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Challenges of energy storage devices in off-grid solar photovoltaic cold-chain systems for COVID-19 vaccine preservation in developing countries

Abstract

The development of Covid-19 vaccines is an immense achievement in the 21st century. However, the complex and super-cold storage requirements for the vaccine preservation in the developing countries and remote areas in the developed countries have been a great challenge. In such low-income countries and the areas, off-grid solar systems are alternatively used but the efficiencies of the solar systems have been significantly hampered by the energy storage system characteristics and capacity. However, the developments of cutting-edge battery technologies and energy storage systems such as lithium batteries, vanadium flow batteries, sodium-ion and solid-state batteries are offering a glimmer of hope for the storage of energy generated through solar power. Nonetheless, the high cost of the storage systems presents a great number of barriers to widespread adoptions and applications of the highly efficient batteries, especially in the low-income countries. In this paper, **the challenges of energy storage devices** in off-grid photovoltaic cold-chain system **for the preservations of the covid-19 vaccines in the developing countries are presented and discussed. Also, different strategies of combating the challenges are provided. It is believed that such** leap into an improved battery storage capacity and quality while lowering the cost significantly will facilitate the move towards the effective decarbonisation of power generation which will contribute to greater resilience and efficiency of solar powered refrigeration systems.

Keywords batteries, cold chain, Off-grid PV system, challenges, COVID-19 vaccines, developing countries

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Introduction

Indubitably, one of the greatest achievements of the 21st century is the development of Covid-19 vaccines. The first coronavirus vaccines developed by Pfizer and BioNTech were found to be 90% effective but required an ultra-low temperature freezer between -80ºC to -60ºC (-112ºF to -76ºF) to be stored (Figure 1). Therefore, the breakthrough was impeded by the requirement of the ultra-cold storage system, the distribution chain to the rural healthcare systems and nursing homes, especially in the developing nations. Also, such a super-cold temperature is an exceptionally low temperature by medical standards coupled with the fact that most hospitals can only refrigerate at around -2ºC to -8ºC (which can cause the vaccines spoilage after five days of production). Using similar technology in 2020, Shingles vaccine was developed but it is required to be stored at -50ºC (-58ºF) while Moderna's vaccine requires -20ºC (-4ºF) to be refrigerated (Figure 1). These set of vaccines do not need to be frozen at such ultra-low temperatures as the vaccine developed by the Pfizer and BioNTech. Nevertheless, the need for super-cold storage systems for the COVID-19 vaccines was a great obstacle not only for the developing nation but also for most sophisticated hospitals in the developed countries. Aside such requirement, there are limited infrastructures in place for the transportations and distributions of the vaccines. Additionally, the costs of cold storage and transport account for four-fifths of the total cost of the vaccination programs. Therefore, developing better approaches would cut down the costs, improve access and potentially save millions of lives. Consequently, a distribution network of ultra-cold freezers and mobile vaccination clinics was developed to reach underserved and remote areas in many states of the world (Figure 1). Developing such ultra-cold freezers was a big challenge as well as a huge opportunity for the medical freezer suppliers. Therefore, vaccines requiring less stringent storage conditions was largely in demand. Consequently, Johnson & Johnson and Novavax Inc developed coronavirus vaccines which can be stored at -2ºC to -8ºC (17.6ºF - 28.4ºF.), the temperature of a regular refrigerator while a US biotech Inovio introduced Covid-19 vaccine that could be kept at room temperature.

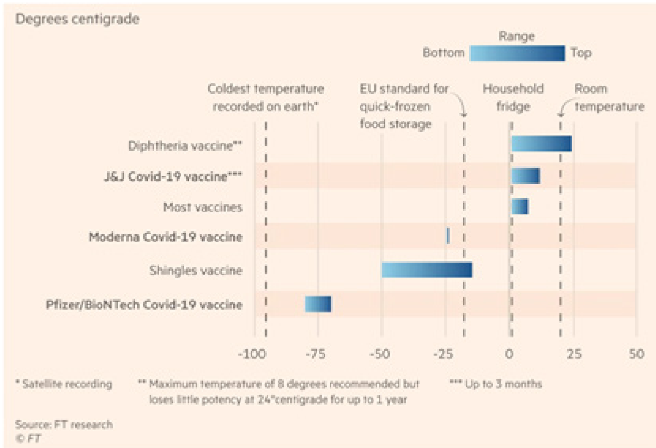

Figure 1 Coronavirus vaccines developments and their required storage temperatures.

