

Dual Role of Residential Battery Energy Storage Systems (BESS) in Residential Solar Energy: Implications for Solar Rebound Effect and Sustainable Development Goals (SDGs)

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Abstract

The swift expansion of residential rooftop solar PV systems has paved new avenues for sustainable development while simultaneously raising concerns regarding solar rebound effects whereby prosumers raise their electricity consumption after installing solar panels and partially offsets the projected environmental benefits. Battery Enabled Storage Systems (BESS) have emerged as a potential solution in this regard by enhancing self-consumption, reducing grid dependence and boosting energy management. However, their influence on solar rebound effect has received limited research attention. This study examines the dual role of BESS in either mitigating or amplifying the solar rebound effect and its broader implications on Sustainable Development Goals (SDGs), particularly SDG 7, 12 and 13. The review indicates that outcomes of BESS emerge from the interplay of technological, behavioral and environmental aspects rather than by technical performance alone. Additionally, strengthening the contribution of BESS to SDGs involves adopting a holistic approach encompassing technological advancement with consumer awareness, responsible consumption and circular economy practices.

Keywords: Solar Rebound Effect, Battery Enabled Storage Systems (BESS), Sustainable Development, Responsible Consumption, Climate Action, Affordable Energy

1. Introduction

Addressing the devastating consequences of greenhouse gas emissions (GHGs), climate change and energy shortage have been one of the many goals under sustainable development goals determined by United Nations General Assembly in 2015. Among 17 sustainable development goals (SDGs), SDG 7 strives to ensure widespread availability of affordable, modern and green energy to all. Attainment of these objectives call for a considerable increase in proportion of clean energy resources in global energy composition which is one of the targets of this SDG. Economies throughout the world have been making strenuous efforts in swapping carbon intensive energy resources with renewable energy resources. The role of renewable energy sources extends beyond delivering access to green and cost-effective energy. It also supports SDG 13 (climate action) by reducing the release of toxic chemicals in atmosphere and moving to a cleaner environment. Transition to green economy also gives emphasis on SDG 12 which urges responsible consumption of resources, adoption of sustainable practices and environmentally responsible consumption. Therefore, while the expansion of renewable energy is indispensable for sustainable development, its long-term environmental and societal benefits depend on ensuring that clean energy technologies are produced, adopted, and utilized in a responsible and sustainable manner (United Nations Sustainable Development Goals).

The concentration of low carbon emission sources in global electricity generation extended to 34% in 2025 from 32% in 2024 and 23% ten years earlier. Among multiple green energy resources, solar PV spearheaded this expansion, accounting for more than three-fourth of new renewable capacity employed globally while the wind energy contributed 20%. Hydropower, bioenergy and geothermal formed the remaining part. Solar PV capacity additions surpassed 600 GW in 2025 reaching cumulative capacity to around 800 GW, becoming the technology with the largest installed capacity globally. Nearly, thirty countries in the world deployed more than 1 GW of solar PV in a single year, almost doubling the figure of 2020 (Global energy review 2026). Total electricity generation in India touched the mark of 1,845.921 billion units (BU) in March 2026, of which sustainable energy

resources furnished 538.97 BU of energy, occupying a share of 29.2%. Installed Capacity of renewable energy sources has risen from 76.38 GW in March 2014 to 274.68 GW in March 2026, interpreting an addition of 198.30 GW. Solar has emerged as a substantial augments of this growth, escalating its base 53.28 times from 2.82 GW in March 2014 to 150.26 GW in March 2026. The residential solar segment is reflecting the most dynamic progress in the India rooftop solar market, anticipating a compound annual growth rate (CAGR) of approximately 22.26% during 2025-2031. This robust growth momentum in India is primarily driven by progressive government policy interventions like Pradhan Mantri Surya Ghar Muft Bijli Yojana, which makes solar PV installation economically viable for residential solar installations through significant fiscal incentives. Rising electricity tariffs in residential sectors across various states, further reinforced the growth of solar energy segment thereby encouraging homeowners to seek cost-effective alternatives. The enforcement of simplified residential solar installation procedure through the national portal, together with the availability of Central Financial Assistance (CFA) of around 40% for systems up to 3 kW and 20% for systems between 3-10 kW, has made solar adoption more accessible to residential prosumers (India Rooftop Solar Market Size & Share Analysis - Growth Trends and Forecast (2026 - 2031)).

