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Energy Storage for Off-Grid Renewables in India

Understanding options and challenges for entrepreneurs

RISHABH JAIN, KARTHIK GANESAN, & RAJEEV PALAKSHAPPA
Team Supervisor & Editor: ARUNABHA GHOSH

ceew.in/publications

Thapar House
124, Janpath
New Delhi 110001
India

Tel: +91 11 40733300

info@ceew.in

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Authors
Rishabh Jain
Karthik Ganesan
Rajeev Palakshappa

Team Supervisor and Editor
Arunabha Ghosh

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A report on Energy Storage for Off-Grid Renewables in India.

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The Council on Energy, Environment and Water (CEEW) is an independent, not-for-profit, policy research institution. CEEW works to promote dialogue and common understanding on energy, environment and water issues in India, its region and the wider world, through high quality research, partnerships with public and private institutions, engagement with and outreach to the wider public. For more information, visit http://www.ceew.in.

Council on Energy, Environment and Water
Thapar House, 124, Janpath, New Delhi 110001, India

ABOUT CEEW

The Council on Energy, Environment and Water is an independent, not-for-profit policy research institution. CEEW addresses pressing global challenges through an integrated and internationally focused approach. It does so through high quality research, partnerships with public and private institutions, and engagement with and outreach to the wider public. In June 2013, the International Centre for Climate Governance **ranked CEEW 15th globally** in its first ranking of climate-related think-tanks and **number 1 in India**.

In under three years of operation, CEEW has: published the 584-page National Water Resources Framework Study for India's 12th Five Year Plan; written India's first report on global governance, submitted to the National Security Adviser; undertaken the first independent assessment of India's 22 gigawatt solar mission; developed an innovation ecosystem framework for India; facilitated the $125 million India-U.S. Joint Clean Energy R&D Centre; worked on geoengineering governance (with UK's Royal Society and the IPCC); created the Maharashtra-Guangdong partnership on sustainability; published research on energy-trade-climate linkages (including on governing clean energy subsidies for Rio+20); produced comprehensive reports and briefed negotiators on climate finance; designed financial instruments for energy access for the World Bank; supported Bihar (one of India's poorest states) with minor irrigation reform and for water-climate adaptation frameworks; and published a business case for phasing down HFCs in Indian industry.

Among other initiatives, CEEW's **current projects include**: developing a countrywide network of renewable energy stakeholders for energy access; modelling India's long-term energy scenarios; supporting the Ministry of Water Resources with India's National Water Mission; advising India's national security establishment on the food-energy-water-climate nexus; developing a framework for strategic industries and technologies for India; developing the business case for greater energy efficiency and emissions reductions in the cement industry; and a multi-stakeholder initiative to target challenges of urban water management.

CEEW's **work covers all levels of governance**: at the global/regional level, these include sustainability finance, energy-trade-climate linkages, technology horizons, and bilateral collaborations with China, Israel, Pakistan, and the United States; at the national level, it covers resource efficiency and security, water resources management, and renewable energy policies; and at the state/local level, CEEW develops integrated energy, environment and water plans, and facilitates industry action to reduce emissions or increase R&D investments in clean technologies. More information about CEEW is available at: http://ceew.in/.

ABOUT THE AUTHORS

RISHABH JAIN

Rishabh Jain is a Research Analyst at CEEW. At CEEW, Rishabh focuses on renewable energy policy, technology and applications, with a keen interest in developing solutions that deliver improved energy services to the poor. He has contributed to CEEW's research and policy projects on assessing the progress of Concentrated Solar Power (CSP) projects during Phase I of India's National Solar Mission, preparing case studies on Results-Based Financing (RBF) to promote off-grid energy access in India for World Bank's Energy Sector Management Assistance Program, investigating the case to scale up off-grid renewable energy solutions through effective networks and policy formation in the clean energy sector in India.

His experience also includes meeting and talking to a range of stakeholders in the off-grid supply chain, including end-users of solar off-grid appliances, to understand the complexities and opportunities in the sector.

Previously he has worked as a research intern at Indian Institute of Science, Bangalore and co-authored a research paper assessing the variation of solar energy in India. He has also worked as an intern at ONergy – a startup aimed to provide innovative energy solutions to the BoP in West Bengal. His work included conducting surveys to understand the local dynamics of the village.

Rishabh holds a B.E. in Mechanical Engineering from Birla Institute of Technology, Mesra. He led the Entrepreneurship Development Cell at his college for one year. He was also a member of Student Alumni Relations Cell (SARC) in college. He is fluent in English and Hindi and speaks Bengali at intermediate level.

KARTHIK GANESAN

Karthik Ganesan is currently Senior Research Associate at CEEW. His areas of focus are economic valuation of energy externalities, energy efficiency and sustainable waste management. He has been a consultant with the Asian Development Bank providing technical assistance on diverse projects ranging from Carbon Capture and Storage (CCS) and health impacts of conventional thermal power. He has also worked in the private sector specialising on new generation optimisation and forecasting techniques and is currently exploring a business case to promote a shift to energy saving practices in the cement industry. He is also taken lead in conceptualising some of CEEW's work on developing a framework to determine strategic industries and technologies for India's future, with a focus on resource security and economic security.

He has a Masters in Public Policy from the Lee Kuan Yew School of Public Policy, Singapore (2012). He has a B.S. and M.S. in Civil Engineering and Infrastructure from the Indian Institute of Technology, Madras (2006).

RAJEEV PALAKSHAPPA

Rajeev Palakshappa works with CEEW as an Associate Fellow on Business-and Innovation-related projects. Rajeev has worked on facilitating stakeholder engagement during the Joint Clean Energy R&D Center Funding Call round as well as conducting & overseeing research for CEEW's work on solar, including building a case and business strategy for a countrywide alliance on energy access and off-grid renewable energy. He is one of the co-authors of the reports on solar.

Rajeev's broader experience covers a mix of project management and consulting across energy and climate change related issues. His experience broadly covers working with multi-stakeholder groups across government, business and NGOs. This includes working on the implementation of the EU Emissions Trading Scheme in the UK; helping Deloitte New Zealand establish a climate change and sustainability service offering; and working with The Climate Group, a UK based NGO, in India on corporate engagement and developing awareness of climate change related challenges amongst the finance sector. He has a particular strength in quickly developing constructive relationships amongst broad groups of stakeholders.

Rajeev holds an Honours degree in Managements Systems and Finance. He is fluent in English and Kannada and speaks conversational Hindi.

ARUNABHA GHOSH

Arunabha Ghosh is CEO of the Council on Energy, Environment and Water (CEEW), an independent, policy research institution in India. In less than three years, Arunabha has conceptualised and led CEEW (http://ceew.in) to the number 1 ranking among climate and energy-related think-tanks in India and 15th globally. With experience in more than thirty countries, Arunabha has devoted his career to public policy. His work intersects international relations, global governance and human development, including climate, energy, water, trade and conflict. He advises governments, industry and civil society around the world on: energy and resources security; renewable energy policy; water governance and institutions; climate governance (financing, R&D, geoengineering); energy-trade-climate linkages; and international regime design. In March 2013, the World Economic Forum selected him as a Young Global Leader. Arunabha's latest initiative is to create a countrywide network of off-grid renewable energy companies to lower their operational costs, and thereby increase the scale of rural energy services.

Dr Ghosh is part of Track II dialogues on energy, water and climate change with the United States, Israel and Pakistan. He formulated the Maharashtra-Guangdong Partnership on Sustainability. Dr Ghosh is also associated with Oxford's Global Economic Governance Programme and its Smith School of Enterprise and the Environment. Previously Global Leaders Fellow at Princeton's Woodrow Wilson School and at Oxford's Department of Politics and International Relations, he was also Policy Specialist at the United Nations Development Programme (New York) and worked at the World Trade Organization (Geneva). He sits on the Governing Board of the International Centre for Trade and Sustainable Development, Geneva.

