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Citizen science and its potential for aiding low carbon energy transitions

Luke Gooding [*], Rachel Mary Pateman, Sarah Elizabeth West

Stockholm Environment Institute, University of York, United Kingdom

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ABSTRACT

Citizen science (CS) has emerged as a powerful approach to engage the public in scientific research across various domains. While it is documented that CS has made significant contributions to sustainability areas such as ecology, environmental science, and biology (Kullenberg and Kasperowski, 2016), the area of energy transition-related CS studies has yet to be documented in detail. This study reviews existing CS projects related to energy transitions, examining their approaches, methodologies, activities, and challenges. It identifies contributions of case studies to showcase the diverse ways CS has been applied to address energy transition challenges.

There are four primary pathways through which CS supports low carbon energy transitions: problem identification and research agenda setting, resource mobilisation, advocacy for transition off fossil fuels and co-evolution of socio-technical aspects. CS empowers communities, fosters participatory approaches, and generates knowledge that informs decision-making processes, ultimately driving positive change towards sustainable and inclusive futures. CS has the potential to advance energy transitions and needs to expand its integration in energy-related research and initiatives. By involving citizens as active participants, CS not only democratises knowledge but also empowers individuals to shape the future of clean energy systems.

Across the nine case study projects activities demonstrate a strong alignment with the diverse aspects required for a successful energy transition. What is more, in empowering communities and adopting participatory approaches, these CS projects generate essential knowledge that informs decision-making processes, thereby facilitating positive changes towards sustainable and inclusive futures. We suggest future routes for citizen action within the energy transition arena.

1. Introduction

Citizen science (CS) is a collaborative approach where volunteers, often without formal scientific training, participate in scientific research. It involves individuals contributing their time, efforts, and observations to assist scientists in collecting data, conducting experiments, or solving complex problems. Through CS initiatives, people from various backgrounds play a role in advancing scientific knowledge and addressing real-world challenges, fostering a deeper connection between science and society. However, biases exist in the disciplines in which CS approaches have been used. Kullenberg and Kasperowski's [1] scientometric analysis shows that CS has prominence in the arenas of biology, conservation, and ecology, with a focus on enabling data collection and classification. They also highlight CS's role in collecting geographic data and contributing to social sciences and epidemiology through the examination of issues related to the environment and health. Across this scientometric analysis, projects related to energy transitions did not feature. Similarly, a review led by Fraisl et al. [2] underscores the alignment of CS with particular Sustainable Development Goals (SDGs). For instance, the many CS initiatives related to preserving biodiversity, monitoring wildlife, and restoring habitats [3,4] align with SDG 15, "Life on Land". Alignment also exists with SDG 11, "Sustainable Cities and Communities", particularly from projects aiming to enhance urban sustainability, monitor air and water quality [5], and bolster community resilience. Finally, significant alignment exists with SDG 3, "Good Health and Wellbeing," where initiatives have targeted disease monitoring, public health research, and understanding the environmental determinants of health [6]. These reviews, however, have revealed far fewer projects in the field of energy contributing to SDG 7, "Affordable and Clean Energy" (see [7], and [8]).

Despite this, we consider CS to have the potential to make valuable contributions to energy transition-related studies, encompassing aspects such as electricity accessibility, the availability of clean cooking fuels and technologies, and the proportion of renewable energy in the overall

* Corresponding author.
E-mail address: luke.gooding@york.ac.uk (L. Gooding).

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energy consumption mix. CS projects in this space could offer crucial data and insights to advance progress towards enabling energy transitions, as well as opportunities for different groups to come together to discuss challenges and solutions. Moreover, beyond data collection, CS plays a pivotal role in bringing partnerships together, developing innovative solutions, and catalysing change. By leveraging the collaborative nature of CS, interdisciplinary teams can work in tandem to address complex energy challenges, fostering a more inclusive and sustainable energy future. In order to explore this potential, here we first outline what CS is, its overlaps with other participatory approaches, and its potential benefits and pitfalls. We then discuss how the practice of conducting CS aligns with sustainability, and specifically in relation to energy transitions. We then report on findings from a systematic review that identified projects in the energy transition space, detailing how they have approached the challenge of enabling energy transitions, the contributions they have made, and areas yet to be explored.

1.1. Citizen science

Over the past two decades, CS has emerged as a legitimate approach for scientific inquiry, mobilising the collective efforts of individuals to contribute to various research endeavours. However, within the broader landscape of participatory science, CS is not the sole approach for engaging non-professionals in scientific activities. Overlapping methodologies, such as crowdsourcing, community-based participatory research (CBPR), and volunteer computing, offer alternative avenues for collaboration between scientists and the public [9]. Each of these methodologies presents advantages and limitations, and they can complement each other in various contexts. For instance, CS projects may incorporate elements of crowdsourcing for data analysis or utilise volunteer computing resources for computationally intensive tasks [10].

However, we deem CS to hold particular value worth investigating due to its focus on democratising scientific research and fostering public engagement with science. Irwin [11] explores the pivotal role of public participation in science and its broader implications for governance and decision-making processes. Traditionally, scientific research has been conducted by experts within institutional settings, with limited engagement from the public beyond passive consumption of scientific knowledge. However, Irwin argues for the democratisation of science through increased public involvement, particularly through initiatives like CS. By actively involving diverse stakeholders in scientific activities such as data collection, analysis, and interpretation, CS fosters a sense of ownership and empowerment among participants, leading to increased support for scientific endeavours and informed decision-making [5]. Moreover, it enriches scientific findings by incorporating local knowledge and perspectives, thereby enhancing their relevance and legitimacy. From a governance standpoint, public participation in science can promote accountability and responsiveness to societal needs, reshaping the dynamics between science, society, and governance. Irwin's work underscores the transformative potential of CS in fostering more inclusive and transparent decision-making processes. Typologies of CS projects often highlight the spectrum of division of agency between participants and the organisations facilitating projects [12]. Where projects involve citizens not just in data collection but also empower participants by including them in establishing the scope of research, analysis and interpretation of data, and dissemination of findings, CS can promote scientific literacy, encourage civic participation, and expand the scope of research projects [13,14]. Moreover, CS has the potential to enhance scientific understanding by tapping into the collective intelligence and diverse perspectives of participants. By involving non-professionals in the research process, CS projects can access vast amounts of data that would otherwise be challenging to obtain [1].

