Utilities Policy 95 (2025) 101914

Contents lists available at ScienceDirect

Utilities Policy

journal homepage: www.elsevier.com/locate/jup

Full-length article

New avenues for community solar adoption research: A qualitative comparative analysis of ten U.S. states

Dong Min Kim [a,*], Shan Zhou [b], Adam M. Wellstead [a]

[a] Department of Social Sciences, Michigan Technological University, United States
[b] Department of Political Science, Purdue University, United States

ARTICLE INFO

Handling Editor: Janice A. Beecher

Keywords:
Community solar
Shared solar
Renewable energy adoption
Qualitative comparative analysis
fsQCA

ABSTRACT

Community solar presents an opportunity for every household and business to harness the advantages of solar energy. In the community solar adoption literature, qualitative and case-specific investigations have suggested potential adoption factors, such as related policies, solar technical potential, and socioeconomic measures. However, limited effort has been devoted to evaluating the complex dynamics of these causal conditions, let alone the development of empirical evidence. This paper fills these gaps using fuzzy-set Qualitative Comparative Analysis (fsQCA) to examine the dynamics of U.S. community solar adoption factors. The application of fsQCA, grounded in set-theoretic principles and truth-table analysis, enables a comprehensive evaluation of the various configurations of conditions that contribute to community solar adoption among the top ten adopting states. The results show that, in the most active states, adoption paths vary in government liberalism. For conservative states, the primary factors were a non-wealthy GDP per capita and strong solar potential. On the other hand, liberal states commonly had strong solar potential and high electricity prices as their common factors for adopting community solar.

1. Introduction

Although rooftop solar photovoltaic (PV) has experienced rapid development in recent years, not everyone has access to the benefits of solar PV since it usually requires ownership over land, buildings, and/or rooftops. In the U.S., a significant portion of households have either no or unviable rooftops for solar PV installation: more than 30 percent of American households rent their homes or apartments (HUD, 2023), and about 50 percent of households cannot host a PV system (Feldman et al., 2015). Community-based solar (community-shared or shared solar) is a solar project or purchasing program within a specific community where multiple customers benefit from off-site solar energy generation, including individuals, not-for-profit organizations, and other groups. Some have suggested mitigating the inequalities and barriers associated with solar power utilization (McLaren, 2014; Funkhouser et al., 2015; Chan et al., 2017; Zhou et al., 2023).

Three popular community solar models have emerged: utility-sponsored model owned and operated by the utilities, Special Purpose Entity (SPE) owned and operated by individual investors through business enterprises, and not-for-profit charitable corporations (Coughlin et al., 2010).[1] Community solar has apparent benefits that are common across all models. First, because of the economies of scale, the average cost of community solar is often much lower compared to rooftop solar installations (McLaren, 2014). Second, a substantial number of subscribers from a community also helps make financing more affordable to customers (Funkhouser et al., 2015). Third, community solar is more equitable than other energy systems (Chan et al., 2017). The required accessibility to the rooftop is no longer a barrier to solar PV adoption, which mitigates the overall equity concern for traditional, distributed solar PV systems. Many state and local governments and utilities have adopted community solar programs to reduce solar adoption inequalities (Zhou et al., 2023).

Given the many benefits, community solar has attracted increasing attention from policy practitioners, energy developers, community organizations, and environmental groups. According to the National Renewable Laboratory (NREL), as of December 2022, there are over 2551 community solar projects in the United States spanning 44 states (Chan et al., 2022). Since 2016, community solar capacity in the United

* Corresponding author. 970 Kent Avenue, Brooklyn, NY, 11205, United States.
E-mail address: dongmin@mtu.edu (D.M. Kim).

[1] There are several different ways to subscribe to community solar, such as panel purchasing, panel leasing, and investing in the system. Subscription methods are largely dependent on the economic circumstances surrounding the chosen model.

https://doi.org/10.1016/j.jup.2025.101914
Received 31 August 2024; Received in revised form 25 February 2025; Accepted 25 February 2025
Available online 8 March 2025
0957-1787/

States has experienced exponential growth, starting at approximately 142 Megawatt-Alternating Current (MW-AC) per year and accelerating to 2080 MW-AC annually by 2021. This significant increase reflects a burgeoning interest and investment in community-based solar projects nationwide.

The community solar scholarly literature has focused on the potential drivers and barriers (Funkhouser et al., 2015; Augustine and McGavisk, 2016; Michaud, 2020), policy and business models (Coughlin et al., 2010; McLaren, 2014; Feldman et al., 2015), and equity concerns (Asmus, 2008; Chan et al., 2017). In sum, vast potential factors influence community solar adoption, such as enabling policies, market conditions, regulation, lower-income communities, utility preferences, and ideologies.

Though these adoption discussions contribute to fundamental knowledge about community solar, it is unclear which adoption factors are more or less important, making it hard for resource-constrained policy actors to act on such knowledge. Moreover, there is a lack of an ex-post analysis of factors leading to the recent deployment of 2000 community solar projects across the United States (Chan et al., 2022). Specifically, Fig. 1 shows that the top four states, Florida, New York, Minnesota, and Massachusetts, have a greater cumulative community solar capacity than all the remaining states combined. We focus on evaluating differences among the top ten states to explain these sizable adoption differences, even among the top leaders,

By employing Qualitative Comparative Analysis (QCA), which specializes in small-N causal analysis, we address the following policy-related questions: 1) which combinations of factors influence community solar adoption? 2) more specifically, how can we explain the comparatively higher rates of community solar adoption in the four leading states? This research contributes to the literature on the latest dynamics of community solar adoption by addressing these two questions.

This paper continues with a thorough literature review identifying driving factors of community solar adoptions. It then explains the fuzzy-set QCA method and the data used for the analysis. The section assumes that the readers are not knowledgeable of QCA. In the subsequent sections, the results of the QCA are discussed, and theoretical contributions and policy implications are presented to share insights from the analysis.

2. Background: driving factors of community solar adoption

This section identifies a range of possible conditions identified in the community solar literature that influence community solar deployment. Policy instruments are often considered important enabling factors. Community solar policies and programs, compensation designs, financial incentives, and renewable portfolio standards (RPS) are the most influential among the others. In addition, other economic and political factors and natural endowment (solar energy resources) were also identified as important contextual influences.