His publications include: Understanding Complexity, Anticipating Change (India's first ever report on global governance, submitted to the National Security Adviser); National Water Resources Framework Study (for India's Planning Commission); India's Resource Nexus (for the National Security Advisory Board); Governing Clean Energy Subsidies (for Rio+20); Laying the Foundation of a Bright Future (on India's national solar mission); Institutional Reforms for Improved Service Delivery in Bihar (on irrigation reform); Harnessing the Power Shift (on climate finance); International Cooperation and the Governance of Geoengineering (for the Intergovernmental Panel on Climate Change); and three UNDP Human Development Reports. He has led research on trade, intellectual property, financial crises, development assistance, indigenous people, extremism and conflict.

Dr Ghosh has presented to heads of state, India's Parliament, the European Parliament, Brazil's Senate, the Andhra Pradesh Legislative Assembly and other legislatures; trained ministers in Central Asia; and hosted a documentary on water set out of Africa, Diary of Jay-Z: Water for Life, honoured at the Webby Awards. His op-eds have appeared in the Business Standard, Financial Express, India Today, Indian Express, Mint, Seminar, Tehelka, and The Hindu. He has delivered public lectures in several countries, and commented on All India Radio, ABC (Australia), BBC, NDTV (India) and Voice of America, among other channels.

Arunabha has been consulted by the Asian Development Bank, DFID (UK), IDRC (Canada), International Energy Agency, International Finance Corporation, IPCC, Commonwealth Secretariat (London), Oxfam International, Transparency International, UK Ministry of Justice, USAID, and the World Bank. He co-chaired the international governance working group for the UK Royal Society's Solar Radiation Management Governance Initiative. He has been an Editor of the Journal of Human Development and Capabilities. In 2011, the Asia Society named him an Asia 21 Young Leader. He is also an Aspen India Leadership Initiative fellow.

Arunabha holds a doctorate and M.Phil. in international relations from Oxford (Clarendon Scholar and Marvin Bower Scholar); an M.A. (First Class) in Philosophy, Politics and Economics (Balliol College, Oxford; Radhakrishnan Scholar); and topped Economics from St. Stephen's College, Delhi University. He lives in Gurgaon, India, and speaks English, Hindi, Bengali and basic Spanish.

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ENERGY STORAGE FOR OFF-GRID RENEWABLES IN INDIA: Understanding options and challenges for entrepreneurs

The intermittent nature of renewable energy sources, such as the sun and wind, leads to large fluctuations in the generation of electricity. Energy storage subsequently becomes important to tap renewable energy in an efficient manner. It is estimated that by 2020, the market potential for energy storage systems in renewable energy applications would be in the vicinity of nearly 6000 MW. Of this, more than 2000 MW would be in the off-grid renewable energy market (IESA 2013).

Currently off-grid entrepreneurs are faced with storage choices that are largely driven by cost, forcing them to disregard other options that exist. Alternative storage options, which are often left in the periphery, offer a range of the benefits for the consumer and the environment at large. While trade-offs are inherent in any technology choice, there must be a comprehensive understanding of the various desirable attributes of storage system, the benefits and potential pitfalls of any choice and most importantly a long term goal on which to focus. By expanding the horizon of choices, off-grid entrepreneurs could examine new applications and business models using various energy storage technologies, support more sustainable environmental management of batteries, and promote innovation in emerging technologies.

This paper seeks to take lay out the available storage technologies in India, discuss challenges faced in moving towards more efficient technologies, and identify potential points of engagement that the Renewable Energy Working Group (REWG) may like to pursue.

1. Energy Storage: Which functions, what scale and at what cost?

Storage technologies are varied and no single solution can score high on all the attributes desired from an ideal storage system. Capacities vary from small scale storage (in the magnitude of few Wh e.g. mobile phone batteries, clocks, remote etc.) to medium size storage (in magnitude of kWh e.g. residential storage) to large sized storage (magnitudes of MWh e.g. grid level storage)

The choice may broadly depend, *inter alia*, on the size of system, the nature of demand from the system, the alternative electricity sources and the marginal cost of peak electricity (IEA-ETSAP 2012). Table 1 broadly identifies a number of available storage technologies. Some are deployed at a commercial scale and others that have demonstrated potential but are yet to be deployed in large numbers.

Table 1: Possible storage technologies

Energy Storage System	Typical Application	Scale / Example
Pumped storage hydro(PSH)	Large energy storage from grid-connected sources at times of low demand	1 MW - > 1000 MW (Bath County Pumped Storage Station, USA – 3000 MW)
Compressed air energy storage (CAES)	Large energy storage from grid-connected sources	1 MW – 300 MW (Gaines, TX, USA – 2 MW)
Superconducting magnetic energy storage (SMES)	Grid stabilisation and frequency control	1 MWh – 200 MWh
Flywheels	Grid energy storage, motive power, large scale UPS services (labs, etc.)	3kWh – 5 MWh
Capacitors and super capacitors	UPS for short interruptions in conjunction with other batteries	
Fuel Cells	Large scale energy storage	0 – 50 MW; 10 kW Fuel cell at Nakskov, Denmark to store Wind Energy from a 600 kW plant
Batteries		
Lead Acid	Automobiles, household backup, industrial backup and grid storage	Varying sizes with the possibility to increase voltage supplied (2 V cells)
Nickel-cadmium	Portable electronics, power tools, emergency lighting Grid energy storage	Varying sizes with the possibility to increase voltage supplied (2 V cells)
Sodium-sulphur	RE stabilization, ancillary services	250kWh – 300 MWh (Rokkasho, Japan – 34 MW)[1]
Lithium-ion	Portable devices, power tools, electric vehicles	Varying sizes with the possibility to increase voltage supplied (2 V cells)
Flow Batteries ▪ Zinc-bromide ▪ Vanadium redox batteries	UPS, peak shaving, load balancing	1 kWh – 10 MWh

Source: CEEW compilation from multiple sources

The scale argument for battery based storage

Most off-grid renewable energy products and systems are in the range of a few Watts to a few hundred kW, and rely on batteries as storage technology. Technologies such as Pumped Storage Hydro (PSH), which represents nearly 99% of the bulk storage capacity in the world (Economist 2012), and Compressed Air Energy Storage are not suited for small scale renewable energy systems due to their scale requirements. There are only three commercial

[1] NGK Insulators: http://www.ngk.co.jp/english/products/power/nas/application/index.html

scale CAES projects that have been implemented and much research is needed to improve the efficiency associated with CAES. Superconducting magnetic energy storage (SMES) and super capacitors also have high implementation costs and are relatively new technologies (Nair 2010). Flywheels are mostly deployed for uninterrupted power supply and power conditioning. An important (and undesirable) feature of flywheels is their high self-discharge rate of between 55% and 100% over a 24-hr period (Beaudin 2010). Scale of implementation and maturity of technologies play an important role in the choice of the appropriate technology. Off-grid entrepreneurs must balance these factors when choosing a storage technology, but often their choices are driven by upfront costs.

The cost argument for battery based storage

The off-grid renewable energy application of energy storage is primarily for solar power based home systems in rural areas, simple lighting and charging solutions or roof-top solar applications in urban areas. The high costs associated with all storage technologies (including batteries) is the most significant barrier to their implementation. While it is difficult to compare cost factors across the various storage solutions listed in Table 1 on account of the variations observed depending on nature of use and charging, we resort to a rudimentary comparison based on cost of these various technologies per unit of power (stored). PSH and CAES exhibit relatively low installation costs and are more economical than most (current) battery based storage solutions with costs in the range of USD 5-100 per kW of installed power capacity. The lowest cost electrochemical storage technologies (i.e. batteries) start at USD 100 per kW (Lead acid, Vanadium Redox) and rises up to a few USD 100 per kW (Nickel based batteries, Sodium sulphur (NaS)) and even USD 1000 per kW (or more) in the case of Li-ion batteries, flow batteries and other technologies such fly-wheels, super capacitors, magnetic energy storage, etc.

Given the combination of scale and cost constraints faced by off-grid entrepreneurs, battery storage becomes a de-facto choice. Batteries are most commonly used for small scale electricity storage because of their high energy densities and relative ease of use (Nair 2010). They are most often used as UPS (uninterruptable power systems) at a household level and for frequency and voltage regulation at the grid/ utility scale.