It is worth noting, however, despite its many benefits, CS is not without its challenges [15], particularly in the context of neoliberalism. Scholars such as Vohland et al. [16] have outlined potential pitfalls associated with CS, including issues related to power dynamics, funding, and governance. In neoliberal contexts where market principles dominate, CS projects may face pressure to prioritise economic efficiency and market-driven outcomes over social or environmental concerns. This could lead to the commodification of scientific knowledge and the instrumentalization of citizen participants to achieve predetermined objectives. Furthermore, neoliberal ideologies may exacerbate existing inequalities in CS, as marginalised communities may lack the resources or capacity to participate fully. This could result in the underrepresentation of certain demographics or perspectives, limiting the diversity and inclusivity of CS initiatives [17].

Additionally, Haklay [14] delves into the multifaceted challenges surrounding data quality within CS projects. CS initiatives often involve the participation of non-experts in various scientific activities, including data collection. While this broadens participation and increases the scale of data collection efforts, it also introduces complexities related to data quality. Factors such as variations in participant skill levels, motivations, and equipment quality can significantly impact the accuracy and consistency of the collected data. Ensuring data reliability becomes paramount, particularly when these data are utilised for scientific research or inform policy-making processes. To address these challenges, Haklay emphasises the necessity of employing appropriate methodologies and tools within CS projects. This may entail developing comprehensive training programs for participants to enhance their data collection skills, implementing robust data validation procedures, and leveraging technology to standardise data collection processes. By bolstering data quality assurance mechanisms, CS projects can maximise the utility of collected data for scientific inquiry and decision-making, ultimately enhancing the credibility and impact of their findings.

As such, while CS offers promising opportunities for societal and scientific advancement, it is essential to critically examine its implementation within neoliberal contexts to mitigate potential pitfalls and ensure equitable and inclusive participation. By addressing issues of power, funding, and governance, CS can fulfill its transformative potential as a collaborative and democratic approach to scientific inquiry.

1.2. Citizen science and sustainability transitions

Sauermann et al. [20] documents three ways CS can support sustainability transitions. First, CS serves as a valuable tool for pinpointing sustainability issues and shaping research agendas, as participants actively engage in defining scientific research and data collection endeavours. Drawing upon local insights and perspectives, CS can align action with sustainability challenges at the grassroots level [18–20]. Furthermore, as CS involves stakeholders in the process of defining research inquiries and priorities, this could increase the possibility that local sustainability concerns receive effective attention, tailored to the local context. Second, CS has the capacity to mobilise resources, both in terms of effort and knowledge. Relying on volunteers who generously devote their time and expertise to scientific initiatives, CS significantly enhances the scale and efficiency of data gathering, analysis, and interpretation. This mobilisation of resources not only amplifies the impact of scientific efforts but can also democratise access to scientific knowledge, enabling non-professionals to contribute their expertise and viewpoints. Where CS is inclusive of a diverse range of participants, projects harness a broader knowledge reservoir and foster innovation in addressing sustainability challenges. Third, CS can facilitate the co-evolution of socio-technical facets within sustainability transitions. For instance, in the case of the MyNatureWatch project, people built wildlife trap cameras, collected data regarding local flora and fauna, and there were additional benefits relating to education and biodiversity improvements [21]. Sustainability transitions necessitate changes in both social and technological realms. CS plays a pivotal role in fostering the harmonious co-evolution of these aspects by convening stakeholders from varied backgrounds, thereby promoting collaboration and co-creation in the pursuit of sustainable solutions.

By involving citizens in the research and advancement of sustainable technologies, policies, and practices, CS initiatives can link scientific progress and the requirements of society. This collaborative process of coevolution can culminate in the creation of solutions that are not only scientifically sound but also culturally and contextually relevant, thus bolstering the cause of sustainability transitions. For instance, in the case of the SuScit project in North London, community insights and experiences were gained to inform a community-led agenda for urban sustainability research and to aid the formation of local transition arenas [22]. Through these avenues, CS contributes significantly to sustainability transitions by empowering communities, promoting participatory approaches, and generating knowledge that informs decision-making processes. By actively engaging citizens, CS can instil a sense of ownership, amplify societal involvement, and propel positive transformations towards a future that is both sustainable and inclusive.

1.3. Citizen science and energy transition alignment

Low carbon energy transitions refer to the fundamental shift in the way societies produce, distribute, and consume energy [23]. This transition involves changes in energy sources, technologies, and the overall energy infrastructure [24]. Energy transitions are driven by a combination of economic, environmental, technological, and societal factors, and they play a crucial role in shaping a sustainable energy future [25]. Indeed, Blohm [26] highlights that an enabling framework for energy transitions requires activities surrounding environmental protection, society and behaviour, equity and justice, knowledge, energy markets, energy policy, finance, legal requirements, infrastructure, institutions, and alignment of interests.

