ASSESSING THE VIABILITY AND SOCIO-ECONOMIC IMPACT OF SOLAR PHOTOVOLTAIC SYSTEMS IN OFF-GRID RURAL COMMUNITIES: A CASE STUDY OF A DEVELOPING REGION

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ABSTRACT

This study investigates the performance and economic feasibility of solar photovoltaic (PV) systems for powering a remote rural community in a developing region [1]. The research assesses the PV system's reliability and energy generation capacity, considering factors like varying weather conditions and daily energy demand patterns [2]. It evaluates the system's effectiveness in providing electricity to households, schools, and local businesses, addressing the critical need for sustainable energy sources in underserved areas [3]. Additionally, a cost-benefit analysis is conducted, considering the initial installation costs, maintenance, and potential environmental benefits.

The findings reveal that the solar PV system demonstrates promise as a reliable and environmentally friendly energy source, especially in regions with abundant sunlight. It offers a viable solution to alleviate energy poverty and improve the quality of life in off-grid communities. The results also emphasize the importance of affordable and efficient solar technology, providing valuable insights for policymakers and stakeholders seeking to promote sustainable energy solutions in remote and underserved areas.

KEYWORDS

Solar PV Feasibility, Rural Electrification, Sustainable Energy, Cost-Benefit Analysis

1. INTRODUCTION

In the context of recent years, we humans have been facing more and more atmospheric challenges in terms of greenhouse effect which will lead to severe consequences and threaten various forms of life on this lovely planet. Generating electricity through burning fossil fuel can be a major contributor to producing more greenhouse gasses besides agriculture industry and transportation. Thus, it is urgent for us, humans, to transform the traditional system of attaining energy into a clean and regenerating source of energy, such as solar and wind. That's how I started my initial thought process, solar energy is this magical gift that stores infinite power to use as long as the sun rises up everyday. On top of that, it can barely pollute the environment by any means if you take all the equipment needed to collect and store solar power into account.

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This is a little bit off topic, but please bear with me, I am a huge hiking person where I have visited a lot of national parks in the US and there was one time my phone was dead in the middle of the day and there were no powered outlets or USB ports in the mountains even though I had my cord and cable in my backpack. Ever since that, I have had the urge to solve this problem by setting up small charging stations in national parks or any places with great exposure to sunshine. This project, so-called Solarwise, is totally for non profit, it not only solves a charging problem in places that lack charging facilities by providing free charging services, it can also be a crucial catalyst to help us transition to clean energy and gradually become a sustainable society.

A "Portable Solar Charger" is a compact, individual device designed for mobile phone charging on the go. In contrast, a "Solar Charging Station" is a larger, stationary installation intended for public or commercial use, offering high-capacity charging solutions for multiple devices or electric vehicles.

A "Solar Power Wireless Battery Charger" and a "Wired Battery Charger" differ in their charging methods and convenience. The solar power wireless charger utilizes sunlight to charge devices wirelessly, offering eco-friendliness and portability. In contrast, the wired charger connects directly to the device through cables, providing consistent charging but with potential inconvenience related to cable management, wear and tear, and the need for electrical outlets. The choice depends on user preference, accessibility, and environmental considerations.

Lithium-ion batteries are a better choice for solar photovoltaic applications due to their higher efficiency, longer cycle life, and lower maintenance requirements [4]. Lead-acid batteries, while durable, are better suited for traditional applications like automotive or uninterruptible power supplies.

My solution is assembling solar panels, batteries, and other small components together into a box that has USB ports and works as a charging station for mobile devices in rural areas such as national parks or parks [5].