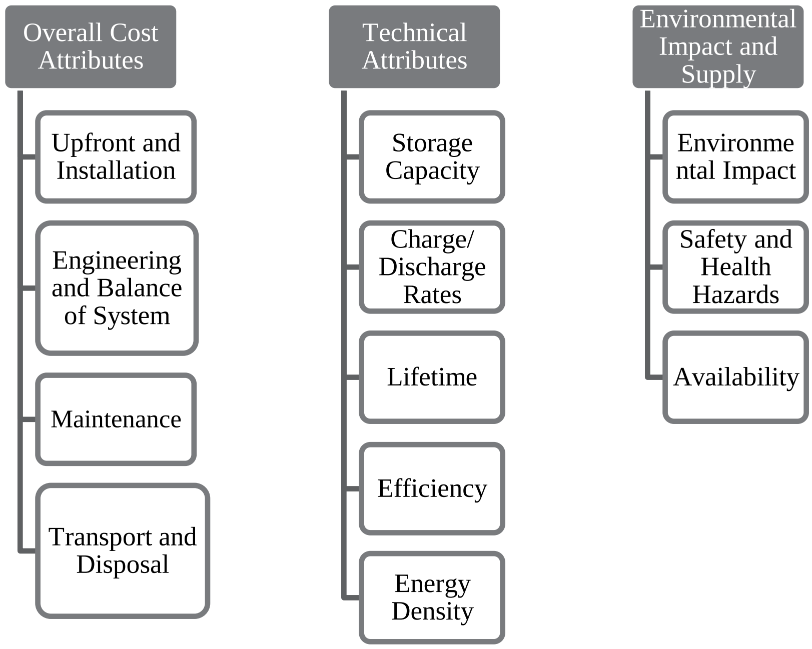
The following section will focus on the assessment of the various battery storage options available to off-grid entrepreneurs. We discuss the attributes of those batteries which have widely found acceptance for use in off-grid and other small scale applications. Sodium-sulphur and flow batteries have not been discussed as they are geared (currently) for utility scale applications. We will also discuss potential points of intervention that may help establish an environment conducive to the development of efficient and cost-effective energy storage systems for off-grid entrepreneurs.

2. Technology Assessment

It has been observed that early users have had a less than satisfactory experience with the first generation of off-grid renewable solutions (including energy storage). Solar systems have failed due to lack of after sales service and due to inappropriate operation of the associated components (specifically batteries).[2] This has led to users taking a cautious approach when buying new systems. Batteries, being a crucial part of the system, require users to follow 'text-book' procedures while charging and discharging batteries to ensure their longevity and so that critical parameters[3] are within the operational envelope.

Batteries used with renewable energy systems have to charge in an unpredictable manner due to sudden variation of sunshine, wind speed or water flow. Often these batteries work on partial charge for few days in a stretch, leading to frequent deep discharge or lack of charge. The entrepreneurs, whom we have consulted, vary between implementing battery solutions that require limited maintenance, but with a reduced lifetime and more hands-on solutions that require regular maintenance, for example topping up with distilled water. Choosing the appropriate storage technology for an off-grid project requires a balance of desirable attributes associated with an efficient storage system. Some of these desirable attributes are listed below (Figure 1).

Figure 1: Factors to be taken into account while choosing storage technology



Source : CEEW analysis

[2] CEEW interaction with stakeholders and users

[3] As explained in Table 1

The technical attributes listed in Figure 1 have been detailed in the table below (Table 2)

Table 2 : Parameters for Performance

Parameter	Description
Energy storage capacity (kWh)	Amount of energy that can be stored in the system
Charge and discharge rates (kW)	How fast energy can be charged/discharged
Response time (seconds, minutes)	Time lag between the demand and supply
Lifetime	It is given as the number of cycles, years or stored/provided energy(kWh), depending on specific technology
Efficiency	It is the ratio of energy discharged by the system to the energy needed to charge it at each cycle and accounts for energy lost in the storage cycle
Energy density (kWh/kg, kWh/m^3, Wh/l) or Power Density (kW/kg, kW/m^3)	Energy density matters for applications where space is a premium.

Source : IEA-ETSAP-(2012) Electricity Storage :Technology Brief, International Energy Agency

Lead-acid batteries

In use for over a century, lead-acid batteries are the oldest and most mature technology available. They have traditionally been used in a number of commercial applications due to their low upfront cost, high reliability and efficiency (70-80%). However lead-acid batteries also have their own limitations in terms of short life cycle (500-2000 cycles) and low energy density (30Wh/kg to 50Wh/kg) due to high density of lead. Lead acid batteries are primarily used for two major applications: 1) Starting and ignition requiring short bursts of strong power e.g. car engine batteries and; 2) Deep cycle, low steady power over an extended duration in UPS for urban homes, solar home systems in rural areas (IEA 2011).

With no single design suitable for all applications, usage specific design is required. Lead-acid batteries can fall within two major categories:

1. Flooded
2. Sealed/valve regulated (SLA or VRLA)
    a. Gel batteries
    b. Absorbed Glass Mat (AGM)

Flooded lead acid batteries have the following limitations. Their orientation should be upright in order to prevent electrolyte leakage and a well-ventilated environment is required to diffuse any gases that might be emitted during the charging or discharging cycle (Albright 2012). Most crucially, the electrolyte concentration needs to be monitored at regular intervals and demineralised water needs to be provided to ensure this. Flooded batteries have been extensively been used for deep cycle applications for many years.

On the other hand, VRLA batteries have been developed for standby power with low depth of discharge characteristics. They do not require addition of water, which makes it low maintenance. This feature enables VRLA batteries to be installed at locations where access is difficult, especially in remote areas. However, it increases the cost and decreases the life of the battery, both undesirable outcomes. One related factor that reduces battery life is ambient temperature. An 8-10 degree Celsius rise in temperature can reduce useful life (in cycles) by nearly half, since water that is incorporated within the gel tends to be consumed at a faster rate than for which it has been designed.

Environmental and Health Impact: The high lead content and the use of sulphuric acid make lead acid batteries environmentally unfriendly. On account of their low energy density and bulkiness, lead acid batteries consume larger amount of raw materials (especially when compared to Li-ion batteries), making a much larger impact on the environment across the entire process chain (cradle to grave). The lead processing industry is also energy intensive and leads to large amount of pollution due to limited controls over the process.

Recyclability: Lead acid batteries can be easily recycled by following the right disposal and handling practices. Recyclers crush the batteries into small pieces and separate the plastic component. The plastic is recycled and the purified lead is delivered to battery manufacturers and other industry. A typical lead-acid battery contains 60%-80% recycled lead and plastic (USEPA 2013).

The Ministry of Environment and Forests notified the ‘Batteries (Management and Handling) Rules, 2001’, which stipulates that 90% of the batteries are to be collected back through dealers. (MoEF 2001). As of September 2010,[4] there were 353 lead acid battery recyclers registered with Central Pollution Control Board (CPCB 2010). However, continuous supply of used batteries at competitive price is a challenge for large scale environmentally sound recycling facilities. They face tough competition from small scale recyclers who operate under greatly reduced efficiencies. These small scale and unregulated recyclers do not face costs pertaining to environmental contamination and the health of over-exposed workers. Hence, they are able to provide better buyback rates to people who are disposing their used batteries, as compared to larger and licensed recyclers. Several studies have also confirmed high lead exposures in nearby communities where such recyclers operate. They also observed that despite regulations in place, only a small percentage of total used batteries are being collected by battery manufacturers (via their dealers and aggregators). There is no penalty for manufacturers who fail to meet the regulatory requirements (Occupation Knowledge International 2010).

[4] No later data available

Though lead is highly toxic, the methods used in the manufacturing and packaging of batteries makes the risk to humans negligible (Albright 2012). However, it does pose a serious health hazard if handled in an improper manner in backyard recycling units, which flaunt most procedural norms in pursuit of low cost recycling.