One example of a way in which energy transitions can occur is via the proliferation of community energy initiatives, which stand as compelling evidence of the potential for active citizen participation in the energy sector. These initiatives are examples of the capacity of citizens to reshape the energy landscape and contribute to sustainability and transition efforts, influencing energy behaviours, energy markets, infrastructures, and community knowledge, to name a few [26]. By actively participating in community energy projects, citizens transcend their traditional roles as mere consumers and emerge as proactive contributors to a cleaner, more sustainable energy future [27]. They become stakeholders, decision-makers, and change agents. This dynamic role redefines the energy landscape, enabling citizens to generate, consume, and even share renewable energy resources, all the while actively engaging in the management and decision-making processes of energy projects [28]. These community energy projects, often localised and community-driven, exemplify the principles of CS by actively involving citizens in data collection, analysis, and decision-making processes [29]. This approach empowers individuals and communities to not only shape their local energy systems and their transition but also to contribute to broader efforts in decarbonization and sustainability. It marks a significant shift from the conventional top-down energy model to a more democratised, grassroots approach [30]. This participatory, community-oriented work aligns well with Irwin's vision of CS emphasising active involvement, localised knowledge, and collective action. Therefore, the integration of CS approaches in enabling energy transitions represents a powerful avenue for democratising the energy landscape and driving meaningful change through collective citizen engagement.

Following Lennon et al. [31], who used the term “energy citizenship” as a potential bridge between CS and energy transitions, we see citizenship as going beyond its traditional confines within state institutions. Citizenship, in this context, extends to active participation in civil society and the private sector, empowering individuals and communities to shape decisions regarding energy production and consumption [31]. Through CS and community energy projects, marginalised voices are included in scientific discourse, challenging traditional power structures and knowledge hierarchies [13]. However, the role of scale in environmental decision-making remains crucial, as decentralisation and community control seek to amplify local voices while acknowledging broader systemic impacts [32]. Ultimately, both CS and community energy projects strive to democratise environmental governance, fostering a more equitable and sustainable future.

2. Approach and purpose of study

We aim to describe the current landscape of citizen science (CS) in the energy transition space, examining how it has been implemented, where it has taken place, who has been involved, and what specific goals and activities CS projects have pursued. By providing an overview of these elements, we offer a view of how CS is contributing to energy transitions. This review highlights case study projects, illustrating the ways in which CS has been applied and the activities that have advanced energy transitions.

In addition to showcasing projects, this review explores future possibilities for CS in energy transitions. We discuss emerging trends and innovative approaches that have the potential to further enhance the role of CS in this space. While acknowledging existing activities, we also recognize the challenges that persist and the areas that require more research. Identifying these gaps is crucial for directing future efforts and ensuring that CS can continue to evolve and contribute effectively to energy transitions.

To address these aims, we explore several key questions. First, we examine how CS projects have approached energy transitions to date, considering the strategies and methodologies they have employed. Next, we look at the specific activities that CS projects have conducted to support energy transitions, detailing the practical steps and initiatives they have undertaken. Finally, we assess the opportunities and challenges facing CS energy projects, evaluating the factors that influence their success and identifying potential barriers to their continued impact.

3. Methodology

Our review adhered to the widely-recognized PRISMA protocol (Preferred Reporting Items for Systematic Review Recommendations) [33] to systematically identify and evaluate relevant studies on the application of CS in energy transition-related research. The systematic literature review process, undertaken to identify relevant projects for our research, was conducted iteratively following established guidelines, with repeated searches across multiple electronic databases to ensure a comprehensive and exhaustive exploration of relevant resources. To maximise the scope of our search and increase the likelihood of capturing energy-related projects, we utilised a diverse range of electronic databases, including those which host CS projects and resources (eu-citizen.science, ECSA (European Citizen Science Association), ZooniverseSciStarter, citizenscience.gov); EU-funded research projects (Cordis); academic literature (Scopus, Web of Science); and academic and grey literature (Google Scholar). By leveraging these platforms, we aimed to access a wide array of academic and non-academic sources, spanning various disciplines and sectors.

The search strategy was intentionally broad, starting with the primary terms “energy,” “energy transition,” and “citizen science.” We then expanded our search by identifying additional related terms from the initial search results. Analysing these results helped us understand the common language used in the literature and uncover potential alternatives. This iterative process optimised our search strategy, ensuring we covered a comprehensive range of energy transition projects and initiatives (Table 1). These terms were entered into the search function of the databases to gain the full roster of resources for screening.

The initial search yielded 1364 resources, which were screened based on their title, webpage content, and/or abstract using three specific inclusion and exclusion criteria (below). This screening process narrowed the selection to 44 resources (Fig. 1). These 44 resources were associated with nine distinct projects (Table 2) that met our criteria.

Table 1
Search terms used for review.

Primary search terms		
"energy"	"Citizen science"	"Energy transition"
Additional search terms		
"solar/photovoltaics"	"electricity"	"system"
"emissions"	"efficiency"	"heating/cooling"
"renewables"	"power"	"generation"
"community"	"consumption"	"decentralisation"
"wind"	"adoption"	"Fossil fuel"
"hydroelectric"	"geothermal"	"nuclear"
"carbon"	"neutral"	"zero"
"Peer-to-peer"	"citizenship"	"Volunteer monitoring"
"Community-based monitoring"	"Public participation in scientific research"	"Innovation community"
"Digital communities"	"forums"	"User communities"

These nine projects were then assessed in depth with full project webpage and publicly available project publications being analysed.

1. Resource details or outlines a specific project rather than presenting a broader exploration of a theme, offering commentary, or delving into conceptual ideas.
2. Includes CS: The project includes a focus on CS, specifically, members of the public participating in research projects voluntarily and not in a professional capacity [45]. Furthermore, we included projects which adhered to the principles of CS as outlined by ECSA [34], which includes the requirement for active participation (i.e. scraping of data from passive participants was excluded).
3. Energy transition element: the project focuses on energy transition, which involves restructuring how societies generate, distribute, and consume energy.

For each of the 9 projects, we then check project websites for any additional project-related information, including project overviews, objectives, outcomes, expected results, employed technologies, participation mechanisms, and the beneficiaries of the initiatives. We collected data from multiple sources, starting with project websites, online reports, and videos. We thoroughly explored project websites to find reports and articles, and we also followed links from project social media accounts. Additionally, we searched academic journal databases such as Web of Science, Google Scholar, and Scopus to locate peer-reviewed articles authored by both project contributors and researchers not affiliated with the project teams. Any relevant documents and files were downloaded and exported to NVivo for further analysis.

