Unleashing Sociotechnical Imaginaries to Advance Just and Sustainable Energy Transitions: The Case of Solar Energy in Puerto Rico

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***Abstract*—A central challenge for energy policy is to simultaneously accelerate the transition to carbon neutrality to tackle climate change while also addressing diverse forms of energy inequality and injustice. In this article, we argue that the public imagination is central to efforts to successfully confront this dual challenge. Specifically, we argue that theories of sociotechnical imaginaries have the potential to be leveraged both to strengthen public support for and engagement in carbon-neutral energy transitions and to identify and catalyze integrated sociotechnical designs and solutions that deliver on both accelerated technological change and just, equitable, and inclusive transitions. To explore these ideas, we present an in-depth case study of an emergent sociotechnical imaginary surrounding solar energy technologies in Puerto Rico. The results of our case study suggest that new imaginaries have the potential both to create powerful public support for renewable energy technologies that can accelerate energy systems change and, at the same time, help illuminate strategies for deploying energy technologies in ways that create meaningful impact and value in people's lives in diverse communities and thus contribute to making energy transitions more just and inclusive.**

***Index Terms*—Energy justice, energy policy, energy transitions, photovoltaics, public imagination, Puerto Rico, sociotechnical imaginaries.**

I. Introduction

A CENTRAL challenge for energy policy is to simultaneously accelerate the transition to carbon neutrality to tackle climate change while also addressing forms of inequality and injustice that permeate past and present energy systems, the differential impacts of transitions on workers and communities, and future designs for sustainable societies and economies [1]. In this article, we argue that *the public imagination* is key to efforts to successfully confront this dual challenge. Recent research highlights the significance of *sociotechnical imaginaries* [2]—collective, institutionalized ways of imagining the relationship between technology and social and economic progress—for a number of key energy policy questions, including: the design and function of energy systems; who is able to participate effectively in energy decision making; and what forms of social collectives and patterns of social and economic life and development get anchored by energy projects, initiatives, and systems [3]–[11]. These questions are important both to defining and accelerating transitions to sustainability and also to ensuring that they are just and inclusive [12]. To date, however, explicit attention to the public imagination of sustainability and energy has been underappreciated and given too little attention in many discussions of energy policy and research.

Consider technology diffusion, which guides U.S. energy policy and research to accelerate the deployment of renewable and other low-carbon energy technologies. The Department of Energy's SunShot program, for example, has strategically targeted rapid reductions in the costs of utility scale, commercial, and residential solar photovoltaic systems to exponentially expand solar markets through enhanced diffusion [13]. To date, this strategy has been successful in accelerating solar energy deployment, but it has, at the same time, helped create and exacerbate inequalities in solar adoption that pose increasingly serious challenges for renewable energy transitions [14]. As we describe in more detail below, technology diffusion offers few tools for addressing inequalities. It also gives little attention to exploring or theorizing how and why publics imagine that different technologies will contribute to improving their lives, generally assuming that this is a matter of consumer preference and marketing. At the same time, as we will also describe more fully below, other potential limits to technology diffusion as an accelerator of solar deployment are also beginning to appear, further supporting new approaches to energy policy.

We propose that greater attention to the public imagination of technology and its ability to improve lives offers a promising alternative way to advance rapid and just energy transitions. In particular, we suggest that theories of sociotechnical imaginaries have the potential to inform new policy approaches that strengthen public support for and engagement

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in carbon-neutral energy transitions and to identify and catalyze integrated sociotechnical designs and solutions that deliver on both *accelerated technological change* and *just, equitable, and inclusive transitions*. To explore these ideas, we present an in-depth case study of an emergent sociotechnical imaginary of solar energy technologies in Puerto Rico. This imaginary evolved over several years following Hurricane María to tightly link the idea of expanding solar energy deployment to the idea of a better future for Puerto Rico, and especially, to greater security, resilience, and justice for low-income communities. The results of our study suggest that new imaginaries can create powerful public support for renewable energy that can accelerate multiple dimensions of energy systems change. At the same time, imaginaries also offer an innovative tool for illuminating how new energy technologies create meaningful impact and value in diverse communities, situated in diverse contexts and confronting diverse social, economic, and environmental challenges. Through such insights, inquiry into sociotechnical imaginaries has the potential not only to illuminate when energy policy and system designs exclude alternatives [6], [12], [14] but also to suggest novel pathways through which technology deployment can be linked to distributed and differentiated projects of social and economic progress and justice [15]–[18].

II. The Limits of Diffusion-Based Approaches

Among policy, business, research, and advocacy communities, it is now widely expected that meeting the threat of climate change will require the widespread deployment of new renewable energy technologies, including solar, wind, batteries, electric vehicles, and hydrogen. To reach net zero CO_2 emissions by 2050, recent studies estimate that the U.S. will need to deploy ~300 GW (gigawatts) of new solar by 2030 and another ~1.2 TW (terawatts) between 2030 and 2050, alongside similar amounts of wind and extensive battery storage [1]. Comparable global estimates find 37–180 TW of deployed photovoltaic capacity would be required, depending on the technological pathway chosen, to meet half of the world's 2050 energy supply [19].

Theories of the technology diffusion approach this problem analogously to physical processes of diffusion, albeit with many different models to explain the timing and processes of diffusion in markets and society [20]–[22]. When new technologies first appear in markets, they are purchased only by a few households or businesses. As more customers are exposed to them, adoption accelerates until most people have purchased them, after which adoption saturates. Two primary drivers contribute to these processes. The first is the stratification of society into early adopters (those willing and able to pay for and excited to purchase technology when it first becomes available), those in the middle of the pack, and late adopters (those either unwilling or unable to pay). The second is cost. Technologies often start out at a relatively expensive level, leaving most people unable or unwilling to purchase them, but come down in price over time, opening up new market segments. Policies grounded in ideas of technology diffusion thus often focus on reducing the price of new technology in the hopes of accelerating people's willingness and ability to pay and therefore increasing technology adoption rates.

In the case of solar energy, diffusion-based strategies have clearly worked to accelerate cost reductions in the solar industry, both through market mechanisms (e.g., economies of scale) and policies that provide purchase incentives, tax credits, or enhanced revenue streams (e.g., feed-in tariffs) to solar purchasers [23]. Cost reductions, in turn, have accelerated solar adoption at much faster rates than many anticipated, leading solar to now be seen by many as a primary tool for meeting global sustainable energy needs by mid-century [24].

Over time, however, two challenges have emerged to diffusion-based approaches to accelerating solar technologies. First, significant inequalities have begun to arise that threaten public support for solar energy [25] and raise important questions about the ethics of energy transitions [26]. Diffusion-based approaches have had their greatest impact on utility-scale and large commercial-scale investments, which have the lowest costs per watt of energy generated. This has tended to steer revenues from solar development toward large investors (e.g., banks, power plant owners, electric utilities, and national retail chains) and away from smaller businesses and lower-income communities. Community-oriented projects, which should benefit from many of the same economies of scale, could help bring the benefits of solar energy to low-income communities but instead have lagged dramatically due to institutionalized legal, financial, and regulatory differences in their treatment [27]. Even among residential solar deployments, which have also grown as a result of diffusion-based strategies, benefits have tended to be stratified by wealth and race in ways that exacerbate other forms of energy and economic insecurities and injustices [28]–[30].