Lithium-ion batteries

Lithium-ion batteries are “deemed” one of the most promising solutions for both large and small scale electricity storage. At present, they are predominantly used in mobile phone, laptops and electric vehicles, but would need further development for application for power storage in other applications.

Lithium-ion batteries have a lithiated metal oxide ($LiCoO_2$, $LiMO_2$, LiNiO2, etc.) as cathode and graphitic carbon as anode. Lithium salts dissolved in organic carbonates serve as an electrolyte. These batteries have high efficiencies of over 90%, long life cycle of 1500-2000 cycles and high energy density of 200Wh/kg, lowest self-discharge (5-8% per month at 21°C, 15% at 40°C, and 31% at 60°C) and have no memory effect (Beaudin 2010). Lithium-ion batteries face a major hurdle in terms of high cost due to special packaging and internal overcharge protection circuits. Several companies are working to reduce the manufacturing cost of these batteries to capture large energy markets (IEA 2011).

Lithium-ion batteries can exhibit discharge times ranging from seconds to weeks making it more flexible and a universal storage technology. Easy monitoring and control of the state of charge is possible. Lithium-ion batteries must be controlled with a monitoring unit to maintain its stability and lifespan. Often internal components and systems are installed providing protection for over-charging, over-discharging, over-current, over-temperature and relief valves to avoid gas over pressure due to over-charging. Although these systems ensure safety, they add volume and complexity, leading to increase in cost (IEA-ETSAP 2012).

Globally, an annual investment of $1 billion is expected in research and development for Li-ion batteries. Most of the R&D for Li-ion batteries is aimed at reducing the upfront cost and further improving the performance of this technology leading to broader use.

In July 2012, Panasonic inaugurated a lithium-ion battery manufacturing unit in China, which would cater to the demand of renewable energy powered households in Europe. These battery modules would have a nominal capacity of 1.35 kWh with a battery management system to control charging and discharging (JCN 2012). Panasonic aims to cut costs by increasing production ratio, procuring materials locally and reducing logistics cost (Panasonic 2012). Some industry study predictions estimate that the prices of Li-ion batteries could fall from the present $500-$600/kWh to $200/kWh by 2020 and $160/kWh by 2025 (McKinsey 2012).

In India, R&D into Li-Ion batteries has been initiated by the National Centre for Photovoltaic Research and Education (NCPRE) at the Indian Institute of Technology, Bombay. During the five-year project, which started in 2009, NCPRE aims to increase the life cycles of the batteries and develop a prototype lithium-ion cell for high energy density applications (NCPRE 2012).

Recyclability: Currently, it does not make economic sense to recycle Li-ion batteries to recover lithium since they contain only small amount of lithium carbonate. The average lithium cost associated with Li-ion batteries is less than three per cent. The lithium produced from recycling is also five times more costly than that produced from the cheapest brine-based process (Waste Management World n.d.). Other cell materials have shown high ability for recovery and recyclability. It is more valuable to recover costlier metals such as cobalt and nickel from these batteries (Albright 2012). Safe disposal is the best way to handle Li-based batteries at the end of their useful life.

Environmental and Health Impact: Li-ion batteries have shown some impact on humans, due to the lithium and copper mining processes. It has also been observed that Li-ion batteries have the highest impacts on metal depletion (when compared to Lead acid, Ni-Cd and Ni-MH) and is one of the most energy intensive batteries in terms of their production along with Ni-MH batteries (McManus 2012).

Primary lithium batteries, which contain metallic lithium,[5] react violently when they come in contact with moisture. For example, heavy equipment operating in disposal sites could potentially crush and expose a charged lithium-ion battery, causing a fire. Hence, before recycling a full discharge must be applied to consume the lithium metal (Battery University n.d.). Lithium ion batteries are safe for human health and heating related failures and hazards in individual cells are rare (Battery University n.d.). However it must be remembered that large battery banks operate with thousands of cells (within the bank) and even with a low probability of failure, can still pose a potential threat.

Availability Risks: The major components of Li-ion batteries require the mining of lithium carbonate, copper, aluminium and iron ore. Lithium is considered a scarce material since it occurs in concentrations lower than 0.01% in the earth's crust. Lithium mining is resource intensive but could consume lesser energy if extracted from brines. Although Lithium is only a minor portion of the battery cell as indicated in Table 3 (below), the low recyclability of Li based batteries significantly increases supply risks.

[5] cell phone and laptops batteries do not contain metallic lithium

Table 3 : Approximate material composition of Li-Ion batteries	
Component	Percentage
Cathode active material	22-28%%
Anode active material	15-18% [6]
Carbon	2-4%
Binder	3-4%
Copper parts	13%
Aluminium parts	12-14%
Aluminium casing	8-9%
Electrolyte solvent	11-14%
Plastics	3-4%
Steel	0.1%
Thermal insulation	1%
Electronic parts	0.2-0.4%

Note: 1. Composition of electrode may vary according to battery manufacturer
Source : Gaines, Linda, Sullivan, Bumham and Belharouak (2011) "Life cycle analysis for lithium-ion battery production and recycling" *90th annual meeting of the transportation research board, Washington DC*: 11-3891

Nickel based batteries

Nickel-Cadmium (Ni-Cd) batteries

A Ni-Cd battery is made up of a positive electrode with nickel oxy-hydroxide as the active material and a negative electrode composed of metal cadmium. They are separated by a nylon divider (Connolly 2010). Nickel-cadmium batteries were invented as early as 1899 but were introduced in large volumes only in the 1960s. Their small size and high rate of discharge capacity revolutionised the usage of portable tools and other consumer appliances for the first time. Ni-Cd batteries are known for their robustness, reliability and service life. They can be operated over a large range of temperature, last for large number of cycles with a long storage life and require only minimal maintenance (Saft Batteries).

Ni-Cd batteries have efficiencies up to 60%-80% and their life span can range upto 10-15 years. These batteries have life of up to 1000 charging/discharging cycles, can respond to full power within milliseconds, and operate over a wider range of temperatures (Connolly,2010; Chen, 2009).

However Ni-Cd batteries have some major limitations in form of high cost (upto $1000/kWh), low energy density and memory effect, thus requiring periodic full discharge to

[6] Lithium constitutes 1-2% of the electrode element

retain capacity (Battery University n.a.). Since renewable energy often includes forecast error and variability, Ni-cd batteries cannot operate economically without creating problems caused by memory effect (Beaudin 2010). However, proper battery management procedures can help overcome these challenges (Chen 2009). Ni-Cd batteries have higher self-discharge rate than either of the options discussed in the section.

Despite such shortcomings Ni-cd batteries are a competitive replacement to lead-acid batteries due to their ability to supply continuous power for long durations and also for their use in applications that require instantaneous power (Nair 2010).

Environmental and Health Impact: Cadmium is highly toxic and can accumulate in the environment by entering into ground and surface water, and can pass to humans through the food chain. It is also responsible for numerous lung and kidney related illness. If absorbed, it can remain the body for decades (Fishbein n.d.).

Nickel-metal-hydride (Ni-MH) batteries

Ni-MH batteries are very similar to Ni-Cd batteries and the only difference between them is that instead of cadmium, hydrogen is used as the active element at the hydrogen-absorbing negative electrode. (Electropaedia n.a.) Ni-MH batteries were patented in 1986 and saw massive advancements later. Since 1991, the energy density has doubled the life span has expanded. Despite price and safety advantages over Li-ion batteries, it is feared that the hype over Li-ion batteries have reduced the popularity of Ni-MH batteries.

Compared to Ni-Cd batteries they have a 25%-30% higher energy density (Nair 2010), are less prone to memory effect and are environmentally friendly due to absence of cadmium. These batteries can be profitably recycled (Battery University n.a.). Ni-MH has its limitations in terms of higher self-discharge rate (higher than Ni-Cd), low energy density (compared to Li-ion batteries), deteriorates during long time storage and should not be stored at high temperatures (Electropaedia n.a.).

Environmental and Health Impact: Ni-MH batteries contain nickel and electrolyte which is considered to be mildly toxic. However, in absence of disposal services it can be discarded with household waste.