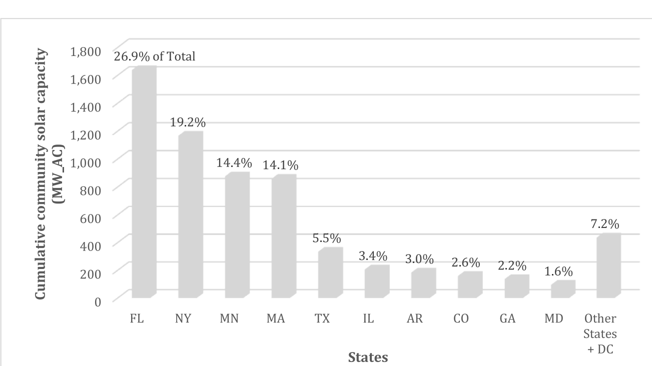

Fig. 1. Cumulative community solar capacity (MW-AC) of the top 10 adopting states as of 2022 (data from NREL).

2.1. Policy instruments

As RPS draws more attention to the state's renewable energy integrations, its impact on community solar adoption seems inevitable. Funkhouser et al. (2015) found that the state RPS supports community solar adoption as it indicates the state is pro-environment and the community solar can satisfy the RPS target. Moreover, some states set RPS, in which Renewable Energy Credit (REC) markets can be formed to increase the adoption rate of community solar (Augustine and McGavisk, 2016). However, when community solar energy is considered a security, the impact of the adoption is not dismissible. The financialization of this shared solar energy production is under high scrutiny by the Securities and Exchange Commission (SEC) due to its nature as a profitable investment. If the solar energy model is classified as a security, it introduces additional complexities and costs to the business. Companies operating under such classification must comply with securities laws designed to protect investors and ensure transparency in financial reporting at the cost of more stringent reporting requirements, regulatory limitations, and potentially higher taxes. These regulations often necessitate thorough disclosures, periodic filings, and adherence to specific operational standards, all of which can increase administrative burdens and operational costs for solar energy businesses. (Feldman et al., 2015).

According to the most recent NREL report by Heeter et al. (2021), 21 states and Washington D.C. have community solar policies with enabling legislation. Cook and Shah (2018) categorized the community solar policy by six key components: program cap, project size cap, geographic location requirements, subscriber eligibility requirements, LMI stipulations, and subscriber compensation. The authors conclude that there is a significant policy variation across the states, and these differences likely influence the community solar deployment in each state. Moreover, according to Funkhouser et al. (2015), the willingness of utilities to participate in community solar is pivotal, regardless of the rationale behind their participation. For instance, a utility can adopt some form of community solar through its program even if there is no state community solar policy.

2.2. Natural endowment, political, and economic factors

Solar energy is a natural endowment, the magnitude of which is dependent on geography. With different amounts of solar energy resources in each state, the technical potential of solar also varies, which may significantly impact project cost and economic viability. Solar technical potential presents technically harvestable solar energy through PV adoption, and it has been previously discussed in a study by Kwan (2012) as positively correlated to solar PV installation. Even though not all sunny states excel in solar development due to other factors, solar technical potential is generally expected to impact community solar adoption positively.

Political factors, particularly political ideology, are pivotal for understanding renewable energy investments and RPS adoption. The literature suggests that more liberal governments tend to support renewable energy worldwide (Abban and Hasan, 2021). Also, RPS adoption literature collectively confirms the liberal government's higher impact on the adoption, though some exceptions exist, such as Texas (Lyon and Yin, 2010; Fowler and Breen, 2013; Thombs and Jorgenson, 2020). Even though community solar may not mean the same as renewable energy investments or RPS, the direction of political impact can still be inferred since the interlinks for using renewable energy to replace traditional energy sources carry similar opposition. Moreover, liberal governments are more likely to project social equity and environmental sustainability (Sterling et al., 2019). In this respect, liberal governments may see community solar as an important tool for achieving energy justice, which can also be inferred from climate justice (Basseches et al., 2022).

Economic conditions can potentially influence the adoption of community solar. The literature views income as an important factor delineating different renewable energy adoption patterns (Omri and Nguyen, 2014). Yi and Feiock (2012) found that increasing state GDP per capita may increase the demand for renewable energy. Sadorsky (2009) also estimated that per capita income positively impacts per capita renewable energy consumption in emerging economies. Though the community solar adoption pattern may follow a similar trajectory as other renewable energy, there could also be multiple counterarguments. First, increased demand could only positively influence rooftop solar rather than community solar because of their difference in adoption factors. Second, lower-income groups may be more likely to be attracted by the economic benefits of community solar. In this sense, examining the impact of economic conditions on community solar energy will help clarify these uncertainties.

Lastly, electricity prices are also positively correlated with the deployment of solar PV (Carley, 2009; Kwan, 2012), and such phenomena may also influence community solar energy. A high electricity price means solar PV can provide more economic benefits by reducing electric bills. For community solar, people have more incentives to enroll when the electricity price and energy burden are high. However, Augustine and McGavisk (2017) concluded that there are different barriers to each state and model. For instance, states with low electricity prices need more community solar incentives to attract system owners and developers, emphasizing that there is no single solution for community solar adoption. Electricity price is, therefore, not easily inferable from past studies and requires further scrutiny.

2.3. Intentionally omitted factors

The compensation design of community solar can be important. Without a utility sponsor, a community solar business model must have a compensation mechanism for the value of generated solar energy. Virtual Net Metering (VNM) connects meters between the community solar and the subscribers without being physically interconnected. It calculates and compensates for the net generation stemming from the community solar and its subscribers and owners (Augustine and McGavisk, 2016). Another way to compensate for the produced solar energy is to have a tariff, such as a green tariff, feed-in tariff, and Value of Solar tariff. Unlike VNM, tariffs tend to evaluate the value of solar energy in a more systemic context, not just net energy balance. In this vein, O'Shaughnessy and Ardani (2020) introduce the five components of solar value: ancillary services, capacity, energy, environment, and transmission and distribution. They conclude that the case studies of New York and California's tariffs were designed to provide practical rates that align with the theoretical considerations. In states where VNM or specific tariffs for community solar are not mandated by law, investor-owned utilities (IOUs) often develop programs to facilitate customer participation. For example, in Florida, IOUs have established community solar programs within their service areas. Under these programs, subscribers are compensated directly by the IOU for the energy generated by their share of the solar project. This approach eliminates the need for external VNM policies or tariffs, as the IOUs internally manage and calculate the net energy contributions from each subscriber's solar panels.

