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Solar energy integration in off-grid communities: empowering remote areas in Bangladesh for sustainable development

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Abstract

Global energy demand rises with population and economic growth. In Bangladesh, the fossil fuel-dependent grid fails to reach coastal areas, so solar home systems (SHSs) provide viable off-grid electrification, though their usage and challenges remain understudied. In this study, we utilized a questionnaire survey at the household level, Focus Group Discussions (FGD), and Key Informant Interviews (KII) with stakeholders to assess the utilization of solar energy, examine the influence of SHS on households' economic activities, and explore challenges in six coastal sub-districts in Bangladesh. Results reveal that 100% of households in the studied region rely on SHS for basic lighting, underscoring a universal need for this fundamental service. Access to electricity significantly enhanced social safety, disaster preparedness and living standard across the sub-districts. The utilization of solar energy had a positive influence on households' economic activities. Notably, 83% of SHS users reported an improvement in their economic well-being, leading to new ventures, including tailoring enterprises (58% of users), and poultry farming (42%). Adverse weather conditions (frequent foggy weather), negatively affected SHS performance, with 68–88% households reported. Concerns about environmental consequences were raised by 84% respondents in Cox's Bazar and 21% respondents in Noakhali. To address the challenges, households employ various strategies including prioritizing essential appliances, reducing working hours at night, and using alternative energy sources to overcome these obstacles. The study findings provide practical insights for policymakers, firms, and NGOs involved in promoting green energy and SHS initiatives for underserved populations. By building partnerships between local governments, microfinance institutions, and community members, policies can be tailored to address barriers such as affordability and accessibility, ultimately promoting greater adoption of SHS and other renewable energy solutions.

Keywords Coastal region · Disaster vulnerable community · Island · Solar energy · Solar home systems · Renewable energy

Abbreviations

FGD	Focus group discussion
GHG	Greenhouse gas
GW	Giga Watt
KII	Key informant interview

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NDC	Nationally Determined Contribution
NGO	Non-government Organization
PRA	Participatory Rural Appraisal
SHS	Solar home system
UDMC	Union Disaster management committee
%	Percentage

1 Introduction

Countries worldwide are already experiencing the effects of climate change, mainly because of burning fossil fuels [1]. Burning fossil fuels, mainly coal, oil, and natural gas, releases a lot of GHGs into the atmosphere, mainly carbon dioxide. Realizing this urgent concern on climate change, countries in the Paris Agreement have stipulated commitments to limit global warming well below 2 °C relative to pre-industrial times [1]. To achieve these goals, countries are increasingly adopting measures to reduce greenhouse gas emissions and to promote a transition towards low-carbon and renewable energy sources [2]. Reliable and sustainable energy sources are necessary to meet the increasing global needs, to drive economic growth, and to address environmental challenges [3]. The absence of energy resources is one of the major obstacles to the growth and development of peripheral areas in developing nations. Many rural areas in developing Asian countries currently lack access to electricity. The high costs of energy transmission and distribution in rural areas have left a large proportion of residential buildings unconnected to the national electric grid [4, 5]. In rural Bangladesh, which is home to almost 62% of the population, around 45% of people have access to electric power.

The primary driver of global electricity production is heavily dependent on finite fossil fuels supplemented by nuclear power, hydroelectric power, and a variety of renewable energy sources including solar and wind. Natural gas and coal-fired power plants have environmental and health hazards since they emit [6, 7]. It is also one of the major factors in the occurrence of global warming caused by the emission of carbon dioxide into the atmosphere. Solar energy is virtually unlimited and can help in stabilizing electricity prices while at the same time opening up a whole array of financial possibilities [8]. The total global solar photovoltaic (PV) capacity has grown rapidly, increasing from 70 gigawatts (GW) in 2011 to 942 GW by 2021 [9]. This amounts to approximately 3.7% of total power generation in 2021. The next few decades are expected to see significant development based on falling costs, policy-induced incentives, and efforts toward climate change mitigation.

Many governments have committed to increasing the use of renewable energy sources (e.g., solar, wind, and hydropower) in line with Sustainable Development Goal 7 (affordable and clean energy). However, the recent report (in 2020) of the United Nations Department of Economic and Social Affairs (UN DoESA) [10], reported that only 11% of the global energy supply is met by renewable energy sources, particularly solar and wind power. Given that global energy demand will increase by 50% by the middle of this century, thus there is a crucial need to increase access to clean and affordable energy. Bangladesh has established its Nationally Determined Contributions (NDCs) to lower GHG emissions by achieving a 5% unconditional reduction by 2030, with the possibility of increasing this target to 15% based on international support. In this regard, the NDC strategy identifies the massive role that solar energy could play in reducing emissions from energy-intensive industries through transition out of non-renewable sources.

In Bangladesh, privately-owned and government-operated power plants depend on the use of fossil fuels as their major energy source for generating electricity [11]. Based on the latest data from December 2022, the major source of electricity generation involves the use of carbon-emitting fuels that constitute about 93% of the total. Natural gas accounts for 52% of generation, followed by furnace oil at 27%, coal at 8%, and diesel at 6% [12] (Fig. 1). The supply of fossil fuels is not sufficient for demand. Bangladesh's gas production capacity cannot meet domestic needs or rising electricity generation demands [13]. This has predicted that the oil and gas reservoirs will be depleted by the year 2025; besides, increasing demand is rising for the exploitation of renewable, environment-friendly alternative energy sources. With over 35% of its population devoid of electricity, the Bangladesh renewable energy landscape is placing heavy emphasis on alternatives such as solar and biofuel for industrial and transportation systems [11], and health and education sectors [14]. Bangladesh has the advantage of abundant solar power due to its sub-tropical geographical location. Solar power, in this regard, is a reliable, economically feasible and secured energy source for the country [15]. Most of the people in Bangladesh live in the rural areas where power supply is in high demand. Solar power has great potential to be a key electric source for the country in the future.

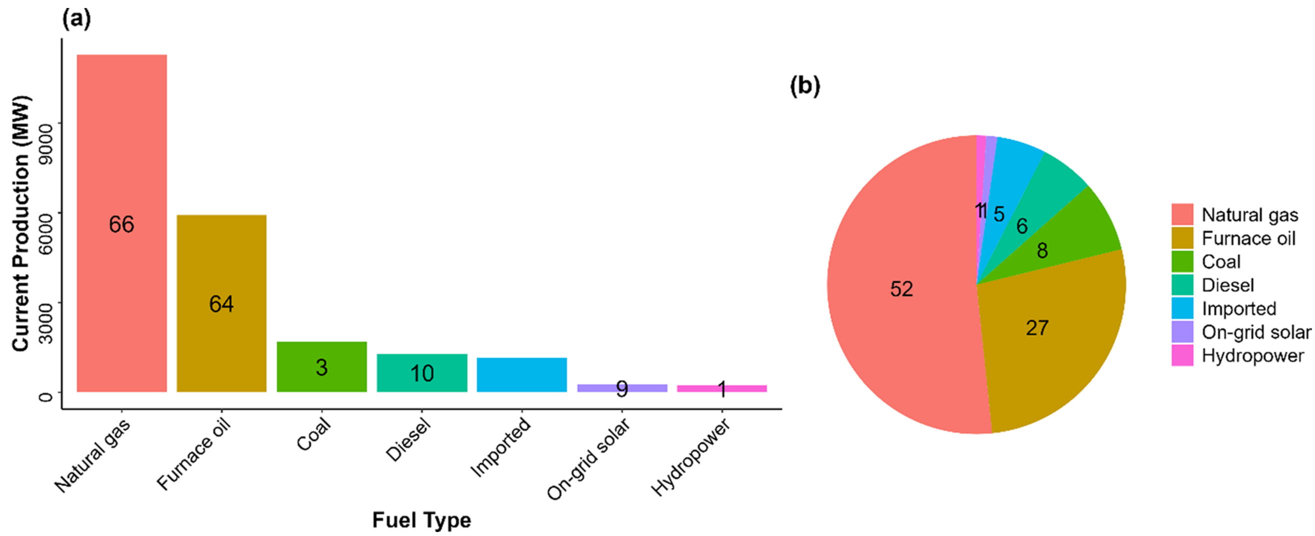

Fig. 1 Grid-connected electricity generation capacity (**a**), and the percentage contribution (**b**) to electricity generation from different sources of energy in Bangladesh as of December 11, 2022, according to the Progress Report (Draft December 2022) by the Bangladesh Power Development Board [12]. The values inside the bars indicate the number of power plants in Bangladesh which contribute to current electricity production

Considering the energy requirements of Bangladesh, SHS offers a financially viable solution for households without access to the main power grid, enabling them to obtain electricity for various electrical devices and lighting purposes [16]. According to the Bangladesh Bureau of Statistics [17], a significant proportion of the country's population, approximately 62%, resides in rural regions that lack complete integration with the centralised national electricity grid. The overwhelming bulk of the population, comprising 62%, resides in regions next to the coast. Most of the urban areas are usually connected to the national grids, but it can't be said to be true for their rural communities dwelling on exposed shores and remote islands, as geographical barriers impede on-grid power networks. The SHS meets the essential needs of families by addressing energy consumption. SHS-generated electricity is used to power low-energy devices such as lights, fans, radios, TVs, CD players, and cell phones. Solar energy has been viewed as one of the viable sources of electricity in remote areas of Bangladesh [18].

The SHS programme was introduced by the Infrastructure Development Company Limited (IDCOL) in January 2003 with the aim of providing essential electricity services, primarily targeting rural households in Bangladesh. The overarching objective of this effort is to ensure universal access to electricity for the whole population of Bangladesh by the year 2021 [19]. Recent research suggests a growing popularity of SHS in rural areas [20–23]. The positive impacts of solar energy on livelihood improvements [24], education [25], and healthcare [26] sectors have been reported in Bangladesh.

However, existing studies have predominantly concentrated on more populated regions, leaving a gap in understanding the implications of SHS in areas without access to the government's on-grid electricity supply (Table 1). For instance, Kabir et al. [22] examined the social consequences of SHS in a rural area within the Tangail district, while Khan and Azad [27] focused on the perceptions and socio-economic impacts of SHS in Gazipur district near the capital city, Dhaka. It is important to comprehensively assess the effects of off-grid electrification on the well-being and economic activities of individuals in areas without on-grid electricity, as the benefits of using both on-grid and off-grid energy sources may not be available to off-grid communities. Additionally, communities connected to the conventional power grid may not fully utilize the potential of off-grid solar energy due to the availability of on-grid electricity. Understanding the impact of SHS on households without on-grid electricity is crucial for policymakers aiming to develop off-grid solar power networks and promote a transition to renewable energy sources. This research will contribute to our scientific understanding of SHS usage, its effects, and challenges, specifically in areas lacking access to the government's on-grid electricity supply. It builds upon previous studies by Mondal and Klein [20], Kabir et al. [22], and Huq [21], which primarily focused on the impact of off-grid electrification in communities already connected to the government's on-grid electricity supply.

While some useful lessons can be learned from existing studies on SHS in Bangladesh, there are also some critical knowledge gaps. Much research targets densely populated urban areas, ignoring the unique challenges faced by isolated coastal areas with limited infrastructure and access to electricity. To address the identified research gap, this study uniquely focuses on households without access to on-grid electricity, contrasting with previous works such as Huq

Table 1 Previous research on solar home systems (SHSs) conducted in Bangladesh

No	Reference	Objectives	Methodology	Key findings
1	Huq [21]	Explore the growth of SHS in the southwest coastal region of Bangladesh and examine how SHS users are benefitting from enhanced livelihood	In-depth individual interview, focus group discussion and household survey	As of June 2017, 262,515 households have SHSs, from which an estimated 1.6 million people benefitted
2	Mondal [4]	Assess the economic sustainability of the SHS in the rural areas in Gazipur district	Questionnaire survey and case story	SHS is financially attractive for small rural businesses and household lighting with entertainment. Without considering the social benefits, the system of using SHS solely for household lighting purposes is not financially and economically feasible
3	Mondal and Klein [20]	Evaluate the impacts of SHSs application on selected villages in the Gazipur district	Questionnaire survey	The users of SHSs experienced both direct and indirect advantages because of adopting the technology
4	Asaduzzaman et al. [13]	Assessing various impacts (direct and indirect) of SHSs on the households	Household survey and simulation analysis	Better education in technology user groups compared to non-user groups. The food security of the technology users is much higher compared to non-users
5	Khan and Azad [27]	Assessment of socio-economic impact and sustainable development of the SHS users in rural areas	Questionnaire survey	The introduction of SHS in rural Bangladesh has resulted in positive effects, particularly in education, communication, healthcare, and social safety
6	Kabir et al. [22]	Ascertain the impacts of SHSs on the lives of the rural population in Tangail district	Questionnaire survey	Installing an SHS enhanced the quality of life and living conditions for rural residents. Improved accessibility to television, radio, cellphones, and the Internet enabled the rural population to engage with a more globalized culture
7	Khan [19]	Provide insight into a functional prosumer-based renewable off-grid direct electricity network	Meta-analysis	Renewable off-grid energy has the potential to enhance overall well-being and foster a stronger socioeconomic consciousness in underdeveloped nations such as Bangladesh
8	Khan [16]	Assessment of impacts, drivers, and barriers of solar electricity Identification of social, economic, and environmental impacts of SHS adoption	Literature review and energy culture framework	Drivers of SHS adoption are dominated by the 'cognitive norms' of the adopters
9	Hossain and Rahman [42]	Evaluate the status of Bangladesh regarding the utilization of renewable energy resources, specifically solar energy	Literature review	Approximately 30% of the rural population still lacks access to grid electricity. This energy shortage can be alleviated by generating electricity from renewable sources (solar energy)
10	Saim and Khan [23]	Aim to problematize SHS as a solution in the rural areas of a remote island	Literature review and questionnaire survey	The primary benefits that households derive from SHSs are predominantly related to nighttime illumination, with 83% of households experiencing this advantage

Table 1 (continued)

No	Reference	Objectives	Methodology	Key findings
11	Ahmed et al. [26]	Explore the possible use of a hybridized energy system (i.e., solar, wind, and diesel) with battery storage in northern region	Multivariate linear regression	Compared to kerosene-based lighting and grid-connected power, the upgraded system has effectively decreased operational CO_2 emissions
12	Hossain et al. [5]	Assess the (i) utilization of solar energy for diverse activities and (ii) influence of SHS on the lives and livelihoods of households in the coastal region	Household survey, focus group discussion, and key informant interview	The most cited impact on community's lives was the enhancement of social security

[21] and Kabir et al. [22], which primarily examined the impacts of SHS in communities connected to the conventional power grid. While prior research has highlighted the benefits of SHS for enhancing livelihoods and social well-being in electrified areas, there remains a critical need to understand the specific challenges and advantages faced by off-grid households. The earlier literature [20–22] on SHS has often indicated benefits such as increased ability to afford education and food, but comprehensive assessment of its direct and indirect impacts on the quality of life and economic activities of the households is lacking. Some research has looked at SHS adoption drivers, but there is a lack of focus on the specific obstacles coastal communities face, such as economic barriers, technical challenges, and cultural perceptions. Additionally, existing studies typically examine SHS impacts without addressing their long-term effects on resilience and community dynamics amid recurring natural disasters and climate change. Addressing these gaps is therefore important to understand the SHS impact on energy access and livelihoods in the challenged communities of Bangladesh. Three questions were considered, underpinning SHS potential in transforming energy access and building resilience in the most vulnerable areas.