Box 1: Technologies under development

Two up and coming technologies which have the potential to provide long-life and environmentally safe battery solutions are discussed below:

1. **Flow assisted Nickel Zinc (Ni-Zn):** Flow assisted Ni-Zn batteries are very similar in design to other nickel batteries with nickel and zinc as electrodes and an alkaline electrolyte. Conventional Ni-Zn batteries had shorter life due to dendrite growth (on the Zn anode), which led to electrical shorting. Improvement in electrolyte flow has reduced this problem and these batteries are being considered again for commercial uses (UEP 2013).

They have higher energy density in comparison to other nickel-based batteries, provide higher voltage and operate over a wide temperature. Few manufacturers have demonstrated the cost to be as low as 25% when compared to lead acid batteries and larger number of life cycles (>5000). These batteries are abuse tolerant, making them safe for usage rugged usage. Both nickel and zinc are non-toxic and can be inexpensively recycled, making them environmentally friendly and a potential replacement for both lead and cadmium batteries. (PowerGenix n.d.)

2. **Lithium Air batteries**: For batteries to compete with fossil fuel-based electricity generation, energy density levels need to be around 1000 Wh/kg. Even doubling the density of current Li-ion technology moves it only to 400 Wh/kg. Lithium-air batteries can offer up to ten times the storage capacity of the Li-ion battery. However, to date these batteries have significant challenges for use in anything outside of highly-controlled laboratory environments. Though these are being developed with electric vehicles in mind, they offer a paradigm shift from what is available today (IEEE 2013).

3. Options for Indian entrepreneurs and consumers

It has been well established in the literature and through our conversations with entrepreneurs and manufacturers that most of the renewable energy systems use the traditional lead acid batteries to store energy. As mentioned earlier, lead acid batteries have been commercially used for over a century and are the most mature technology available. Though these batteries are low cost and have high reliability, they have drawbacks in the form of heavy weight, short life, regular maintenance requirement, low energy density and even the occasional health hazard from acid-fumes. Inefficient charging and discharging can further decrease the useful life of batteries. This is prevalent in many existing installations where users opt for deep discharges to get the maximum out of every charging cycle.

Conventional lead acid batteries require periodic monitoring for water levels and require a top up. This poses a problem in areas where maintenance is not feasible or there is poor consumer/vendor follow up. Low-maintenance gel batteries have been developed where sulphuric acid is mixed with silica fume, which causes it to stiffen. This reduces the weight of the battery by 15%-20% but increases the cost by 25%-30%.

Lithium-ion batteries offer the best energy density (upto 630 Wh/l), efficiency (90%) and durability with low self-discharge rates (5%-8% per month at 21°C). They clearly score well on their technical attributes. However Li-ion batteries are still expensive at round USD 500 per kWh and there is some way to go before complete safety of the battery has been established (IEA-ETSAP 2012). Nickel-based batteries suffer from a similar cost disadvantage as the price of nickel, which is used in significant quantities, is high and India is not a large producer of the metal.

In the absence of a commercial alternative, lead acid batteries have been recommended by the Ministry of New and Renewable Energy. The government provides a 40% subsidy on benchmark prices for small systems (for pre-approved systems below 210Wp). The subsidy also covers the cost of batteries. While the solar panels have a warranty of twenty years, batteries have a five year warranty at best and this is realised only with good care and practices. Users who own these systems face challenges in accessing upfront finance and find it very difficult to replace batteries. Some enterprises encourage users to periodically set aside a small amount for battery replacement.

Table 4: Desirable attributes when choosing a storage technology for off-grid solutions in India

Overall criteria	Attributes	Why and where is it desirable?
Cost	Affordability	Given the market being served, the most crucial element in choice of a suitable battery (Lead acid leads the way)
	Low maintenance requirement	In areas where periodic maintenance is not possible or not desirable these batteries perform better but not without a loss in life span (VRLA, Li-ion and Ni-based batteries all are good options)
Technical	High energy density	Mobile applications imply that low weight and easy of transportation score high on the desirability chart. Renting models involving women customers also necessitates the need for a lighter battery (Li-ion batteries well ahead of the curve)
	Ability to handle intermittency of charging	Given the stop and start nature of solar and wind power, a battery may not go through a steady charging cycle. In areas of high variation, this attribute is crucial (Li-ion and Ni-MH are well adapted to this)
	Minimum memory effect	Only nickel batteries exhibit this trait and frequent cycles of full discharge would be needed. However all batteries exhibit loss of life cycle as a result of partial discharging and charging (Lead Acid, Lithium Ion do not exhibit memory effect)
	Low self-discharge rate	In remote areas where charging cycles are not frequent and use is intermittent, it is necessary for charged batteries to maintain the stored energy for the longest duration possible (Lead acid and Li-ion score high)
	Resilient to ambient temperature variations observed in India	Most batteries lose crucial life cycle when used at ambient temperatures which are frequently seen across the Indian landmass. It is necessary to choose a battery that performs well in the local conditions, especially the maintenance free varieties (VRLA most susceptible and Li-ion the least)
Environmental Impact and Supply	Post use handling processes	After the useful life of the battery, there must be suitable processes in place to return the battery to an authorised recycling or disposal facility. Users must be informed about these options (Lead acid batteries pose the biggest challenge. The others, can be disposed along with conventional wastes)
	Health and safety	During regular use (and sometimes during extraordinary circumstances), the battery must not pose any risks to the health and safety of users by way of harmful fumes, fires, short-circuits, etc. Users must be instructed on the right procedures to charge, discharge and store the battery and other components (Lead acid batteries pose highest risk, especially at the manufacturing and recycling stages for people involved in the industry)

Source: CEEW analysis

A few enterprises have also successfully implemented a rental model for solar lighting. An entrepreneur owns a kiosk where he/she charges the battery in the day time and rents them in the evening or the consumer visits the kiosk to rent the battery. Since the batteries are heavy, transportation becomes a tiring process for both entrepreneurs and consumers, especially female entrepreneurs. It also increases transportation costs if the batteries are supplied by motorised vehicles.

Challenges such as short life, after sales maintenance and heavy weight pose a major drawback for battery storage solutions. These challenges may be overcome if technologies such as nickel batteries, lithium-ion, lithium air, fuel cells, etc. become commercially viable. Though each technology has its own limitations, batteries with longer life and minimum after sales service may hold the key to increasing the sale of renewable energy systems.

A useful list of attributes to check for, both as users or vendors of battery storage is presented above (table 4). An indicative choice of battery, best suited to address each issue, is also provided. While the ranges (for the various parameters) have been discussed and summarised in this paper, it is necessary to establish these independently from a manufacturer, before choosing a specific battery technology for an application.

4. Policy & regulatory framework

Potential interventions at the policymaker level could take place in three areas: attributes of battery technology, consumer practices, and innovation.

1. *A differentiated incentive mechanism to broaden the market for battery based storage and shift away from the current dominance of lead acid storage.*

The current system of benchmark prices leaves little room for people to opt for innovative solutions keeping in mind the long term impact of their choices. Instead it becomes a race to the bottom to find the cheapest possible battery solution to their storage needs. Government of India provides financial support for entrepreneurs through subsidies. The support depends on the size whether storage is built in or not. For pre-approved systems with battery storage (< 210 Wp with a battery backup of three days), the government provides 40% subsidy on the benchmark price of INR 270. For systems greater than the above capacity the government provides a capital subsidy of 30% on the benchmark prices and a soft loan of 5% with boundary conditions.[7] The benchmark prices for systems have been illustrated below (Table 5). It can be seen that the top-up on the benchmark costs associated with the provision of battery is a mere INR 60 – INR 80 (per Wp). This essentially means that the government expects storage solutions to be procured at the lower end of the cost spectrum and not a choice based on what is the most suitable solution keeping in mind the various desirable attributes of a good energy storage system.