Second, challenges have begun to arise to the potential for diffusion-based strategies to continue to accelerate solar development enough to decarbonize energy systems by 2050. These include: technical hurdles in the integration of renewables into grid-based electricity systems [31], especially when combined with social patterns of energy demand that poorly match solar generation patterns [32]; shifts in costs from solar panels to installation and balance-of-system costs that are not as easily reduced through technology innovation [33]; snarls in global supply chains that limit availability of key materials or technologies and slow or even reverse price declines [34]; social and industrial opposition to renewable energy projects, e.g., due to concerns about land use or impacts on utility business models [35]; and rising costs of land and transmission lines to connect rural projects to urban centers [36]. Growing doubts also question whether markets can accelerate fast enough, even with substantial policy incentives, to meet ambitious decarbonization targets and address other critical challenges for global energy systems, including to enhance energy access worldwide, to promote energy justice, and to decrease energy vulnerabilities facing many communities in an era of rising climate risks [37].

III. Public Imagination as an Alternative Approach

To help develop and design strategies to meet these challenges, we propose an alternative approach focused on the value people imagine renewable energy technologies have for

their lives and for their communities. In economics, this value is generally modeled as the willingness of people to pay for new technologies via direct purchase. This view is too limited, however, especially for technologies like energy systems that are not simple consumer technologies but rather complex systems with deep implications for people's lives and livelihoods. Throughout the history of the electricity industry, e.g., the perceived public value of low-cost electricity to society led governments in the U.S. and around the globe to create exceptions to market competition rules for monopoly electric utilities [38], to build government-owned electric utilities [39], [40], and to promote the development of customer-owned cooperatives in order to accelerate the universal, equitable availability of the technology [41]. Today, electricity remains a critical infrastructure in the eyes of policymakers and the public, subject to a wide array of policies designed to ensure continued functioning and broad access.

Theories of *sociotechnical imaginaries* were developed precisely to explain how and why new forms of public imagination emerged around energy technologies [42], how and why they were linked in people's minds to projects of national advancement [4], [40], and how they became embedded in the intertwined reconstruction of social, economic, and technological constitutions that occurred as new energy systems were built in the late 19th and early 20th centuries [43].[1] Explorations of sociotechnical imaginaries emphasize the significance of deep-seated forms of social imagination within groups or cultures that tie ideas about technological progress to shared understandings of what it means to live a good life [2]. Sociotechnical imaginaries have been demonstrated to shape the values that different cultures attach to different technologies, leading to divergent patterns of technology innovation. They also evolve over time, causing significant changes in how people value technologies and their willingness to support different pathways of technology development [47].

Theories of sociotechnical imaginaries complement ideas of technology diffusion. They help explain, for example, why people are willing to pay for new technologies like solar energy, not only through direct consumer purchases (e.g., rooftop solar systems) but also via other pathways, such as paying increased taxes to finance public investments in renewable energy, paying higher utility bills to offset renewable energy integration into the grid, having a greater willingness to tolerate the visual impact of large-scale renewable energy projects on cherished landscapes, committing the time, and effort necessary to plan community solar projects, or being open to behavioral changes to better fit energy demand to renewable energy generation. In this approach, factors that matter in terms of the willingness of people or organizations to engage with and pay for new technologies are, first, the value they imagine the technology has for improving individual or collective life, and, second, the degree to which such ways of imagining the world are collectively held and institutionalized within a given society. Where this value is imagined as financial, it fits classical technology diffusion models; where imagined value takes other forms, such as ideas of critical infrastructure, sustainability, security, resilience, or social justice, then new approaches grounded in imaginaries may prove more fruitful.

The question we explore in this article is whether broadly-held sociotechnical imaginaries can shift with regard to new technologies in ways that accelerate transformation to low-carbon energy systems (e.g., because broadly-held views of that technology shift in relationship to societal definitions of what it means to live a good life, or, alternatively, because notions of the good life change in ways that alter the relevance of that technology) while also making energy systems more socially just and inclusive. We are especially concerned with the sociotechnical imaginary surrounding solar energy. The past half-century of investment in solar energy research and development demonstrates the existence of a strong sociotechnical imaginary in favor of solar energy among an elite community of scientists and engineers [48]. The question now is whether new sociotechnical imaginaries in favor of solar energy can develop across a much wider range of communities, institutions, and the public.

We explore these questions in the context of the recent experiences of the people of Puerto Rico with solar energy. We suggest experiences in the months following Hurricane María, coupled with discourse in the media about Puerto Rico's future interpreting those experiences, significantly altered the sociotechnical imaginary of Puerto Ricans surrounding solar energy and battery storage technologies. This shift in imagination, our findings indicate, fundamentally recalibrated the engagement of Puerto Ricans in solar energy solutions and their willingness to "pay" for them, in the broader sense of putting in the money, time, and effort necessary to figure out how solar energy can be made to work in diverse Puerto Rican communities and contexts. In the process, the new imaginary laid the foundations for a very different calculus of solar investment going forward. Consistent with theories of sociotechnical imaginaries, we will argue that this shift resulted from a fundamental reevaluation among Puerto Ricans of the relationship between solar energy and the possibilities of a future good life in Puerto Rico. Our findings also demonstrate an important feature of solar imaginaries in Puerto Rico: a high degree of flexibility in how people imagine the sociotechnical relationships between solar energy and the good life that has enabled and accelerated broad engagement with solar energy across diverse communities and contexts, including among very low-income communities.[2]

[1]For those unfamiliar with the conceptual foundations of sociotechnical imaginaries [44], these theories were developed in the field of science and technology studies as part of a broader effort to understand the co-production [45] of technology and social order, i.e., how social and economic forces shape the development and configuration of new technologies and technological systems even as societies and economies simultaneously reconfigure identities, discourses, representations, and institutions around and through the development and deployment of new technologies and systems [46].

[2]Puerto Rico is among the poorest regions of the United States, with a median household income of approximately one third of the U.S. median household income and roughly half the median household income of low-income states, such as Mississippi and Alabama. More than 50% of Puerto Ricans live below the poverty line and are eligible for federal nutritional assistance. Within Puerto Rico, there are also high levels of income inequality, with significant fractions of Puerto Ricans living on U.S. $10 000 of annual household income or less.