One of the more ostensible policies for community solar is the federal tax credit or Investment Tax Credit (ITC). The tax credit used to be 30% of the investment for residential adopters in 2019. Over the 5 years, it was planned to phase out. However, the Inflation Reduction Act changed its bonus tax credit so that the solar energy tax credit for the community continues beginning in 2025 (Congressional Research Service, 2021; EPA, 2024). There is some debate in the literature regarding the effectiveness of tax credits. According to Funkhouser et al. (2015), the impacts differ considerably among community solar stakeholders. For instance, utilities only benefit a little from the tax credit since they need to share it with their customer, but the private actors could take more advantage due to their project size and design. Moreover, Augustine and McGavisk (2016) argue that the ITC is hard to take advantage of for most community solar projects because it requires the investors to have a significant passive income and tax basis, making ITC not readily available for SPE and not-for-profit entities. In this regard, financial incentive policies have a relatively weak impact on community solar adoption.

3. Data and methods

3.1. Theoretical development of QCA

Developed initially by Ragin (1987) and widely utilized across social science disciplines such as political science and public policy, QCA combines qualitative and quantitative methods (Fernandez-Esquinas et al., 2021). QCA is a method that merges the contextual richness of qualitative approaches with the broad applicability and numerical rigor of quantitative methods, making it especially suited for asymmetric analysis (Ragin, 1987). In the center of QCA lie the necessary and sufficient conditions, and it utilizes set theory to apply the principles of equifinality, multiple conjunctural causation, and causal asymmetry (Schneider and Wagemann, 2009). Equifinality is the premise that different combinations of causal conditions are equally effective in affecting the outcome. Multiple conjunctural causation implies multiple paths to outcome, each with a combination of conditions. Lastly, causal asymmetry asserts that one cannot infer an explanation for the absence of an outcome solely from the explanation for its occurrence. On top of the above set theory, QCA utilizes the logic of proposition and Boolean algebra to analyze multiple configurations of the causal conditions.

In the context of policy analysis, QCA has been used for both exploratory and theory-led applications. For instance, Cacciatore et al. (2015) use QCA as an exploratory tool to analyze the patterns of 'clustered Europeanization' stemming from the EU 2020 strategy. On the other hand, Pahl-Wostl and Knieper (2014) assess the 27 water governance systems for climate change adaptation, which is based on a strongly theory-led typology of the coordination and centralization of governance regimes. QCA's advantage in policy analysis is evident in that it focuses on the necessary and/or sufficient conditions for the outcome. Identifying the conjunctural patterns is natural to QCA, embracing the complex nature of the policy analysis rather than overly simplifying. Moreover, its capability to analyze small to intermediate N observations fills the gap between qualitative and quantitative methods. Despite its limitation of cross-sectional characteristics, there are specific and applicable policy analysis contexts in which QCA can outweigh other methodologies.

3.2. Case and condition selections of fuzzy-set QCA

QCA research often consists of the following components: case, condition, and membership. The case refers to configurations of conditions and their outcomes. This study's cases represent the top ten states with community solar projects. The conditions are factors identified in the literature review for their potential impacts on the outcome of interest, the community solar adoption. Lastly, the membership delineates whether a case has condition (1) or not (0).

There are two main QCA approaches: crisp and fuzzy. Crisp set uses binary conditions for membership, whereas fuzzy set uses the degree of membership. Memberships of both sets have a value between 1 and 0, but fuzzy has a membership degree gradation of 0.05–0.95. For example, although a binary condition can represent presidential election results, the state's solar technical potential could be better represented as a continuous variable. Hence, fuzzy set QCA is more appropriate for analyzing factors influencing community solar adoption since significant portions of the conditions identified through the literature review are continuous (e.g., income and natural resource endowment).[2] For fuzzy set QCA, the fsQCA 4.1[3] was used for the calculations and analysis.

3.2.1. Cases

The qualitative and quantitative nature of QCA allows continuous adjustment to the research design. Case (state) and condition (adoption factors) selections are pivotal steps of QCA as they can largely influence the analysis result. In QCA, the case selection processes are relatively progressive rather than definitive, meaning it is common practice to choose initial cases and conditions and then adjust as the analysis continues. Moreover, the qualitative aspect of QCA brings powerful insights into those adjustments. For instance, when the result of QCA flags a lack of explanatory power for a specific condition configuration, it is readily possible to identify which states belong to the configuration and qualitatively compare them for any potential explanation. Once reviewed, the new information could be operationalized as another design condition.

It is also important to note the relationship between representativeness and case selection. Though, in statistical analysis, case selection directly relates to the generalizability of the outcome, comparative case studies select cases in response to the research question (Thomann and Maggetti, 2017). In this sense, ten states with the higher cumulative community solar capacity are selected as the cases. This research compares these states to identify factors driving substantial adoption in states like Florida and New York. Unlike statistical analysis, in which selecting a dependent variable could introduce a design flaw, QCA effectively examines the diverse adoption levels even among the states that have already adopted community solar.

The outcome of the case is the cumulative capacity of community solar (MW-AC). It refers to the total installed and operational capacity (measured in megawatts, MW) of solar energy projects categorized as community solar. The analysis does not adjust the cumulative capacity based on state population, as no significant relationships were observed. For instance, despite having the largest population in the U.S., California did not rank among the top 10 states for cumulative community solar capacity. In contrast, Minnesota, with only about one-fifth of Texas' population, holds the third highest cumulative capacity.