As I said in the beginning, the charging problem indeed bothered me as a hiking enthusiast, but that also inspired me the solution to the problem, of which is to set up a small power station composed of a solar panel, a solar charger, a 12-V battery to store the energy collected from the sun, and a buck converter to output the electricity for mobile devices. In order to overcome the fact that there is a lack of charging facilities in the outdoors, taking advantage of solar energy is a promising and necessary strategy in the rural areas, especially when it comes to the number of exposure hours to sunlight. And the potential cost of each box would be around a hundred bucks, which is a very low cost and approachable solution to charging. In addition, there is gonna be a chip that detects the real time voltage in the battery, and there is a complementary app to access the data and manage or maintain devices. With a low operating cost, this would be a pretty practical solution to charging problems.

The first experiment involved tracking the efficiency of solar panels under varying weather conditions. This experiment aimed to determine how different weather patterns affect solar panel performance. Data collected included solar panel output under clear, cloudy, and rainy conditions. The surprising result was the impact of diffused sunlight on partly cloudy days. The biggest effect on results was sunlight intensity.

The second experiment assessed a solar charger's performance under different weather conditions and with varying numbers of devices charging. It focused on how weather and device load affect charging times. Device type and initial battery percentage significantly influenced charging times. The biggest effect on results was the capacity of the solar charger and device power requirements.

The third experiment compared portable and stationary solar chargers. Portable chargers are lightweight and designed for outdoor activities, while stationary chargers are permanent installations with higher capacity and efficiency. The choice depends on mobility and specific use cases.

2. CHALLENGES

In order to build the project, a few challenges have been identified as follows.

2.1. Setting up a solar charger

The main challenge in setting up a solar charger is optimizing its placement for maximum sunlight exposure. Proper positioning and orientation are critical to ensure the charger receives sufficient sunlight throughout the day. Factors such as shading from nearby objects, the angle of the solar panels, and the geographical location must be carefully considered. Achieving the ideal placement can be challenging, as it often requires accurate alignment and adjustments to harness the most energy efficiently. A suboptimal location may result in reduced charging capacity, impacting the charger's performance and effectiveness in harnessing solar energy [6].

2.2. Charging multiple phones from a single battery

Charging multiple phones from a single battery presents several challenges. First, managing the distribution of power to ensure all devices receive an even charge without overloading the battery is complex. Proper voltage regulation and circuitry are necessary to prevent overcharging or undercharging. Balancing the power demands of multiple devices can lead to slower charging times. Additionally, the capacity of the battery limits the number of devices and charging cycles. Heat generation from simultaneous charging can also reduce battery lifespan and necessitates efficient heat dissipation [7]. Efficient power management and smart circuitry are key to addressing these challenges.

2.3. Monitoring and maintaining a solar charger

Monitoring and maintaining a solar charger involves various challenges. Firstly, continuously monitoring the system's performance can be complex, requiring data collection tools and sensors. Identifying issues like reduced panel efficiency, wiring problems, or battery degradation is crucial but may not always be straightforward. Maintenance can be challenging due to environmental factors like dust, dirt, and weather, which can affect solar panels and connections. Ensuring safety during maintenance procedures and addressing wear and tear over time is essential. Finally, understanding and performing timely maintenance tasks often demand technical knowledge and expertise, making regular upkeep a critical aspect of solar charger sustainability.

3. SOLUTION

The solar panel in this setup serves a dual purpose, as it not only generates power but also charges a battery for energy storage. The particle boron, a specialized monitoring device, plays a crucial role in this system [8]. It constantly tracks several key parameters, including the power being generated by the solar panel, the battery's charge level, and the power output from the charger that supplies power to various devices undergoing charging.

Using its cellular connectivity capabilities, the particle boron transfers all this data to a centralized database hosted by Firebase [9]. This database acts as a repository for all the information collected from each charging station within the system. Thanks to this remote data transmission, users can access the status of every charging station from a dedicated mobile app [10]. This feature ensures that individuals have real-time visibility into the performance and status of the entire charging infrastructure, providing a convenient and efficient way to manage and monitor the charging process.