Table 5 : Benchmark prices of solar systems (November 2012)

System Capacity	With Battery (Rs/Wp)	Without Battery (Rs/Wp)	Difference (Rs/Wp)
<210 Wp	270	160	110
210Wp – 1kWp	240	160	80
1kWp – 5kWp	220	160	60
5kWp – 10kWp	220	140	80
10kWp – 100kWp	200	140	60
100kWp – 500kWp	-	130	

Source : MNRE (2012) "Amendment in the benchmark cost of Off-grid and Decentralised solar application programme" available at http://mnre.gov.in/file-manager/UserFiles/amendmends-benchmarkcost-aa-jnnsm-2012-13.pdf; accessed 29 April 2013

[7] Availability of loans at a 5% depends on user type and capacity of the system installed. The details on the boundary conditions are available at http://nabard.org/pdf/Eng%201%20solar%20circular-01-11-10%20with%20encl.pdf; accessed 31 May 2013.

In order to even consider alternative technologies, entrepreneurs and consumers have to be swayed away from the cost argument through other means that provide a benefit stream over the life of the battery either in monetary terms (via differential subsidies) or otherwise (viz. health benefits, ease of use, low maintenance level, etc.)

2. *Improve compliance among consumers in furthering environmentally sound practices when it comes to recycling*

Current measures by the Indian government to only allow licensed recyclers to bid for used imported batteries are a step in the right direction. However, as noted, domestically sold batteries are not fully recovered by licensed recyclers. It is necessary to come up with incentives to increase compliance among domestic buyers. For example: a scheme which charges a small refundable deposit at the time of purchase which will be returned along with a 'recycle' value for the used battery. This approach could ensure that consumers are motivated to use accredited suppliers as well as certified recyclers. While the MNRE would be the nodal agency to issue such a directive the onus is very much on a mix of private entrepreneurs, manufacturers, aggregating agencies and the consuming public to ensure that compliance rates in recycling and recovery remain high, thereby reducing the environmental load of battery disposal. The state pollution control boards (SPCBs) would also need to play an important role in enforcing the standards.

3. *Innovation and R&D in battery technology, specific to off-grid consumers' needs, must be promoted actively*

The MNRE recognises that stand-alone systems today are monopolised by lead acid batteries. There is an understanding and a sense of urgency to enhance the battery cycle life to get at least 10 years of operating life. Further, it is also necessary to develop non-lead acid batteries (MNRE 2012). However, much of this has not translated to research efforts on the ground. NCPRE, a research centre at IIT Bombay, focuses on this R&D and is supported by the MNRE. However, they are still in the early stages of developing prototypes. The broad objective of battery related R&D is "*to establish a minimum capability for testing and characterization of lithium-ion batteries and materials, to evolve indigenous methodologies for the production of battery-grade active materials*" (NCPRE 2012). These are modest targets at best and there is no critical mass in the research community to increase the momentum of the process. The research happening in the private domain (under battery manufacturers) is currently catering to the demand from large consumers like mobile towers and power generators, who are consumers of large scale storage solutions. Innovation in this area, while beneficial to battery development, leaves the off-grid space in the periphery and government attention is required to ensure appropriate solutions are developed. Off-grid renewable energy applications account for only 10%-12% of the overall demand for energy storage by the year 2020 (IESA 2013)

5. Role of the Renewable Energy Working Group

Based on the above discussion and recognising REWG as a forum to collectively push for innovations in the policy framework for off-grid renewable energy, we recommend the following for its consideration.

- *Push for a stringent regime on environmental impact monitoring.* In the absence of well enforced environmental regulations, neither the consumer nor the manufacturer has any incentive or faces any penalty upon non-conformance. In this situation, the burden of ethical use and disposal of lead acid batteries (or any battery) falls on renewable energy entrepreneurs. Therefore, it is in their interest to have a proper mechanism that lets them deliver the most efficient technologies at the best price without having to fret over the abuse of the products and environment at large.

- *Work towards the establishment (and enforcement) of performance benchmarks on battery manufacturers.* The subsidy and financing structure to support RE entrepreneurs forces them to adopt less efficient battery technologies, albeit at the lowest cost. The inherent risks and inefficiencies associated with these technologies also have a negative impact (both financial and reputational) on the individuals and businesses if batteries regularly breakdown or have a truncated lifecycle.

- *Serve as a platform to understand potential new business models that could open up using alternative battery technologies.* For example, it has been observed that the service network constraints of an enterprise can sometimes drive their choice of battery technology. A small enterprise with limited after sales support may prefer sealed lead acid batteries, with a trade-off in terms of reduced life and higher cost. On the other hand, an enterprise with a wide after sales network may prefer flooded lead acid batteries where water needs to be added periodically – either by a technician or informed end-users. Another group of entrepreneurs also rent out charged batteries, but are hampered by the weight of using lead-acid batteries – something that could be overcome by lighter li-ion batteries. Utilising REWG's platform would help to inform members about upcoming and alternative technologies and what it may mean for their business models, helping them make the most appropriate choices based on parameters other than cost

WORKS CITED

Battery technology charges ahead. July 2012. http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead.

Albright, Greg, Jake Edie, Said Al-Hallaj. *A comparison of lead-acid to lithium-ion in stationary storage application, Lead acid versus lithium-ion white paper.* All Cell Technologies , 2012.

AMG. *A comparison of lead acid to lithium ion in stationary storage applications.* 30 April 2013. http://www.altenergymag.com/emagazine/2012/04/a-comparison-of-lead-acid-to-lithium-ion-in-stationary-storage-applications/1884.

Battery Canada. *Battery Facts and Myths.* 11 May 2013. http://www.batterycanada.com/battery_facts.htm.

Battery University. *Alternate Battery Systems.* n.d. http://batteryuniversity.com/learn/article/alternate_battery_systems (accessed June 26, 2013).

—. *How to recycle batteries.* n.d. http://batteryuniversity.com/learn/article/recycling_batteries (accessed May 22, 2013).

—. *Li-ion safety concerns.* n.d. http://batteryuniversity.com/learn/article/lithium_ion_safety_concerns (accessed May 22, 2013).

—. *Nickel-based Batteries.* n.a. http://batteryuniversity.com/learn/article/Nickel_based_batteries (accessed May 22, 2013).

Beaudin, Marc, Hamidreza Zareipour, Anthony Schellenberglabe and William Rosehart. “ Energy storage for mitigating the variability of renewable electricity sources: An updated review.” *Energy for Sustainable Development*, 2010: 14 (302-314).

Chen, Haisheng, Cong T, Yang W, Tan C, Li Y, Ding Y. “Process in electrical energy storage system: A critical review.” *Progress in Natural Science*, 2009: 19 (291-312).

Connolly, David. *A Review of Energy Storage Technologies for the intergration of fluctuating renewable energy.* University of Limerick, 2010.

CPCB. “LEAD WASTE RE-PROCESSORS.” *Central Pollution Control Board.* 23 September 2010. http://www.cpcb.nic.in/divisionsofheadoffice/hwmd/lead.pdf (accessed May 20, 2013).

Economist. *Economist.* 3 March 2012. http://www.economist.com/node/21548495?frsc=dg|a.

Electropaedia. *Nickel Metal Hydride Batteries.* n.a. http://www.mpoweruk.com/nimh.htm.

EPA. *Wastes – Resources Conservation – Wastes & Materials.* 30 April 2013. http://www.epa.gov/osw/conserve/materials/battery.htm;.

Fishbein, Bette. *Industry Program to Collect Nickel-Cadmium (Ni-Cd) Batteries.* n.d. http://www.informinc.org/recyclenicd.php (accessed May 22, 2013).

Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li,. "Progress in electrical energy storage system: A critical review." *Progress in Natural Science,* 2009: 291-312.

IEA. *The role of energy storage for mini-grid stabilization.* Paris: International Energy Agency, 2011.

IEA-ETSAP, IRENA. *Electricity Storage: Technology Brief.* International Energy Agency, 2012.

IEEE. *IEEE Spectrum.* 14 May 2013. http://spectrum.ieee.org/nanoclast/green-tech/advanced-cars/nanoscale-peak-at-lithiumair-batteries-promise-better-electric-vehicles (accessed June 20, 2013).