1) What is the usage of SHS in geographically isolated coastal regions of Bangladesh?
2) How does the implementation of SHS affect the quality of life and economic activities of households?
3) What obstacles do coastal communities face in adopting SHS?

To conduct a comprehensive analysis of the impacts of off-grid SHS on the welfare and economic activities of communities, as well as the challenges they face in using SHS, we have selected six coastal districts in Bangladesh: Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar. These districts have experienced a significant loss of cultivable land, as 38% of the land has been affected by riverbank erosion over the past three decades [28]. Moreover, these regions are known to experience some of the worst natural disasters, such as that caused by the Bhola cyclone in 1970, which had an estimated death toll of over 300,000 people [29, 30]. The communities residing in these areas have become increasingly vulnerable due to the frequent occurrence and intensification of tropical cyclones and tidal surges. Notable examples include Sidr in 2007, Aila in 2009, Bulbul in 2019, Yass in 2021, and Sitrang in 2022 [31–35]. People of these areas have conventionally depended on diesel generators and kerosene (propane) lamps for their energy requirements. In recent past years, the introduction of SHS brought an alternative way of electrification to these off-grid societies. As such, due to their geographical locations, susceptibility to natural disasters, and poor accessibility to the centralized power grid, there is an imperative need to understand how households in these areas perceive the use of SHS, what impacts its use has had on them, and the barriers that they experience while using this source of sustainable energy.

To address the research questions, we established the following three objectives: (i) to examine the usage of SHS in geographically isolated coastal regions, (ii) to analyse the effects of SHS on the quality of life and economic activities of households, and (iii) to identify the obstacles faced by coastal communities in adopting SHS.

Understanding how SHS is applied in the geographically isolated coastal regions helps to come up with effective deployment strategies. Coastal areas have unique challenges, such as limited infrastructure and natural disasters, which may affect the effectiveness of the solar energy solution. The study can, therefore, provide insights on best practices and context-specific adaptations that improve the utility of SHS through the examination of actual use. It is relevant to assess the impact of SHS on the quality of life and economic activities to understand the overall value of solar energy solutions. Access to reliable electricity can obviously improve living conditions, enhance educational opportunities, and provide facilitation to small businesses. Identifying the barriers to the adoption of SHS is very crucial in formulating strategies aimed at promoting their wide application. The challenges that coastal communities may face, regarding affordability, maintenance, technical knowledge, and cultural acceptance, should be surmounted. Identification of these barriers is important, as the study could then inform policymakers and implementers about necessary interventions to overcome these barriers, ensuring the successful implementation and long-term sustainability of SHS initiatives.

The present study has added a new dimension to the existing studies on applications, impacts, and issues of the use of SHSs, particularly in the geographically isolated coastal areas of Bangladesh. This has brought into focus some of the specific challenges and opportunities regarding implementing SHS in far-flung, climate-change-vulnerable areas that have limited access to conventional sources of energy. This is, therefore, a significant study for Bangladesh with a large population that faces socio-economic vulnerabilities along the coasts and at climate change risks. Through in-depth interviews and focus group discussions, we capture rich qualitative data that reveals the nuanced impacts of SHS on well-being, economic activities, and social dynamics in these underserved areas. This combination of qualitative methods and geographical specificity not only enhances the depth of our findings but also provides critical context for policymakers and stakeholders looking to develop targeted interventions. By illuminating the lived experiences of off-grid households, our research aims to inform more effective strategies for promoting renewable energy adoption and improving the quality of life in isolated communities.

2 Materials and methods

2.1 Study area

For this study, we specifically chose 12 unions, which are the smallest administrative units, from six sub-districts (Patharghata, Kalapara, Charfasson, Hatiya, Sandwip, and Kutubdia) belong to six districts (Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar) in Bangladesh. We considered one sub-district from each district. The rationale for selecting these sub-districts is based on their geographic vulnerability. The selected sub-districts in the central and eastern coastal regions of Bangladesh are the most exposed areas to the Bay of Bengal (Fig. 2). To ensure a representative sample, we selected two unions from each sub-district, resulting in a total of 12 unions included in the study (Fig. 2). Coastal communities in these sub-districts are particularly susceptible to the adverse impacts of climate change, including sea-level rise, storm surges, and increased frequency and intensity of extreme weather events [36–38]. By covering unions from six different sub-districts, we aimed to explore the geographical variability in the usage, challenges, and economic impacts of SHS. This design not only enhances the validity of our findings but also provides a framework that can be replicated in similar contexts to assess the impacts of SHS on coastal communities worldwide.

2.2 Ethical considerations

The necessary consent was received from the research ethics board affiliated with the Centre for Coastal Development in Bangladesh (CCD-ResP-2022/04-162(2)). We adhered to the ethical guidelines for the involvement of human beings as outlined in the Declaration of Helsinki by the World Medical Association. The individuals chosen as respondents for the household survey, FGD, and KII were informed about the aims of the study. The participants were additionally assured that their viewpoints, data, and apprehensions would be treated with confidentiality and anonymity, ensuring that their personal information would not be disclosed for the purposes of reporting and analysis. The research was conducted in accordance with ethical principles for the protection of human participants, which encompassed considerations such as upholding human dignity and minimizing the collection of personal data. The written consent was obtained from the participants of the household surveys, and KIIs and FGDs.

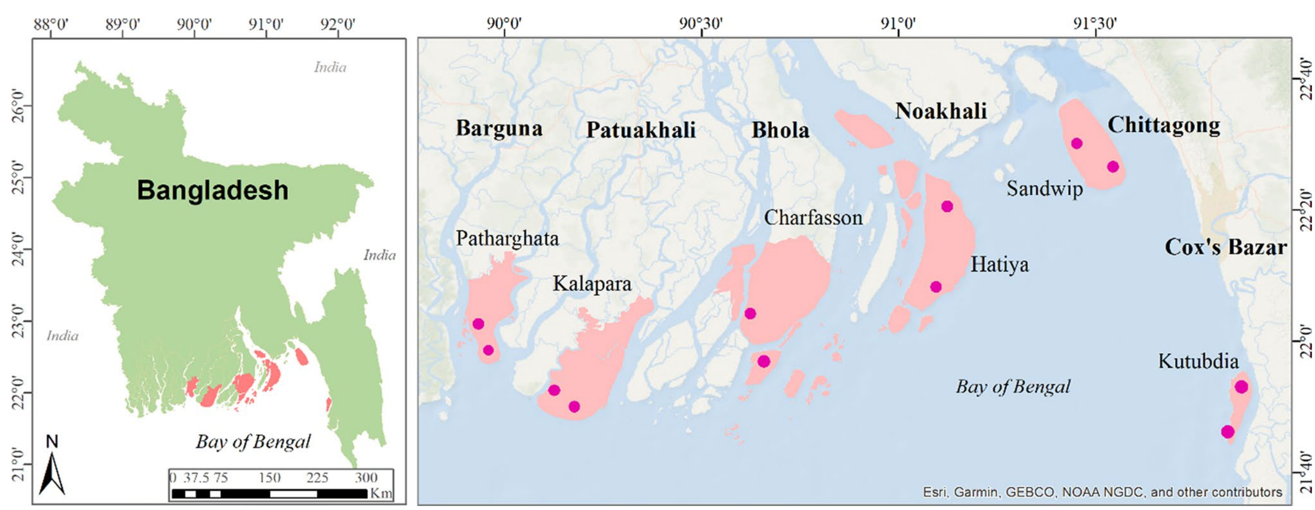

Fig. 2 Location map of the study areas (12 unions) under six exposed sub-districts (Patharghata, Kalapara, Charfasson, Hatiya, Sandwip and Kutubdia) across six districts (Barguna, Patuakhali, Bhola, Noakhali, Chittagong and Cox's Bazar), situated in the central and eastern coastal regions of Bangladesh

2.3 Sampling criteria

Household sampling criteria To ensure a representative sample for the household survey, we established criteria for selecting participants. Households were included based on their engagement with SHS, specifically focusing on those that had installed SHS. To enhance validity of our results, we divided households into those that have used the system for a period of over one year and less than one year. A random sample of 434 households from an approved list of SHS users was provided, with the help of local government and NGOs so that representation of the sampled households could be carried out accordingly.

Focus Group Discussion (FGD) Members for FGDs were selected with due consideration to ensure they represent a wide variety of professional fields and peoples working at different levels within the community. This included businessmen, agriculture workers, fishermen, and educators to make sure that there was good representation of perspectives regarding the use of SHS. In addition, local authorities and representatives of relevant sectors, such as agricultural officers and staff involved in disaster management, have been added to FGDs to help the discussion through their experiences of being active actors of development at the community level and/or renewable energy.

Key Informant Interview (KII) The KIIs were designed to extract detailed insights from knowledgeable individuals with expertise in solar energy-related topics. These are key informants who play active roles within the local context-for example, Union Parishad Chairmen, members involved with disaster management committees, NGO representatives involved in solar assistance initiatives-which ensure that variegated knowledge, perception, and experiences of a wide variety of stakeholders are considered for holistic analysis of challenges, barriers, and facilitative opportunities regarding the implementation of SHS.

2.4 Sampling design and data collection

Given the large geographical coverage in our studied districts, we employed systematic sampling to select the study unions (smallest administrative unit). We applied a set of criteria for selecting the 12 unions (2 in each district) from the most exposed coastal sub-districts in respective district. Firstly, we considered the unions with limited access to an on-grid power network. Secondly, we focused on the unions located in areas more exposed to the River and Bay of Bengal. Thirdly, we selected unions that were highly vulnerable to natural disasters, including tropical cyclones, storm surges, floods, riverbank erosion, and water and soil salinity. Lastly, we consulted with elected representatives and the disaster management committee for further input. Through this systematic sampling approach, we identified 12 unions from the coastal regions of Bangladesh. This systematic sampling method ensured that we selected unions from the coastal regions of Bangladesh that are particularly underserved, where on-grid electricity supply is often limited or non-existent. By covering unions from six different sub-districts, we sought to capture the comprehensive scenario and challenges faced by these underserved coastal communities, who are particularly vulnerable to the adverse effects of natural disasters, climate change, and sea level rise.

In this study, the qualitative and quantitative data was collected between 17 January and 4 July 2023 (Fig. 3). Collection of quantitative data at the household level was done by administering a semi-structured questionnaire, which is included as supplementary information SI 1. We also carried out qualitative questionnaires with a diverse range of participants comprising community people, government officials and staff, elected representatives, business community representatives, and personnel from NGOs. The combination of quantitative and qualitative methods of data collection allowed us to comprehensively understand the selected unions and the experience they had.

Quantitative data To gather quantitative data at the household level, we employed a semi-structured questionnaire survey, as presented in Supplementary Information (SI) 1. The questionnaire consists of 24 questions that are carefully prepared with regard to realizing the objectives of this study. It focused on several dimensions relating to the use of solar energy, the consequences on life and livelihood because of the usage of the energy, and the challenges encountered while implementing SHS. Preliminary information to identify the users of the SHS was obtained from Union Parishad, a local governmental administrative organ along with local nongovernmental organizations who are directly involved in the SHS activities.