The cold chain requires three major pieces of infrastructure, namely, airplanes, trucks and cold storage warehouses (Figure 2). The connection and utilizations of the infrastructure largely depends on the location of the vaccine production and the points of demand. Transportation and distributions of the vaccines in most developing countries are serious bottleneck due to lack or inadequate transportation network, uncertified airports for plane landing and weak cold-chain infrastructure. It was revealed that about 25% of vaccines are degraded by the time they arrive at their destination. Exposing vaccines to temperatures outside its range causes damage to the vaccines even at a high spoilage rate. This results in an immense financial loss and a huge delay in vaccinations which consequently increases the deaths rate and causes slow economic outputs. This odious situation is due to the fact that the investments in cooling technologies and cold-chain infrastructure lags behind the high-speed leap of vaccine development. Additionally, the fortification of the cold chain for the distributions, preservations and storage of the vaccines requires constant supply of electricity. Such requirements are difficult to attain from the grid systems in most developing countries and remote areas where there is no access to the utility grid. Therefore, in such nations, off-grid solar systems are widely used to meet their energy demands. Consequently, UNICEF targeted to install 65,000 solar-powered cold fridges in low-income countries by the end of 2021 (The Financial Times, 2021). Undoubtedly, such need for the solar refrigeration system is a big advance for better infrastructures, not just for Covid-19 vaccines but also for other vaccines of similar requirements. However, the efficiencies of the solar systems have been seriously hindered by the energy storage characteristics and capacity of the available batteries in the low-income countries. This is because, in most developing countries, lead acid batteries are widely used for energy storage in On-grid with batteries, Off-grid and hybrid solar systems. However, these batteries are not the best choice for use in the cold-chain required off-grid PV systems. Moreover, other types of batteries such as lithium-ion batteries are too expensive to procure by the low-income countries' end-users. Additionally, since the knowledge and technology of lithium-ions batteries are not well matured like the lead acid batteries in such countries, there are issues on the applications and integration/compatibility of relatively new emerging batteries for the solar refrigeration systems. Therefore, in this work, the challenges of energy storage devices in off-grid photovoltaic cold-chain system for the covid-19 vaccine preservations in the developing countries are presented and discussed.

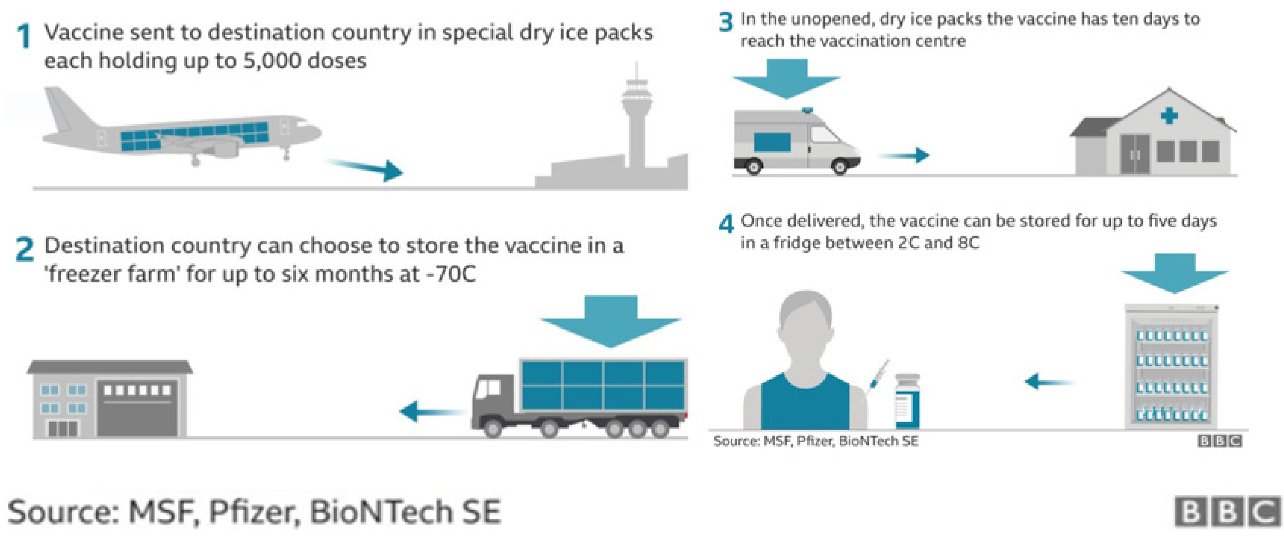

Figure 2 Transportation chain of vaccination against coronavirus.