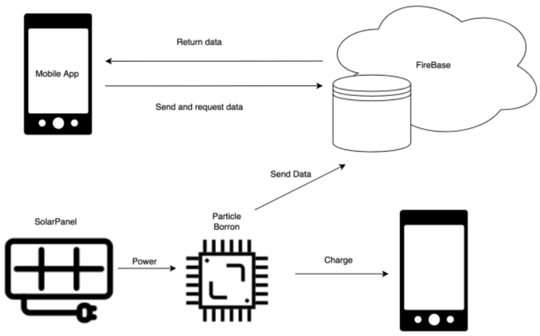


Figure 1. Overview of the solution

Device registration is a core component that plays a pivotal role in any modern and connected system, especially in the context of IoT (Internet of Things) and networked devices. This process involves adding new devices to a network or system, and it is fundamental for ensuring the seamless operation, security, and manageability of the devices within that network.

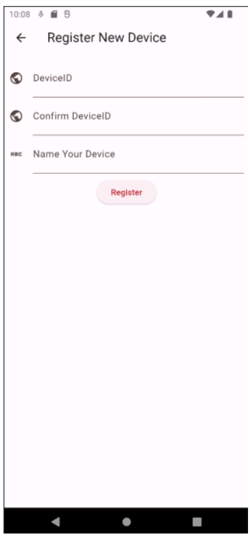
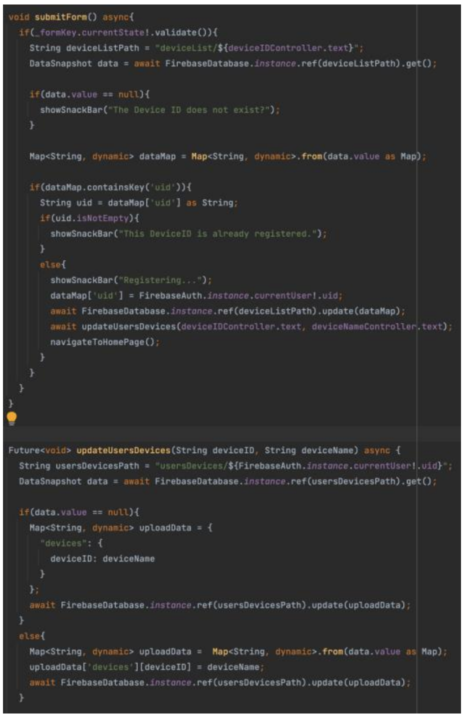


Figure 2. Register page



```dart
void submitForm() async{
  if(_formKey.currentState!.validate()){
    String deviceListPath = "deviceList/${deviceIDController.text}";
    DataSnapshot data = await FirebaseDatabase.instance.ref(deviceListPath).get();

    if(data.value == null){
      showSnackBar("The Device ID does not exist?");
    }

    Map<String, dynamic> dataMap = Map<String, dynamic>.from(data.value as Map);

    if(dataMap.containsKey('uid')){
      String uid = dataMap['uid'] as String;
      if(uid.isNotEmpty){
        showSnackBar("This DeviceID is already registered.");
      }
      else{
        showSnackBar("Registering...");
        dataMap['uid'] = FirebaseAuth.instance.currentUser!.uid;
        await FirebaseDatabase.instance.ref(deviceListPath).update(dataMap);
        await updateUsersDevices(deviceIDController.text, deviceNameController.text);
        navigateToHomePage();
      }
    }
  }
}

Future<void> updateUsersDevices(String deviceID, String deviceName) async {
  String usersDevicesPath = "usersDevices/${FirebaseAuth.instance.currentUser!.uid}";
  DataSnapshot data = await FirebaseDatabase.instance.ref(usersDevicesPath).get();

  if(data.value == null){
    Map<String, dynamic> uploadData = {
      "devices": {
        deviceID: deviceName
      }
    };
    await FirebaseDatabase.instance.ref(usersDevicesPath).update(uploadData);
  }
  else{
    Map<String, dynamic> uploadData =  Map<String, dynamic>.from(data.value as Map);
    uploadData['devices'][deviceID] = deviceName;
    await FirebaseDatabase.instance.ref(usersDevicesPath).update(uploadData);
  }
```

Figure 3. Screenshot of code 1

The provided code is used in a Flutter application and is responsible for device registration and association with user accounts in a Firebase Realtime Database. It validates user input, checks the existence of a device in the database, and updates user-device associations. It also displays relevant messages to the user. The submitForm function handles the device registration, and updateUsersDevices function manages the user's list of associated devices in the database. If the device is not in the database, it shows an error message. If the device is already registered, it displays a message indicating that. If the device is not registered, it updates the database with the user's ID and device information, and it updates the user's list of devices. Finally, it navigates the user to the home page of the application.