At the outset, a total of 434 homes were picked randomly from the pool of engaged SHS users for the purpose of conducting a questionnaire survey (Table 2). The purpose of our household survey is to evaluate the various applications, effects, and difficulties related to SHS. Consequently, we have chosen to separate the 58 households

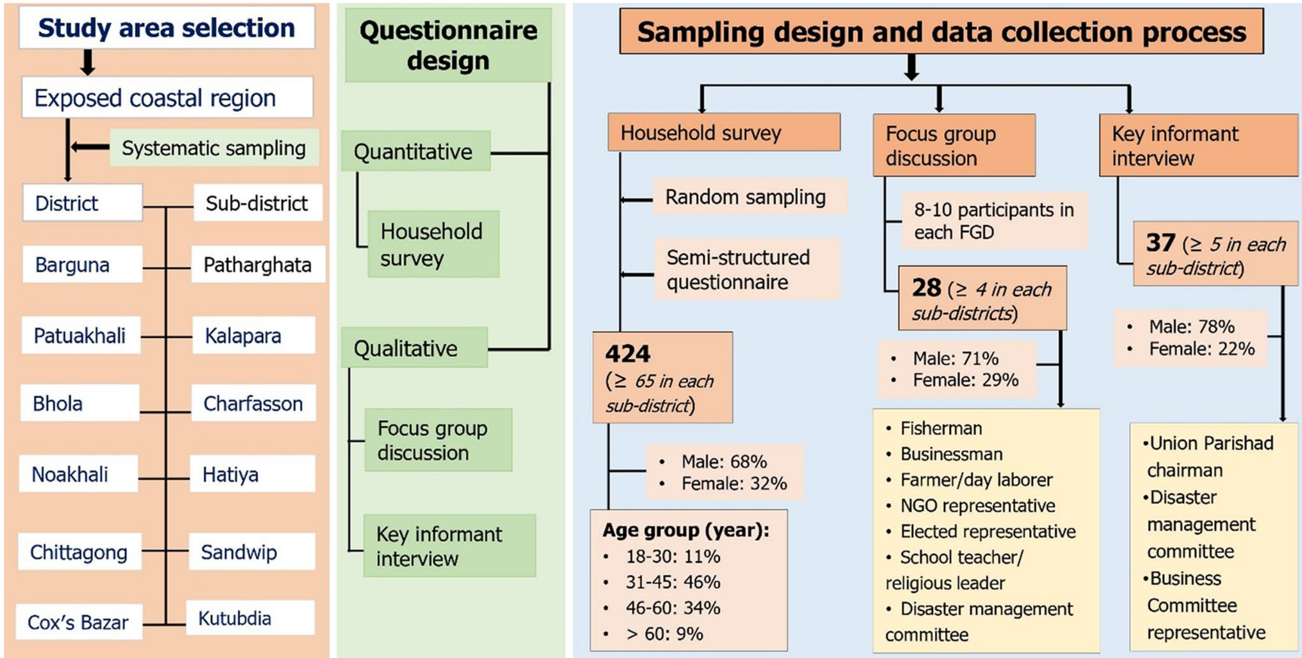

Fig. 3 The working methods and materials applied for conducting quantitative (household survey) and qualitative (focus group discussion and key informant interview) studies along with demographic information of the respondents in the six sub-districts in coastal Bangladesh. The questionnaires for household surveys, focus group discussions and key informant interviews are provided in the supplementary materials (SI 1–3). The distribution of the respondents in both quantitative and qualitative samples is shown in Table 2. The socio-economic profile (income, age and education) of the respondents from the household surveys is given in Table 3

Table 2 Distribution of quantitative samples at the household level and qualitative samples (focus group discussion [FGD] and key informant interview [KII]) at the sub-district level under 6 districts in the coastal region in Bangladesh

District	Sub-district	No. of household	No. of FGD	No. of KII
Barguna	Patharghata	69	4	6
Patuakhali	Kalapara	65	4	5
Bhola	Charfasson	75	5	7
Noakhali	Hatiya	73	6	8
Chittagong	Sandwip	68	5	5
Cox's Bazar	Kutubdia	74	4	6
Total		424	28	37

that installed SHS within a period of less than 1 year, as these households may not have encountered any obstacles linked with SHS. Subsequently, data was gathered from the designated 364 households, and 58 households who have installed SHSs within < 1 year. The data of the remaining 12 households was eliminated due to incomplete or missing information. The sampling intensity is deemed appropriate for conducting a quantitative analysis, considering the relatively smaller number of SHSs in these unions.

At the household level, we initially provided a comprehensive overview of the study and obtained informed consent from the households to partake in the survey. Subsequently, we proceeded to inquire using a pre-established questionnaire that had undergone a rigorous process of piloting, modification, and validation prior to data collection. The questionnaire was initially presented in Bengali format. Following the completion of household surveys, we proceeded to translate the questionnaire into English. The utilization of quantitative data in this study served to enhance and corroborate the findings and insights obtained from the qualitative analysis.

Qualitative data For completeness and details, we conducted a qualitative assessment parallel to the household questionnaire. We consulted with government departments, village leaders, traders, and any other key informants. We collected the data qualitatively using several Participatory Rural Appraisal (PRA) tools. These included FGDs and KIIs. FGDs are discussions carried out in groups to obtain information, opinion, and experience of the people in the community. KIIs were conducted with key persons possessing valued knowledge and expertise in matters that respond to the objectives of the study. The subsequent section provides a comprehensive account of the data collection process utilising FGD and KII, as well as the allocation of the sample or respondents within these two methodologies.

Focus Group Discussion To gain a comprehensive comprehension of current practices in the field of SHS, as well as to ascertain individuals' perspectives and apprehensions regarding the consumption of solar energy, a series of FGD were conducted with a cohort of participants. This approach has proven to be successful in revealing individuals' viewpoints and attitudes, as well as in highlighting significant concerns and obtaining recommendations from intentionally chosen members of the community [39]. A total of 28 FGDs were conducted in six sub-districts (Fig. 3, Table 2). Each FGD consisted of 8 to 10 participants. The FGD comprised a diverse range of participants, encompassing individuals from various professional backgrounds such as business, agriculture, fishing, and education. Additionally, the FGD featured representatives from governmental positions, including an agriculture officer and an elected ward member. Furthermore, the FGD incorporated perspectives from individuals involved in disaster management, healthcare, and NGOs. To acquire the necessary information, we made efforts to ensure the inclusion of a diverse range of occupations among the participants selected for the FGD.

Prior to conducting the FGD, a comprehensive overview of the FGD process and the intended utilization of the study findings was provided to the participants. The discussion was aided by employing a series of questionnaires, and comprehensive notes were taken in the Bengali language. Each FGD had a duration of one hour. The FGD was comprised of three distinct components. In the first component, participants stated their personal details, encompassing age, gender, and household particulars. Section 2 of the document provided an overview of SHS, encompassing its associated expenses, applications, and effects. In the final section, the issues associated with the consumption of solar energy were examined through the formulation of several inquiries pertaining to energy.

Key Informant Interview The utilization of the KII is a crucial method for acquiring a comprehensive understanding pertaining to a specific establishment. Key informants were identified based on their competency and readiness to provide information on solar energy-related topics within the 12 selected unions in the six sub-districts (Fig. 3). In this study, a total of 37 KIIs were conducted to gather valuable insights and perspectives. We interviewed 37 individuals representing various stakeholders, including Union Parishad Chairmen, members of the disaster management committee, representatives from the business committee, sub-assistant agriculture officers, and representatives from NGOs involved in solar assistance interventions (Fig. 3). To collect relevant data on the challenges, barriers, and prospects associated with solar energy in the study area, we utilized a questionnaire (SI 3). During the interviews, we actively facilitated the process and took notes to ensure accurate documentation of the information provided. Like the household survey and FGDs, the interviews were conducted in Bengali to ensure effective communication and understanding with the participants.

2.5 Data analysis

The quantitative data analysis of the household survey involved the application of descriptive and statistical methods. A summative content analysis approach was utilized to analyze the qualitative data obtained from the KIIs and FGDs. Summative content analysis involves identifying and quantifying specific words or content within a script to gain a comprehensive understanding of their contextual usage [40]. In the qualitative components, we manually searched for selected words related to various aspects of SHS use, including lighting, income generation, charging, night-time education, and more.

We also examined the impacts of SHS, such as safety, disaster response, school attendance, communication, and economic benefits. To assess the impacts of SHS, the collected information (based on 10 questions) of household survey (Supplementary Information SI-1) was processed. These questions were designed to gather information regarding the benefits of SHS use, the influence of SHS on the family, the impact on children's education, the utilization of solar energy for alternative income generation, the involvement of women in income-generating activities associated with solar energy, the number of solar-powered electric appliances in the household, the previous sources of nightlight before SHS installation, a comparison of the advantages and disadvantages of earlier and current energy sources, and the need for other energy sources such as kerosene lamps or candles and associated expenditure. By quantifying and analyzing the responses, we were able to derive numerical indicators and metrics that provided a measure of the impacts of solar energy on respondents' livelihoods. By analyzing the responses to these questions, we assessed the varied impacts of SHS on households, including improvements in quality of life, enhanced educational opportunities, potential income generation, gender dynamics, appliance ownership, and the shift from traditional energy sources to cleaner and more reliable solar energy.

Additionally, we identified challenges associated with using SHS, such as adverse weather conditions, installation costs, installment payments, repair time and expenses, environmental pollution, and health risks. The frequency of each identified term was calculated, and the source or speaker was noted. These frequencies were then graphed according to three main themes: usage, impacts, and problems. Given the various challenges reported by the substantial number of households across the sub-districts, we further documented the strategies taken by these households for overcoming these challenges. To achieve this, we utilized the 'wordcloud' package in the statistical software R [41]. Based on the frequency of the mentioned strategies, we created a word cloud to visually represent the most prominent strategies that households adopt to address their challenges.

Using a one-way ANOVA, we evaluated the significance of differences of various usage, impacts, and challenges. We employed boxplots to illustrate the percentage of households for each category of SHS usage, impacts, and challenges. Additionally, we created bar plots to represent the percentage of households within each category for SHS usage, impact, and challenges in respective sub-districts. Finally, we utilized one-way ANOVA to compare the significant differences in SHS impacts among the six districts. The research area map was created using ArcMap 10.4, while the boxplots and bar charts were generated using the statistical software R version 4.0.3 [41].

3 Results and discussions

3.1 Households' socio-economic profile

The results show the major occupation of the household in six districts (Fig. 4). In Barguna, fishing was the major activity which comprised 38.7% of the economic activities of the district, while agriculture comprised 27.4%. Similarly, Patuakhali also shows a high dependency on fisheries as it comprised 48.3% of its economic activities, while agriculture comprised 21.7%. The agricultural activities in Bhola weighed 31% of the economic engagement besides a sizeable 43.7% in fishing. Noakhali exhibited a similar pattern, with agriculture contributing 39.1% and fishing 32.8% of its economic activities. On the other hand, Chittagong had a dominant fishing sector that comprised 52.5% and agriculture comprised 29.5% of its economic activities. Finally, Cox's Bazar relied mostly on fisheries, making up 51.7% of its activities, while agriculture consisted of 20% (Fig. 4).

Across the districts, the distribution of respondents' income levels revealed variations (Table 3). In Barguna, many respondents (45.16%) fell within the $100–$200/month income range, while in Patuakhali, the largest proportion (64.81%) belonged to the same income range. Bhola exhibited a similar pattern, with 49.28% falling within the $100–$200/month range. Notably, the income distribution in Chittagong skewed towards the $100–$200/month range (64.41%), while Cox's Bazar had a relatively higher proportion (37.93%) within the $200–$300/month range. In general, the highest income range above $300/month was observed in Noakhali (14.52%) (Table 3).

The age composition of respondents varied across the districts (Table 3). In Barguna, the largest age group was 31–45 years (59.68%), while in Patuakhali, respondents were relatively more evenly distributed among the age groups, with 31–45 years as the largest group (40.74%). Bhola also demonstrated a similar pattern, with the 31–45 years age group being the most prevalent (49.28%). In Noakhali, the age distribution was relatively balanced, with the 31–45 years

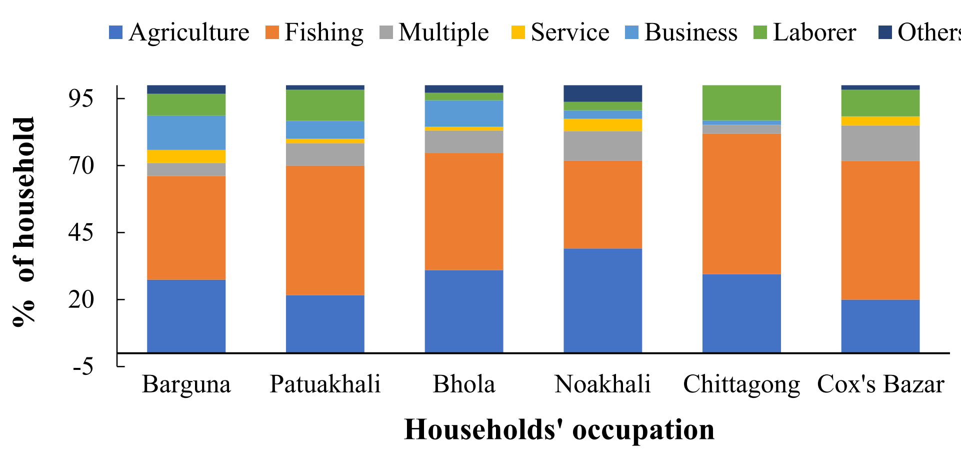

Fig. 4 The main occupation of the studied households in six coastal districts

Table 3 Socio-economic profile (income, age and education) of the household survey respondents in Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar districts

Socio-Economic Profile	Barguna (%)	Patuakhali (%)	Bhola (%)	Noakhali (%)	Chittagong (%)	Cox's Bazar (%)
Income level						
Less than $100/month	17.74	9.26	14.49	12.90	3.39	10.34
$100—$200/month	45.16	64.81	49.28	41.94	64.41	44.83
$200—$300/month	27.42	18.52	30.43	30.65	27.12	37.93
Above $300/month	9.68	7.41	5.80	14.52	5.08	6.90
Age group						
18–30	6.45	24.07	4.35	11.29	6.78	15.52
31–45	59.68	40.74	49.28	50.00	40.68	36.21
46–60	27.42	33.33	34.78	29.03	49.15	31.03
Above 60	6.45	1.85	11.59	9.68	3.39	17.24
Education level						
No formal education	17.74	27.78	26.09	33.87	18.64	25.86
Primary education	69.35	53.70	52.17	46.77	57.63	51.72
Secondary education	9.68	12.96	18.84	11.29	18.64	17.24
Higher education	3.23	5.56	2.90	8.06	5.08	5.17

The percentages represent the proportion of respondents falling into each category within each district.

age group representing the largest proportion (50.00%). Chittagong exhibited a higher proportion of respondents in the 46–60 years age group (49.15%), while Cox's Bazar had a more significant representation of respondents above 60 years (17.24%) (Table 3).