These findings are drawn from a mixed-methods study of the public imagination of solar energy in Puerto Rico, integrating insights from multiple qualitative methods. Imaginaries are complex to study, observationally, requiring mapping of particular imaginative framings of technology and its relationship to public values about the good life; the ways those imaginative framings shape and get shaped by particular visions of the future; and the extent to which they are collectively held and/or institutionalized in public discourse and decision making. This is particularly challenging for studies of the dynamics of imaginaries, which require following these variables over time. Absent large-scale measurements of public attachments to particular imaginaries over time (which do not exist, either in general or for this case), qualitative approaches seek traces that reveal the evolution of imaginaries over time and their degree of adoption in diverse expressions and representations of the future, either that circulate in society (e.g., in media, technical publications, or legal, regulatory, or judicial texts) or that are stimulated through conversation (e.g., via participant observations, interviews, ethnographic methods, or community engagement techniques). This study uses several such approaches, including participant observations by researchers of energy debates in Puerto Rico in the years before and after Hurricane María; textual analyses of technical and legal documents and media stories that discuss solar energy in Puerto Rico over the past 20 years; interviews with more then 100 individuals in Puerto Rico energy policy and markets, including solar business owners, solar customers, activists, policy leaders, and journalists; and sustained engagement with several communities in Puerto Rico working on community-based solar projects.[3] From this extensive evidentiary base, we have been able to assess and track the content of solar imaginaries in Puerto Rico and their adoption by various groups, which we present in the sections below.

Our analysis of the Puerto Rico case supports two important ideas worthy of further exploration and inquiry for their potential to help accelerate just deployment of low-carbon energy technologies to meet the climate challenge. The first is the power of imagination to buttress the willingness of people to put money, time, and work into efforts to deploy solar energy. Opportunities to leverage the power of imagination exist for both businesses, who can engage new customers' imaginations to expand solar markets, and policymakers, who can more creatively position low-carbon energy as a tool for helping individuals and communities reach their goals. The second is the flexibility of the solar technology as a tool for tackling individual, community, and organizational goals, which can open up new ways of linking low-carbon energy innovation to people's values. Unfortunately, the current imagination of solar energy in markets and policy is overly narrowly focused on utility-scale power plants and large rooftop systems for wealthy homeowners or commercial businesses, which leaves many people and organizations out of the picture. Our findings suggest many more options exist, especially at the community-scale and for low-income customers [27]. With new flexibility in solar designs and regulatory rules to unleash people's imagination, e.g., in Puerto Rico, available reconstruction funds could be used to cover the capital cost of widespread solar rooftop deployment [49], accelerating the deployment of solar energy, especially among low-income communities. Thus, the flexibility of solar has implications for both the pace of solar adoption, which can grow if new configurations allow for solar to reach new groups that cannot access existing solar solutions, and for energy justice, if those new groups include low-income or indigenous communities, communities of color, or others who have not benefited from solar or who have been excluded from or experienced past injustices from energy systems [50].

[3]These methods were reviewed by the Institutional Review Board of Arizona State University, acting on behalf of the involved research institutions, and the study followed the approved ethical guidelines, including obtaining informed consent from all participants and prior co-design and agreement on the research agenda from engaged communities.

IV. A New Sociotechnical Imaginary of Solar Energy

In *Dreamscapes of Modernity*, Sheila Jasanoff defines sociotechnical imaginaries as "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology" [51]. Building on this definition, analyses of sociotechnical imaginaries have explored ways that communities or cultures tell stories about or draw connections between the development of technology (either as a general concept or in the form of particular technologies, such as photovoltaic solar panels) and the potential to improve people's lives and livelihoods [25]. Sociotechnical imaginaries need not be universally shared. Indeed, they are often contested and in competition with alternative imaginings of the power of technology to help society [10], [52]. Nonetheless, imaginaries acquire power as their core ideas become widely discussed, deliberated, and taken up as provisional truths within social, media, and/or policy discourses and used as the foundation for individual, organizational, and/or collective decision making [53]. In the process, the formation of new imaginaries provides an avenue by which people's mental maps about the future can shift, bringing about significant changes in how they view and value the relationship between technology and social or public goods [54].

In this section, we describe how, in the wake of—and deeply intertwined with—the power outages that followed Hurricanes Irma and María in September, 2017, a new sociotechnical imaginary emerged linking the deployment of solar energy to the creation of a more resilient and sustainable future for Puerto Rican communities. Our findings suggest that this imaginary is characterized by three key elements. The imaginary specifically identifies solar energy as a crucial technology for the future of Puerto Rico. It emphasizes the value of solar technologies primarily for resilience, rather than sustainability. Finally, it highlights solar as a bottom-up strategy for households and communities to provide security in the face of systematic failures of higher-order systems and institutions, such as Puerto Rico's electricity grid, electric utility, and government. In this section, we review the historical emergence and consolidation of this new imaginary and situate it,

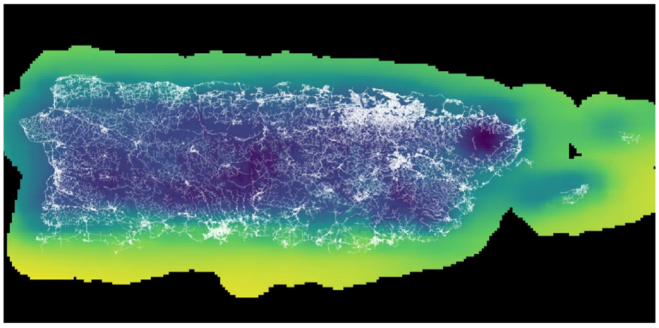

Fig. 1. Solar energy potential in Puerto Rico, layered over a map of the archipelago's electricity distribution grid.

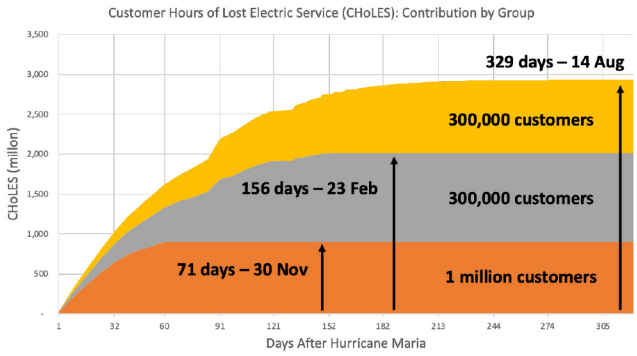

Fig. 2. Customer hours of lost electric service (CHoLES) in Puerto Rico following Hurricane María. Illustrating the deep inequalities and vulnerabilities of Puerto Rico's energy system, the final 200 000 customers reconnected lost one-third of the total customer hours without electricity. From Castro-Sitiriche, M., J. Gomez, and Y. Cintrón, "The Longest Power Blackout in History and Energy Poverty," International Conference on Appropriate Technology 2018, Porto-Novo, Benin, November 2018. http://bit.ly/CHoLESpaper.

briefly, in the longer history of Puerto Rico's imagination of the possibilities of solar power.

Puerto Rico's public, policy, and scientific engagement with solar energy began well before 2017 (Puerto Rico's solar energy potential is shown in Fig. 1). In 2004, Puerto Rico legislators created a tax exemption for renewable energy investments and funded research into the potential for renewable energy technologies to create a more sustainable future [55]. One product was a study by the University of Puerto Rico summarizing the potential for wind, ocean, biomass, and solar technologies to contribute to *Achievable Renewable Energy Targets for Puerto Rico's Renewable Energy Portfolio Standard* [56]. New legislation over the next decade further encouraged renewable energy development, both by homeowners and investors in utility-scale power plants, resulting, by 2017, in the construction of eleven small solar power plants, two somewhat larger wind plants, and approximately 10 000 rooftop solar systems.