The review of CS project documents within the qualitative data analysis tool NVivo centred on understanding how projects enable energy transitions. Using thematic analysis, key themes and codes were identified inductively, to encapsulate the varied ways projects have occurred to date, and what activities have been carried out.

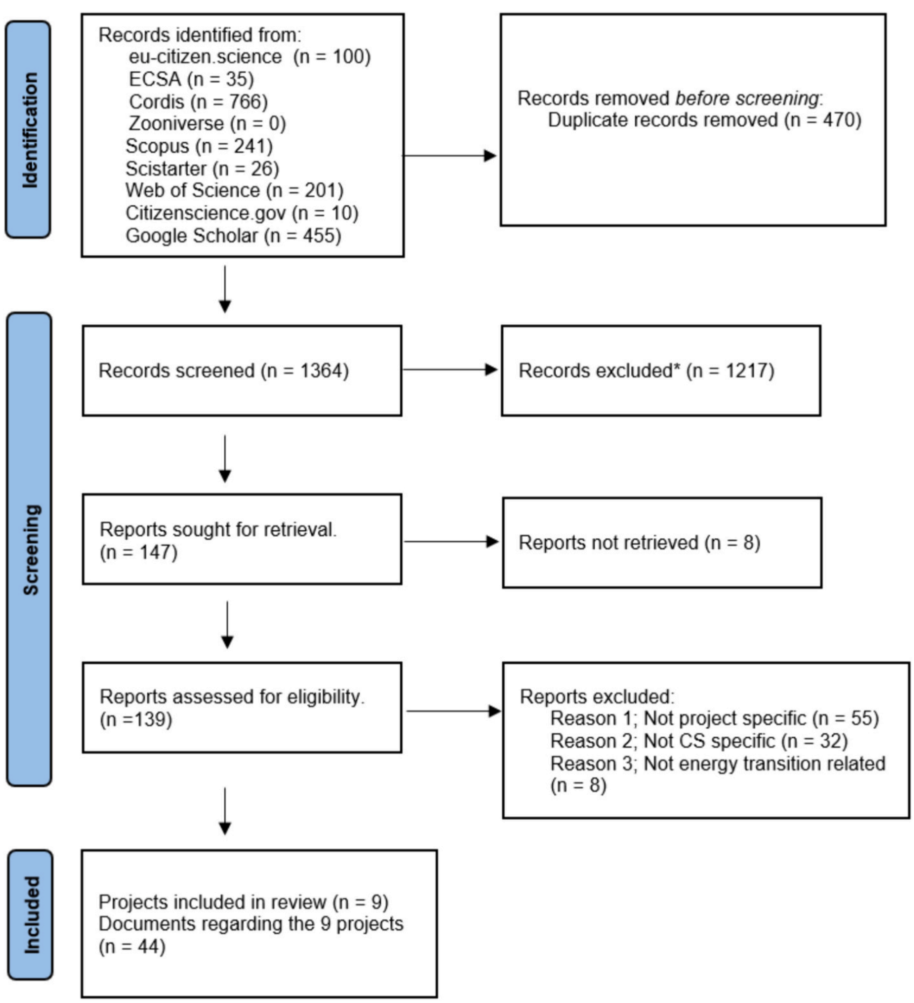

Fig. 1. Process of identifying projects for inclusion.

Table 2
Overview of CS Energy Projects emergent from review. Text in Approach taken is a synthesis of documents about the project.

Project	Approach taken (synthesised from project descriptions)	Location	Funder and data ownership
Step Change - Energy Communities/ Tenant Electricity (Step Change-Tenants)	Step Change-Tenants examines neighbourhood electricity sharing in German energy communities through three case studies over a year. It involves citizen contributors and explores energy-sharing models and energy citizenship across communities. Citizen scientists, residents, and tenants engage through community meetings, online forums, and workshops, registering via project websites, community outreach, or utility companies. Data collection utilises smart metres and online platforms to monitor energy consumption, peak usage times, and efficiency improvements, benefiting participating communities, residents, and energy service providers.	Germany	Data ownership resides within the project consortium (Horizon 2020 funded).
AURORA	The AURORA project looks to empower citizens using advanced photovoltaic technology, fostering local energy communities (in the UK, Denmark, Slovenia, Portugal and Spain) for systemic change in the energy sector. It prioritises transparency, equity, and sustainability. Citizen scientists include homeowners, renters, and local community members engaged via online surveys, community events, and neighbourhood workshops. Registration is available online or at community events. Using online surveys and data analytics tools, the project collects data on energy preferences, energy source preferences, and renewable energy adoption rates. Beneficiaries include local communities, energy policymakers, and renewable energy providers.	UK, Denmark, Slovenia, Portugal and Spain	Data ownership rests within the project consortium, funded by Horizon 2020.
STEP Change-Demonstration of the Potential of Renewable Energy for Productive Use in Rural Uganda	Step Change-Uganda demonstrates renewable energy's impact in rural agricultural areas, addressing energy demands sustainably. Rural farmers and community members participate in renewable energy installations, training programs, and entrepreneurial initiatives. Registration occurs through local hubs and workshops. Solar panels, wind turbines, and data collection tools gather information on energy usage and economic impact.	Uganda	Data ownership rests within the project consortium, funded by Horizon 2020.
Generation Solar	GenerationSolar promotes solar energy adoption and community engagement across Europe. Homeowners and renewables enthusiasts participate through an online platform, self-registering their solar installations. Data monitoring systems track solar energy generation and consumption, collecting information on energy savings and environmental impact. Beneficiaries include homeowners and the wider community.	Across Europe	Data ownership rests within the project consortium, funded by Horizon 2020.