The educational attainment of respondents also varied across the districts (Table 3). In Barguna and Patuakhali, most respondents had primary education (69.35% and 53.70%, respectively). Bhola also had a substantial number of respondents with primary education (52.17%). Noakhali had the highest proportion of respondents with no formal education (33.87%), while Chittagong and Cox's Bazar had a relatively higher percentage of respondents with primary education (57.63% and 51.72%, respectively). The percentage of respondents with higher education was relatively low across all districts, ranging from 2.90% in Bhola to 8.06% in Noakhali (Table 3).

3.2 Use of solar energy

The analysis of electricity usage reported by the participants in the coastal areas of Bangladesh revealed interesting insights into the socio-economic dynamics and energy needs of these communities. Across all study areas, 100% of households relied on electricity for lighting, indicating a universal need for basic lighting (Fig. 5). The percentage of households using electricity for charging devices varied, ranging from 85% in Barguna to 100% in Cox's Bazar. This highlights the widespread reliance on electricity for charging devices, with Cox's Bazar having the highest dependence. Electricity usage for studying reported by the participants ranged from 71% in Patuakhali to 88% in Cox's Bazar. While many households in all areas utilized electricity for studying, Cox's Bazar exhibited the highest reliance on electricity for educational purposes.

The percentage of participants using electricity for entertainment activities varied, ranging from 37% in Bhola to 82% in Cox's Bazar. Cox's Bazar demonstrated the highest engagement in entertainment activities requiring electricity, while Bhola had the lowest. Involvement in shop-keeping activities requiring electricity varied, ranging from 17% in Bhola to 54% in Cox's Bazar. The percentage of participants engaged in tailoring and utilizing electricity ranged from 8% in Bhola to 24% in Patuakhali and Cox's Bazar. The involvement of households in poultry farming activities requiring electricity varied, ranging from 6% in Barguna to 18% in Cox's Bazar. The electricity usage in fish farming reported by the participants ranged from 16% in Patuakhali to 58% in Chittagong. Patuakhali had the highest reliance on electricity usage for irrigation, while Bhola had the lowest (Fig. 5).

The study found that the electricity usages reported by the participants varied significantly ($p < 0.01$, Fig. 6) and majority of the participants reported that their solar energy is primarily used for lighting, charging, and studying purposes (Fig. 6). Additionally, it is employed in fish farming, entertainment, small-scale businesses (such as shops and tailoring),

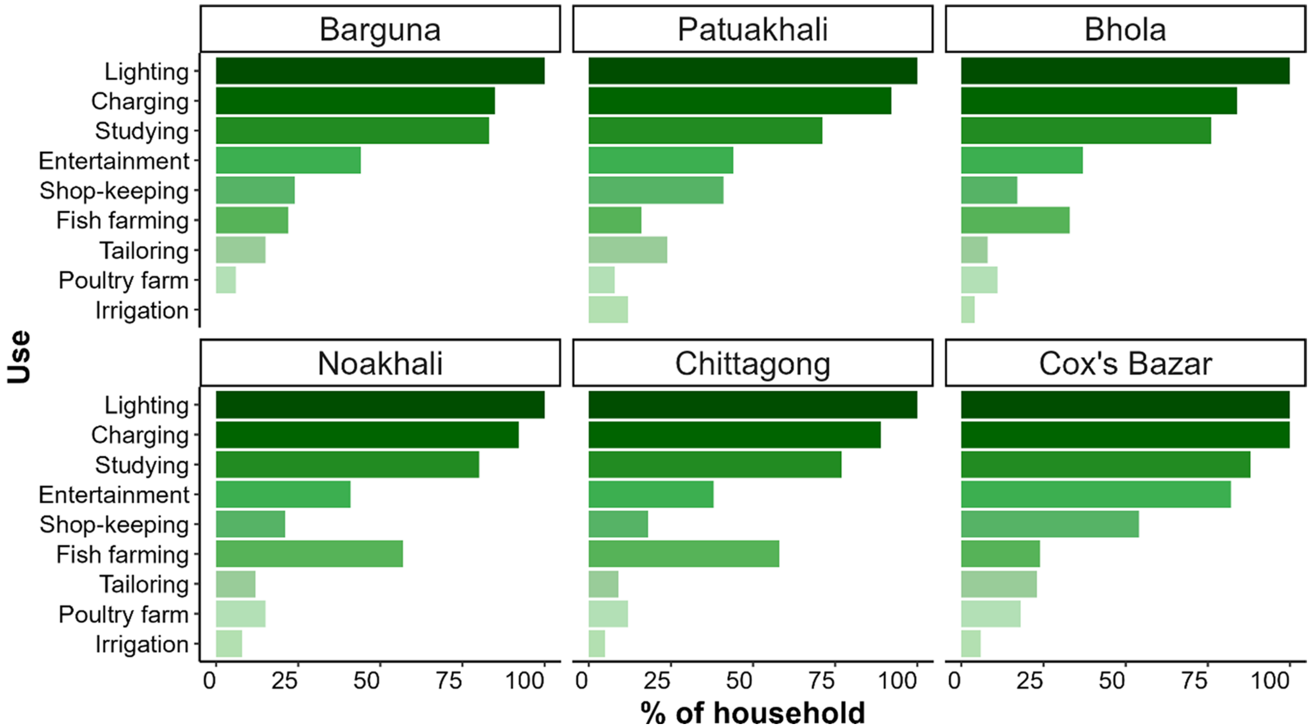

Fig. 5 Electricity usage for multiple purposes reported by the participants in Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar districts in Bangladesh

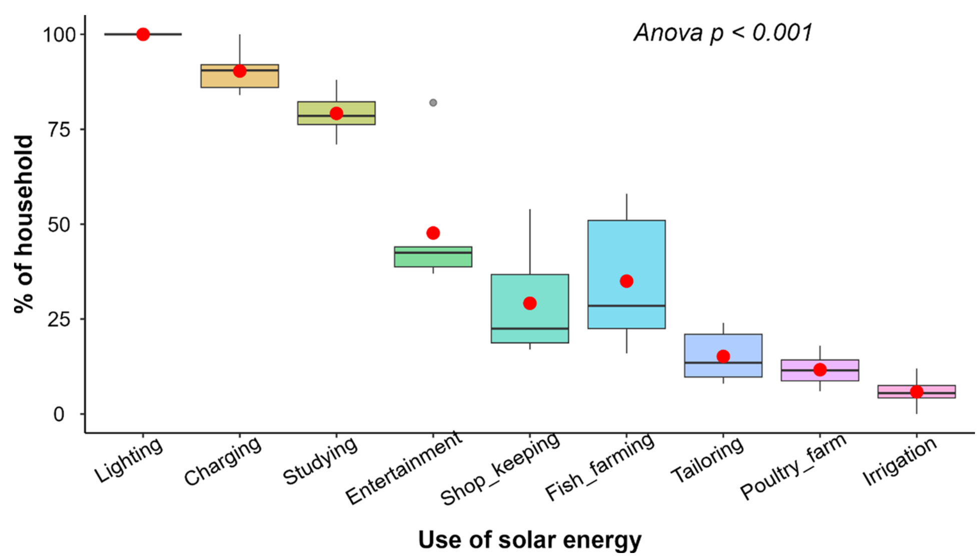

Fig. 6 Solar energy utilization for multiple purposes reported by the participants in all 6 districts in Bangladesh. The red circles inside the boxes represent the mean percentage of households using solar energy. The horizontal solid lines within the boxes indicate the median percentage of households using solar energy. The *p*-value ($p < 0.001$) shown in the plot denotes a significant difference in solar energy usage across the studied districts. The outliers are represented by grey circles

poultry farming, and irrigation. These diverse applications highlight the versatility and socio-economic benefits of solar energy in the communities studied.

The findings of solar energy usage reveal several noteworthy trends and variations across different study areas. Firstly, lighting remains an undisputed necessity in all the households, with 100% relying on electricity for just this very basic need. In this respect, electricity stands out as a vital component in providing light and thus meeting one of the key needs within these communities. Results also show that gadgets are charged with heavy reliance on electricity at all sites, but with varying percentages. A big portion of households in all regions use electricity during educational activities.

LED lighting is considered superior in terms of quality and convenience. Solar lighting systems extend working hours in rural communities, boosting productivity and economic activities. Illumination is crucial for study, household work, comfort, and security. Our study supports the findings of Kabir et al. [22], who reported that 64% of respondents indicated that lighting was the main factor influencing their decision to choose SHS. The disparity in the percentage of SHS between the study of Kabir et al. [22] and our findings may be attributed to several causes, including but not limited to differences in study location, accessibility of other sources of energy, socio-economic status, and the impact of exogenous shocks like natural calamities. Kabir et al. [22] concentrate on the Ghatail sub-district within the Tangail district, which is connected to the on-grid electricity network, whereas our study locations are situated in coastal areas characterized by restricted or limited access to this on-grid supply. In disaster-prone coastal areas, power is often intentionally shut down, making SHS essential for consistent lighting during calamities. SHSs are crucial for household tasks, sustaining commercial operations, and facilitating education [5, 42]. Due to limited alternative power sources, coastal marketplaces rely on diesel generators for 4–6 h. SHSs are also used for commercial purposes and recreational activities, including television usage. Our study aligns with Huq's study [21] in the southwest coastal region of Bangladesh, which found similar SHS usage for commercial activities and recreation. Our content analysis also revealed higher frequencies of words like 'charging,' 'entertainment,' 'lighting,' and 'shopkeeping' compared to 'studying' and 'irrigation' across sub-districts, consistent with the household survey results.

Entertainment activities vary across the study areas, with Cox's Bazar having the highest engagement and Bhola the lowest. This suggests differences in access to entertainment devices and the level of entertainment-related activities. Shop-keeping activities also vary, with Cox's Bazar having the highest percentage of households engaged in such activities, indicating more commercial and business activities in that area. Tailoring activities involving electricity show relatively lower involvement across all study areas, with Patuakhali and Cox's Bazar showing similar levels of participation and Bhola having the lowest engagement. The use of solar energy for these economic activities in our study is also evident in several other studies in rural Bangladesh [21, 23, 26, 27].

Poultry farming activities requiring electricity vary across areas, with Cox's Bazar having the highest engagement. This highlights the importance of electricity in supporting poultry farming practices and suggests potential economic opportunities in this sector in Cox's Bazar. Similar findings were observed in a recent study in Khulna and Bhola districts [5], which reported that poultry farming is emerging in coastal communities because of the accessibility of required electricity from solar power. Fish farming activities requiring electricity also display significant variation, with Chittagong showing the highest involvement and Patuakhali the lowest. This indicates the influence of geographical factors and local industry dynamics on the adoption of electricity for fish farming. Lastly, the percentage of households requiring electricity for irrigation is relatively low across all areas, with Patuakhali having the highest reliance. This suggests that irrigation practices in these areas may still mainly rely on traditional methods rather than electricity-powered systems.

3.3 Impacts of solar energy on lives and livelihoods

3.3.1 Impacts of solar energy on social safety and education

The study's results demonstrate the significant impact of electricity access on various aspects of socio-economic development in the coastal areas of Bangladesh (Figs. 7, 8 and 9). The impacts of SHS on the lives and livelihoods of the studied households among the six districts varied significantly for all socio-economic and health aspects (all $p < 0.05$, Fig. 7). In all the districts studied, access to electricity contributes to social safety, education, better management of disasters, and communication (Figs. 8 and 9). The significant contribution to improvement in social safety is greatly recognized by 94% of households in Barguna and 100% in Noakhali. It indicates how important electricity is in making people feel safer and allowing them to react properly in the case of an emergency in these villages. Access to electricity brings benefits in education, as evidenced through positive impacts across all districts of the survey area, ranging from 52% in Patuakhali to 76% in Cox's Bazar (Fig. 8), reflecting the importance of electricity in easing educational pursuits and thus improving learning outcomes.