The widespread devastation wrought by Hurricanes Irma and María created a different kind of opening for debates about solar energy in Puerto Rico. The two hurricanes destroyed much of the electricity grid, leaving all of Puerto Rico without power for over a month, many without power for 4–6 months, and some places without power for 11 months (Fig. 2 shows the cumulative hours without power suffered by electric utility customers in the year following the hurricanes). Nor, even after power was restored, did the system perform well for many parts of Puerto Rico. Power outages remain routine in many places, lasting for hours and sometimes days or weeks. Almost everyone owns a generator. In 2020, a series of earthquakes again brought the grid down everywhere and left substantial parts of Puerto Rico without power for over a month. These cumulative disasters disrupted millions of peoples' lives, severely damaged Puerto Rico's economy, exacerbated the exodus of people leaving the islands, and resulted in thousands of deaths [57].

Within weeks after Hurricane María, a handful of solar companies mobilized philanthropic efforts to bring solar systems to Puerto Rico to provide emergency power. Their efforts received little attention until environmental reporter Brian Kahn wrote a story for *Gizmodo* positioning Puerto Rico as a focal moment in the push to replace fossil fuels with renewable energy, asking whether the disaster might offer an opportunity to use solar energy to rebuild Puerto Rico's electricity grid in a more sustainable and resilient fashion [58]. Kahn's story caught the attention of Scott Stapf, a public relations expert and advocate for sustainability, who forwarded the story on Twitter with the provocative tagline: "Could @elonmusk go in and rebuild #PuertoRico's electricity system with independent solar & battery systems?" Musk Tweeted that, indeed, he could, if that's what the government and people of Puerto Rico wanted. Within hours he received a reply from Puerto Rico's then governor, Ricardo Rosselló, "@elonMusk Let's talk. Do you want to show the world the power and scalability of your #TeslaTechnologies? PR could be that flagship project" [59].

A notable element in Kahn's story and Musk's response was the addition of the battery to the solar narrative. Musk's company Tesla manufacturers batteries for electric vehicles and markets batteries as a home electricity backup system known as Powerwall. In Puerto Rico, however, batteries had a different resonance. In 2016, in a highly publicized dispute, customers of Sunnova, which then leased more than half of all household rooftop solar energy systems in Puerto Rico, filed a complaint with regulators asking to be released from their contracts because the systems failed to produce energy during frequent electricity grid outages [60]. As is common in the U.S., Sunnova's systems were "grid-tied" to benefit from net metering policies allowing sale of excess electricity to the grid. Without batteries, however, the systems automatically shut off during grid outages to prevent risks to workers trying to restore power. As a result, the systems provided no backup power when the grid went down, a fact that does not impact most U.S. residents, who have extremely reliable power, but which raised problematic questions given Puerto Rico's regular electricity outages.

While Musk's interest in Puerto Rico faded quickly, ultimately resulting in a modest solar and battery system to provide emergency power for a San Juan hospital for children, his exchange with the governor sparked widespread engagement, inside and outside Puerto Rico, in the possibilities of solar energy for the archipelago's energy future. A cascade of news stories about solar possibilities in Puerto Rico appeared in *The New York Times*, *Washington Post*, *PBS*, *NPR*, *BBC*,

WBUR, and more specialized environmental and energy media. Puerto Rican teen Salvador Gomez Colon garnered worldwide attention for his campaign to provide solar lanterns to those without power, ultimately landing a joint appearance in 2020 with Greta Thunberg on the first youth panel ever hosted by the World Economic Forum [61]. A collaboration between the University of Puerto Rico-Mayagüez and the Institute of Electrical and Electronics Engineers built solar "Oasis de Luz" in remote communities, allowing people to charge their phones and refrigerate critical medical supplies [62]. The Cucubanos initiative by Casa Pueblo provided 60 houses with small solar systems that provide savings that range from U.S. $40 to U.S. $100 monthly [63]. The Rocky Mountain Institute, one of the oldest solar advocacy organizations and the brainchild of solar pioneer Amory Lovins, established a major initiative to advocate solar energy solutions to the crisis [64]. And philanthropic organizations, coordinated by groups, such as Resilient Power Puerto Rico and the Clinton Foundation, ultimately built over 400 standalone solar and battery projects to provide reliable power for critical infrastructure facilities, such as police and fire stations, hospitals and clinics, and schools [65]. Wealthy Puerto Ricans and many businesses also invested in solar energy, doubling the number of distributed rooftop systems in the year following the hurricanes [66].

For a variety of reasons, this enthusiasm for solar energy had little short-term impact on the reconstruction of Puerto Rico's electricity system. Hence, in 2021, solar remained a small portion of Puerto Rico's electricity supply. Due to concerns about grid reliability, few of the utility-scale solar power plants built pre-2017 returned to service quickly, even though most suffered little to no damage. Funding for grid reconstruction was largely provided by FEMA, whose legal rules prohibit the use of reconstruction funds except to rebuild infrastructure as it was before. By late 2017, reconstruction was principally being carried out by a coalition of public electric utilities from across the U.S. who approached it as a problem of restoring power, rather than constructing a new energy future for Puerto Rico. Consequently, Puerto Rico's electricity grid was ultimately rebuilt much as it was prior to 2017. Old and decaying parts of the system that escaped destruction in the hurricanes or earthquakes, such as teetering grid poles, were left in place, all but guaranteeing that grid instability remains a fact of life. Oil and coal-fired power plants were repaired and used to restore power, investments were made in natural gas infrastructures to modernize their operations, and plans were laid to privatize the management of electricity distribution, which was finalized in June 2021.

Yet, even as electricity grid reconstruction proceeded along this conventional path, and arguably in part because it did, despite the continuing unreliability of the grid and widespread public controversy over utility and government decisions, solar energy took root in and acquired a significant place in the Puerto Rican imagination of the energy future. As we will describe in greater detail in the next section, after 2017, solar energy markets, social activism around solar energy, policy actions to require renewable energy investments, and bottom-up action by Puerto Rican households and communities to imagine and build solar-powered futures exploded across Puerto Rico.