Solar energy, photovoltaic systems design and integration

Solar energy is an abundantly available, absolutely free and virtually an inexhaustible renewable source of energy which produces little or no greenhouse gases, notable reductions in the consumption of the finite fossil fuels, carbon footprint and worrying climate changes. It has been widely utilized for electrical power generation, water heating, heating of buildings, **ventilation, cooking, lighting, transportation, etc.** In an installed solar power system, electric current in form of direct current flows from the solar panels through the solar charge controller and the bank battery bank, before it is finally converted into alternating current by an inverter in order to power loads operating on alternating current. In such power set-up, the *solar panels* convert light from the sun to electricity through their solar cells while the *solar charge controller* (charge regulator or battery regulator) regulates the rate of current being delivered to the battery bank, and protect the batteries from overcharging and over-discharging. The *batteries* which act power backups device stored generated energy from the solar powers while the *inverter* converts the generated direct current (DC) from the solar panels to alternating current (AC) to power the AC loads connected to the solar PV system. In all solar systems, it is required to include AC and DC safety disconnects.

The installations of solar power system are of three types namely On-grid (grid-connected, grid-tie or grid-feed, utility-interactive, grid intertie, and grid backfeeding) PV system, Off-grid (stand-alone) PV system and Hybrid PV system. Each of these types of the solar PV system has a unique setup which has direct impact on the equipment used, costs and savings, and the ease or complexity of installation. However, our focus in this paper is the Off-grid (stand-alone) PV system.

Off-grid/stand-alone solar pv system

Off-grid (stand-alone) PV system as the name implies is not a grid-connected system as shown in Figure 3. Therefore, such system needs energy storage devices in form of batteries to function. It is an ideal and very useful system for rural or remote areas that are not connected to the grid system. This solar power system is suitable for small electric loads, highly beneficial in a place where there is no access to the utility grid and where the solar systems is found to be cheaper than extending power lines to certain remote areas. It can be seen as an energy self-sufficient system which is a form of energy security. Such a system is not affected by power failures on the utility grid. However, this system can only power the connected loads based on the amount of energy that the battery can supply. Therefore, one of the major components in off-grid system is the battery and such must be given good considerations. As pointed out previously, in all solar systems, it is required to include AC and DC safety disconnects, and for off-grid solar systems, one additional DC disconnect is installed between the battery bank and the off-grid inverter. This is used to switch off the current flowing between these components for the sake of maintenance, troubleshooting and protection against electrical fires. Examples of Off-grid solar PV system such as solar water pumping systems, solar home/street lighting systems, solar powered refrigerator etc.

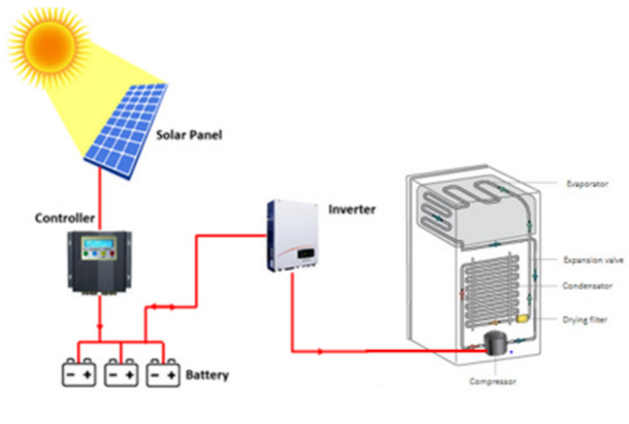

Figure 3 Off-grid/Stand-alone PV vapour compression refrigeration system.