3.3.2 Impacts of solar energy on disaster response, communication and health

Disaster response was significantly facilitated by electricity, as seen in high percentages across the study areas. This includes 67% in Barguna, 65% in Patuakhali, and 100% in Chittagong and Cox's Bazar. Reliable access to electricity enables better preparedness and response during natural disasters. Communication was greatly enhanced with electricity, contributing to improved connectivity and access to information (Fig. 9). High percentages were reported in all areas,

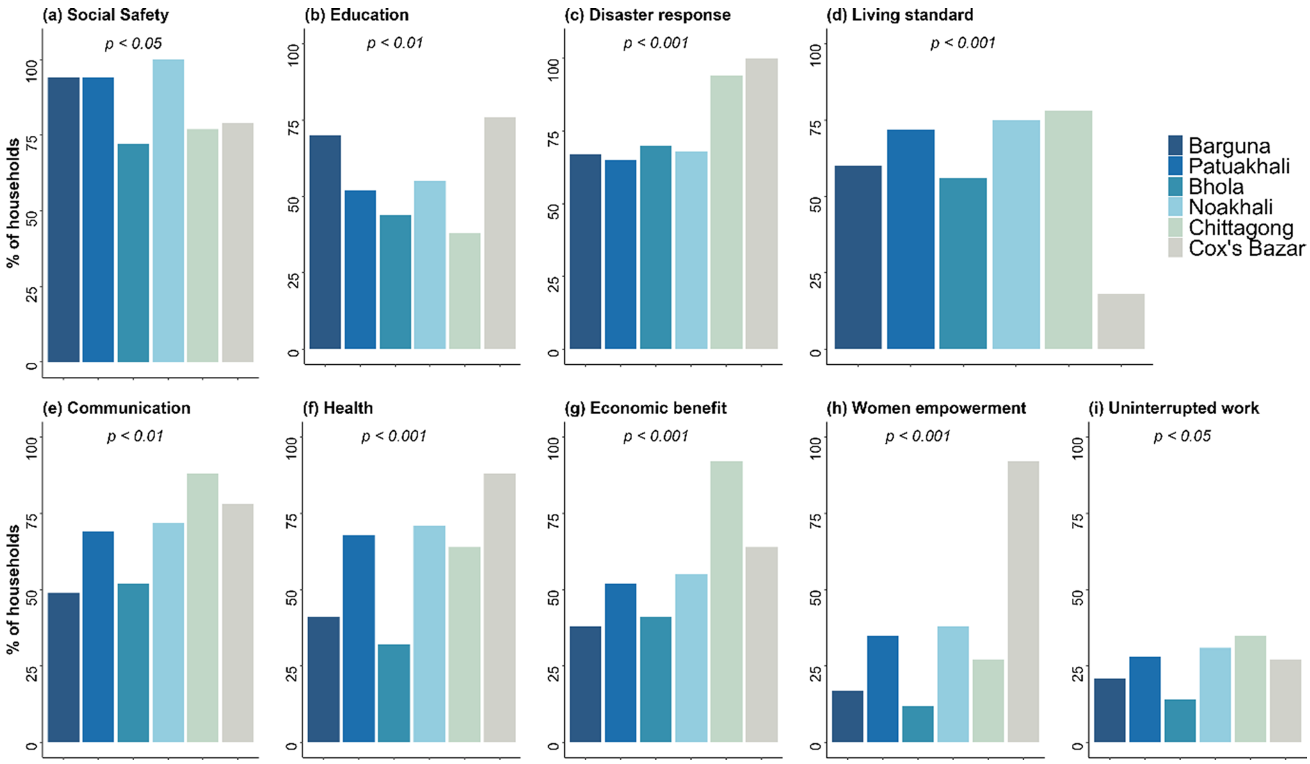

Fig. 7 Variations of the impacts of solar energy on (**a**) social safety, **b** education, **c** disaster response, **d** living standard, **e** communication, **f** health, **g** economic benefit, (women empowerment (h), and (**i**) uninterrupted work of the studied households across the six districts in Bangladesh. The *p* values ($p < 0.05$, $p < 0.01$, and $p < 0.001$) on top of each plot represent the level of significance of the differences of each impact among the six districts

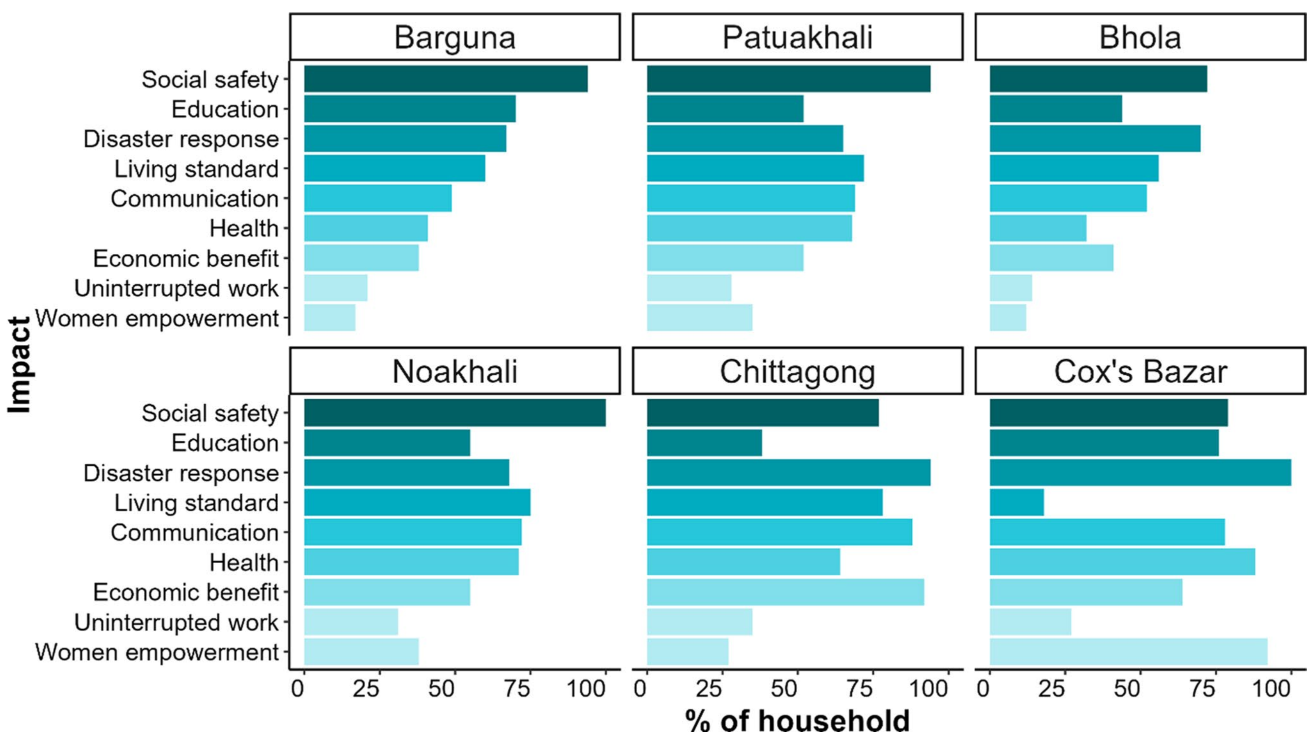

Fig. 8 Impacts of solar energy on various socio-economic and health aspects of the studied households in Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar districts in Bangladesh

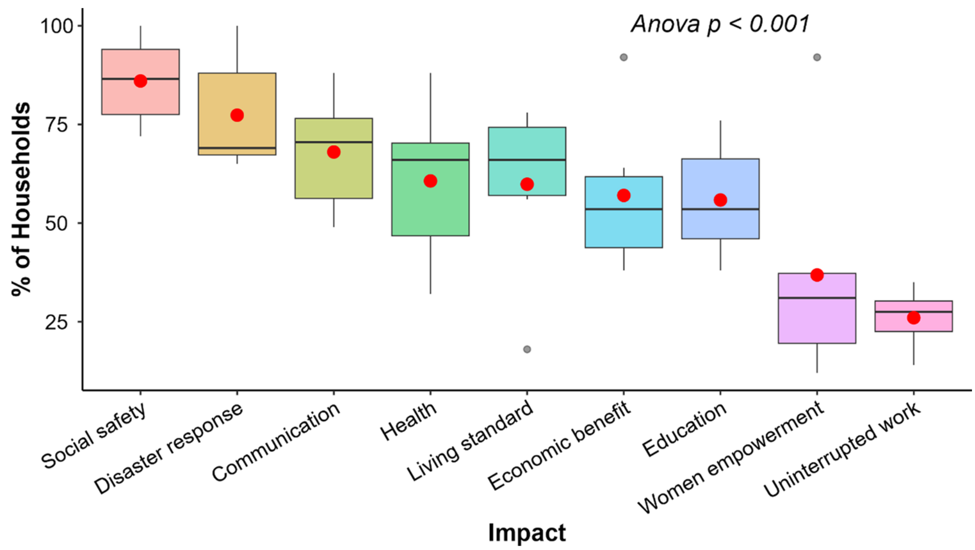

Fig. 9 Impacts of solar energy on various socio-economic and health aspects of the studied households of six districts in Bangladesh. The red circles inside the boxes represent the mean percentage of households reported the various impacts of solar energy on their lives and livelihoods. The horizontal solid lines within the boxes indicate the median percentage of households reported the various impacts of solar energy on their lives and livelihoods. The *p*-value ($p < 0.001$) shown in the plot denotes a significant difference in impacts of solar energy on various socio-economic and health aspects across the studied districts. The outliers are represented by grey circles

with the range from 49% in Barguna to 88% in Chittagong (Fig. 8). This highlights the importance of electricity in bridging communication gaps and facilitating social interactions.

SHS has been shown to have numerous positive impacts on the health of individuals and communities (Fig. 7f). One of the most significant benefits is the reduction in indoor air pollution. In our study areas where kerosene lamps are commonly used for lighting, the emissions from these sources can lead to respiratory issues and other health problems. By replacing these traditional energy sources with solar energy, households enjoy cleaner air, thereby reducing the incidence of respiratory diseases, particularly among vulnerable populations such as children and the elderly. For example, 88%, 71% and 68% of the households in Cox's Bazar, Noakhali, and Patuakhali districts, respectively reported that SHS installation has positive impacts on the health conditions of their household members (Fig. 8).

3.3.3 Impacts of solar energy on economic activity, and women empowerment

Furthermore, electricity plays a vital role in improving living standards, health facilities, and economic benefits. These impacts were reported in varying degrees across the study areas, indicating the positive influence of electricity on overall well-being and economic activities. While women empowerment and uninterrupted work show relatively lower impacts overall (Fig. 9), there are significant variations among the study areas (Fig. 8). Cox's Bazar stands out with high percentages for women empowerment (92%) and uninterrupted work (27%), suggesting a more pronounced influence on gender equality and economic productivity in this area (Fig. 8).

Economic benefit in terms of income generation after the installation of SHS has been increased in the substantial number of households in all districts (Fig. 7). For example, 92% of the studied households in Chittagong district reported their income generation after the installation of SHS. Nearly half of the studied households in other districts also reported their higher income after SHS installation compared to the income before SHS installation (Fig. 7g).

3.3.4 Relevancy of observed household-level findings with FGDs, KIIs and previous studies

The examined communities highlighted various direct and indirect benefits of SHS for both individual households and the community. Social safety emerged as a concern at the household, community, and village levels. Although solar lighting was recognized as contributing to social safety, ensuring overall safety is challenging due to the dispersed nature of SHS users. It is important to note that a considerable number of households in the community still rely on alternative energy sources like kerosene lamps for lighting, alongside SHS.

Our study's findings on the impacts of SHS on education (Figs. 8 and 9), particularly the increased study hours in the evening and before examinations, are consistent with the findings of Huq [21], who reported that solar lighting enhances the reading experience for students. The majority of respondents with school-going children indicated that their SHSs are extremely beneficial for nighttime education. During examination periods, these households often prioritize study time by turning off other energy-consuming appliances to extend the hours available for studying. However, households with higher battery capacities (80–130 A-hours) benefitted from longer-lasting energy support at night compared to those with lower capacities (20–40 A-hours), which is more common in our study areas. The observed trend of increased study hours at households in our study aligns with a study conducted in river islands of northwest Bangladesh [43]. Although we did not evaluate the student attendance rate, Kudo et al. [43] observed that the provision of solar lighting initially led to a rise in school attendance among 1292 students in elementary and secondary schools. Solar lighting is anticipated to offer a conducive environment for studying, hence enabling students to allocate additional time for completing their academic assignments [43].

During the FGD involving various stakeholders, a high school teacher expressed that "*certain households have been provided with SHS by NGOs at a reduced interest rate. The teacher further noted that the school attendance of students belonging to these households has witnessed an upward trend. The academic performance of these students is superior in the classroom setting*". One possible reason for the improvement in academic performance is that access to reliable electricity allows students to study in well-lit conditions during the evening, which promotes better concentration and extends study hours, especially during examination periods. Households with SHS can prioritize their children's education by reducing the use of other energy-consuming appliances, thereby dedicating more time to studying. According to this schoolteacher, "*assessing the success of these pupils within a limited timeframe is challenging, yet there is a general trend of improvement observed among these children*."

Concerning disaster response, a notable majority of the participants, namely more than 60%, indicated that SHS substantially influenced addressing disasters, particularly those caused by tropical cyclones and storm surges. According to Hossain and Hossain [44], the examined sub-districts in Bangladesh are classified as regions that have seen a significant impact from disasters [45]. Communities susceptible to catastrophes are provided with advance warning signals, typically by text messages and phone calls, both before and during such calamities. These signals notify individuals to seek refuge in nearby cyclone-shelters as a precautionary measure. The qualitative findings of our study further supported the households' responses regarding the positive impact of SHS on disaster preparedness. Solar energy enables households to recharge their mobile phones, allowing them to access up-to-date information and make necessary preparations.

According to a representative from the Union Disaster Management Committee (UDMC) in a sub-district, "*our geographical location is surrounded by the Meghna River and the Bay of Bengal, exposing our community to annual tropical cyclones, floods, and storm surges. Most of our residents are engaged in fishing as their occupation, which requires venturing into the River and Bay of Bengal regardless of prevailing weather conditions or disaster warnings. One positive aspect is that we receive warning signals through mobile phones, allowing us to communicate with our families and take preventive actions. While it is acknowledged that not everyone in our community can afford it, the availability of subsidized SHS provided by the government brings hope to households in this area. It enables them to establish a more resilient community, better prepared to withstand and recover from disasters*".

During the KII conducted with elected leaders, specifically the Union Parishad Chairman, it was expressed that the utilization of solar power has significantly improved the well-being and economic prospects of disadvantaged communities. This is attributed to the consistent availability of energy, which enables the operation of contemporary technologies such as televisions, mobile devices, and video players. Certain shopkeepers have expanded their operations, thereby enabling them to augment their earnings and enhance their socio-economic standing. We also noted that women generate cash through tailoring, particularly during religious and cultural festivities, so enabling them to derive satisfaction from their earnings.

The installation of SHS has been identified as a significant outcome in promoting women's empowerment. However, one of the primary barriers to SHS adoption among women is rooted in traditional gender roles, which often limit their decision-making power regarding household energy choices. In many communities, energy-related decisions are predominantly made by male family members, restricting women's ability to advocate for or access renewable energy technologies. Additionally, economic disparities further exacerbate this issue, as women may have limited access to financial resources necessary for investing in SHS. This lack of financial autonomy not only hinders individual access to clean energy but also perpetuates broader societal inequalities.