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Table 2 (*continued*)

Project	Approach taken (synthesised from project descriptions)	Location	Funder and data ownership
Power to the People (PTTP)	PTTP enhances rural solar installation mapping accuracy by gathering data from citizen scientists. Participants, including homeowners, renters, and community members, engage through online platforms and community events. Data collection, focusing on energy usage habits and preferences, utilises mobile apps, online dashboards, and smart devices.	Uganda, Kenya, and Sierra Leone	Data owned by project institutions and funded by a UKRI CS Exploration Grant.
OpenPV	The Open PV Project collaboratively gathers photovoltaic installation data from government, industry, and individuals. With over 400,000 installations collected since 2011, it offers insights into U.S. solar trends and costs, empowering photovoltaic consumers to analyse industry trends. Citizen scientists participate through an online platform, registering on the website. Data monitoring systems track solar energy generation and consumption, collecting solar energy generation and usage data. Beneficiaries include householders and the photovoltaics industry.	United States of America	The data is owned by the US National Renewable Energy Laboratory.
Mothers Out Front	Mothers Out Front's "Gas Leak Detective" program mobilises community members from Worcester, Massachusetts to identify urban gas leaks, empowering them to advocate for energy justice through community engagement and policy discussions, driving efforts towards transitioning away from natural gas for a sustainable energy future. Citizen scientists participate through training programs, online platforms, community meetings, and policy engagement, registering online or at community events. Methane detectors are used to collect gas level and locational data. Beneficiaries include the local community and gas companies.	Worcester, Massachusetts	Data ownership is shared between Mothers Out Front, Wylie Environmental Data Justice (WEDJ) lab, and Arizona State University.
PSLifestyles-Campus to World	The "Campus to World" initiative, led by the University of Applied Sciences of Bonn-Rhein-Sieg, drives CS efforts in energy transition through "CitizenLabs." Participants, including students, businesses, and policymakers, collaborate on challenges related to energy transitions and Sustainable Development Goals. Their contributions, such as assessing household devices and discussing environmental impact, inform climate solutions to reduce ecological footprints. Citizen scientists engage in evaluating household devices and co-creating energy sector business concepts. They self-register through promotion on social media channels and regional mass media. Household energy use detection devices are utilised to collect energy use data within homes.	Bonn, Germany	Data ownership rests within the project consortium, funded by Horizon 2020.
FULFILL	FULFILL employs CS to explore how	Germany, Denmark,	Data ownership lies within the

(*continued on next page*)

Table 2 (*continued*)

Project	Approach taken (synthesised from project descriptions)	Location	Funder and data ownership
	lifestyle changes and citizen engagement can accelerate Europe's energy transition. Embracing sufficiency principles, it aims to reshape societal norms, infrastructure, and regulations to reduce energy demand and greenhouse gas emissions while enhancing well-being. The project defines and expands the concept of lifestyle change, examining its implications for decarbonization strategies across various European contexts, including the role of municipalities and intentional communities. Citizen scientists, members of sustainability initiatives, participate through interviews, selected from sustainable living initiatives. Energy supply/use detection devices are used to collect data on energy usage needs within households. Beneficiaries include citizens and decision-makers, both business and political.	Latvia, Italy, France	project consortium, funded by Horizon 2020.

4. Findings

4.1. How have CS projects approached energy transitions to date?

Nine CS energy transition-related projects were identified, and their approaches are shown in Table 2.

Thematic analysis revealed that the nine projects have utilised CS approaches to contribute to energy transitions via **four** distinct pathways (Fig. 2).

The first, and most common, pathway uses CS to collect energy-related data from citizen lifestyles to understand energy usage patterns, behaviours, and energy cultures. Projects like Step Change - Tenants, PSLifestyles, and AURORA focus on gathering energy-related data and understanding the ways in which people view and use energy. By involving citizens in data collection, researchers can create a comprehensive view of energy consumption patterns and the cultural aspects that influence energy choices. AURORA provides personalised emissions profiles and tracks progress over time, aiming to help individuals become more conscious of their energy-related behaviours and motivate them to make sustainable changes. The aggregated data can also contribute to targeted advice and policy recommendations to support the transition to low-emission energy practices, as shown by project AURORA with the production of guidelines and suggestions for policymakers to promote, create, implement, and manage energy communities. Plus, in the case of FULFILL, the focus of data collection is on illuminating what sufficient lifestyles can look like and routes in which we can evolve to consume less but retain a quality of lifestyle.

The second pathway uses CS to map energy installations to establish if renewable energy targets are being met. For example, GenerationSolar and OpenPV have created a database of solar installations to generate maps that display the location and number of installations, with a view to establish more accurate understandings of installations. The inclusion of a gaming element encourages engagement and enables users to spot energy installations, which can enhance public awareness and understanding of renewable energy technologies. Such maps can also assist researchers, policymakers, and businesses in identifying gaps and opportunities for further renewable energy deployment and integration. PTTP uses CS to fill in data gaps of solar installation in rural areas in Kenya, Uganda, and Sierra Leone, where satellite imagery is low quality, thereby aiding rural electrification efforts in developing countries.

The third pathway involves using CS to explore new opportunities for renewable energy installations. STEP Change-Uganda harnesses the power of CS to investigate and identify the potential for renewable energy in various regions and communities. This project engages local residents in the data collection process, empowering them to contribute to the assessment of renewable energy prospects. By involving citizens, the project gathers empirical evidence and valuable insights on how off-grid renewable energy solutions can enhance agricultural development and improve rural livelihoods in Uganda. The concrete evidence gathered from these citizen-driven efforts demonstrates successful experiences and highlights potential opportunities for scaling up. This, in turn, informs decision-makers and stakeholders about the significant value and impact of investing in renewable energy for productive agricultural activities.