This growing enthusiasm for solar energy across numerous facets of Puerto Rican society and institutions is grounded, we argue, in the three key elements of the new solar imaginary we identified at the beginning of this section. The core element of the imaginary is *the explicit identification of solar energy as a crucial technology for Puerto Rico's energy future*. *Queremos Sol*, "We Want the Sun," [67] proclaims the name of one of the leading initiatives advocating today for solar energy as the core foundation for Puerto Rico's energy future. This stands in contrast to earlier discourses and policies, such as the *Achievable Targets* report of 2009 [56] and 2004 renewable energy legislation, which situated solar energy as one among many available renewable energy resources. The imaginary also emphasizes *the power of solar energy, combined with batteries, to contribute to a more resilient energy future*. This also departs from earlier solar discourses, which emphasized sustainability and cost savings through net metering as the key benefits of solar. Thus, as illustrated by the controversy over Sunnova's systems [60], neither utility-scale nor rooftop systems in Puerto Rico, pre-2017, included batteries. By contrast, today, batteries are seen as directly addressing the core post-María challenge for Puerto Rico's electricity grid: its systematic unreliability and vulnerability to future disruption. As a result, few solar systems are sold without batteries, despite their cost and the low average income of Puerto Rican households. Finally, the post-2017 imaginary posits *solar energy as a bottom-up alternative to the electricity grid for households and communities* to enhance energy and human security and lessen reliance on an electricity grid, utility, and government that many no longer trust. While a portion of solar systems are still integrated with the grid, their batteries, and inverters also allow them to operate independently of the grid, and many other systems are being installed as off-grid backup power supplies. For many Puerto Ricans, the bottom-up opportunities offered by solar energy reflect an explicit concern about energy justice for poor and remote mountain communities, many of whom have historically suffered from unreliable electricity service, energy burdens exacerbated by the high price of electricity in Puerto Rico, and unjust environmental risks associated with the burning of fossil fuels to generate electricity [68].

V. The Power of Imagination

In the previous section, we characterized a new way of imagining solar energy emergent in Puerto Rico after 2017 and the particular ways that it linked solar energy to visions of a more resilient and just future for Puerto Ricans. In this section, we document the transformation of this new way of imagining solar energy into a full-fledged sociotechnical imaginary, tracking its increasingly widespread adoption by Puerto Ricans, institutionalization as a feature of Puerto Rico's public imagination, and growing power in public discourses and decision making that, together, are reshaping the design of solar technologies and the trajectory and pace of solar energy technology deployment.

In 2020 and 2021, we conducted interviews with more than a hundred Puerto Ricans about the current state of the energy situation, the history of the energy crisis since the hurricanes in 2017, opportunities and challenges for energy policy, and their perspectives on solar energy, specifically, as a solution for Puerto Rican energy dilemmas. Our interviewees included Puerto Ricans from all walks of life and numerous Puerto Rican institutions, including business, policy, and civic leaders, activists, journalists, researchers, community organizers, and members of the public. Surprisingly, not one of our participants offered a negative overall assessment of solar energy, nearly all were extraordinarily positive about the roles that solar energy can and should play in creating new energy systems in Puerto Rico, and most specifically articulated the value of distributed solar technologies (e.g., rooftop solar) to a more resilient Puerto Rican future less reliant on an unstable grid.

Building on this preliminary clue into the broad spread of new ways of imagining solar in Puerto Rico, we began looking for additional evidence of the growing power and influence of solar energy in Puerto Rico's public imagination. One prominent example that epitomizes both the power and limits of changes in the imagination of solar energy in Puerto Rico since 2017, is Law 17, the Puerto Rico Energy Public Policy Act, signed by Governor Rosselló on 11 April 2019 [69]. The policy commits Puerto Rico to achieve 100% renewable electricity by 2050, making the colony one of the first in the U.S., alongside California, Hawaii, and New Mexico, to enact a 100% clean energy target into law. The significance of this achievement should not be underestimated. In recent years, U.S. climate and solar energy advocates have identified legal requirements for eliminating carbon emissions—whether established through legislation or regulation—as the gold standard for climate action. At the same time, skeptics of such targets argue that many questions remain about whether targets will ever turn into concrete plans to implement the transition. These questions are exacerbated in Puerto Rico, where energy regulatory institutions have historically been weak, utilities have largely been given free rein to determine their own infrastructure plans, and the transition is now complicated by the privatization of the electric utility [70]. Considerable doubt has been expressed about whether and how the law's targets will be met by the new utility, Luma; how the law will be applied to Luma's operations; what consequences will flow if renewable energy targets are not met; and whether and how future legislatures will act to strengthen, alter, or weaken the law's provisions [71]. Doubts have also been expressed about whether the law goes far enough to address energy inequality and injustice in Puerto Rico, especially in terms of its lack of clear strategies for bringing solar to Puerto Rico's lowest-income communities [72].

While the law is framed in terms of *renewable energy*, new ways of imagining solar were crucial both to the legislature's passage of the law and to shaping its provisions. Although clean energy targets are often driven primarily by concerns about sustainability, climate change, and the reduction of carbon emissions, and those concerns were not irrelevant in Puerto Rico's energy deliberations, the law's design clearly prioritizes resilience and reliability and the value of solar in achieving that. Provisions in the law call, for example, for the overall grid structure to be rebuilt around smaller microgrids that can sustain electricity provision independently from one another. They also explicitly support ambitious investments in distributed solar systems and battery storage to allow communities, businesses, and households to power themselves when the grid goes down. The law eases permitting requirements for rooftop, commercial, and community solar, guarantees net metering, and prohibits new taxes from being imposed on solar system owners. Subsequent to its passage, media commentary highlighted the law's importance for advancing solar energy—and the importance of solar energy in meeting the law's goals—with widespread support in the solar industry. SunRun CEO Lynn Jurich, for example, celebrated the law's passage: "Rosselló's approval of transformational clean energy law marks a historic day for all Puerto Ricans. Embracing technology like home solar and batteries will play a critical role in accomplishing these trailblazing goals, putting the people of Puerto Rico at the center of the solution with local jobs and clean, resilient, reliable, energy for homes across the island" [73].

New ways of imagining solar energy have also shaped recent planning by electricity managers and regulators. In January 2019, for example, Puerto Rico's electric utility filed a 20-year integrated resource planning exercise (through 2038), with revisions in February and June [74]. These plans were criticized by many for over-relying on investments in natural gas instead of renewables. These criticisms followed a major public dispute throughout this period over the conversion of two oil-fired power plants to natural gas and the proposed construction of a new LNG terminal to serve Puerto Rico, both of which were extremely controversial. Despite these well-justified concerns, however, the details of the plan reveal that solar has transformed thinking about the future of the Puerto Rico grid. For example, in 2038, the plan forecasts a peak electricity demand of 2.67 GW, over a third of which is anticipated to be met by investments in energy efficiency and customer solar generation. The latter is projected to be 1.18 GW, which is a remarkable number. On average, that level would amount to approximately 1 kW of solar generation per household. By comparison, a recent study estimated that a 2-kW solar system would provide 50%–100% of energy needs for 42% of Puerto Rican homes (see Fig. 3) [75]. The plan modeled several scenarios, all of which met the renewable energy targets specified by Law 17 entirely through new deployments of solar energy. The scenario identified in the plan as "preferred" includes 2.8 GW of new utility-scale solar, in addition to 1.2 GW of new distributed solar, and 1.3–1.6 GW of battery electric storage, most built before 2025. The result, in 2038, in the preferred scenario, is an energy mix dominated by solar and batteries. In 2020, the Puerto Rico Energy Bureau, which regulates the electricity sector, approved the plan but rejected the utility's request to further upgrade its thermal plants to natural gas. Instead, the regulator directed the utility to install 3.5 GW of solar and 1.36 GW of batteries by 2025 [76]. The same questions surround these plans as for the energy law, of course, especially with regard to whether