3.2.2. Conditions

The selected conditions and their corresponding descriptive statistics, which are listed in Table 1, are RPS policy stringency, state community-solar-related policy stringency (excluding utility program), solar energy potential, government ideology (1 for the democratic party), per capita GDP, and electricity price. The RPS policy stringency represents how firm a state policy is toward employing renewable energy. Also, the state community-solar-related policy stringency shows the strength of community solar-enabling policies. Conditions for compensation schemes have been integrated into the community-solar-related policy stringency. The state compensation scheme is not required for community solar adoption, so it can only add stringency to the community solar policy. The solar energy potential provides comparable state natural endowments. Government Ideology, per capita GDP, and electricity price present the state's political and economic conditions. Lastly, the financial incentive was omitted as a potential condition since the literature dismisses the impact of tax credits on community solar.

Table 1
Descriptive statistics for the QCA conditions.

Variable	Mean	Std. Dev.	Min	Max
Outcome				
Cumulative Community Solar Capacity (MW-AC)	565	536	95	1636
Conditions				
RPS Stringency	2.4	2.2	0	5
State Community Solar Policy	2.6	2.1	0	5
Solar Potential (GW)	4704	5965	73	20626
Government Ideology (Liberal)	0.7	0.5	0	1
GDP Per Capita ($)	66595	9357	51636	83461
Electricity Price (Cents/kWh)	11.23	2.87	8.98	18.35

We gathered secondary data to operationalize these conditions. The cumulative community solar capacity in megawatts-AC was sourced from the "Sharing the Sun" NREL database (Chan et al., 2022). RPS and Community solar policy data were sourced from the State Policy Opportunity Tracker (SPOT). Appendix Ashows that SPOT tracks each state's strengths by asking several key questions. If a state marks yes for all questions for RPS, the state scores 5 points. For the state community solar policy, the question about the presence of a utility program was omitted since all 10 states of interest have at least one program run by a utility. Moreover, the group or virtual net metering question considers the state's support for compensation schemes. The solar potentials were sourced from NREL's Renewable Energy Technical Potential (Lopez et al., 2012). The technical potential is a physically harvestable energy capacity that disregards market, economic, or policy factors. The state's presidential election percentage is included as a condition that represents the political context of a state. Government liberalism is based on the presidential election results in 2020. 2021 GDP per capita is sourced from the Bureau of Economic Analysis (BEA). Lastly, the 2021 electricity price was obtained from the Energy Information Administration (EIA). It provides the average retail electricity price for each state. The entire data collection was aimed at gathering 2021 data. However, there were conditions with some exceptions: policy stringency data published in 2022, time-independent solar energy potential, and government ideology, which used 2020 presidential election data.

When defining the qualitative language of the condition, descriptive statistics provides the ranges at which the definition can be best described. For instance, to utilize the fuzzy set QCA, the conditions needed to be calibrated to range between 0.05 and 0.95, where a lower number presents non-participation in the membership. The calibration is done using each condition's respective membership thresholds, and the thresholds carry a descriptive nature, which will be discussed in the next paragraph. Furthermore, calibration is also an interactive process, similar to condition selection. Such an iterative process ensures optimal results that embody existing knowledge and theories. In fsQCA, the calibration uses log odds to distinguish full-membership (0.95), crossover point (0.5), and non-membership (0.05) thresholds. At the crossover point, a case is neither clearly "in" nor clearly "out" of a condition, making it a crucial point for analyzing the degree to which a case exhibits a particular characteristic.

3.3. Fuzzy-set calibration

Fuzzy-set calibration requires adjusting each condition's membership threshold, and the threshold decides when the continuous variable becomes either membership or non-membership. Table 2 shows the calibration thresholds for each condition. After the log odds calibration, when a condition's value is greater than 0.95, it was assigned a full membership. Similarly, non-membership was given when the calibration score was less than 0.05. For instance, the fuzzy score must pass the full-membership threshold of 3000 GW for solar potential to be considered qualitatively strong. These thresholds are found based on

[2] It is essential, however, to note that both crisp and fuzzy sets were attempted multiple times to fine-tune the design, which aligns with existing literature (Mello and Ragin, 2021).

[3] fsQCA 4.1 software can be downloaded from: https://sites.socsci.uci.edu/~cragin/fsQCA/publications.shtml.

Table 2
Fuzzy score calibration.

	Conditions (abbreviation)	Full Membership (0.95)	Cross-over Point (0.5)	Non-membership (0.05)
High Cumulative Community Solar Capacity (MW-AC)	**COM**	500	200	50
Strong RPS Stringency	**RPS**	5	3.5	2
Strong State Community Solar Policy	**CSPS**	5	2.5	2
Strong Solar (GW) Potential	**SPO**	3000	1000	500
Government Ideology (Liberal)	**DEM**	1	0.5	0
Wealthy GDP Per Capita	**GDPPC**	70000	60000	55000
Expensive Electricity Price (Cents)	**EP**	13	11	10

contextual knowledge and descriptive statistics.

The calibration threshold rationale for the cumulative community solar capacity was centered around the capacity at which a state should be considered amassing the most significant adoption of community solar. Even though the average capacity is 565 MW-AC, the community solar adoption threshold is 800 MW-AC for full membership. At less than 565 MW-AC, the threshold considers cross-over to non-membership.

As mentioned above, RPS stringency scores were based on the questionnaire shown in Appendix A. Out of five key stringency questions, more than three had to be checked to be considered stringent, hence the cross-over point at 3.5. Moreover, the non-membership is set at 2 for filtering out the no RPS and voluntary RPS states. The descriptive word 'strong' allows one to examine each state's RPS qualitatively and evaluate its impact on community solar adoption throughout QCA without losing its qualitative value, which is not readily possible for traditional regression analysis. Similarly, a strong state community solar policy was set for a cross-over point of 2.5. Though full and non-membership are the same as that of the RPS stringency, the cross-over point is different because a firm community solar policy has a relatively low hurdle, suggesting that the state has a firm policy if it consists of at least one community solar policy and proper metering system.

Furthermore, the solar technical potential, GDP per capita, and electricity price were also set thresholds based on descriptive statistics. The cross-over points for these conditions were set to distinguish states with "higher than" and "lower than" the averages. Government ideology was already divided into full/non-memberships, full membership being liberal.