The fourth pathway uses CS to generate pathways for advocacy for a transition to cleaner energy. The Mothers Out Front project does this by engaging participants in identifying urban gas leaks, both addressing immediate safety concerns and promoting broader discussions on transitioning away from natural gas. This project is part of a coalition called the Gas Transition Allies (GTA) which brings together researchers, whistleblowers, unions, and grassroots organisations to address Massachusetts' leaking pipeline infrastructure [35]. Through CS methodologies, individuals become actively involved in monitoring and addressing energy-related issues in their communities. This grassroots engagement fosters awareness and looks to empower participants to advocate for cleaner, safer energy alternatives. By highlighting the importance of detecting and addressing gas leaks, Mothers Out Front effectively advocates for a shift towards renewable energy sources and promotes collective action towards a more sustainable energy future.

Across the nine projects, six collaborate and work with homeowners or renters, reflecting the focus of projects in this space on domestic energy use and energy practices. Aside from these six, STEP Change - Uganda looks to foster participation with another group, entrepreneurs, FULFILL looks to view energy use across wider aspects of lifestyles, not just within the home, and Mothers Out Front looks to engage community members from Worcester, Massachusetts, in gas leak detection to advocate for energy transition activities from utility companies. The majority of the projects required participants to register to take part via visiting project websites, with only some projects, such as FULFILL, selecting participants from established sustainable initiative communities and groups. This, therefore, requires self-selecting participants to have a level of awareness of the projects, ability to visit websites, digest information, and register. As such, this highlights how CS and energy transitions to date have been coupled via the reliance on aware and

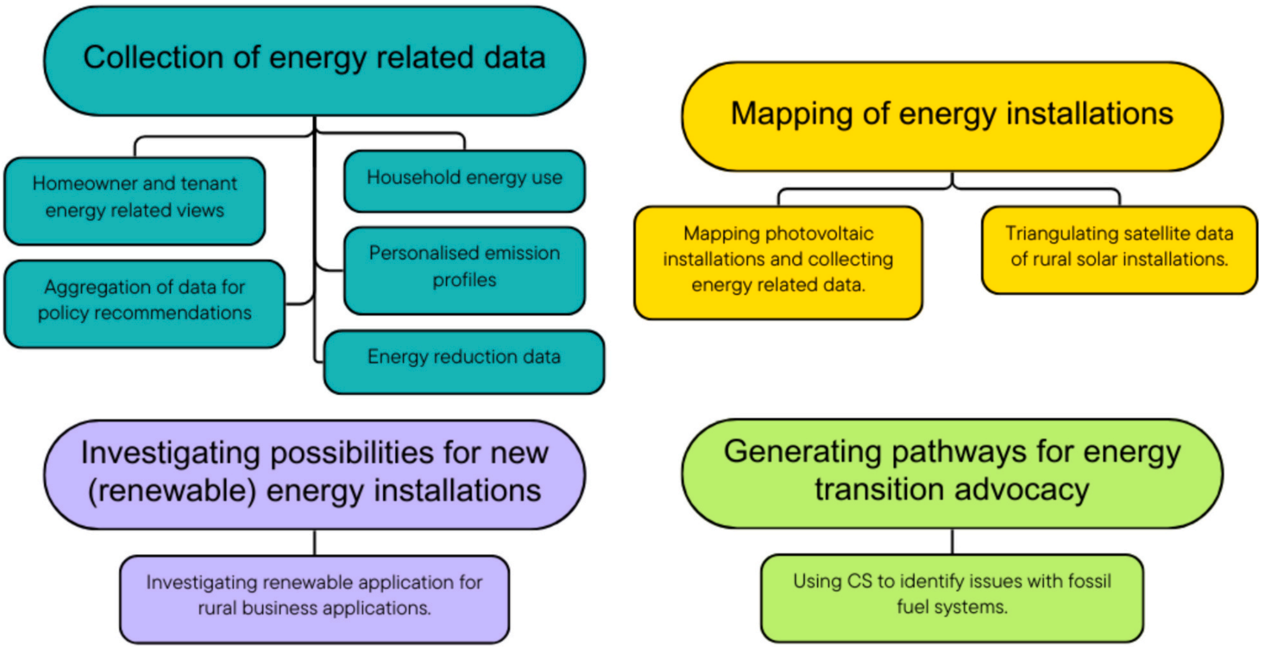


Fig. 2. Approaches adopted by CS energy transition related projects.

engaged populations of participants with internet access, for instance. In terms of the actual involvement and participation routes for citizens, six of the nine projects utilised community events, workshops, and online forums or surveys to foster participation. These were used to gain insights into energy use behaviours and to understand energy needs. In the remaining projects, such as GenerationSolar and OpenPV, participation was via the installation of solar panels and submission of energy-related data, and in Step Change - Uganda, the engagement with local entrepreneurial programs surrounding renewables.

The majority of projects used renewable energy technology to collect data and used data analysis tools to ascertain energy production and/or energy consumption patterns. For example, in STEP Change - Tenants, data is collected regarding home energy usage, and for GenerationSolar data is collected from solar photovoltaic panels to provide energy production figures. In the case of PTTP, apps are also utilised to offer participants a route to enter data regarding energy usage habits, preferences, and community energy initiatives, this is also bolstered by an online dashboard and smart energy devices. The exception is Mothers Out Front project which does not directly interact with renewable energy sources. Document searches revealed that each project retained data ownership within the principal organisations or affiliated research institutions. This complies with regulations like the UK's GDPR. However, it raises concerns about neoliberal practices, as citizens contribute data without equitable access or compensation, effectively engaging in unpaid labour. This dynamic highlights the potential exploitation of citizens' efforts in a system where data is valued but not democratically controlled or fairly compensated.

4.2. *What specific activities have CS projects carried out?*

In this section, we build on the approaches used by CS energy transition projects by delving deeper into how the nine CS energy focused projects have aided energy transitions, and the activities generated by projects (see Table 3).

Inductive coding revealed seven types of activities carried out by projects. All projects generated novel datasets. Furthermore, projects such as Step Change - Tenants, PSLifestyles, and FULFILL generated contextual information to develop further understanding of energy usage, the adoption of energy-saving measures within communities.