Despite these challenges, the positive impacts of SHS on gender equity are noteworthy. Access to reliable electricity can significantly enhance women's quality of life by facilitating educational opportunities and income-generating activities. For example, with SHS, women can study or work after dark, thereby increasing their productivity and skills. Furthermore, reliable energy access enables women to engage in home-based businesses and enhances their participation in community activities. The ability to access information through media and communication devices also empowers women, fostering greater confidence in their roles both within the household and in the community. The SHS programme has had a significant impact on the implementation of alternative income-generating activities at the household level. This observation became apparent during the FGD, in which we documented that women were discussing their sources of income derived from tailoring and chicken farming inside their households. "*A mother of three children reported that she successfully established a modest tailoring enterprise owing to a consistent and reliable energy provision. She also stated that I provide financial support to my family during daytime hours, and I engage in employment activities from the evening until 10 pm. It is worth noting that my job hours may be extended during festival periods*". According to the working lady, the absence of consistent lighting from the SHS would have rendered it unfeasible to generate income and provide support to her family. Several participants in the FGD also expressed that women are engaging in poultry farming using SHS. This is because poultry requires an optimal ambient temperature.

The aforementioned phenomenon was witnessed during our visit to the residences of the FGD participants within the unions of the Patuakhali, Barguna, and Chittagong districts. In 2019, a widow residing near the Union Parishad was granted a SHS by a micro-credit organization. "*She asserts that despite experiencing multiple instances of poultry chick mortality and a significant decline in income until 2018, she was able to recuperate her losses over the past five years, attributing this success to the implementation of SHS*". The achievements of these women have had a significant impact on their communities, particularly on the younger generation, in terms of entrepreneurship in fields such as tailoring and poultry farming. Certain retail electric businesses have also implemented multiple SHS to offer services, including charging facilities, to local communities. These facilities enable individuals to recharge their electric lights, mobile phones, and electric car batteries.

One KII respondent from Noakhali districts expressed a sense of optimism and hope surrounding the adoption of SHS in the region. The respondent stated that "*SHS gives us hope to change our lives*." This sentiment highlights the transformative potential of solar energy for the local population. The KII respondent went on to note that many young people and students are directly benefiting from access to solar energy. This suggests that solar power is not only improving household-level energy access, but also enabling educational and developmental opportunities for the younger generation.

Field observation has revealed the emergence of electric vehicles, specifically referred to as 'rickshaws' and 'easy bikes' for passenger transportation, as well as 'vans' for goods transportation, within all sub-districts. The FGD conducted in most sub-districts highlighted the growing prevalence of electric vehicles, as reported by service providers. According to a spokesperson from the business committee in Patuakhali, Noakhali, and Cox's Bazar districts, electric vehicles have been prevalent in metropolitan areas over the past decade. However, individuals inside our community are unable to access such vehicles due to the absence of adequate charging infrastructure. Several electric shopkeepers have been offering this service through SHS for the past six to seven years, resulting in a significant impact on vehicle operators who have chosen to convert their vehicles into electric ones. This assertion aligns with the findings of Chowdhury et al. [46], who saw a surge in the adoption of electric vehicles in urban areas of Bangladesh, and Hossain et al. [5], who reported the impacts of SHS on economic growth in coastal communities. Considering the growing demand for electric vehicles in rural areas, enhancing solar energy in coastal Bangladesh is imperative. Several recent studies have reported this growing demand for solar energy in rural communities for economic activities [58–60].

Our study respondents emphasized the significant impact of SHS on their livelihoods. Fishermen rely on solar lights generated by their SHS for nocturnal fishing activities and the creation of fishing equipment. Farmers use solar lights to prevent damage from nocturnal creatures and during the nocturnal rice husking phase. These diverse applications of SHS contribute to economic prosperity and align with the findings of Huq [21] and Hossain et al. [5]. The implementation of SHS positively influences the lives and livelihoods of coastal communities, offering alternative sources of income, extended working hours, and promoting women's participation in various sectors.

3.4 Challenges faced by the households

3.4.1 Challenges associated with weather and cleanliness

The study examined the challenges faced by households in different coastal areas of Bangladesh regarding their access to electricity. The results highlight common and distinct patterns across the study sites (Figs. 10 and 11), with specific percentages shedding light on the prevalence of these challenges. Foggy weather emerged as a significant challenge

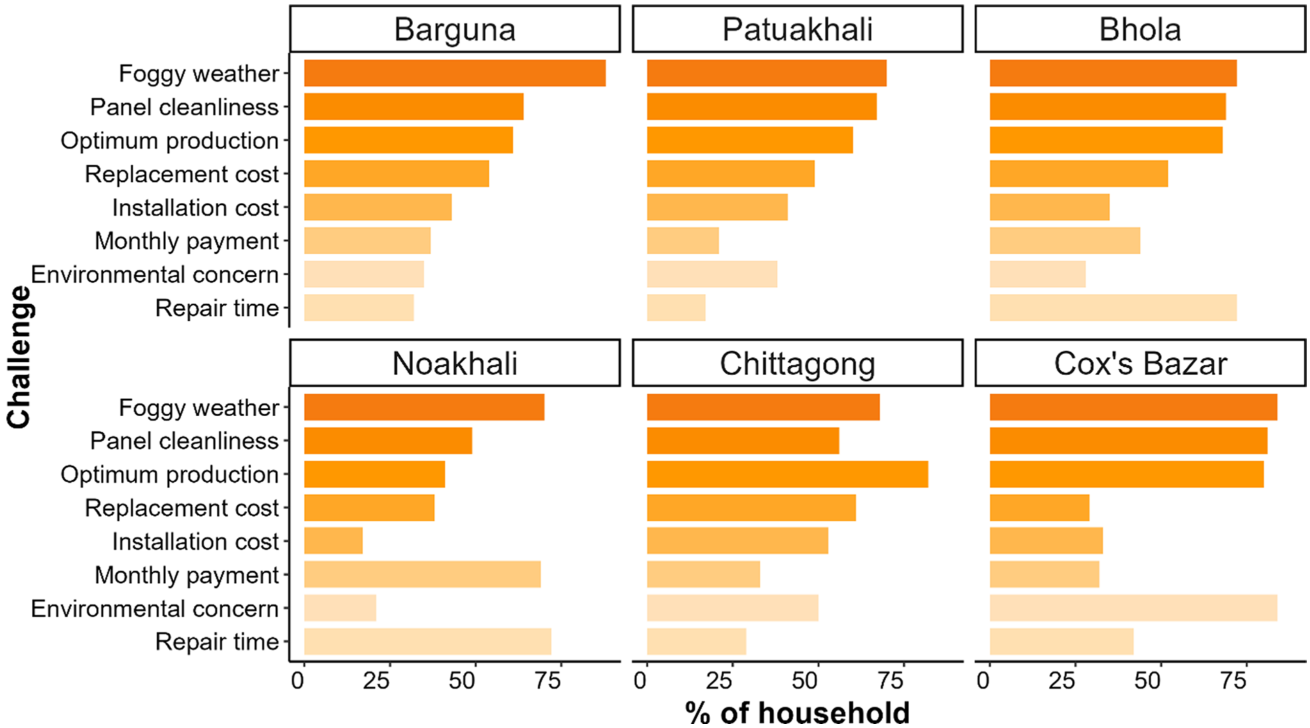

Fig. 10 Challenges faced by the households in using solar energy in the studied households in Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar districts in Bangladesh

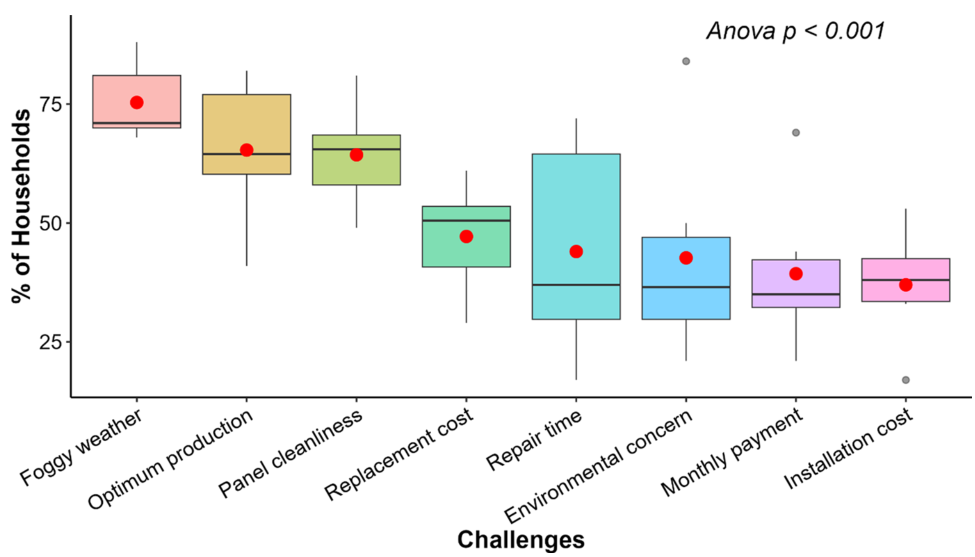

Fig. 11 Challenges in using solar power in the studied households of six coastal districts. The red circles inside the boxes represent the mean percentage of households reported the various challenges associated with the use of solar home systems (SHS). The horizontal solid lines within the boxes indicate the median percentage of households reported the various challenges associated with the use of SHS. The *p*-value ($p < 0.001$) shown in the plot denotes a significant difference in challenges associated with the use of SHS across the studied districts. The outliers are represented by grey circles

in all study areas, with the highest reported percentage of 88% in Barguna and the lowest reported percentage of 68% in Chittagong (Fig. 10). This indicates that the coastal regions experience frequent foggy conditions, which significantly impact electricity generation and availability. Panel cleanliness was identified as a prominent challenge in most study sites, with the highest reported percentage of 81% in Cox's Bazar and the lowest reported percentage of 49% in Noakhali.

Achieving optimum production was a common concern across several study areas, with the highest reported percentage of 82% in Chittagong and the lowest reported percentage of 41% in Noakhali.

3.4.2 Challenges associated with monetary and environmental issues

Replacement and installation costs were identified as challenges in the study areas. The highest reported percentage for replacement costs was 61% in Chittagong, while the lowest reported percentage was 29% in Cox's Bazar (Fig. 10). Additionally, the highest reported percentage for installation costs was 53% in Chittagong, and the lowest reported percentage was 17% in Noakhali. Environmental concerns were raised in some study sites, with the highest reported percentage of 84% in Cox's Bazar and the lowest reported percentage of 21% in Noakhali. Repair time and monthly payment affordability were highlighted as challenges. The highest reported percentage for repair time challenges was 72% in Bhola and Noakhali, while the lowest reported percentage was 17% in Patuakhali. The highest reported percentage for monthly payment affordability challenges was 69% in Noakhali, and the lowest reported percentage was 21% in Patuakhali (Fig. 10).

3.4.3 Challenges faced by the new users

In the case of households whose SHS's age is less than 1 year, results reveal that the most significant challenge faced by households across the districts is the impact of foggy weather, which affects between 28 to 61% of the population (Fig. 12). Optimum production is another key concern, with 23% to 37% of households reporting issues related to it. Panel cleanliness and installation cost are also notable problems, affecting 18% to 24% of the population. Monthly payment is a moderate concern in some areas, with up to 24% of households reporting it as an issue. However, environmental factors, replacement cost, and repair time do not seem to be major problems in these regions. In Barguna, the primary issues are foggy weather (61%), optimum production (23%), and panel cleanliness (18%), with installation cost (13%) also a concern. Patuakhali faces similar challenges, with foggy weather (52%), optimum production (32%), and panel cleanliness (24%) being the main problems, while installation cost (11%) is a moderate concern (Fig. 12). Bhola's key problems are foggy weather (34%), optimum production (32%), and installation cost (24%), with monthly payment (24%) also a

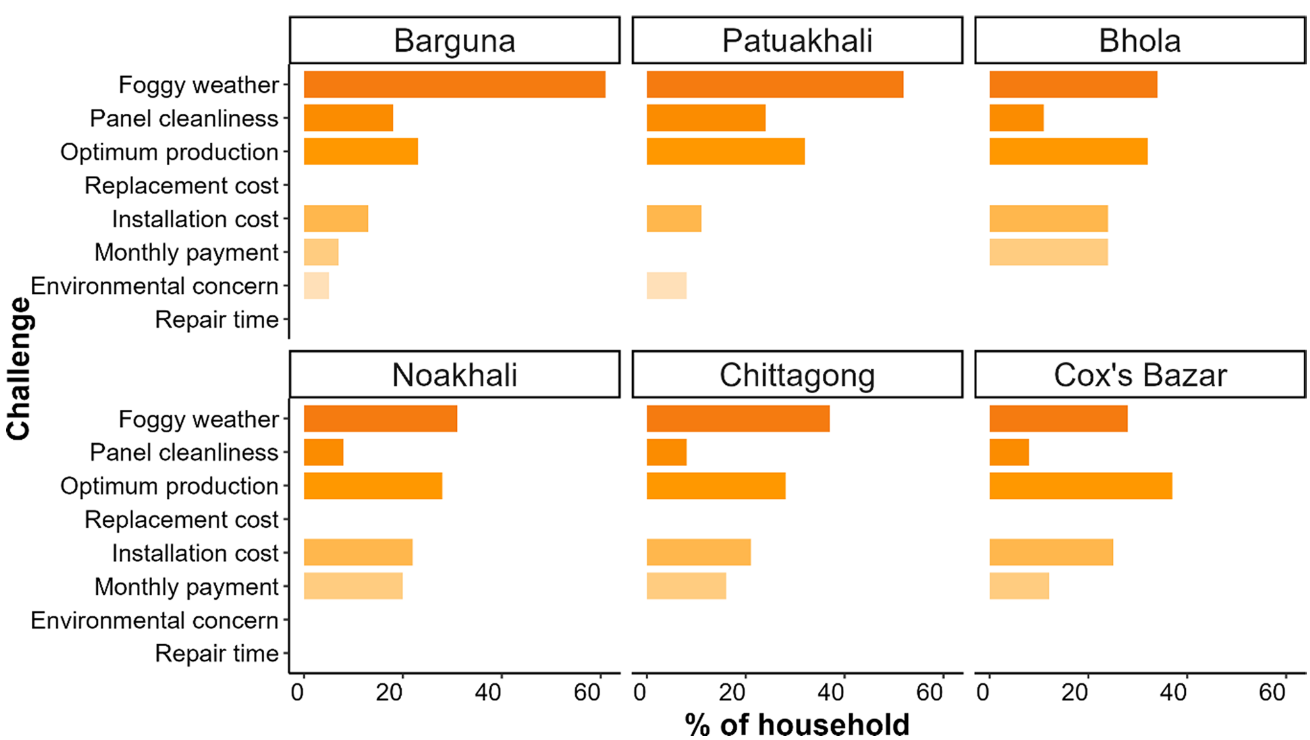

Fig. 12 Challenges faced by the households who are using solar energy less than 1 year in the studied households in Barguna, Patuakhali, Bhola, Noakhali, Chittagong, and Cox's Bazar districts in Bangladesh

notable issue. In Noakhali, the primary challenges are foggy weather (31%), optimum production (28%), and installation cost (22%), and monthly payment (20%) is a moderate concern. Chittagong's main issues are foggy weather (37%), optimum production (28%), and installation cost (21%), with monthly payment (16%) being a relatively lower concern. Cox's Bazar faces similar challenges, with optimum production (37%), foggy weather (28%), and installation cost (25%) being the key problems, while monthly payment (12%) is a relatively lower concern (Fig. 12).