3.4. Necessity and sufficiency analysis

Central to QCA analysis is the consistency and coverage of a condition combination (Mello and Ragin, 2021). Here, consistency measures the extent to which an empirical relationship between a condition or combination of conditions and the outcome aligns with set-theoretic necessity and/or sufficiency (Ragin, 2008). In other words, consistency represents how much of the causal condition is a superset of the outcome. In this research, high consistency implies that a condition or a configuration of conditions has advanced community solar adoption. On the other hand, coverage evaluates the empirical significance or relevance of a consistent superset. If a condition has a high coverage, it implies that it can explain much of the outcome. For instance, in Table 3, Strong RPS Stringency has a consistency of 0.48, suggesting that Strong RPS Stringency yields strong community solar adoption (outcome) in 48% of the cases selected. On the other hand, 0.78 coverage suggests that Strong RPS Stringency as a causal factor covers 78% of the cases with community solar adoption.

Table 3
Analysis of necessary conditions.

Conditions	Consistency	Coverage
Strong RPS Stringency	0.48	0.78
Strong State Community Solar Policy	0.53	0.66
Strong Solar (GW) Potential	0.74	0.64
Is Government Liberal	0.65	0.61
Wealthy GDP Per Capita	0.62	0.69
Expensive Electricity Price	0.44	0.97

In QCA, necessity analysis is conducted first to identify conditions that always lead to the outcome. We applied fsQCA software to evaluate whether any single condition is necessary for community solar adoption, using consistency value to find necessary conditions. As seen in Table 3, however, there are no conditions with a high consistency (higher than 0.9) AND relatively high coverage (higher than 0.5). Such a result suggests that all conditions are prone to be sufficient and should be analyzed through a separate fsQCA approach called truth table.

Table 4 is the Fuzzy Truth Table. A truth table is an analytical tool QCA uses to process logical minimization and find solutions. Initially, it contains all logically possible combinations of conditions, but it reduces logical remainders[4] and combinations with low consistency. The fsQCA program uses the calibrated conditions to calculate the membership consistency. As stated, at first, the truth table has all potential configurations, 2^k, where k is the number of conditions. In the table, the conditions section has all the adoption factors of interest, and 1 and 0 designations mean the presence and absence of the condition. In the applied algorithm, conditions with a fuzzy score greater than 0.5 were assigned a value of 1, while those with a score less than 0.5 were assigned a value of 0. Consequently, the algorithm precluded the possibility of a fuzzy score precisely equal to 0.5. When a fuzzy score of 0.5 was encountered, the corresponding condition underwent recalibration to align with the binary classification system employed by the program. The table initially contained 64 configurations with an empty COM (the outcome variable - community solar adoption) binary column, highlighted in light yellow in Table 4. In order to fill it in for each configuration, there is a particular set of procedures. First, a frequency threshold for configurations is needed. Frequency is the number column in the truth table and presents several states that belong to a specific combination. Ragin insists on using 1 to 2 for the threshold for a relatively small total N and a more substantial number for a larger N. Then, the configurations with omitted numbers (combinations without any member states) were dropped. With the remaining 21 configurations, the COM column was filled in by giving a score of 0 for the configurations that do not have a raw consistency value higher than 0.75. If higher than 0.75, COM is assigned 1. Proportional Reduction in Inconsistency (PRI) consistency is used to check the simultaneous subset of being sufficient for both the outcome and the negation of the outcome. PRI consistency should also be higher than 0.6 and closely follow raw consistency.

After editing the table, the analysis was run through the fsQCA program. It first provides a set of consistencies. Then, the program produces three sets of solutions. First, a complex solution shows all possible configurations after logical operations. Second, a parsimonious solution can be found from the complex solution based on the

[4] Logical remainders are logically possible combinations but not present in the real data. In QCA, the remainders and counterfactuals are used interchangeably.

Table 4
Fuzzy truth table.

Conditions from Table 3						Frequency		Outcome		
RPS	CSPS	SPO	DEM	GDPPC	EP	number	Case	COM	raw consist.	PRI consist.
1	1	1	1	1	0	1	MN	1	1	1
1	1	0	1	1	1	2	NY, MA	1	0.94	0.94
0	0	1	0	0	0	3	AR, TX, FL	1	0.77	0.68
0	1	1	1	1	0	2	CO, IL	0	0.61	0.29
0	0	1	1	0	0	1	GA	0	0.46	0.21
1	1	0	1	1	0	1	MD	0	0.15	0.01

simplifying assumptions. The parsimonious solution accounts for easy and difficult counterfactual cases (Ragin, 2008). Lastly, an intermediate solution can be formulated by including only theoretically plausible, easy counterfactuals. When creating an intermediate solution term, the emphasis is not on scrutinizing every truth table row for counterfactuals but evaluating complex and parsimonious solution terms. The solution process involves determining which individual conditions can be eliminated from the complex solution while keeping parsimonious solutions and adhering to directional expectations (Schneider and Wagemann, 2009).

4. Fuzzy-set QCA results

While using the fsQCA program, theoretical and substantive knowledge is required to process the logical elimination of counterfactuals. The causal conditions' theoretical contribution to the outcome is manually selected from *present*, *absent*, or both *present* and *absent*. For example, while strong RPS may support community solar adoption, its absence is not necessarily impactful. Hence, RPS's theoretical contribution occurs only when it is *present.* On the other hand, based on the data collection, political ideology will influence adoption when political conditions are *present* (liberal) and *absent* (conservative). In this sense, the literature also suggests that the directional expectations are that the presence of a strong state community solar policy, strong solar potential, and high electricity price are causally linked to the strong community solar adoption, as opposed to when they are absent. On the other hand, similar to government liberalism, high GDP per capita is not yet apparent in its directional impact on the outcome, suggesting that the condition's presence and absence could both be associated with adoption. After confirming these theoretical assumptions on fsQCA software, fuzzy set solutions are calculated, as shown in Table 5.