IESA. *Energy Storage in India: Market Overview.* Pune: India Energy Storage Alliance, 2013.

JCN, Japan Corporate News. *Panasonic to Begin Mass-production of Long-life Lithium-ion Battery System for Solar-powered Homes in Europe.* 4 June 2012. http://www.environmental-expert.com/news/panasonic-to-begin-mass-production-of-long-life-lithium-ion-battery-system-for-solar-powered-homes-in-europe-297749 (accessed April 30, 2013).

McKinsey. *Battery technology charges ahead.* July 2012. http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead.

McManus, M.C. "Environmental consequences of the use of batteries in low carbon systems : The impact of battery production." *Applied Energy*, 2012: 228-295.

MNRE. *Ministry of New and Renewable Energy.* 2012. http://www.mnre.gov.in/schemes/r-d/thrust-areas-2/solar-pv-4/ (accessed May 30, 2013).

MoEF. *Batteries (Management and Handling) Rules, 2001.* 16 May 2001. http://www.envfor.nic.in/legis/hsm/leadbat.html.

Nair, N.-K.C., N.Garimella. "Battery energy storage systems: Assessment for small scale renewable energy integration." *Energy and Buildings*, 2010: (42) 2124-2130.

NCPRE. *National Centre for Photovoltaic Research and Education.* 2012. http://www.ncpre.iitb.ac.in/page.php?pageid=17&pgtitle=solar-pv-systems-and-modules (accessed May 30, 2013).

NCPRE, National Centre for Photovoltaic Research and Education. *Solar PV Systems and Modules.* n.d. http://www.ncpre.iitb.ac.in/page.php?pageid=17&pgtitle=solar-pv-systems-and-modules (accessed April 30, 2013).

Occupation Knowledge International. *Lead Battery Recycling in India.* US: OK International, 2010.

Panasonic. *Panasonic Inaugurates New Lithium-ion Battery Plant in China to Respond to Global Demand.* 17 July 2012. http://news.panasonic.net/archives/2012/0717_11435.html (accessed April 30, 2013).

PowerGenix. *Nickel-Zinc High Discharge Battery Technology Benefits.* n.d. http://www.powergenix.com/?q=nizn-battery-technology-benefits (accessed June 26, 2013).

Saft Batteries. *Nickel Cadmium.* n.d. http://www.saftbatteries.com/Technologies_Nickel_NiCd_293/Default.aspx (accessed May 22, 2013).

Trojan Battery Company. *Comparing deep-cycle flooded batteries to VRLA batteries.* 2012. http://www.trojanbatteryre.com/Tech_Support/ComparingFlood2VRLA.htmll (accessed April 30, 2013).

—. *Comparing deep-cycle flooded batteries to VRLA batteries.* 2012. http://www.trojanbatteryre.com/Tech_Support/ComparingFlood2VRLA.html (accessed April 30, 2013).

UEP. *Rechargeable Nickel-Zinc Batteies - Low Cost systems for long-life peak shaving.* New York: CUNY, 2013.

UPSonNet. *Pros and Cons of Lithium Ion Versus Lead Acid UPS Battery* . July 2011. http://www.upsonnet.com/Newsletter2011/July-Pros-and-Cons-Li-Ion-v-VRLA-UPS-Battery.html.

USEPA. *Wastes – Resources Conservation – Wastes & Materials.* 30 April 2013. http://www.epa.gov/osw/conserve/materials/battery.htm;.

Waste Management World. *The Lithium Battery Recycling Challenge.* n.d. http://www.waste-management-world.com/articles/print/volume-12/issue-4/features/the-lithium-battery-recycling-challenge.html (accessed May 2013, 22).

What's the best battery. 30 April 2013. http://batteryuniversity.com/learn/article/whats_the_best_battery.

Appendix 1: Comparison of small scale storage technologies

Technology	Lead Acid	Li-ion	Ni-Cd	Ni-MH
Cost ($/kWh)	150-200	500-600	600	540
Efficiency (%)	70-80	>90	60-70	60-80
Lifetime (years)	4-8	3-7	< 10	< 10
Lifetime (cycles)	500-1500	1500-2000	<1000	<1000
Energy Density (Wh/kg)	30-50	200-300	50-75	70-100
Operating Temperature (°C)	+10 to +30	-10 to +50	-30 to +60	-20 to +50
Charging Temperature (°C)	25 or less is recommended	0 to 40	0 to 45	0 to 45
Self-Discharge at 25°C in % loss of charge per month	5	10	20	30
Maintenance Requirement	Yes	No	Yes	Low
Environment and Health Implications	Low if recycled	Environmentally friendly	High, due to presence of cadmium	Low
Recyclability	Can be easily recycled	Recycling of batteries is in infancy	Should be recycled in dedicated facilities	Recommended

Note: The data points in the table have been compiled from multiple sources and may vary according to manufacturer and usage and should only be used as an illustrative comparison.
Source: CEEW Compilation

Appendix 2: Scope of the paper

1. Assess the current state of storage options for off-grid renewables in India, including technologies and scale of deployment. This assessment will also include a brief comparison of storage options used internationally and articulate what policies and regulations have resulted in the gradual evolution of batteries used in off-grid systems in India.

2. Assess battery storage options that are being developed/ in existence around the world against the following criteria:

   a. *Costs*

   b. *Technical / Performance (maturity and outlook)*

   c. *Environment and Health Impacts (along with supply side)*

3. Identify potential policy and regulatory shifts required to facilitate a move towards more efficient and scalable battery technologies.

4. Identify potential role for REWG members: policy advocacy for standardisation, certification etc.; and facilitating an ecosystem in the country focused on R&D and manufacturing of batteries for renewable energy.

CEEW PUBLICATIONS

Books/Reports	
• Arunabha Ghosh et al. (2012) *Concentrated Solar Power: Heating Up India's Solar Thermal Market under the National Solar Mission*, Report (Addendum to Laying the Foundation for a Bright Future: Assessing Progress under Phase I of India's National Solar Mission), September, New Delhi, Council on Energy, Environment and Water; and Natural Resources Defense Council	
• Arunabha Ghosh, with Himani Gangania (2012) *Governing Clean Energy Subsidies: What, Why and How Legal?*, August, Geneva: International Centre for Trade and Sustainable Development	
• Rudresh K. Sugam, and Arunabha Ghosh (2012) *Institutional Reform for Improved Service Delivery in Bihar: Economic Growth, Agricultural Productivity, and a Plan for Reorganising the Minor Water Resources Department*, Research Report submitted to the Government of Bihar, July, New Delhi: Council on Energy, Environment and Water, and International Growth Centre, Patna	
• Council on Energy, Environment and Water; and Natural Resources Defense Council (2012) *Laying the Foundation for a Bright Future: Assessing Progress Under Phase 1 of India's National Solar Mission,* Interim Report, April, pp. i-37	
• Arunabha Ghosh, Arundhati Ghose, Suman Bery, C. Uday Bhaskar, Tarun Das, Nitin Desai, Anwarul Hoda, Kiran Karnik, Srinivasapuram Krishnaswamy, Radha Kumar, Shyam Saran (2011) *Understanding Complexity, Anticipating Change: From Interests to Strategy on Global Governance*, Report of the Working Group on India and Global Governance, December, pp. i-70	
• Martin A. Burton, Rahul Sen, Simon Gordon-Walker, and Arunabha Ghosh (2011) *National Water Resources Framework Study: Roadmaps for Reforms*, October, New Delhi: Council on Energy, Environment and Water, and 2030 Water Resources Group, pp i-68	
• Martin A. Burton, Rahul Sen, Simon Gordon-Walker, Anand Jalakam, and Arunabha Ghosh (2011) *National Water Resources Framework Study: Research Report Submitted to the Planning Commission for the 12th Five Year Plan*, September, New Delhi: Council on Energy, Environment and Water, and 2030 Water Resources Group, pp. i-584	
• Arunabha Ghosh (2010) *Harnessing the Power Shift: Governance Options for International Climate Financing*, Oxfam Research Report, October, pp. 1-90	
Papers/Book Chapters	
• Arunabha Ghosh, and David Steven (2013) 'India's Energy, Food, and Water Security: International Cooperation for Domestic Capacity', in *Shaping the Emerging World: India and the Multilateral Order*, edited by Waheguru Pal Singh Sidhu, Pratap Bhanu Mehta, and Bruce Jones, Washington, D.C.: Brookings Press	
• Rajeev Palakshappa et al. (2012) 'Cooling India with Less Warming: The Business Case for Phasing-Down HFC's in Room and Vehicle Air Conditioners,' Council on Energy, Environment and Water; Natural Resources Defense Council; The Energy and Resources Institute; and The Institute for Governance and Sustainable Development, November	
• Vyoma Jha and Rishabh Jain (2012) 'Results-Based Financing for Off-grid Energy Access in India,' *Case-study on the Economics of Results-Based Financing in Study by Vivideconomics for Energy Sector Management Assistance Program (ESMAP)*, World Bank, Washington DC, October	