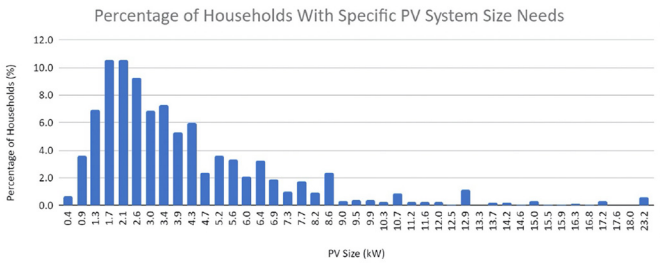

Fig. 3. Percentage of households in Puerto Rico whose energy needs could be met by a PV system of a given size. From an analysis by M. Castro-Sitiriche in Y. Rivera-Matos, *et al. The Evolving Solar Energy Innovation Ecosystem in Puerto Rico*, Technical Report, Arizona State University and the University of Puerto Rico-Mayagüez, 2021. http://cohemis.uprm.edu/solar2020/pdf/EvolvingSolarEnergy_March2021.pdf.

and how they will shape the planning of the newly privatized utility.

This institutionalization of new ways of imagining solar and battery systems in important political, legal, and energy rules and plans has been complemented by other sites of emergent imagining that are just as significant. Distributed solar energy markets have been brisk, for example, since 2017, with many more solar systems installed and, just as importantly, many new solar businesses. Data on Puerto Rican energy trends is scarce, including solar, but in September 2018, *Bloomberg* cited figures from the Solar Energy & Storage Association that rooftop solar installations in Puerto Rico had nearly doubled from roughly 12 000 to 22 000 in the 12 months following Hurricane María and that revenues grew substantially at several key solar companies [66]. Given the struggles that almost everyone in Puerto Rico faced with basic survival during this period, and the severe limits imposed on imports, this is an impressive achievement. And, while many businesses we spoke with indicated that solar sales waxed and waned subsequently (and there is not yet a consistent quantitative dataset available post-2018 on rooftop solar), data that does exist suggests solar and battery installations continued at a rapid pace. For example, solar imports into Puerto Rico in 2020 reached similar numbers of panels as 2018 (∼110 000) and higher total capacity (41 MW versus 35 MW) and grew even further in the first four months of 2021 (annualized 158 000 panels and 58 MW) [77]. That comports with a recent *Bloomberg* report that the private utility Luma registered an additional 20 000 and more rooftop systems between the commencement of its operations in June 2021 and May 2022, at a pace of 2100 systems per month. This puts Puerto Rico among the top 10 U.S. states or territories for solar adoption on a per capita basis [78]. Qualitatively, our observations and interviews also suggest that many new solar businesses have launched since 2017 and advertising for solar systems has grown markedly in Puerto Rico media.

Importantly, for our argument, solar markets have also been transformed by the imperative embedded in the new imaginary that solar systems comprise "solar plus storage" so that they can contribute to improved energy security and resilience. Unlike much of the rest of the U.S.,[4] where electric power utilities dominate battery investments and where the large majority of rooftop solar systems are sold without batteries, Puerto Rican businesses, households, and communities now identify solar and batteries as an alternative to generators for backup power. Few solar systems are sold today in Puerto Rico without batteries. This is especially notable given the high levels of poverty in Puerto Rico and the high costs of solar and storage systems. This creates a real struggle for solar businesses and for those looking to go solar in Puerto Rico, as it significantly restricts the forms and sizes of systems people are able to buy or lease.

The new solar imaginary thus poses a particular challenge for low-income communities, who want solar yet struggle to find available solutions in solar markets that fit their budgets. Consequently, one of the most interesting facets of solar development in Puerto Rico in recent years has been the emergence of bottom-up, community-driven initiatives to develop and deliver solar energy solutions for low-income households. These efforts are largely grassroots, often but not always supported by local community organizations, with at best modest philanthropic support and little support from the Puerto Rican or U.S. government. As we will describe in the next section, these initiatives vary considerably from community to community, rooted in the specific challenges, goals, and contexts of each community, although a few efforts are underway to build initiatives that span several communities and encourage cross-community learning. Despite these differences, and the challenges they face with affordability, many are delivering solar and storage solutions for their communities. In a number of instances, households are paying considerable sums for those solutions, which illustrates, even at the lowest income levels, the imaginary is motivating a higher willingness to pay for solar solutions that fit into individual and community needs.

Finally, to return to Puerto Rico energy policy, the solar imaginary has motivated ambitious new proposals to spur more rapid adoption of solar and storage systems in Puerto Rico, in the service of long-term energy resilience. Here, we briefly review the three most advanced proposals that have received considerable attention in public and policy deliberations. The first, advanced by an author of this article, calls for providing small emergency backup solar and storage systems to the last 200 000 households to have grid electricity service restored after the hurricanes [80]. These households are exceptionally vulnerable to future hurricanes and are also among the poorest in Puerto Rico, making the provision of reliable power in a future disaster a crucial lifeline. They also have relatively low electricity consumption, meaning that even very small solar and storage systems could satisfy critical electricity needs and avoid repetition of dangerously long periods without power (see Fig. 3).

A second proposal, which has garnered widespread attention within Puerto Rico, including in the most recent election

[4]A similar shift to adding batteries to rooftop systems is now happening in California in the wake of the reliability problems created by wildfires over the past few years [79].

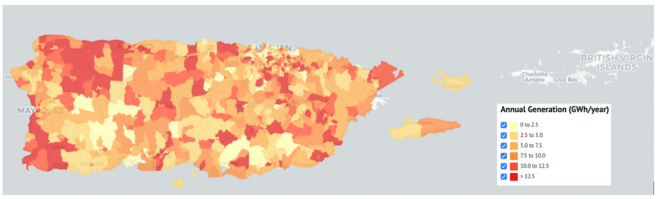

Fig. 4. Annual technical potential for rooftop PV solar energy generation in LMI communities by Census tract in Puerto Rico as calculated by the U.S. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/78756.pdf.

for governor, was released in early 2021 by a coalition of energy advocacy groups, Queremos Sol [49]. They proposed to use U.S. $9.6 billion in federal funding to install rooftop solar energy systems on every house in Puerto Rico. A recent study evaluating the proposal showed, "in 15 years, 100% of homes could meet their critical needs with solar and [Puerto Rico] could generate 75% of our electricity from distributed renewable energy" [81]. A study by the National Renewable Energy Laboratory also published data showing the technical potential for solar generation from rooftop systems in Puerto significantly exceeds residential electricity consumption, both for Puerto Rico as a whole and for low-income communities (see Fig. 4) [82].

Finally, although not yet finalized, the U.S. Department of Housing and Urban Development is working in partnership with Vivienda, the Puerto Rico housing authority, on a new community development block grant program that will potentially include funding for solar energy systems that contribute to community resilience. In an early draft, households would be eligible for "improvements which include the installation of a solar (photovoltaic) system with a battery system for essential plug loads to supply energy in the event of a power outage situation and installation of a water storage system" [83].