For the QCA, core conditions refer to those that persist in the parsimonious solution, representing essential factors for the outcome. In contrast, peripheral conditions appear in the intermediate solution but are absent from the parsimonious solution, indicating factors that play a role but are not fundamental in the most simplified model (Fiss, 2011). As mentioned above, parsimonious solutions are calculated with the steepest logical minimizations through easy and difficult counterfactual assumptions. Thus, these solutions provide a more generalizable analysis. Additionally, during the solution calculation process, prime implicants are evaluated. A prime implicant represents the minimal combination of conditions sufficient to produce a specific outcome. In some cases, prime implicants may share certain conditions, necessitating user input to select the most theoretically sound combinations. However, this study did not encounter any overlaps among prime implicants.

The first configuration states that a not liberal government leads to community solar adoption, regardless of other conditions, and it covers about 0.40 of the adoption outcome. Moreover, the second configuration states that expensive electricity prices lead to community solar adoption, regardless of other conditions. The third parsimonious configuration states that [strong RPS AND high solar potential] lead to community solar adoption, regardless of the remaining conditions. The overall parsimonious solution demonstrates high coverage and consistency: states that are not liberal OR states with high electricity prices OR states with [stringent RPS policy AND high solar technical potential] vastly adopt community solar.

The negation of the outcome analysis is also important since QCA is based on set theory, where the relationship between conditions and outcomes can be asymmetric, meaning what explains the presence of an outcome might not be the same as what explains its absence. Analyzing the outcome's presence and negation provides a comprehensive understanding of the complex relationships between conditions and the outcome of interest. Configuration 4 in Table 5 shows that not strong community solar adoption (outcome negation) was a superset of [not expensive electricity prices AND not high solar technical potential].

The findings of this core condition analysis from the parsimonious solution suggest three causal paths: non-liberal states, high electricity prices, and high solar potential with strong RPS in the state. Though core conditions are essential information that dictates the causal paths, these simplified condition statements can further benefit from peripheral condition analysis. As Ragin and Fiss (2008) suggested, causal coreness can be evaluated by examining the intermediate solution and analyzing the evidence's strength relative to the outcome. Thus, intermediate solutions are also examined to provide more detailed causal configurations. As shown in Table 6, intermediate solutions are represented in a more graphically readable manner to ease the analytic difficulties (Fiss, 2011).

Intermediate solutions show the complexity of factors driving community solar. By making a solution table, results can be visualized better for comprehension. In Table 6, one can easily spot cases where a driving factor is effective when negated. For instance, liberal government is a driving factor for Configurations 2 and 3 but not for Configuration 1. GDP per capita is similar in that they do not show uniform patterns. In this sense, configurations should be examined individually, which is the essence of QCA's equifinality and conjunctural causation.

Table 5
Fuzzy set solutions.

Parsimonious Solution				
Condition Configuration	Raw Coverage	Unique Coverage	Consistency	Cases
(1) ~ DEM	0.40	0.34	0.78	TX, FL, AR
(2) EP	0.44	0.26	0.97	MA, NY
(3) RPS * SPO	0.24	0.08	1	MN
Solution Coverage	0.87			
Solution Consistency	0.88			
Parsimonious Solution (Outcome Negation)				
Condition Configuration	Raw Coverage	Unique Coverage	Consistency	Cases
(4) ~ EP* ~SPO	0.25	0.25	0.94	MD
Solution Coverage	0.25			
Solution Consistency	0.94			

~ is the negation of the condition (i.e., ~RPS is not strong RPS stringency).
The multiplication symbol (*) denotes a logical "AND," indicating that all conditions connected by this symbol must be satisfied for the outcome to occur.

Table 6
Intermediate Solutions Table.

	Configurations from Table 5			Outcome Negation
Conditions	(1)	(2)	(3)	(4)
Strong RPS Stringency (RPS)			⬤	●
Strong State Community Solar Policy (CSPS)		●	●	●
Strong Solar Potential (SPO)	●		⬤	⊗
Is Government Liberal (DEM)	⊗	●	●	●
Wealthy GDPPC (GDPPC)	⊗	●	●	●
High Electricity Price (EP)		⬤		⊗
Consistency	0.77	0.96	1.00	0.99
Raw Coverage	0.34	0.34	0.24	0.22
Unique Coverage	0.32	0.19	0.08	0.22
Solution Consistency	0.85			0.99
Solution Coverage	0.66			0.22

⬤- core condition,●- periphery condition,⊗- negated core condition, ⊗ - negated periphery condition, empty - does not care

*4.1. Configuration 1: less wealthy "**conservative**" states motivated by natural endowment*

Regardless of the other conditions, [not liberal AND with no wealthy GDP per capita AND strong solar capacity] are sufficient conditions to adopt a large amount of community solar. It is important to note that the core causal path in this configuration is being a conservative state. Also, it is critical to clarify that negating wealth (~GDPPC) does not indicate that a state is poor. Instead, it signifies that the state is not categorized as wealthy compared to all states. This finding broadens our understanding of how community solar adoption can flourish across diverse political and economic contexts, not just those traditionally associated with higher GDP and liberal governance.

As can be seen from Table 5, Configuration 1 was derived from Florida, Texas, and Arkansas. They are conservative states that rank in the lower 50% by GDP per capita in the United States but have attractive solar potential. Although it would not be appropriate to attribute the adoption from conservative states solely to GDP per capita and solar potential, QCA provides a valuable set of causal links to community solar adoption. Even with high solar potential, these states have missed the opportunity for residential and commercial distributed solar, including rooftop solar (Institute for Local Self-Reliance, 2023). Hence, due to more flexible business models and affordable financing options, community solar may seem a more viable option to maximize the use of their natural endowment (McLaren, 2014; Funkhouser et al., 2015).

Moreover, conservative states tend to adopt community solar for economic rather than policy-based reasons. For instance, in Florida, Texas, and Arkansas, RPS and state community solar policy strengths are generally weak or nonexistent, suggesting that monetary benefits—rather than social equity or justice—motivate community solar development. As discussed in the adoption factor section, Configuration 1 highlights how the dynamics of community solar adoption differ from those of broader renewable energy initiatives. In these conservative contexts, financial considerations and natural resource abundance play a central role in driving community solar projects, underscoring a distinct pathway compared to states with stronger policy frameworks.