As good as the renewable energy source is, its applications especially in off-grid (standalone system) in the developing countries have been serious impeded by energy storage systems. While the cost of solar panels and other connected components have decreased significantly over the past decade, the prices of solar batteries for energy storage are increasingly high coupled with the fact that batteries can only able to supply electricity for a few hours based on their designed capacities. The high capital cost of batteries is the main barriers to the deployment of the solar systems in the developing countries. For example, in a typical solar project in Nigeria, the cost of battery accounts for over 50% of the project's capital expenditure.

Challenges of batteries in solar powered refrigeration systems

The key to unlocking the full potential of the solar refrigeration systems is in the developments of highly efficient and low-cost solar batteries. This is because, one of the biggest challenges with solar vaccine storage system in the developing countries is the batteries which are still quite costly and capacity limited. Therefore, development of an effective cold-chain solar system requires technological innovation and breakthrough in the capacity, long-lifespan, low-cost, high-security in energy storage systems. In the energy storage systems, there are four major types of batteries which are lead-acid, lithium-ion, nickel cadmium, redox flow and sodium sulphur batteries. Their technology maturity, efficiencies, power rate, service life, cost and applications are presented in Table 1.

Lead acid batteries **(**flooded and sealed types**)** can be classified as either shallow cycle or deep cycle depending on the intended function and safe depth of discharge. They are common choice and widely used for energy storage in on-grid, off-grid and hybrid solar PV systems. However, this type of batteries is not the best choice for off-grid solar system because the standalone systems largely depend on the lifecycle cost of the systems, which are majorly driven by the cost and the frequency of exchanging the batteries.[1] Additionally, the batteries have high self-discharge rate, frequent maintenance requirement, higher environmental impact (lead poisoning accounts for at least 0.6% of global diseases (WHO, 2009)), low cell voltage, slow charging, seriously affected by longer durations in low states of charge, short lifespan, low discharge power, not good lifetime when deep cycled, age faster when kept in a low state of charge, etc. Moreover, such batteries have possible leakage of acid due to damage or spillage, noxious fumes given off during the charging process, low energy density (energy capacity per kg of weight), relative slow charging and their heavy weight.[1] Although, this type of batteries is the cheapest solar batteries, for the low-income countries, they are expensive and such makes the cost of energy storage system too high to afford in those regions. Therefore, there is a serious and urgent need for highly efficient, environmentally friendly, inexpensive energy storage systems especially for low-income countries.

Table 1 Comparative analysis of various types of electrochemical energy storage technologies[15]

Category		Technology maturity	Efficiency (%)	Power rate(MW)	Service life(year)	Cost (¥/kW)	Application
Lead-acid battery	Traditional lead-acid battery	Commercial	70-85	0-20	5	500-1000	Transportation, communication, national defense, aviation, etc
	Lead-carbon battery	Demonstration	70-85	0-20	8-May	6400-10400	Peak load shifting, reserve power supply, etc
Lithiumion battery	Lithium iron phosphate battery	Demonstration Commercial	90-95	0-32	8	3200-5800	All aspects of generation, transmission, distribution and use, including stabilizing renewable energy output, frequency regulation auxiliary service, peak load regulation, power battery
	Lithium titanate battery	Demonstration Commercial	>95	0-32	10	9000	
	Nickel-cobalt-manganese lithium battery	Demonstration Commercial	>95	0-32	8	4000-5000	
Redox flow battery	Vanadium redox flow battery	Demonstration	75-85	0.03-10	15	17500-19500	Peak load regulation large-scale grid-connected renewable energy, UPS, emergency power supply, etc
	Zinc bromine flow battery	Demonstration	75-80	0.05-2	10	12500-15000	The user side
Sodium sulfur battery		Commercial	87	0-50	15	13200-13800	Load regulation, peak load shifting, large-scale grid-connected renewable energy, power quality, etc

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Nickel-Cadmium batteries have several advantages over lead acid batteries such long life, low maintenance, excellent low temperature capacity retention, high durability, unique ability to function at extreme temperatures, survivability from excessive discharges, low maintenance and non-critical voltage regulation requirements. Unfortunately, cadmium is a highly toxic element with high environmental impact if not properly disposed. Also, they are very expensive and available in limited quantities.