VI. A Plurality of Imagined Possibilities

The power of sociotechnical imaginaries is often attributed to their ability to persuade audiences to become participants in a shared vision of the future. Yet, comparative analyses show that cultures and countries often differ in how they collectively imagine the proper relationship between technology and the social or public good [84]. This *interpretive flexibility*—the ability for diverse social values and contexts to shape trajectories of technology development—is a well-known feature of technological change [85]. We suggest here, grounded in the experience of Puerto Rico with solar energy, that interpretive flexibility in how solar technologies are designed, financed, and integrated into users' lives also has a powerful potential to contribute to the possibility of unleashing solar imaginaries in the service of tackling climate change and enhancing energy justice.

Since 2017, as we discussed above, there has been a deep shift in the energy imagination of Puerto Ricans toward renewable energy. Elsewhere in the United States, wind and solar tend to be coupled in the imagination of carbon-free power, and wind has historically developed more rapidly than solar, overall, due to earlier price competitiveness and a view that its variability better matches the needs of the grid. Interestingly, Puerto Rico has extensive potential wind resources [56], yet wind has garnered little attention in public and policy dialogues in the years since the hurricanes. The reason seems straightforward: wind power depends on a functioning electricity grid. Because the efficiency of wind turbines scales with the square of the length of the turbine blades, wind power benefits dramatically from being built in taller, utility-scale applications rather than in people's backyards [86]. Without a viable grid, and faced with the prospect that the grid will be knocked down, again, by future hurricanes or earthquakes, wind power would address concerns about carbon emissions but do little to nothing to shore up the resilience and energy security of Puerto Rico, for either individual businesses or households or the archipelago as a whole. Only in places like the Orkney Islands, off the north coast of Scotland, where it is both frequently dark (and thus less ideal for solar) and the wind blows constantly, do small-scale wind turbines make a lot of sense as a distributed energy resource [87].

Solar is different. Solar panels generate the same amount of energy whether you deploy them individually or in enormous, utility-scale power plants. The amount of power that photovoltaic technologies generate per square meter is also useful for many applications. Together, these two features mean that small-scale systems, however deployed, are often meaningful for individual, household, or community needs. Around the world, this has resulted in widespread adoption of both rooftop and community-scale applications of solar as distributed energy resources, and this flexibility has emerged as a key feature of Puerto Rico's new solar imaginary. Where they have had the financial means to do so, as we observed above, individual households and businesses have accelerated their adoption of rooftop solar solutions. Yet, traditional rooftop solutions, especially when batteries are included in the mix, remain very expensive for many Puerto Ricans, and the unfortunate fact is that solar installers have not yet found workable business models or solutions for solar and storage that work for low-income households. As a result, many who would like to leverage solar panels and batteries to improve energy security find themselves unable to do so, and so continue to rely on alternatives, especially generators, which are more affordable in the short term but dramatically more expensive over the long term.

In response, a number of communities in Puerto Rico are pursuing bottom-up, grassroots efforts to design community-based solar and storage solutions for energy security. These initiatives are notable for the level of commitment and effort that people are putting into them. Energy security matters in Puerto Rico and, fueled by the emerging solar imaginary, many of the initiatives have worked for years to find ways of putting solar to work to support communities. This has resulted in a diversity of ways of seeing solar as contributing to positive outcomes in community life and a diverse suite of solar technology designs.

In one illustrative extremely low-income community, for example, community members have volunteered to learn how to install solar and battery systems in order to reduce the costs of the small emergency backup systems they are installing

(they still pay an electrician to certify the installations). Combined with a group buying strategy, which further reduces costs, they have, over a period of several years, brought down costs to a (barely) affordable level, such that 30% of the households in the neighborhood now own an emergency backup solar system. In this community, the vision is to ensure that each household has the wherewithal to survive, and that they learn to work better together to achieve that goal. Importantly, this community is part of a network of communities across Puerto Rico who are sharing lessons, and several other communities are now pursuing similar strategies for encouraging household solar adoption.

In a second community, in a different part of Puerto Rico, a community water association, which provides local water services to neighborhood houses, leveraged savings on its electric bill to invest in solar and storage to power the system's water pumps, thus making the water system less vulnerable to electricity grid outages and freeing up financial resources to invest in other community projects. They are now seeking to expand the use of solar and batteries to provide electricity services for the community, even as they pursue other avenues to provide other critically needed communal services, such as healthcare.

In a third community, local businesses have banded together to build a solar and storage system to reduce costs and enhance energy security, pledging to use half of the savings to buy small rooftop systems for low-income neighbors. Their vision is a thriving community that ultimately provides security for all. In yet another community, small solar and storage microgrids serve clusters of 2–5 houses, in an effort to claim independence from the electricity grid. And there are many more communities who are discussing how they might leverage solar to meet their future needs and goals, many actively supported in their efforts to design and implement solutions by a diverse array of local community activists, community-support organizations, philanthropic foundations, researchers, and others.

These initiatives illuminate the degree of customizability available in the exercise of solar self-imagination in communities as they invest time, effort, and resources into efforts to chart more resilient and sustainable energy futures. No two communities are the same. They are concerned about different things and have different priorities, face different circumstances, and have different resources to draw upon, different degrees of social solidarity, and different suites of individual and collective capabilities. They have different needs, wants, values, and pre-existing commitments and different social, economic, and biophysical geographies. All of these factors shape their particular interpretations and imaginations of how solar can best be put to use—and what kinds of solutions they think would be workable for their particular circumstances. In the pursuit of solutions that work for each community, this fertile ground of diverse interpretations of how to put solar to work in valuable ways has generated many different designs of solar systems. In turn, the ability to adapt solar system design to particular community values, needs, and capabilities has allowed solar to be deployed in many more communities, to greater community benefit, leading to potential new business models for the solar industry.

This customizability is crucial because the more traditional solar and storage solutions offered in the marketplace and from policy institutions do not work for these communities. Indeed, given the varieties of discussions under way in Puerto Rico communities for how solar might serve them, the current imagination of the solar market and policy institutions feels unfortunately impoverished. Many members of these communities, for example, have looked at solar company websites or talked to solar installers and found on offer only rooftop systems designed for customers who can afford significantly larger systems. Many policymakers, electric utilities, and financial institutions, too, have resisted diversified community solutions in favor of either utility-scale power plants or standardized approaches to individually purchased household rooftop systems, for a variety of reasons, related both to financial returns and ease of adoption and/or implementation.[5] Yet, it is also apparent that failing to accommodate a wider and more heterogeneous array of community solar ideas and innovation is significantly slowing solar adoption in Puerto Rico (and elsewhere). At the same time, the lack of options for low-income communities to access solar energy and the benefits it provides is increasingly fueling complaints that solar markets and policies are perpetuating long-standing forms of energy and environmental injustice that have long undermined those in poverty. Interpretive flexibility is thus a potentially critical tool not only for accelerating solar adoption by expanding solar access to new groups but also advancing a just transition [16].