Beyond data collection, these projects also bring about change by identifying suitable locations for renewable energy installations and actively facilitating their implementation. For example, STEP Change - Uganda focuses on pinpointing rural areas in Uganda for clean energy solutions, fostering localised energy systems. GenerationSolar goes further by installing and testing various solar technologies to promote renewable energy adoption. Advocacy is a core element of these initiatives. AURORA and PTTP use their findings to influence policies that align with community preferences and raise awareness about transitioning to cleaner energy. Mothers Out Front advocates for shifting from natural gas to renewable energy by highlighting the community harm of gas leaks. Engaging the public is also crucial. Projects like STEP Change - Tenants, AURORA, Mothers Out Front, PSLifestyles, FULFILL, and PTTP organise discussions and events to involve citizens in decision-making. AURORA's citizen labelling scheme drives behaviour change, similar to carbon footprinting strategies. Both AURORA and PSLifestyles explore new business models, such as solar power generation, to test their effectiveness in meeting user needs and showcase the potential for innovative approaches to steer energy transitions. These projects demonstrate that CS goes beyond data collection; they lead initiatives to advocate for policy changes, engage the public, and explore innovative business models, highlighting the significant role of CS in aiding energy transitions.

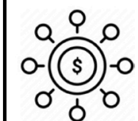
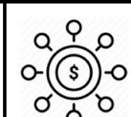
4.3. *What are the challenges and opportunities for CS energy transition projects?*

The challenges for CS energy projects presented here are derived from document analysis of project publications and journal articles relating to the nine energy projects.

4.3.1. *Challenges*

The initial key challenge facing CS in its role of facilitating an energy transition revolves around the need for high quality data, particularly concerning installation prerequisites. For example, in the context of mapping areas with the potential for renewable energy development, a high degree of data reliability is indispensable. This reliability extends to the level of resources that may be allocated for site exploration following data analysis. This was a particular notion raised in the case of PTTP,

Table 3
Project activities supporting energy transitions.

	Production of novel datasets	Conduction of site identification	Technology testing / validation	Enablement of policy advocacy	Generation of public engagement	Conduction of Impact assessments	Testing of business models
Step Change - Energy Communities/ Tenant Electricity							
AURORA							
STEP Change-Uganda							
GenerationSolar							
Power to the People							
OpenPV							
Mothers Out Front							
PSLifestyles							
FULFILL							

with participants highlighting the challenges of working with low quality images and ensuring accuracy of submitted data and input [36].

Secondly, there's the issue of inclusivity and representation in who participates in CS energy transition projects. This issue is also pertinent in CS more widely, with Pateman and West [17], highlighting the consequences for data and decision-making that arise from lack of diverse participants. Relatedly, CS projects must ensure that project beneficiaries are fully acknowledged and comprehended. This recognition is crucial for preventing undue advantages for some groups while others bear disproportionate burdens stemming from project costs. Three of the nine projects opted for a closed registration approach, where project leaders specifically selected groups and communities to target potential participants. For instance, this selection process might involve choosing homeowners of particular types or members of specific agricultural co-operatives. While this targeted approach is deemed advantageous for recruiting citizen scientists, it also raises concerns about the possibility of overlooking potential groups or participants who are not given the opportunity to self-register. The other projects opted for self-registration, with project websites providing information for interested individuals to interact with before emailing project organisers to volunteer their involvement. This approach offers a potential avenue for participation for all individuals (provided they have internet access and visit the website). However, it also raises questions about the equality of access for those without internet access and necessitates awareness of the project and website in order to volunteer, identified as an issue in CS by Aristeidou and Herodotou [37]. This knowledge prerequisite may potentially skew participation in favour of existing citizen scientists or recurring volunteers.

The third key challenge for projects is to ensure sustained involvement from participants. Eight of the nine projects looking at energy transitions rely on crowdsourced or contributory data participation types. Although valuable in generating data, there is a risk that without deeper participation, members of communities may become dabblers and droppers [38] and not engage in the long term with projects and the task of generating an energy transition. A final key challenge that emerged was that of privacy and data security. Step Change - Tenants, PSLifestyles, FULFILL and AURORA look to collect data about participants' energy behaviour, which can include electricity usage patterns, heating, and cooling habits, and more. The collection of such granular data raises concerns about the exposure of sensitive information. As such there is the requirement for a suitable data management strategy, including proper anonymization and data storage techniques to protect individuals' identities while still allowing for meaningful analysis.

Table 4
Mapping CS and components of an energy transition framework.

Energy transition framework areas (Bholm, 2021).	Criteria	Associated deliverables from CS projects (table 3 origin)
Environmental and ecological protection		
Society, culture, and behaviour	Consumer acceptance	
	Social acceptance	
	Public awareness and contributions	
Equity and justice	Distributional equity	
	Climate and resource justice	
Knowledge	School education	
	Highly skilled workers	
	Highly skilled policy makers and decision makers	
	Information and awareness	
Energy markets	Liberalisation of energy market	
	Elimination of trade barriers	
	Strengthening domestic economies	
	Market infrastructure	
	Ownership structure	
Energy policy	Regulatory body to promote the use of CO2 neutral technologies	
	Good governance	
	Long-term predictability	
Finance	Financial co-operations	
	Economically viable cost structures	
	Competitive and reliable capital market	
	Adequate energy pricing	
	Financial participation	
Legal requirements	Standards, codes, and certification	
	Elimination of administrative barriers	
	Legal aspects	
Infrastructure	Strengthening existing local infrastructure	
	Efficient power grid operation	
Institutions	National systems of innovation	
	Independent professional institutions	
	Research and development	
Clash of interests	Lobbyism	

4.3.2. Opportunities

Blohm [26] details 11 elements essential for facilitating an energy transition. Here we map the nine reviewed projects against these elements. By aligning with key components outlined by Blohm [26], we assess these projects' impact in relation to energy transition goals and identify areas for future exploration (Table 4).