Flow or redox flow batteries offer high efficiency, with possible depth of discharge of 100% but with low energy density which make them quite large in order to store a significant amount of energy. Their large size makes them a costly and impractical option for solar refrigeration systems and household applications. Consequently, there is a need for the applications of alternative energy storage systems which have long cycle life, high safety, low toxicity, low self-discharge rate, lightweight, lower environmental impact, maintenance free and a good lifetime when deep cycled. Hence, lithium-ion batteries are developed.

Lithium-ion batteries are types of rechargeable batteries which uses the reversible reduction of lithium ions to store energy. This class of batteries are of different types such as lithium cobalt oxide, lithium nickel oxide, lithium nickel cobalt aluminium oxide, lithium nickel cobalt magnesium oxide, lithium manganese oxide, lithium nickel manganese cobalt oxide, lithium-iron-phosphate, etc.[2,9–14] In this group of high energy density batteries, lithium cobalt oxide ($LiCoO_2$) battery has been applied as energy storage system but its major drawbacks such as accelerated aging at high currents and low thermal stability when operating in temperatures between 100 and 150°C,[12] high risk of thermal runaway or combustion and low self-discharge rate, high have limited its wide range of applications Therefore, lithium nickel oxide ($LiNiO_2$) battery was produced by partial substitution of cobalt in lithium cobalt oxide with nickel in order to reduce the cationic disorder in lithium cobalt oxide. However, the lithium nickel oxide battery is thermally disturbed even more thermally unstable than lithium cobalt oxide.[11] Lithium nickel cobalt aluminium oxide ($LiNi_xCo_yAl_zO_2$) battery is a widely applied type of lithium battery but it causes fast capacity decrease rates at elevated temperatures of operation.[11]Also, the batteries have high risk of thermal runaway. Lithium manganese oxide ($LMnO_2$) battery comes with change in the structure during the lithium-ion extraction. However, such modification has a negative impact on cycle life of the battery. Also, the magnesium in the type of battery tends to dissolve into the electrolyte when it is not cycled.[14] Good cycle stability at 50°C is achieved in Lithium nickel manganese cobalt oxide (LiNiMnCo) battery but comparatively high cost, risk of thermal runaway, voltage instability and the unique voltage profile, which lacks the expected flat region found in the cells of thermal, electrical and chemical stable lithium batteries such as lithium iron phosphate batteries, are some of the significant issues in the applications of the LiNiMnCo battery.[2] Hence, lithium-iron-phosphate battery is highly considered and widely applied. The lithium iron phosphate ($LiFePO_4$) **battery** is a more mature and stable lithium-ion technologies[9] with excellent thermal and chemical stabilities as well as a very good cycle life and power capability. It is found to be the safest lithium battery type because it has the safest chemistry of all the lithium batteries. It is free from thermal runaway risk because it is cobalt-free and nickel-free. However, the needs for an affordable and inexpensive energy storage have generated the development of sodium-ion batteries.

Sodium-ion batteries are among the newly emerging battery technology with the same general operating principles as lithium-ion batteries but the lithium ions are replaced with sodium ions. The batteries come with promising cost, safety, sustainability and performance advantages over the current commercialised lithium-ion batteries.[16] However, their present immature supply chain is inhibiting their opportunities for taking a global market-leading role in energy storage technology.

Emerging energy storage integration and proper installations barriers

Despite the benefits of the energy storage devices (lithium-ion and sodium-ion batteries), there remain a number of barriers to the widespread adoption of the energy storage system in the low-income countries. Since the lithium iron phosphate and sodium-ion batteries are relatively new emerging energy storage devices especially to developing countries as compared with lead-acid battery (which has mature/well-understood technology and knowledge about its installations and application), their proper installations and the specific precautions for their usage are not well known to most technicians and installers in the countries. Due to the lack of knowledge about the compatibility of the energy storage systems with the other solar power components, the installations of the batteries come with several issues especially in developing countries. The common problems about the use, compatibility and installation of these types of batteries for stand-alone and hybrid solar power systems include lack of

1. selection of proper solar charge controller which are meant for or compatible with the lithium iron phosphate and sodium-ion batteries
2. parameter setting of the charging and discharging voltage and current of the charge controller for these types of batteries
3. adoption of the solar inverter that is compatible with the batteries
4. usage of recommended charger for the grid-connected systems
5. installation of battery management system in the batteries, etc.
6. It should be noted that these batteries are more susceptible to damage under certain conditions such as overcharging, undercharging and overheating if the above issues are not properly resolve before and during installations.

