iloc[0][5] - chareq.iloc[0][1]
matrix.iloc[3][0] = chareq.iloc[0][6] - (matrix.iloc[3][1] + matrix.iloc[3][2])

#c,a,b
matrix.iloc[4][2] = chareq.iloc[0][2]
matrix.iloc[4][0] = chareq.iloc[0][4] - chareq.iloc[0][2]
matrix.iloc[4][1] = chareq.iloc[0][6] - (matrix.iloc[4][2] + matrix.iloc[4][(2+1)%3])

#c,b,a
matrix.iloc[5][2] = chareq.iloc[0][2]
matrix.iloc[5][1] = chareq.iloc[0][5] - chareq.iloc[0][2]
matrix.iloc[5][0] = chareq.iloc[0][6] - (matrix.iloc[5][2] + matrix.iloc[5][(2+2)%3])


matrix


#####
#SOLVE FOR SHAPLEY VALUE
#####

shapley = pd.DataFrame(index=["Shapley","% contribution"],columns = players)

# average matrix for each player
for x in players:
    shapley[x]["Shapley"] = stat.mean(matrix[x])
    shapley[x]["% contribution"] = shapley[x]["Shapley"] \
                                / chareq.loc[0][coalitions[math.factorial(num_players)]] \
                                * 100
shapley
```