3.4.4 Strategies to overcome the challenges

The word could visualization reveals a variety of strategies employed by households to overcome challenges associated with SHS (Fig. 13). The most frequently mentioned strategies included prioritizing essential appliances (36 mentions), seeking assistance from local technicians (32 mentions), reduced working hours at night (29 mentions), and using alternative energy sources (24 mentions). Other notable strategies were cleaning the panels during the dry season (17 mentions), increasing battery storage capacity (15 mentions), and taking loans from microfinance organizations (16 mentions). Additionally, households sought support from vendors (20 mentions) and local government (14 mentions) and upgraded to energy-efficient devices (14 mentions). The findings underscore the proactive approaches households adopt to mitigate challenges related to SHS, emphasizing the importance of prioritizing essential needs and seeking external support for effective energy management.

3.4.5 Relevancy of observed household-level challenges with FGDs, KIIs and previous studies

Despite the various applications of SHS and their significant impact on the lives and economic activities of coastal communities, households have identified obstacles in adopting and utilizing this sustainable energy source. Obtaining a consistent energy supply from SHS is challenging due to the sub-tropical nature of the study sites, which leads to foggy weather in winter and gloomy meteorological conditions. The perceived deficiencies of SHS are attributed to inadequate technical expertise and subpar sales and servicing. The findings of our study align with those of Kabir et al. [22], which

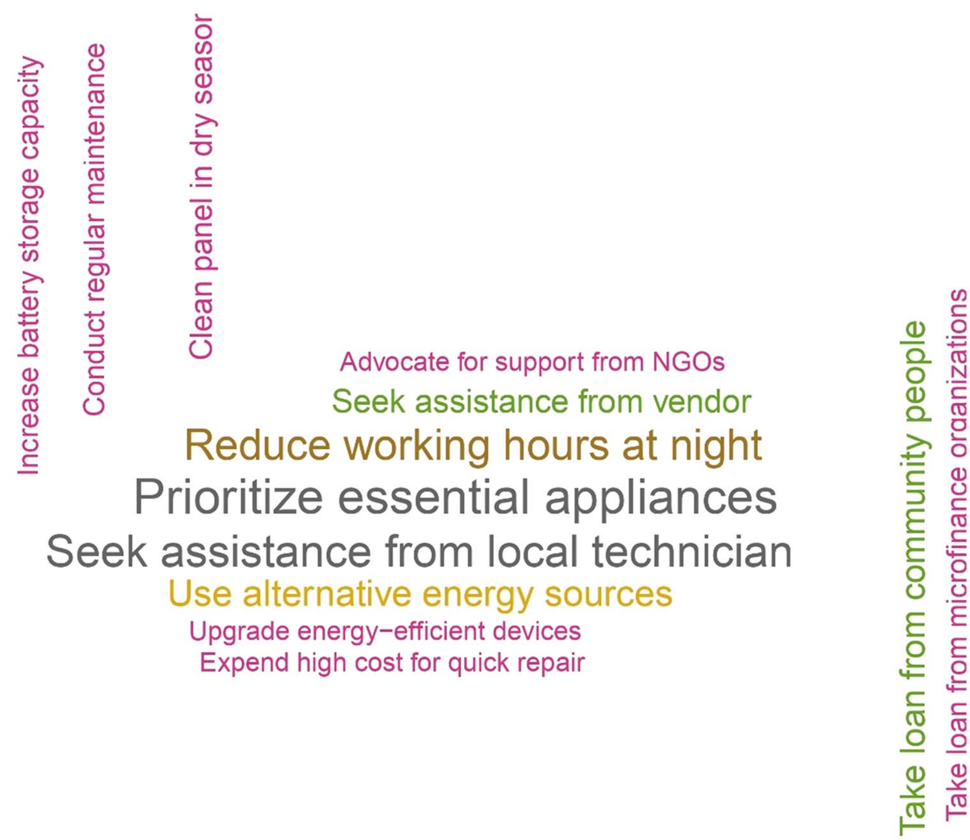

Fig. 13 Word cloud illustrating the predominant strategies employed by households across the sub-districts to overcome challenges associated with solar home systems (SHSs). The size of each word corresponds to its frequency of mention, highlighting the most adopted strategies

stated that 37% of households encountered challenges in meeting the initial down-payment and subsequent monthly payments.

The majority of SHS in the households we examined were more than six years old, and these households' expressed dissatisfaction with the suboptimal performance of their SHS. Previous research conducted in rural locations [5, 20, 23] has also documented the inferior performance of SHS. However, the suboptimal performance of SHS cannot be simply attributed to the increasing age of the systems. Panel cleanliness also plays a significant role, as our findings indicate that the second highest number of households reported not cleaning their panels since installation. It is recommended that solar panels be cleaned every six months to uphold their production efficiency and effectiveness. Within the designated study locations, it was observed that households exhibited a certain degree of hesitancy when it came to the maintenance of solar panels, primarily due to the installation of SHS on the rooftops.

While households are provided with information regarding the regular cleaning of solar panels by the SHS servicing company, many household respondents indicated two main reasons for not performing the cleaning themselves. Firstly, they mentioned the need for a large ladder to access the rooftop, which they do not possess. Secondly, they pointed out that during the monsoon season, the panels naturally become clean because of rainfall. It should be acknowledged that the studied areas exhibit a significant presence of dust, smog, and dirt due to their geographical location along the coast and on islands. These localities experience elevated levels of dust generation due to activities such as agricultural field preparation, crop harvesting and processing, and the burning of wood and rice husks for cooking purposes. A recent study conducted in Dhaka city, Bangladesh [47] found that the decreased effectiveness of SHS during the winter season is related to the accumulation of dust on the solar panels. The issues that were recorded in the household survey were similarly observed in the content analysis of qualitative data. In our study, several words such as 'foggy weather', 'panel cleanliness', and 'optimum output' were found to occur more frequently compared to other mentioned words.

One potential solution is the establishment of community-based maintenance programs. These programs can empower local technicians and train community members to perform regular maintenance on SHS, including cleaning solar panels and troubleshooting minor technical issues. By fostering local expertise, these initiatives not only ensure the longevity and efficiency of the systems but also create job opportunities within the community. Moreover, community engagement in maintenance can enhance users' sense of ownership and responsibility towards the SHS, leading to more consistent care and attention.

In addition to maintenance programs, implementing policy incentives for end-of-life SHS recycling can address environmental concerns related to waste management. Policymakers can promote initiatives that encourage manufacturers to take back old or damaged solar panels and components, ensuring proper recycling and disposal. This could be facilitated through extended producer responsibility (EPR) policies, which hold manufacturers accountable for the entire lifecycle of their products. By creating a structured recycling program, communities can minimize the ecological impact of SHS while also potentially recovering valuable materials for reuse.

Furthermore, awareness and education campaigns can play a vital role in addressing the barriers to SHS adoption. Providing information on the importance of panel maintenance, environmental sustainability, and the correct disposal of solar components can empower users to take proactive steps in caring for their systems. Workshops and training sessions can be organized to educate community members about best practices for SHS upkeep, thereby increasing system efficiency and user satisfaction.

The extended duration required to fix the impaired appliances of SHS can be attributed to the lack of proficient technicians at the community level. Consequently, these appliances are predominantly dispatched to expert technicians situated at the district level, which is geographically distant from the study locations within our community. In certain instances, households sought assistance from local service providers who imposed exorbitant repair fees. Due to a lack of technical proficiency in managing solar appliances, most households we have examined exhibit hesitancy in engaging with the operation and maintenance of malfunctioning units.

Our study recognizes that coastal communities are not homogenous entities, and each sub-district may have unique characteristics and circumstances that influence the challenges encountered in adopting and utilizing SHS. For instance, while panel cleanliness emerged as a common challenge in our study, the extent and nature of this challenge may vary across sub-districts due to factors such as proximity to urbanized areas, presence of dust or pollen-rich environments, or the nature of local livelihood activities. Similarly, foggy weather, another challenge identified in our research, exhibited variations in intensity and frequency across different sub-districts. Some sub-districts may experience prolonged periods of foggy weather, while others may have intermittent foggy conditions. These challenges (foggy weather and panel cleanliness) observed in our study are also evident in a recent study in coastal Bangladesh [5], which reported that foggy weather during monsoon affects the optimal production of solar energy. Furthermore, affordability is a key challenge, and its magnitude can differ across sub-districts due to variations in income levels, economic activities, and cost structures. Sub-districts with higher poverty rates or limited economic opportunities may face more significant affordability constraints compared to those with more robust local economies. Recognizing these variations is essential for designing targeted and effective financial assistance programs that address the specific affordability challenges faced by different sub-districts [58].

The prominence of strategies in overcoming the challenges reported by the households (Fig. 13) such as prioritizing essential appliances and seeking assistance from local technicians highlights a practical approach to energy management. By focusing on essential needs, households can optimize the use of available resources, ensuring that critical functions are maintained even in the face of challenges. The household reduction of working hours at night is one of the frequent modifications made, indicating a major adjustment from the limitation of SHS. This approach reflects realistic ways in which energy availability influences lifestyle and daily routine choices. The emphasis on the use of alternative sources of energy further points toward diversification in energy solutions that could be resilient and dependent upon a single source of energy. Engagement with external support systems in seeking help from vendors or the local government brings out the role of community and institutional resources in surmounting SHS-related issues. Cleaning of panels during the dry season and increase in battery storage capacity are proactive maintenance practices reflecting optimization strategies for SHS performance. These acts may also symbolize improved awareness of the household on the essence of regular upkeep and investment in the energy system.

Collaborative efforts between policymakers and local stakeholders can ensure that policy interventions are culturally appropriate, locally accepted, and effectively address the unique challenges present in each sub-district. Additionally, flexibility in policy implementation is key. Recognizing the variations across sub-districts implies that a one-size-fits-all approach may not be effective. Policymakers should allow for the adaptability and customization of interventions based on the specific needs and circumstances of each sub-district [60]. This could involve providing different levels of financial support, prioritizing specific maintenance practices, or tailoring awareness campaigns to address the specific challenges and opportunities identified in each sub-district.

While solar power is often regarded as a promising source of renewable energy, the potential environmental consequences stemming from the disposal of damaged solar appliances and electronic trash in both rural and urban regions have received limited attention in the literature [48–50]. It is uncertain if the disposal of solid household trash generates a greater amount of pollution compared to non-renewable energy sources, such as fossil fuels. In this study, our objective was to evaluate the level of concern among SHS users regarding the environmental and public health implications associated with the disposal of their damaged SHS components. A small proportion of participants expressed apprehension regarding the potential health consequences, impact on aquatic resources, and degradation of soil, water, and the environment resulting from their disposal of trash into nearby water bodies and land areas.

According to a recent study by Tasnim et al. [51], the presence of lead-acid batteries and other forms of discarded solar panels has been increasing in Bangladesh. This rise raises concerns about potential risks to human health and the environment. During the FGD, it was observed that a purchaser of recycled plastic at the union level in Barguna district mentioned segregating various types of waste materials such as plastic water bottles, packaging items, and iron products. However, they occasionally come across additional items like batteries, metal frames, cables, metal fixtures, damaged solar lanterns, and glass and plastic components of SHS. The waste generated from SHS is classified as hazardous waste, like other forms of electronic waste like discarded televisions, batteries, computer accessories, and LED bulbs [52–54]. However, due to the relatively small volume of SHS waste purchased and the absence of a separate market at the district level, there is no practice of segregating SHS waste from other hazardous waste.

The latest National Environment Policy-Bangladesh 2018 outlines the principles of managing electronic trash (e-waste) through the reduction, reuse, and recycling approach. However, it is worth noting that the policy does not explicitly classify waste from SHS as e-waste. Furthermore, the E-waste Management Rules of 2017 establish various classifications for electronic trash. However, it is worth noting that the end-of-use SHS were not explicitly categorized as e-waste within these regulations [55]. There is a lack of clear indication or guideline within the current administrative units, such as the Union Parishad at the union level and Upazila Parishad at the sub-district level, regarding the proper handling of electronic waste (e-waste) originating from SHS. Due to the absence of stringent restrictions, households commonly engage in the improper disposal of their irreparable SHS by depositing it in their backyards, along roadsides, and in bodies of water [56].