• Arunabha Ghosh (2012) 'Industrial demand and energy supply management: A delicate balance,' *Empowering growth - Perspectives on India's energy future, A report from the Economist Intelligence Unit*: 26-32, October	
• Arunabha Ghosh, Benito Müller, William Pizer, and Gernot Wagner (2012) 'Mobilizing the Private Sector: Quantity-Performance Instruments for Public Climate Funds,' *Oxford Energy and Environment Brief*, The Oxford Institute for Energy Studies, August, pp. 1-15	
• Sachin Shah (2012) 'Institutional Reform for Water Use Efficiency in Agriculture: International Best Practices and Policy Lessons for India,' CEEW Working Paper 2012/3, April	
• Arunabha Ghosh (2011) 'Seeking Coherence In Complexity: The Governance Of Energy By Trade And Investment Institutions,' *Global Policy* 2 (Special Issue): 106-119	
• Arunabha Ghosh (2011) 'Strengthening WTO Surveillance: Making Transparency Work for Developing Countries,' in *Making Global Trade Governance Work for Development*, edited by Carolyn Deere-Birkbeck. Cambridge: Cambridge University Press	
• Jason Blackstock, and Arunabha Ghosh (2011) 'Does geoengineering need a global response - and of what kind?,' *Background Paper*, Solar Radiation Management Governance Initiative, Royal Society UK, Chicheley, March	
Policy Briefs & Legislative/Government Briefings	
• Rudresh Sugam and Urvashi Sharma (2013) "Private sector participation in water management and water for all," Issue brief for the Second CEEW-Veolia Water Roundtable on Urban Water Management, 11 February	
• Rudresh Sugam (2012) "Water Utility Management in the Urban Water Sector," Issue brief for the First CEEW-Veolia Water Roundtable on Urban Water Management, New Delhi, 20 December	
• Karthik Ganesan (2012) "Climate Change and Business Leadership: Pathways to GHG Emissions Reduction and Sustainability in the Indian Cement Industry," Paper presented at the Third National ICRN Conference on Climate Change, Indian Institute of Science, Bangalore, 4 November	
• Vyoma Jha (2012) "Trends in Investor Claims over Feed-in Tariffs for Renewable Energy," Investment Treaty News, July	
• Arunabha Ghosh (2012) "Water governance priorities in India, South and East Asia, the case for integrated energy, environment and water plans, and Rio+20 goals," Briefing to the Brazilian Federal Senate, Environment, Consumer Rights and Oversight Committee & Agriculture and Land Reform Committee, Rio de Janeiro, 20 June	
• Arunabha Ghosh (2011) "Briefing on global governance to Ambassador Shivshankar Menon, National Security Adviser, Government of India," Prime Minister's Office, 20 December	
• Arunabha Ghosh (2011) "Governing clean energy subsidies: Why legal and policy clarity is needed," *Bridges Trade BioRes*, November	
• Vyoma Jha (2011) "Cutting Both Ways?: Climate, Trade and the Consistency of India's Domestic Policies," *CEEW Policy Brief*, August	
• Arunabha Ghosh (2010) "Negotiating around Tradeoffs: Alternative Institutional Designs for Climate Finance," *European Climate Platform Report* No. 10, Centre for European Policy Studies, Brussels, 9 December	
Selected Keynote Lectures & Speeches	

• Suresh Prabhu (2013) "Role of stakeholders in increasing food production," Keynote lecture at the National conference on *Doubling Food Production in Five Years*, New Delhi, 4 February	
• Arunabha Ghosh (2013) "Renewable Energies and Trade: Addressing tensions and challenges," Speech at a high-level policy dialogue at the World Trade Organisation meeting of Ambassadors, Geneva, 21 January	
• Arunabha Ghosh (2012) "India's Energy Scenarios: Planning for the Future," Lecture at the University of Petroleum and Energy Studies (UPES), Dehradun, 3 December	
• Rajeev Palakshappa (2012) "Laying the Foundation for a Bright Future," Presentation at the INTERSOLAR India 2012 Conference, Mumbai, 5 November	
• Ambassador Shiv Shankar Menon (2012) "Resources and National Security," Keynote Address by India's National Security Adviser, on CEEW's Second Anniversary, New Delhi, 23 August	
• Arunabha Ghosh (2012) "Sustainable Development in a Deeply Globalised Economy," Speech during the Rio+20 United Nations Conference on Sustainable Development, Rio de Janeiro, 20 June	
• Suresh Prabhu (2012) " Overview of India's clean energy markets," Speech at the NRDC and Environmental Entrepreneurs roundtable on Advancing Clean Energy Opportunities in India, San Francisco, 7 June	
• Arunabha Ghosh (2012) "Governing Clean Energy Subsidies: The Case for a Sustainable Energy Agreement," Global Green Growth Summit, Seoul, 11 May	
• Arunabha Ghosh (2012) "Governance in the face of uncertainties: data gaps, institutional coordination, and multiple level decision-making," Workshop on Climate Change and Water Cycle and Communicating Uncertainty, Princeton University, Princeton, 31 March	
• Arunabha Ghosh (2012) "Case for an integrated energy, environment and water approach in Rajasthan," Confederation of Indian Industry Rajasthan State Annual Session, Jaipur, 17 March	
• Suresh Prabhu (2011) "Tangible Reforms in Governance Process: Effective Leadership, is at the Heart of it All, in 21st Century India," Good Governance Dialogue Series by the Friends of Good Governnace (FOGG), December	
• Arunabha Ghosh (2011) "Geopolitics of energy security: Five framings from a global Indian perspective," Lecture at Aspen España – ESADEgeo conference on The Coming Energy Market, Madrid, 24 November	
• Arunabha Ghosh (2011) "Why is climate change such a wicked problem?," Lecture at China Foreign Affairs University, Beijing, 23 September	
• Arunabha Ghosh (2011) "Governing geoengineering: Play, pause or stop, and how," Lectures at Chinese Association for Science and Technology Annual Meeting, Tianjin , 21 September 2011; and Chinese Academy of Social Sciences, Beijing, 26 September	
• Arunabha Ghosh (2011) "Four transitions in global governance," Keynote lecture at the 10th Anniversary of the Clarendon Fund Scholarships, University of Oxford, Oxford, 17 September	
• Arunabha Ghosh (2011) "International Cooperation and the Governance of Geoengineering," Keynote lecture to the Intergovernmental Panel on Climate Change, Expert Meeting on Geoengineering, Lima, 21 June	
• Arunabha Ghosh (2011) "Designing Climate Finance Institutions," New York University-UAE Ministry of Foreign Affairs Workshop on Climate Finance, NYU Abu Dhabi Campus, Abu Dhabi, 22 January	
• Arunabha Ghosh (2010) "Should bottom-up meet top-down? Lessons for institutional design in climate governance," Post-Copenhagen Global Climate Cooperation: Politics, Economics and Institutional Approaches, Shanghai Institutes for International Studies, and Friedrich Ebert Stiftung, Shanghai, 29 September	

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