The DeviceDetailPage widget is designed to display all the data from a solar charger, including various details about the charger, such as voltage and potentially other information like location. It appears to provide a comprehensive view of the solar charger's information, making it a central point for users to access and understand the status and characteristics of the charger.

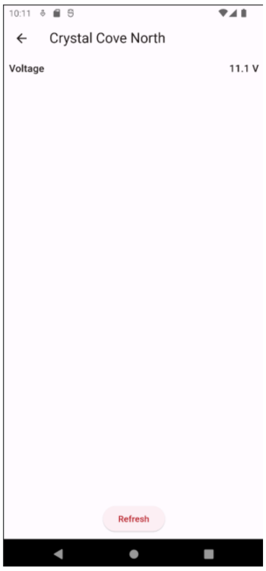
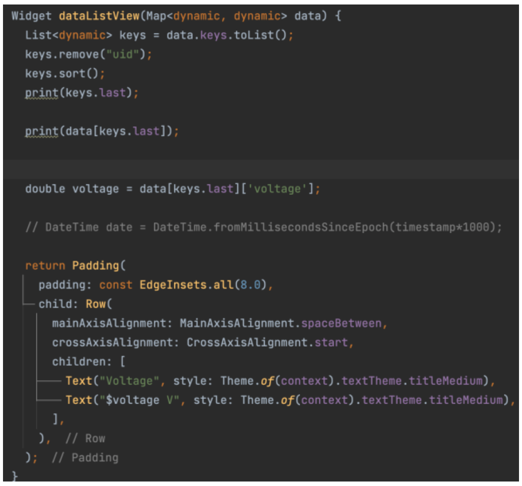


Figure 4. Crystal cove north



```
Widget dataListView(Map<dynamic, dynamic> data) {
  List<dynamic> keys = data.keys.toList();
  keys.remove("uid");
  keys.sort();
  print(keys.last);

  print(data[keys.last]);


  double voltage = data[keys.last]['voltage'];

  // DateTime date = DateTime.fromMillisecondsSinceEpoch(timestamp*1000);

  return Padding(
    padding: const EdgeInsets.all(8.0),
    child: Row(
      mainAxisAlignment: MainAxisAlignment.spaceBetween,
      crossAxisAlignment: CrossAxisAlignment.start,
      children: [
        Text("Voltage", style: Theme.of(context).textTheme.titleMedium),
        Text("$voltage V", style: Theme.of(context).textTheme.titleMedium),
      ],
    ), // Row
  ); // Padding
}
```

Figure 5. Screenshot of code 2

Thank you for the additional context. Given that this widget is used to display data about a solar charging station from a Firebase Realtime Database, it's clearer how the code operates. The widget is designed to show information about the charging station, such as the voltage, and it's expected that other station details like location might be displayed as well.

The code, as explained earlier, focuses on displaying the voltage data. If there are other fields or attributes about the charging station that you want to display alongside voltage, you can expand this widget to include those as well. Essentially, you can customize this widget to show a range of information about the solar charging station, making it a versatile component for presenting real-time data to users.

The home page of the application serves as the central hub where users can view a list of registered solar charger systems. These systems are typically used for harnessing solar energy and converting it into electrical power. The primary purpose of the home page is to provide users with an overview of the available solar charger systems and access to their details.