Economic feasibility is one of the predominant motivators of solar panel adoption. Multiple investigations have confirmed that households exhibit a greater tendency to adopt solar systems because of their reduced bill and payback period (Khalid et al., 2021; Liang et al., 2022). Rohankar et al., (2016) also highlighted that presence of central and state government policies like tax concessions, accelerating depreciation and subsidies on installation favorably impacted the financial attractiveness of solar panels. Billing mechanisms like net-metering further improves the economic viability of rooftop solar by allowing residences to offset their grid electricity purchase with export of solar produced electricity. Existing literature identified that net-metering reduces the transmission losses in addition to reducing dependence on grid and ensure greater power supply (Zahid et al., 2020). The intention of incorporating solar panels extends beyond financial consideration. Concern and awareness towards environment have also prompted large numbers of households to replace conventional electricity with solar based clean energy. Economists reported positive association between environmental concern and willingness to adopt cleaner sources of energy reflecting that higher degree of environmental awareness leads to higher chances of switching to solar based energy (Aggarwal et al., 2019; Asif et al., 2022). Besides, actions and behaviors of an individual are shaped by society as well. Likelihood of adopting PV increases when greater number of households in society including friends and family have a positive attitude towards this technology and have already installed it or willing to do so (Asif et al., 2022; Barnawi et al., 2023).

Government has always promoted solar energy programs under the presumption that each kilo-watthour of electricity derived from solar PV systems will substitute the same amount of electricity produced by carbon-based energy sources like natural gas. From this viewpoint, any escalation in solar based electricity production will lead to an equivalent drop in grid electricity demand if a consumer's electricity consumption stays the same. In real world, however, this full displacement is hardly realized. Solar panel installation brings down the electricity bill of residences and the average price which they pay for electricity. This makes electricity more cost-effective, and households may respond by consuming more electricity than before which triggers rebound effect. The term rebound effect was first identified by William Stanley Jevons in his book "The Coal Question" written in 1865. He observed that improvement in the efficiency of steam engines made coal economically viable which led to its increased demand and eventually raised its consumption. He referred this phenomenon as Jevons paradox (Alcott, 2005). After that, various economists like Daniel Khazoom and Leonard Brookes reiterated this effect, which was dubbed by the US economist Harry Saunders as Khazoom-Brookes postulate. Since then, a handful of studies have sought to quantify the rebound effect corresponding to new energy technologies and efficiency gains. Recently researchers have started studying about the rebound effect of solar PV systems in residential sector and defined it as an post-installation intensification of electricity consumption or other forms of energy usage (Galvin, 2021; Jajoo & Soni, 2024; Sakshi Jajoo & Mamta Soni, 2025). Since, Households adopting solar PV systems consumes electricity produced by their solar panels, they came to be known as prosumers by various researchers, meaning those who generate as well as consume electricity (Boccard & Gautier, 2021; Deng & Newton, 2017; Galvin, 2021). Occurrence and magnitude of solar rebound effect (SRE) among residential prosumers is influenced by a diverse range of interconnected drivers including economic incentives, behavioral responses and