Collectively, the nine identified projects meet most of Blohm's elements. Environmental and ecological protection is at the core of mitigating climate impact, intricately linked to the imperative for an energy transition. CS projects spearhead site identification, gather data, and advocate for net-zero carbon technologies, supporting climate change mitigation while protecting environments. On the societal front, CS delves into energy behaviour and technology assessment, fostering policy shifts and public engagement to reshape attitudes and actions towards energy. Projects focused on equity and justice strive for fairer access to electricity and renewables in developing regions, supplying data and championing policies that support this shift, easing the burden on vulnerable nations and assessing energy access in underserved communities. Additionally, education initiatives, knowledge exchange, and lobbying for policy change form the backbone of these projects, spreading awareness and bolstering renewable energy technologies and policy frameworks.

However, while some projects target ownership structures in local solar efforts, exploring areas like market liberalisation and emerging technologies presents untapped potential in the energy market realm. Similarly, the lack of a direct focus on financial aspects within energy transitions, along with projects targeting areas like market liberalisation and emerging technologies, highlights opportunities for further exploration and development.

5. Discussion

The scarcity of CS initiatives dedicated to enabling energy transitions is potentially rooted in several complex factors. One primary challenge lies in the multifaceted and intricate nature of these endeavours. Energy transition initiatives demand a mix of diverse skills, ranging from environmental science and technological expertise to nuanced policy-making insights and community engagement [39–41]. The requirement for an amalgamation of such a comprehensive skill set within a project could hinder the emergence and proliferation of these initiatives in the landscape of energy transitions. Another significant hurdle contributing to this scarcity could be the constraint of resources, both in terms of funding and available skills. These projects necessitate substantial financial investment and enduring commitment, which serve as important barriers to entry.

Language and timeframe may also be influencing factors, with the relative scarcity possibly attributed to the novelty of the concept of energy transitions. This evolving field, although gaining momentum, is still relatively new, with its comprehensive understanding and widespread acknowledgment taking time to permeate various sectors and attract a broader range of participants, including within the realm of CS. This permeation (or lack of it) may also be influencing the language choice by actors in this space. While CS may indeed be present within this landscape, it might not always be explicitly labelled as such (and therefore not present via search criteria). Instead, 'participatory methods' or other terms might be utilised, which, although embodying the essence of CS, might not be immediately recognized under the conventional label, leading to the perception of a scarcity that might not accurately reflect the breadth of active engagement within energy transitions, a notion also detailed by Haklay [42].

The following recommendations may help increase the number of energy related CS projects. Firstly, a facilitation of collaboration among existing CS projects dedicated to energy transitions could be crucial. By fostering knowledge exchange and building dedicated platforms, these initiatives can share insights and resources, creating a collective learning environment that strengthens their impact within the energy domain. This in turn may overcome resource limitations, with strategic partnerships with governmental bodies, energy sectors, investors, and philanthropic organisations possibly ensuring the long-term viability and influence of CS initiatives focused on energy transitions. Secondly, raising awareness about the role of CS in energy transitions is pivotal. Targeted campaigns and educational programs should emphasise the public's influence in shaping sustainable energy systems, engaging diverse stakeholders, including communities, policymakers, and industry players. Clearer terminology and broader awareness initiatives within CS, specifically related to energy transitions, are necessary. Recognizing participatory methods, even beyond explicit "citizen science" labels, will highlight their active role in energy-related endeavours, minimising misunderstandings about their presence and impact.

However, it's crucial to acknowledge inherent limitations in CS efforts for energy transitions. Challenges like scalability, data quality, inclusivity, and resource constraints may hinder their full potential. Addressing these limitations demands ongoing refinement, heightened community engagement, and proactive measures to ensure equitable and accessible participation. Recognizing and tackling these challenges will significantly enhance the effectiveness and impact of CS in driving energy transitions towards a more sustainable future.

Literature on non-participation in CS energy transition projects reveals that not all initiatives empower participants equally. In the context of renewable energy initiatives, understanding the complex dynamics of power, agency, and contestation becomes crucial. Drawing on the insights of Blacker et al. [43], who emphasise how CS can transform power and political contestation into technical discussions, Pandey and Sharma [44] offer a nuanced perspective. They argue that marginalised groups may strategically choose non-participation as a means to reclaim agency in energy transitions. By opting out of mainstream renewable energy initiatives, these communities resist being co-opted by dominant power structures and assert their independence in shaping energy transition trajectories. This highlights the significance of recognizing non-participation as a deliberate strategy utilised by marginalised groups to challenge prevailing power dynamics and assert their right to self-determination in the energy transition journey.

6. Conclusion

This paper has demonstrated the significant potential of CS in aiding the crucial transition to affordable and clean energy. While CS has already made substantial contributions across various sustainability domains, its intersection with energy transition research remains relatively underexplored, with only a handful of CS projects in this space. Our findings have illuminated the transformative power of CS in addressing this critical aspect of global sustainability, particularly showing that projects can meet a variety of criteria necessary for an energy transition.

CS offers a multi-faceted approach to energy transition. It not only seeks to engage and empower communities but also serves as a catalyst for problem identification, research agenda setting, and resource mobilisation. By fostering participatory approaches and generating valuable knowledge, CS can be a driving force behind informed decision-making processes and the advancement of clean energy systems. It democratises knowledge, allowing individuals to actively shape the path towards a sustainable and inclusive energy future. Challenges around ensuring data quality, promoting inclusivity, sustaining community involvement, safeguarding privacy and data security, and managing expectations will need to be addressed in order to have impactful CS projects in the energy transition space. To harness the full potential, there are remaining gaps for energy transition CS projects to conduct activities surrounding energy markets, institutions surrounding energy transitions, and the finances of energy as a transition occurs.

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CRediT authorship contribution statement

Luke Gooding: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rachel Mary Pateman:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Sarah Elizabeth West:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Data availability

Data will be made available on request.

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