Here's how the home page works:

1. List of Registered Solar Charger Systems: The home page displays a list of solar charger systems that have been registered by users. These systems are typically associated with specific device IDs and may have names or other identifying information. Each system is presented as a card or list item.
2. Access to Details: Users can click on a solar charger system from the list to access more detailed information about that particular system. This detailed information may include data such as voltage, location, battery charge status, and other relevant details.
3. Register New Solar Charger System: The home page often includes an option for users to register a new solar charger system. This allows users to add new systems to the list, providing the necessary information such as device ID and a system name.
4. Navigation: The home page provides navigation options for users to move between different sections of the application, including accessing the details of individual solar charger systems, registering new systems, and possibly other features or settings.
5. User-Friendly Interface: The home page is designed to be user-friendly and visually appealing, making it easy for users to quickly identify and access the solar charger systems they are interested in.

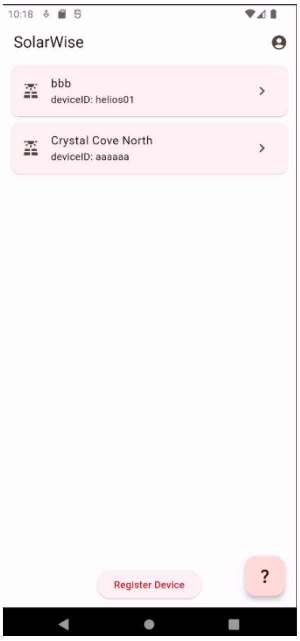


Figure 6. Solarwise

```dart
Widget devicesListView(Map<dynamic, dynamic> deviceListMap){
  List<dynamic> keys = deviceListMap.keys.toList();

  return Column(
    children: [
      Expanded(
        child: ListView.builder(
          itemCount: keys.length,
          itemBuilder: (context, index){

            String deviceID = keys[index];
            String deviceName = deviceListMap[keys[index]];

            return Padding(
              padding: const EdgeInsets.only(right:8.0, left:8),
              child: Card(
                child: ListTile(
                  title: Text(deviceName),
                  subtitle: Text("deviceID: $deviceID"),
                  trailing: const Icon(Icons.chevron_right),
                  leading: const Icon(Icons.solar_power),
                  onTap: (){
                    navigateToDeviceDetailPage(deviceID, deviceName);
                  },
                ), // ListTile
              ), // Card
            ); // Padding
          }
        ), // ListView.builder
      ), // Expanded

      Padding(
        padding: const EdgeInsets.all(8.0),
        child: ElevatedButton(
          onPressed: navigateToRegisterDevicePage,
          child: const Text("Register Device"),
        ), // ElevatedButton
      ), // Padding
    ],
  ); // Column
}
```

Figure 7. Screenshot of code 3

The provided code is a Flutter widget named devicesListView that's responsible for displaying a list of devices from a given deviceListMap. This widget generates a user interface where devices are listed, and each device is represented as a card with device information. Here's a detailed explanation of its functionality:

This widget takes a deviceListMap as input, which is expected to be a map where the keys are device IDs, and the values are device names. It extracts the keys from this map, which represent the device IDs.

In summary, the devicesListView widget creates a scrollable list of devices with their names and IDs, each represented as a card. Users can click on a device to access more detailed information, and they have the option to register a new device using the provided button. This widget is useful for presenting and managing a list of devices in a user-friendly manner within a Flutter application.

4. EXPERIMENT

4.1. Experiment 1

Localized Weather Conditions: Solar charging systems often rely on weather data to predict energy production. A potential blind spot in the program could be its ability to accurately account for microclimates or localized weather conditions. Testing how the system performs in areas with unique weather patterns, such as coastal regions with frequent fog or areas with sudden microbursts of rain, would reveal if the program adequately adjusts for these variables.