Combating the challenges through emerging battery technologies

While the above outline challenges are significant, they are not insurmountable. The developments of cutting-edge battery technologies and energy storage systems such as lithium iron phosphate, sodium-ion, vanadium flow, and solid-state batteries are offering a glimmer of hope for solar energy storage systems. The various ways to combat the issues are outlined as follows:

Introduction of Lithium iron phosphate batteries in the solar cooling system

Lithium iron phosphate battery as a type of deep-cycle batteries, is one of the most popular types of lithium batteries for various solar applications in the recent years. Lithium iron phosphate batteries have the merits of long charge durations. They are ideal choice for an off-grid photovoltaic system. This is due to their high energy density (160 Wh/kg(cell)), good energy efficiency, long cycle life, relatively low cost compared to li-ion, high safety, low toxicity, low risk of thermal runaway or combustion (since it is cobalt-free and nickel-free), low self-discharge rate, high capacity, lightweight, lower environmental impact, maintenance free, high cell voltage, fast charging, high temperature stability, unaffected by longer durations in

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low states of charge, high discharge power, a good lifetime when deep cycled, etc. Lithium iron phosphate batteries have 4 to 5 times the cycle life and 8 to 10 times the discharge capacity of conventional lithium batteries. At the same weight, $LiFePO_4$ batteries are 30-50% lighter than ordinary lithium batteries. The total lifespan (cycles) is about 2000-10,000 cycles with the capacity still reaching 80%, which is 6-7 times higher compared to lead acid batteries over the entire lifetime.[1] $LiFePO_4$ are lighter, more durable and have higher discharge power than regular or traditional lithium batteries. It offers a longer lifespan than lithium-ion batteries. The long cycle life of $LiFePO_4$ has been seen as a major advantage because the battery can typically go through thousands of charge cycles (which make them to be used for a longer time before any considerations for its replacement). $LiFePO_4$ batteries also have a high energy density (which allows them to store a large amount of energy in a compact size). The battery is environmentally friendly as it does not have any hazardous or noxious substance. They are safer and more stable alternative to other lithium-ion batteries, such as lithium cobalt oxide ($LiCoO_2$) batteries. They are less prone to thermal runaway as in the case of lithium-ion batteries. They are more portable having specific volume and weight of 65% and 1/3 of lead-acid batteries, respectively.[5] They are very good solar power system option for remote areas, where safety awareness is very low. Additionally, these advantages have made the batteries to be highly valued in energy storage technology, backup power system, vehicle use utility-scale stationary applications, electric vehicles, commercial batteries, solar power applications as well as other renewable energy storages, etc.

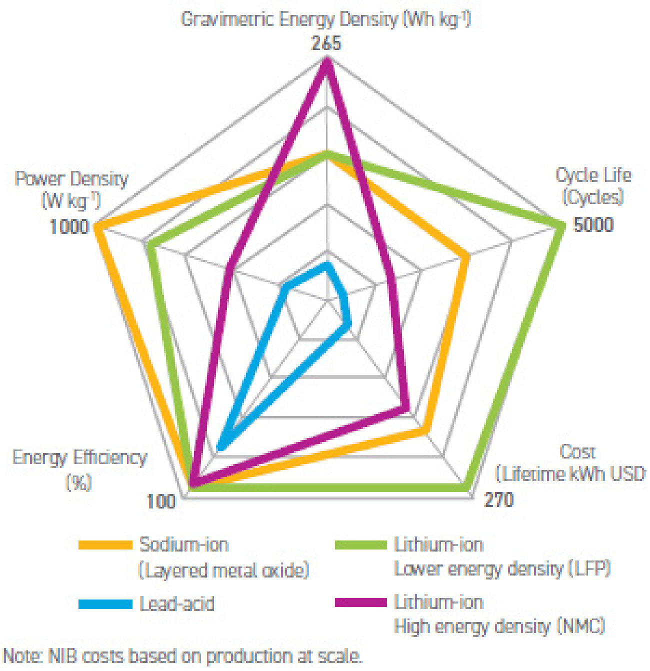

Figure 4 A comparison of selected figures-of-merit for sodium-ion, lithium-ion and lead acid batteries.[16–20]