The waste collection process in the local community involves primarily youngsters who gather various types of rubbish, such as plastic, metal, glass, and e-waste. These collected materials are subsequently sold to local marketplaces. While government departments and NGOs do engage in awareness-raising initiatives pertaining to disaster risk reduction, livelihood improvement, food security, adaptive agriculture, flood preparedness, agroforestry, fish farming, and women empowerment [57], it is worth noting that the promotion of awareness regarding e-waste management is notably lacking in the areas we have studied. During an FGD conducted in Bhola district, certain participants expressed that the mismanagement of solid household garbage has become a prominent concern within our community. Nevertheless, it was acknowledged that we are confronted with numerous additional challenges that require our attention and action. Additionally, there is a lack of comprehensive information regarding treating this waste. It is strongly recommended that NGOs, government departments, and marketers of hazardous substances take the initiative to furnish essential information to enhance the efficacy of hazardous waste management.

3.5 Integration of renewable energy sources and net-zero approach

The integration of solar energy systems with other renewable energy sources, like wind, is being increasingly recognized as a necessary approach towards smoothing out the fluctuations of solar-based power generation and towards better meeting the energy needs of a particular area or district [61, 62]. While solar energy has its many advantages, such as broad resource availability and environmental friendliness, it still suffers from the influences of meteorological conditions and cyclic day-night variations. This creates great intermittency and is always challenging to achieve a constant power supply. The integration of the wind energy system will hence leverage the complementarities of solar and wind power. Wind energy also depends less on weather conditions and hence generates electricity on days of low sun. Wind turbines are able to capture the kinetic energy from the winds, conversing them into electrical energy while providing a steady and continual source of power.

Recent research has underscored the importance of this integration to enhance the use of renewable energy sources [61–63]. Through the combination of solar and wind energy systems, communities are able to create a more balanced and robust energy framework. This integration not only bolsters the overall reliability and stability of the power supply but also diminishes dependence on fossil fuel-based energy sources, thereby promoting sustainability within the energy sector. Coupling solar with wind energy systems also creates avenues for increased utilization of the available resource. Different regions have different patterns of winds and solar radiation, and hence, by tapping these sources together, that would, to a larger extent, tap the ultimate renewable energies at the community level in different regions. Besides, the intermittent of all these renewable sources can be improved further with the addition of smart grid technologies, energy storage, and sophisticated control systems. These strategies allow for better monitoring of the fluctuations in energy production and consumption, with the assurance of a reliable and balanced electricity service.

The net-zero approaches in built environments, alongside the integration of solar energy systems with other renewables, is emphasized in recent studies [62, 63]. By striving to achieve a balance between energy consumption and renewable energy generation, buildings can significantly reduce their carbon emissions. This approach involves energy-efficient design strategies, renewable energy technologies, and optimized energy management systems [64]. The integration of solar and wind systems in buildings plays a vital role in on-site energy generation. Additionally, energy-efficient building practices contribute to the net-zero approach by reducing energy demand and minimizing losses. Adopting a net-zero approach aligns with global climate change mitigation efforts, offers economic benefits, and drives innovation in the renewable energy sector [65].

3.6 Policy recommendations for SHS adoption and utilization

Our study has identified several areas on which policymakers might place special attention in promoting the adoption and utilization of SHS in coastal communities. Guided by the various challenges identified in this study, for instance, policymakers should consider developing policies that improve access to technical expertise and supporting services for SHS installation, maintenance, and troubleshooting. This may include the need to develop such training programs and provide resources toward the building of local technical capacity for them to handle operation and maintenance duties effectively.

Our results emphasize the need for explicit policies that target financial obstacles of SHS adopters. Policymakers might consider allowing payment installments or offering subsidies or soft loans to make access more feasible and increase the ability of households in coastal areas to adopt SHS. Additionally, the development of a partnership or initiative by the finance institutions and microfinance institutions will ensure access to finance is available for the specific needs of the coastal communities to overcome the high upfront cost of installing SHS.

Policymakers should foster partnerships with NGOs that specialize in renewable energy financing. By leveraging these partnerships, governments can facilitate the establishment of programs that offer reduced interest rates for SHS loans. To encourage NGOs to offer competitive interest rates for SHS financing, policymakers should consider providing incentives, such as risk guarantees or subsidies. These measures can lower the financial burden on NGOs, allowing them to extend favorable loan terms to households.

Governments can enhance the effectiveness of solar energy initiatives by offering more grant projects specifically designed for NGOs that implement solar energy-related activities. By providing financial support to these organizations, governments can empower them to develop and execute innovative projects that promote the adoption of SHS in underserved communities.

Moreover, these grants can encourage NGOs to collaborate with local governments, community leaders, and private sector partners, fostering a multi-stakeholder approach to solar energy deployment. By aligning NGO projects with government energy policies and community needs, this strategy can ensure that resources are effectively utilized and that projects have a lasting impact.

Government lined departments could introduce financial incentives specifically for the purchase and installation of home battery systems. This would lower the upfront costs for households, making it more feasible to integrate these systems with existing SHS. Such incentives can address the challenge of intermittent energy supply, ensuring that households have access to stored energy during peak demand.

Furthermore, our study underscores the importance of regular panel cleaning and maintenance for optimal SHS performance. Policymakers should incorporate awareness campaigns and educational programs to promote the understanding of proper maintenance practices among SHS users. This can include providing guidelines, conducting workshops, and establishing community-based initiatives that encourage regular cleaning and maintenance schedules. Additionally, policymakers should facilitate the availability of maintenance services and support, particularly in remote coastal areas where technical assistance might be limited.

Finally, our research highlights the need for appropriate end-of-life management strategies for SHS components. Policymakers should develop policies and regulations ensuring proper disposal and recycling of system components, minimizing environmental impacts and promoting sustainable practices. This can involve establishing collection centers or recycling programs specifically designed for SHS components, as well as promoting the use of environmentally friendly materials during system manufacturing.

3.7 Policy implications for renewable energy

The findings from our study offer valuable insights that can inform future renewable energy policies not only in Bangladesh but also in other regions facing similar energy access challenges. By highlighting the specific benefits and obstacles encountered by SHS users, this study can help policymakers design targeted interventions that address the unique socio-economic and environmental contexts of different communities.

One key implication is the need for policies that support local capacity building. Our findings indicate that communities utilizing SHS often rely on local technicians for installation and maintenance. Therefore, policies that promote training programs for these technicians can enhance the sustainability of SHS initiatives. This approach not only empowers local individuals but also ensures that communities have access to reliable support, reducing downtime and increasing user satisfaction.

Additionally, our research underscores the importance of community engagement in the implementation of renewable energy projects. Policymakers should consider strategies that actively involve community members in decision-making processes, ensuring that their perspectives and needs are addressed. By fostering partnerships between local governments, NGOs, and community members, policies can be more effectively tailored to promote renewable energy adoption and address potential barriers such as affordability and accessibility. Building on the successful interventions of the Infrastructure Development Company Limited (IDCOL), the Bangladesh government can expand its projects for SHS. This successful model can be adapted in other regions by establishing similar government-backed financing mechanisms.

The Bangladesh government can draw inspiration from the successful model implemented in India. The SHS program in India has demonstrated effective collaboration between local governments and microfinance institutions [66]. The Indian government, through initiatives like the National Solar Mission, has partnered with microfinance institutions to provide loans for solar installations, supported by government subsidies. This approach has significantly increased solar adoption in rural areas [66], showcasing the potential for similar strategies in Bangladesh. While similar initiatives are underway in Bangladesh, they have not achieved the same level of success as those in India. By adapting this model, the Bangladesh government can enhance its efforts to promote SHS and improve energy access for underserved communities.

Lastly, the findings of this study might serve as a model to extend the projects on renewable energy to other communities with similar socio-economic characteristics. By documenting the successes and best practices identified in our study, the research can provide a framework that decision-makers in various contexts can adapt and implement. This may also refer to financial mechanisms, such as microcredit or subsidized loans, which shall make access to solar home systems more viable among economically vulnerable households.

3.8 Limitations

The study was conducted in six sub-districts that are highly susceptible to disasters, which may limit the generalizability of the findings to other regions. The sample size is rather small in relation to the overall population in respective sub-districts who should actually be targeted, so the generalization of findings should be cautiously considered to larger populations. This study relied on subjective data from household surveys that are prone to response biases and inaccuracies. Participants may have given socially desirable responses or may not have correctly remembered their experience with SHS. Although validation and reliability check of the data were made, one must be cautious in drawing conclusions based merely on self-reported information. The results may reflect unique socio-cultural, economic and environmental situations in this area. This was an important consideration when generalizing the findings of this study into any other setting or region that may differ on some parameters.

4 Conclusions

In the context of supplying essential electricity to communities, particularly in distant areas where the expansion of the national power grid is difficult, time-consuming, and economically inefficient, the use of SHS has demonstrated its efficacy as a viable and environmentally friendly alternative energy source. The government has thus embarked, through the facilitation provided by IDCOL, on addressing the assurance of access to electricity as a means of improving the livelihood of the coastal population. For this process, the program targeted communities living in geographically vulnerable areas with power supply as a key input through SHS. The study explored the utilization and consequence of SHS within communities in six highly disaster-vulnerable sub-districts. This was done through an assessment of the utilisation of solar energy in various activities that emanated, the impacts of SHS on livelihoods and day-to-day living, and the challenges faced in the adoption of SHS.

The analysis of household electricity usage in coastal areas of Bangladesh reveals a universal need for lighting, with 100% of households relying on electricity, while also highlighting the widespread dependence on electricity for charging devices and studying. The study highlights the significant impact of electricity access on various aspects of socio-economic development in the coastal areas of Bangladesh. Electricity plays a crucial role in enhancing social safety, education, disaster response, and communication. It also contributes to improving living standards, health facilities, and economic benefits. While there are variations among the study areas, the findings emphasize the importance of electricity in improving overall well-being and economic productivity in these communities.

The implementation of SHS has brought numerous positive effects on the lifestyles and economic activities of coastal communities. However, the study also reveals several challenges faced by households in accessing electricity through solar systems. These challenges include panel cleanliness, foggy weather, replacement and installation costs, achieving optimum production, environmental concerns, repair time, and monthly payment affordability. The findings highlight the need for addressing these obstacles to ensure sustainable and reliable access to electricity in coastal areas.

By addressing the following research directions, we can further deepen our understanding of the potential of SHS as a sustainable energy solution and contribute to the well-being, resilience, and development of coastal communities.

1. *Technological innovations and integration* There is a need for research into technological innovations and integration options for SHS in coastal areas. Exploring emerging solar technologies, such as smart grids, energy storage systems, and mini-grid solutions, can expand the reach and effectiveness of renewable energy in remote regions. Investigating the integration of SHS with other renewable energy sources, such as wind, can also enhance the reliability and resilience of the electricity supply.

2. *Climate change resilience and adaptation* Investigating the role of SHS in building climate change resilience in coastal communities is important. Research should explore how SHS can contribute to disaster preparedness, early warning systems, and adaptive capacity. Assessing the potential of SHS to provide reliable electricity during extreme weather events, as well as its integration with climate change adaptation strategies, can enhance community resilience and reduce vulnerability.
3. *Long-term impact assessment* Future research should focus on conducting long-term impact assessments of SHS in coastal communities. This includes evaluating the sustained benefits of electricity access on socio-economic development, education, health outcomes, and environmental sustainability over extended periods. Longitudinal studies can provide valuable insights into the lasting effects of SHS on community well-being and inform future energy planning strategies.
4. *Policy evaluation and enhancement* Future research may evaluate the effectiveness of existing policies and regulations in promoting SHS adoption and identify areas for improvement. Assessing the impact of policy frameworks, financial incentives, and supportive measures on the scalability and sustainability of SHS projects can help refine policy approaches and ensure their alignment with the specific needs of coastal communities.
5. *Gender perspectives and women's empowerment* Research should explore the gender dimensions of SHS implementation and assess the differential impact on women's empowerment and economic opportunities. Understanding how SHS can contribute to improving gender equality, addressing women's specific energy needs, and enhancing their participation in decision-making and income-generating activities is crucial for achieving sustainable development in coastal areas.
6. *Economic viability and financing models* Future research should focus on assessing the economic viability of SHS in coastal communities and exploring innovative financing models. Investigating the cost-effectiveness of SHS installations, analyzing the payback period, and evaluating the potential for income generation through the productive use of electricity can provide insights into the financial sustainability of SHS projects. Additionally, research on microfinance initiatives, community-based financing models, and public–private partnerships can help make SHS more affordable and accessible to coastal households.
7. *Community engagement and participation* Research should explore effective approaches for community engagement and participation in the planning, implementation, and maintenance of SHS projects. Understanding the social dynamics, local needs, and cultural aspects of coastal communities can inform strategies for fostering community ownership and ensuring the long-term sustainability of SHS initiatives.

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Author contributions KJS collected the data and wrote the first draft of the manuscript, MLH analysed data, prepared the figures and tables and wrote the main manuscript text. JL revised the manuscript text. All authors reviewed the manuscript.

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Data availability Data is provided within the manuscript and supplementary information files.

Declarations

Ethics approval and consent to participate The necessary consent was received from the research ethics board affiliated with the Centre for Coastal Development in Bangladesh (CCD-ResP-2022/04-162(2)). We adhered to the ethical guidelines for the involvement of human beings as outlined in the Declaration of Helsinki by the World Medical Association. The research was conducted in accordance with ethical principles for the protection of human participants, which encompassed considerations such as upholding human dignity and minimizing the collection of personal data. The written consent was obtained from the participants of the household surveys, and KIIs and FGDs.

Competing interests The authors declare no competing interests.

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