1. Baseline Data Collection: Start by collecting baseline data on a clear, sunny day. Record the efficiency of the solar panels as well as the weather conditions. This will serve as the control group.
2. Weather Conditions Variation: Over the course of several months, intentionally expose the solar panel system to various weather conditions. Ensure you have days with different weather patterns, such as sunny days, cloudy days, rainy days, and overcast days.
3. Efficiency Measurement: Continuously measure and record the efficiency of the solar panels during each weather condition. Efficiency can be calculated by measuring the energy output of the panels in kilowatt-hours (kWh) and comparing it to the expected output based on the panel's specifications.
4. Data Analysis: After collecting data for different weather conditions, analyze the results to identify trends and correlations between weather variables and solar panel efficiency. Look for patterns that indicate how temperature, sunlight intensity, cloud cover, and precipitation impact efficiency.

```
| Date       | Weather Condition   | Temperature (°C) | Sunlight
Intensity (lux) | Cloud Cover (%) | Precipitation (mm) | Solar Panel
Efficiency (%) |

|------------|---------------------|------------------|-------------
------------|-----------------|---------------------|---------------
----------|

| 2023-05-01 | Sunny               | 28°C             | 120,000
| 10%             | 0 mm                 | 90%                      |

| 2023-05-02 | Cloudy              | 22°C             | 40,000
| 75%             | 0 mm                 | 65%                      |

| 2023-05-03 | Rainy               | 18°C             | 10,000
| 95%             | 5 mm                 | 40%                      |

| 2023-05-04 | Overcast            | 20°C             | 30,000
| 100%            | 0 mm                 | 55%                      |

| ...        | ...                 | ...              | ...
| ...             | ...                  | ...                      |
```

Figure 8. Figure of experiment 1

Surprising Observations and Possible Explanations:

1. Rainy Days: You might find that the efficiency drops significantly on rainy days, which could be expected due to reduced sunlight. However, some surprising variations may occur. The surprising aspect could be how much efficiency decreases on different rainy days, which might be influenced by factors like the intensity of rain and cloud cover during the rain.
2. Overcast Days: Efficiency on overcast days may be better than expected. This could be due to a phenomenon known as the "edge of cloud effect," where the diffused sunlight on partly cloudy days can enhance efficiency.
3. Cloudy vs. Overcast Days: You might observe that the efficiency on cloudy days is sometimes higher than on overcast days, which might be due to variations in cloud thickness and how it scatters or blocks sunlight.
4. Temperature Effect: Unexpected efficiency fluctuations on sunny days might be due to the influence of temperature. Higher temperatures can reduce efficiency in some solar panel types, while others are less affected.

Biggest Effects on Results:

The biggest effects on the results are likely to be:

1. Sunlight Intensity: The intensity of sunlight has a substantial impact on solar panel efficiency. Cloud cover and rain reduce this intensity, resulting in lower efficiency.
2. Temperature: For some solar panels, temperature can significantly affect efficiency. High temperatures can lead to reduced efficiency.
3. Cloud Cover: Cloud cover directly affects how much sunlight reaches the panels. Thicker clouds block more sunlight, leading to lower efficiency.
4. Rain: Rain not only reduces sunlight intensity but can also affect the cleanliness of the panels, potentially reducing efficiency.

   Analyzing the data and identifying these factors' impacts would help in understanding how solar panel efficiency varies with different weather conditions and guide strategies for optimizing performance in varying weather patterns.

4.2. Experiment 2

Charging many devices simultaneously can strain electrical circuits, lead to slower charging speeds, and necessitate complex power management to ensure efficient and safe energy distribution.

In this experiment, a variety of devices will be charged to assess the solar charger system's ability to charge multiple devices simultaneously while the solar panels are disconnected. This scenario simulates nighttime or low-light conditions when solar energy isn't available. The selected devices will include a mix of smartphones, tablets, and laptops, each with known battery capacities and the capability to track their own battery percentages. By excluding the solar panels from the equation, the experiment will focus solely on the solar charger's power management and distribution capabilities. This setup will help evaluate the charger's performance in distributing stored energy to multiple devices efficiently and whether it can balance the power load effectively. The collected data will provide valuable insights into the system's capacity and reliability under different charging scenarios, with applications ranging from outdoor adventures to emergency situations.