VII. Leveraging Sociotechnical Imaginaries to Advance Just and Sustainable Energy Transitions

The findings of our study of Puerto Rico's experience with shifting solar imaginaries presented above offer a number of lessons for broader efforts to leverage the power of public imagination to accelerate carbon-neutral energy transitions.

The Power of Imagination to Transform Social Expectations Is Substantial: Through 2017, solar energy occupied a modest place in Puerto Rico energy debates. Today, that has changed. Solar is front and center in conversations about how to create more secure, resilient, and sustainable energy systems for the Boricua people, including for the most vulnerable. Puerto Ricans are now committed to a solar-led vision of the future. They see real value in solar that has increased their willingness to pay, including for battery storage. And they are investing, individually and collectively, in solar systems. Installed capacity for a distributed solar generation has more than tripled in the past few years. Higher prices, per watt, are being paid for solar systems, in order to incorporate storage. There is a universal expectation that distributed solar adoption will continue to grow substantially. And new policies and rules

[5]From a theoretical perspective, the narrowing of imagined possibilities around a single technology model is referred to as "closure" and acts to restrict interpretive flexibility and even to "black box" the technology by rendering invisible the possibility of other possible technological designs [85].

mandate that solar serve as a foundational element of the electricity system going forward, including both distributed and utility-scale investments.

Transforming Imagination Into Practice Requires Work, Time, and Negotiation: An established aspect of imaginaries is their evolution in relationship to social practices, as people work to adapt their ideas to diverse goals. This work is nontrivial and, over time, can significantly transform the application, tenor, and even conceptual foundations of the initial imaginary. Flexibility of innovation should be expected in efforts to leverage sociotechnical imagination to accelerate adoption of clean energy technologies. Even as individuals, groups, organizations, and communities engage with and come to see new connections between technologies and improved lives, the work of acquiring and integrating new technologies into daily routines and practices is difficult and frequently, contested [88]. This is true for solar in Puerto Rico. For example, even the smallest emergency backup systems being purchased by some Puerto Rican households and communities require a major outlay of funds for purchasers. Communities do considerable work to figure out how to create workable financial possibilities. Community solar initiatives in Puerto Rico similarly find negotiations necessary to sort out how to put solar to work to benefit the community, how to bring systems into being, and how to govern their operations. These challenges are parallel to more well-known challenges, at larger scales, that confront integrating significant quantities of solar energy into electrical grid infrastructures, which requires reorganization not only of technological systems but also business models, operational routines, and regulatory rules. In the process of working out how to do this integration, whether at household, community, or utility scales, ideas are evolving about what solar can and cannot accomplish, under what situations, to create diverse forms of societal benefit.

Flexibility Has Benefits in Unleashing the Benefits of Sociotechnical Imagination: One lesson of our research is that, while the conviction that solar energy is key to Puerto Rican energy futures is widely shared and deeply held, broad diversity exists in the more detailed stories and sociotechnical designs imagined and fashioned by different communities to make solar work. Across Puerto Rico, communities confront different needs, possess different resources, values, and capabilities, and pursue different goals in their solar investments. Not surprisingly, therefore, they explore differently configured solar solutions, including variations in both the social and technical aspects of solar systems (e.g., the small emergency solar backup solutions adopted in one community, the solar-powered water pumps in a second, more traditional rooftop solutions for small businesses and wealthier households, etc.). Unleashing the potential of solar energy could thus be catalyzed by accommodating and supporting a more variegated landscape of sociotechnical imagination that engages diverse groups and responds positively to divergent ideas and values. *This has powerful implications for energy justice, opening new pathways for more equitable distributions of the benefits of solar technologies.* To date, however, business and policy communities in Puerto Rico have been insufficiently flexible in their proffered solar models to respond to these diverse imaginations and, as a consequence, have fallen short in enabling individuals, households, and communities to move as quickly to adopt solar as they would like.

Solar businesses, in particular, have an opportunity to reach significant new markets [89] by embracing this resource of diverse imaginaries. If they can find ways to engage low-income communities as customers, e.g., by opening up new product lines (not everyone needs or can afford a 5–10 kW system with a 10+ kWh battery, yet this is the standard product, and few if any very small systems are currently on offer), and if they can help find new ways to allow low-income communities to invest in such systems over time (e.g., via affordable financing options from local banks), then they may be able to reach many more customers while simultaneously accelerating solar deployment to tackle climate change.

Energy policies may also be able leverage public capital to advance distributed solar energy solutions for low-income communities. For example, in Puerto Rico, federal community development block grants are now beginning to support long-term reconstruction and economic development, yet currently available programs seem to offer little in the way of support for bottom-up community solar innovation, nor do they make it easy for low-income communities to access solar solutions.

Electric utilities can also do more to leverage public solar imaginaries. Particularly in cases like Puerto Rico, or for municipal and public sector utilities, where business models for electric utilities are not tied to the ownership of power plants, distributed solar innovation has a strong potential to support rapid adoption of low-carbon electricity generation by drawing in private investments to supplement the financial capabilities of the utility or municipality. When homeowners add solar and storage to the grid, they displace the need for the utility to purchase a comparable amount of solar and storage, while also potentially reducing the need for new transmission investments to bring utility-scale solar electricity to customers [90]. For investor-owned utilities, if communities are excited about solar, working with them to invest in and build solar systems that are owned by the utility can generate a host of additional benefits for communities besides low-carbon electrons (e.g., shade, local electricity system resilience, community revenues, public art, etc.), while also improving community relations.

Finally, we note that *research on solar imaginaries and their potential to help advance energy transitions remains nascent and would benefit from significant additional investment*. The case study presented here is suggestive but also limited in scope and uniquely conditioned by the significant energy insecurities confronting Puerto Rico communities. There is a need for a much more nuanced understanding of how solar imaginaries work; how they are similar or different from place-to-place; and whether and how differences in imagination matter. For example, comparative observations and analysis of how and why, under different kinds of circumstances, people come to see solar energy as an exciting prospect for themselves, their communities, or their regions would offer important insights into what it might take to unleash imaginaries as a tool for accelerating low-carbon energy transitions. At the same time, there is a parallel opportunity to use

forward-looking experiments in social, market, cultural, or policy imagination to explore potential levers for strengthening solar imaginaries, how and for whom they work, to what extent they alter willingness to pay for solar energy, and how those changes can accelerate just and equitable pathways for widespread solar adoption around the globe. Finally, research would be valuable on the role of social and political power in shaping imaginaries. Clearly, in the case of energy in Puerto Rico, the vision of a solar powered, resilient future remains in deep contestation with a more conventional imaginary of power plants and electricity grids, grounded in the work, ideas, and institutionalized power of Puerto Rico's electric utility. What are the pathways by which such conflicts play out? How and under what conditions can imaginaries ultimately transform the practices and politics of powerful institutions? Vice versa, how can powerful actors mobilize and manipulate imaginaries to resist change? Understanding these competing dynamics, how can imaginaries be leveraged as a tool for just and sustainable energy transitions?

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