*4.2. Configuration 2: more wealthy liberal states with strong community solar policies motivated by "**high electricity prices.**"*

Regardless of other conditions, states exhibiting [a firm community solar policy AND a liberal government, AND wealthy GDP AND high electricity prices] demonstrate sufficient factors to increase community solar adoption substantially. Our findings underscore that high electricity cost is a core factor within this synergy, driving states to seek cost-effective renewable solutions. The results are exemplified by New York and Massachusetts, where robust policies (such as virtual net metering and targeted community solar incentives) are paired with governments inclined to prioritize clean energy. In keeping with broader research on renewable energy demand and consumption, wealth also plays a key role, supporting fiscal capacity to invest in new programs, offer incentives, and fund pilot projects (Yi and Feiock, 2012; Sadorsky, 2009). The confluence of these attributes not only aids in financing and implementing community solar projects but also fosters public support for such initiatives. Moreover, as previous studies on solar PV adoption suggest, the ability of community solar to address rising energy expenses further solidifies its appeal (Carley, 2009; Kwan, 2012).

Furthermore, a strong state community solar policy typically underscores social equity by incorporating energy justice objectives into its design. This emphasis aligns with research on the influence of government ideologies on policy development (Sterling et al., 2019; Basseches et al., 2022). In many liberal-leaning states, community solar programs explicitly include provisions to expand access to lower-income households and historically underrepresented communities. Such measures may involve tiered subscription rates, on-bill credits, or incentives for developers who integrate equitable participation criteria. By embedding social equity principles into the policy framework, these states address both environmental and socioeconomic dimensions, thereby broadening the impact and inclusivity of community solar adoption. These findings reinforce the idea that progressive policy orientations often link environmental goals with broader social considerations.

*4.3. Configuration 3: more wealthy liberal states with strong community solar policies motivated by "**strong RPS and natural endowment.**"*

Regardless of the electricity price, states with [strong RPS AND wealthy GDP per capita AND liberal government AND strong state community solar policy AND high solar potential] are sufficient to adopt large community solar capacity. While this pathway also presupposes a wealthier GDP per capita, a liberal government, and robust community solar policies, it contrasts with Configuration 2 by emphasizing RPS targets and natural endowment over energy costs. Minnesota provides a clear example of this solution: its stringent RPS goals (requiring 55% renewable energy by 2035 and aiming for 100% clean energy by 2040) have motivated widespread community solar adoption (Renewable Energy Objectives, 2023). Indeed, Minnesota's community solar garden program is one of the largest in the nation, reflecting the state's commitment to meeting RPS requirements through accessible solar initiatives (Funkhouser et al., 2015). Further bolstered by a comparatively healthy economy, Minnesota has been able to finance and incentivize solar projects effectively, capitalizing on a solar resource base sufficient to support sizeable installations. This combination of economic strength, policy ambition, and favorable conditions underscores how states in Configuration 3 can leverage community solar to fulfill aggressive clean energy targets, offering a blueprint for similarly situated regions.

4.4. Configuration 4: (outcome negation) importance of "***natural endowment and electricity prices***" on community solar adoption

In the outcome negation analysis, [Not high solar potential AND not high electricity price AND strong RPS policies AND strong community solar policies AND wealthy AND democratic] is sufficient for negating the outcome. In other words, the absence of high solar potential and high electricity prices is sufficient for states not to adopt community solar extensively—even when they possess otherwise favorable attributes, such as wealth, liberal governance, strong RPS, and robust community solar policies. The analysis highlights the causal asymmetry in play, meaning that the factors explaining the presence of the outcome (extensive adoption of community solar) may differ from those explaining its absence. A particular set of factors may be sufficient for widespread community solar, while an entirely different configuration can account for its absence. This distinction highlights how outcomes in QCA often hinge on context-specific combinations of policy, economic, and environmental factors rather than a single universal causal path. It is also worth mentioning that Colorado, Illinois, and Georgia were omitted from the negation analysis due to their consistency scores not meeting the 0.75 threshold.

The key insight from this configuration is that even when multiple factors seem well-aligned—such as a state being wealthy, liberal, and having strong RPS and robust community solar policies—the absence of high solar potential and elevated electricity prices can still inhibit widespread community solar adoption. Despite favorable socioeconomic and political conditions, Maryland exemplifies this scenario: its relatively moderate solar irradiance and lower electricity costs limit the incentive for large-scale community solar development. By illustrating this causal asymmetry, the findings underscore how environmental and economic contexts often prove decisive, offering a more nuanced understanding of the complex interplay between state-level conditions and renewable energy outcomes.

These four solution pathways emphasize the complex interplay of factors shaping community solar adoption. In particular, states with high adoption can be broadly grouped by their government ideology: conservative governments often advance community solar with minimal policy support, while liberal governments rely more heavily on policy interventions. Additionally, among liberal states, electricity prices and solar potential emerged as decisive sufficiency conditions for extensive community solar growth. Using parsimonious solutions in a fuzzy-set QCA, our analysis achieved a coverage of 0.66 and a consistency of 0.85. In addition, outcome negation analysis achieved 0.22 coverage and 0.99 consistency, adding to a robust explanatory model for community solar adoption across the United States.

5. Theoretical contribution, policy implication, and limitation

5.1. Theoretical contribution

The fuzzy-set QCA unveils how different combinations of adoption factors can reach the observed outcome. Rather than finding a general tendency from the entire population, which requires numerous data points, this research uses QCA to focus specifically on why some states acquire much more community solar, even amongst the adopting states. This question is especially difficult for quantitative methodologies since community solar is relatively new and selective. However, QCA's greatest advantage is that it embraces the equifinality and dynamics among conditions in small to intermediate-N studies. The most essential insight is that the adoption factors present varying impacts depending on the circumstances.