Device Type	Device Battery Capacity (mAh)	Initial Battery Percentage (%)	Charging Time (minutes)
Smartphone	3000	20%	
Tablet	5000	10%	
Laptop	40000	5%	

Figure 9. Figure of experiment 2

Surprising Observations and Possible Explanations:

1. Device Type Variance: It's possible that charging times for different device types vary significantly. For example, laptops may take longer to charge than smartphones and tablets due to their higher battery capacity. This would not be surprising but is an important observation.
2. Initial Battery Percentage Influence: The initial battery percentage of each device might have a noticeable effect on charging times. Devices starting with lower initial percentages may take longer to charge to the same target percentage. This could be an interesting point of analysis.
3. Charging Efficiency: Surprises might occur if the charging times are significantly longer or shorter than expected based on the device specifications and the solar charger's capacity. Unexpectedly long charging times could indicate inefficiencies in the charging process.

Biggest Effect on Results: The type of device and its initial battery percentage are likely to have the most substantial impact on the results. Devices with higher battery capacities will generally take longer to charge, and devices with lower initial battery percentages will also take longer to reach a specific charging level. The solar charger's capacity and power output will also play a significant role, as it needs to provide sufficient power to multiple devices simultaneously. Overall, understanding the devices' power requirements and the charger's output capacity is crucial for accurate charging time predictions.

5. Related Work

A portable solar charger is designed for mobility, making it ideal for outdoor activities. It's compact, lightweight, and often includes a built-in battery. However, it has limited capacity and is primarily suitable for charging small devices like smartphones. In contrast, a stationary solar charger is larger and permanent, often mounted on rooftops or in outdoor locations. It typically has higher capacity, can charge multiple devices simultaneously, and may be grid-connected. Stationary chargers are more efficient and suitable for residential or commercial use, while portable chargers are convenient for on-the-go, single-device charging, and outdoor adventures. The choice depends on your specific requirements and mobility needs.

A wired charger connects to a device using a physical cable. It offers consistent and efficient charging with a direct connection, but it can be less convenient due to cable clutter, wear and tear on cables, and the need for a physical plug point. In contrast, a wireless charger uses electromagnetic induction to charge devices without physical connections. It's convenient, reducing cable clutter, but may have slower charging speeds and requires precise alignment of the device on the charger. Wireless chargers often use Qi technology and are becoming more common for smartphones and other devices, offering a cable-free and clutter-free charging experience.

Charging a lithium-ion battery using a solar panel differs from a lead acid battery in several key ways. Lithium-ion batteries are more energy-efficient and have a longer cycle life, making them ideal for solar charging. They charge quickly and store energy efficiently. In contrast, lead acid batteries are less efficient and have a shorter cycle life. Solar charging may take longer, and the batteries are bulkier. Lithium-ion batteries also require more sophisticated charge controllers to avoid overcharging, while lead acid batteries are more forgiving. Overall, lithium-ion batteries are a superior choice for solar charging due to their efficiency, longer life, and lighter weight, even though they are more expensive.

6. CONCLUSIONS

Solar charger systems are a valuable and eco-friendly way to generate electricity from the sun. However, they also have certain limitations and challenges that need to be considered. Limited Use at Night: Solar power generation ceases at night, which means additional energy sources or energy storage solutions are required for 24/7 power supply [14]. A way to circumvent this problem is to use a bigger battery and solar panel to charge the battery. Efficiency: Solar panels have limited energy conversion efficiency, typically around 15-20%. This means that a significant amount of sunlight is not converted into electricity. As time goes on solar panels become more energy efficient and cost effective.

In conclusion, solar charger systems offer a promising path towards sustainable and clean energy generation [15]. While they have limitations, including weather dependency and initial costs, ongoing advancements in technology and energy storage solutions continue to make solar power an increasingly viable and environmentally responsible choice for individuals and organizations worldwide.

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