Applications of nanotechnology in the energy storage system

The nanostructured materials architecture has provided an excellent solution to overcome several basic difficulties in standard battery materials.[21] The applications of nanomaterials have shown a great deal of promise in improving energy storage systems, such as batteries and supercapacitors and enhancing solar cell efficiency. In fact, the various challenges in the energy sector, including energy conversion, storage, and efficiency can be addressed through nanotechnology. Therefore, the nanotechnology-based techniques have revealed great deal of benefits for enhanced safety and materials' properties, cyclability, power density, and energy.[21, 22]

Adoption of Sodium-ion batteries in the cold-chain system

Sodium-ion batteries are among the latest emerging batteries that have attractive prospects for stationary storage applications where lifetime operational cost, not weight or volume, is the overriding factor.[17] The inherent affordable cost, safety, abundant availability of their raw materials, enhanced battery energy density, cycle life sustainability, inherent potentiality of carbon-neutral energy storage solutions, ease of transportation, more attractiveness for safety-critical applications, rapid scalable energy storage which are suitable for an expanding list of applications, and performance advantages over current commercialised lithium-ion and lead-acid batteries (Figure 4) have provided them huge potentials for business opportunities and benefits for a wide range of applications and commercialization.[16,17] They are well suited for applications where the key considerations are cost, sustainability, power density, temperature range and safety, rather than energy density.[16] The widely available and inexpensive raw materials for the batteries and a rapidly scalable technology based around existing lithium-ion production methods have made them to be more advantageous than lithium-ion batteries. Also, this type of energy storage device is free from safety, environmental and ethical issues associated with lead-acid and lithium-ion batteries.[16]

Government interventions and financial supports in research and developments

It is believed that with government incentives, leasing options, financing, and advancements in energy storage technology, solar power refrigerating systems will become easily accessible and viable option for the end-users especially in the developing countries. Additionally, with many companies and individuals investing in research to create more efficient and cost-effective energy storage solutions, it is predicted that the installed costs of energy storage device could further decrease by between 50% and 66% by 2030, which is a substantial increase in the market share for storage [15]. Also, by creating a more supportive environment by the policymakers for solar storage systems through updating regulations and policies that will greatly accommodate renewable energy sources. Additionally, provision of incentives and subsidies by the government/policymakers for individuals and organizations that invest in the local productions of the solar energy storage systems. The local productions must aim at high quality energy storage systems with significant reduction in the cost. This can be achieved through improving technical performance, establishing efficient supply chains and achieving economies of scale. These proposed solutions will obviate the challenges of the energy storage devices.

Conclusion

In this work, it has been shown that the challenges of solar energy storage present significant constraints to its adoption especially in off-grid refrigeration system for the storage of COVID-19 vaccine. However, the development of cutting-edge battery technologies and energy storage systems such as lithium batteries, vanadium flow batteries, and solid-state batteries is offering a glimmer of hope for solar energy storage. Nonetheless, the high cost, system characteristics and capacity of the storage systems present a great number of barriers to widespread adoption and applications of the batteries, especially in the low-income countries. In order to mitigate the challenges, the following solution strategies are proposed:

1. Provisions of government incentives, leasing options, subsidies, financing and advancements in energy storage technology with a highly concentrated target towards making solar power refrigerating systems easily accessible and become viable option for the end-users especially in the developing countries.
2. Development well organized programs geared towards encouraging many companies and individuals to invest in the research and developments of more efficient and cost-effective energy storage solutions.
3. Creation of a more supportive environment (by the policymakers) for sustainable energy storage devices and solar powered systems through updating regulations and policies that will greatly accommodate renewable energy sources.
4. Provision of incentives and subsidies by the government and policymakers for individuals and organizations that invest in the local productions of the solar energy storage systems.
5. Setting up of effective policies and programs that focus on improving technical performance, establishing efficient supply chains and achieving economies of scale.
6. It is therefore believed that if the proposed solutions are adopted, there will be significant reduction in the challenges of the energy storage devices. Such solutions will make solar power refrigerating systems easily accessible and become viable option for the end-users in the developing countries.

Acknowledgments

None.

Conflicts of interest

There is no conflict of interest.

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