The first key causal path for community solar adoption among the highest-adopting states is whether the state is liberal or conservative. Conservative states are influenced by regional solar potential and GDP per capita. On the other hand, liberal states are commonly influenced by electricity prices and solar potential. Surprisingly, the lack of community solar policy in conservative states is not a setback for the adoption, which presents a counterintuitive insight into community solar adoption literature. Moreover, the direction of GDP per capita's impact is opposite for liberal and conservative states. Further qualitative evaluation of the lack of adoption from wealthy conservative and non-More wealthy liberal states could explain this direction difference. The second pivotal observation stems from the liberal states. Some liberal states exhibit variation in the factors driving community solar adoption, with some being more influenced by stringent Renewable Portfolio Standards (RPS) and high solar potential, while high electricity prices predominantly impact others. This observation highlights the nuanced difference between need-based adoption (driven by high electricity prices as a pressing economic necessity) and policy-based adoption (guided by strong renewable energy mandates and favorable natural endowments) among liberal states. Moreover, the analysis of the negated outcome underscores that the absence of high electricity prices and low solar potential form a clear causal pathway to a lack of significant community solar adoption. These findings emphasize the general importance of solar potential and electricity prices for the liberal states.

These qualitative analyses are possible due to the mixed nature of the QCA. When looking through each solution configuration, there are valuable qualitative insights that large-N statistical analyses cannot readily provide. For instance, strong RPS is not a dominant adoption factor for the highest community solar capacity since conservative states and liberal states with high electricity costs are not influenced by the RPS. Also, the state community solar policy is mainly absent in the conservative states, suggesting the heightened impact of community solar utility programs compared to state policy. Lastly, the solutions derived from QCA suggest that government liberalism is not a prominent distinguishing factor in adoption. Both liberal and non-liberal governments adopt community solar projects, highlighting a shared interest in community solar across the political spectrum in the United States. These observed divergences in adoption conditions underscore the necessity for a customized approach to support community solar in each state.

This exploratory research utilizing QCA represents a pioneering effort in empirical studies on community solar adoption, concurrently serving as a proof-of-concept for employing QCA in energy policy research. In this respect, subsequent research endeavors can change the angle at which the adoption is viewed to facilitate in-depth analysis with different qualitative measures, thereby shedding light on multi-faceted aspects and intricacies within specific states or groups of states. This study thus serves as an inaugural step in the empirical exploration of community solar adoption while laying the groundwork for future research to delve deeper into the intricacies of this dynamic and evolving field.

5.2. Policy implication

This research also provides meaningful insights for policy actors. As mentioned above, certain conditions' presence and/or absence change how states adopt community solar. Hence, policy actors can make tailored decisions considering the dynamic relationships among the conditions. For instance, condition configuration differences exist between strong RPS states and no strong RPS states. If a policymaker wants to increase community solar adoption further, one will need to emphasize different adoption factors depending on the level of RPS adoption. Furthermore, states with community solar adoption that is not policy-driven should be examined by the policy actors as it directly provides the effectiveness of the policy.

Moreover, this study represents a first step in explaining the landscape of community solar development in the United States. The findings invite future discussions and research to further understand how policies can be customized in specific social, economic, and political contexts to promote community solar development. For instance, how can conservative states with more wealth adopt community solar? What is the effectiveness of the state community solar policies when states like Florida lead in community solar without them? How do different types of utilities (i.e., public and private) influence community solar adoption?

5.3. Limitations

A key limitation of this study is the reliance on state-level data, which was the most feasible given the availability and robustness of community solar-related data at the time of the research. This state-level focus may have glossed over important regional variations that could provide deeper insights into the factors influencing community solar adoption. In particular, having reliable and comparable data on the number of installations available could have enhanced our understanding of adoption trends, especially in states where smaller, community-driven projects are common. Furthermore, if project-level data on installations becomes consistent, it could substantially improve the analysis by providing insights into the average size of community solar projects. This approach would allow for a more detailed examination of project distribution and scale, which may vary significantly across states and regions.

Additionally, this study could not account for regional differences in electricity prices and policies/programs, which will likely play a significant role in shaping community solar adoption. While these factors could strengthen the analysis, the lack of available, consistent data on these variables limited our ability to incorporate them into the comparative context. Operationalizing these regional factors would have required alternative methods, which were beyond the scope of this research. Future research could build on the state-level analysis of strong community solar adoption to delve into the regional and territorial characteristics of the electricity market and policy environment. Researchers could gain a more nuanced understanding of the unique dynamics and local drivers influencing community solar adoption within specific regions by employing qualitative approaches.

Lastly, while our analysis is explicitly framed as exploratory research, and we acknowledge the constraints imposed by the current state of community solar development, it is critical to emphasize that the results are more indicative than definitive. This research purposefully utilizes a small subset of all U.S. states to analyze what configurations of conditions most advance community solar adoptions. Hence, our analysis may limit the transferability of the findings to all 50 states, and we caution readers against overgeneralizing the conclusion.

6. Conclusion

With the rapidly increasing popularity of community solar as a vehicle for proper energy transition, more in-depth comprehension of the adoption factors is pivotal. Hence, this research addresses the complex relations of the community solar adoption factors using fuzzy-set QCA. The resulting causal paths show that the most active states vary in government liberalism. For conservative states, the primary adoption factors were a non-wealthy GDP per capita and strong solar potential. On the other hand, high electricity prices and strong solar potential were key sufficient conditions when liberal states adopted community solar at a large scale. Likewise, QCA provides a complex yet qualitatively in-depth understanding of the interactions among different factors, which is often overlooked by the quantitative approaches. This exploratory QCA research on community solar adoption factors is a proof-of-concept for energy policy research and a basis for future research on community solar.

CRediT authorship contribution statement

Dong Min Kim: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shan Zhou:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Adam M. Wellstead:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

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

Appendix A

A. RPS and Community Solar Policy Data from SPOT

RPS Questions
1. Does the state have a portfolio standard?
2. Is the standard mandatory?
3. If the state has a mandatory RPS, is the target at least 30%?
4. Does the mandatory RPS's primary tier exclude non-renewable or legacy renewable energy facilities?
5. Does the mandatory RPS apply to all electric providers?
Community Solar Policy Questions
1. Does state policy exist?
2. Does the state allow virtual or group net metering?
3. Does the policy apply to residential and commercial customers?
4. Does the policy apply to all electric providers in the state?
5. Is the program uncapped?

Data availability

Data will be made available on request.

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