climatic conditions. The current body of literature has attempted to unearth determinants shaping the phenomenon of solar rebound effect. Some researchers found that liberal tariff structures implemented to promote solar panel adoption persuaded prosumers to consume more owing to price and income effect. A study conducted in Sydney using econometric modelling observed a rebound effect ranging from 16.7% to 20.9% owing to the feed in tariff policy. He further observed that higher the feed in tariff higher is the solar rebound effect (Deng & Newton, 2017). Another study explored that 1kWh increase in solar generated electricity stimulates an upsurge in electricity consumption by 0.18kWh owing to the price elasticity (Qiu et al., 2019). Similarly, a rebound effect of 7% was revealed among Dutch households as switching to solar panels reduced their electricity bills (Aydin et al., 2023). Study conducted in Wallonia also revealed that presence of net-metering and tradable green certificate scheme encouraged people to install solar PV with capacity of more than actually needed, which provide them with free electricity and prompts them to overconsume it (Boccard & Gautier, 2021). The literature also demonstrates that economic benefits cannot fully explain the change in electricity consumption behavior of residences after installing solar panels. Behavioral and psychological factors have also an important influence on post-adoption electricity usage. It is asserted that the installation of solar panels made people raise their electricity consumption level on the ground that they have already met their environmental obligations through installation of solar PV systems, so now it is permissible to do so. Researchers named this behavior as moral licensing wherein performing good behavior allows a person to carry out activities that they would otherwise refrain from but that are immoral and undesirable. Several researchers found moral licensing to be a potential predictor of SRE. (Beppler et al., 2023; Galvin, 2021; McCarthy, 2024). Besides, solar rebound effect of 12%-15.2% was found in Germany and it was revealed that pre-installation consumption has a significant and negative impact on solar rebound effect. Efficient, low-consuming households install PV systems to increase their electricity usage, possibly for self-sufficiency. Whereas high-consuming households do so to reduce costs, which may in turn promote conservation. Therefore, more efficiently the household lived before adoption the lower is the SRE (Poier & Bucksteeg, 2025). Climate also played a major role in solar rebound effect. In a study, conducted in San Diego, SRE ranging from 4.9% to 8.3% across four different geographical locations was observed and it was revealed that climate of a region more significantly affect electricity consumption as opposed to income and housing size of people living in that region (Kim & Trevena, 2021).

Solar rebound effect raises an important concern regarding the positive outcomes of residential solar panels on environment. Although, solar produced energy is a great alternative of conventional sources in reducing carbon footprint of economy, an increase in consumption of electricity post-installation would partially decrease the expected reduction in carbon emissions and would create difficulty in estimating the future energy demand. Consequently, actual climate mitigation outcomes depend not only on adoption of solar panels, but also on how residences modify their consumption behavior after solar installation. In this context, Battery Enabled Storage Systems (BESS) have gained substantial recognition as one of the plausible mechanisms to optimize the performance of solar panels. By storing excess solar based electricity produced during day and to be used during evening and night hours (when there is low or no solar energy generation). Storage systems can facilitate self-consumption, reduce dependence on grids and strengthen the potential of residential solar panels to fulfill sustainability goals. However, at the same time energy storage systems may create new pathways through which prosumers might increase their electricity consumption further.

Existing studies on battery storage systems have predominantly focused on technical performance, economic feasibility and environmental impacts. Comparatively little attention has been paid to understanding how these systems impact electricity consumption behavior and environment particularly in relation to solar rebound effect. Moreover, limited efforts have been made to synthesize impact of BESS for UN SDGs, particularly SDG 7, SDG 12 and SDG 13, from the perspective of developing country like India. To address these gaps, this review makes three research objectives (RO).

- **RO1:** To synthesize the facilitating mechanisms through which residential BESS may mitigate the solar rebound effect.
- **RO2:** To examine the constraining mechanisms that may amplify rebound including behavioral responses, economic barriers to adoption and environmental cost associated with it.

- **RO3: (A)** To discuss the broader implications of Facilitating mechanisms for SDGs 7, 12, and 13 from an Indian perspective.

RO3: (B) To discuss the broader implications of Constraining mechanisms for SDGs 7, 12, and 13 from an Indian perspective.

In doing so, the review provides a nuanced understanding of the dual role of residential BESS in supporting sustainable energy transitions.

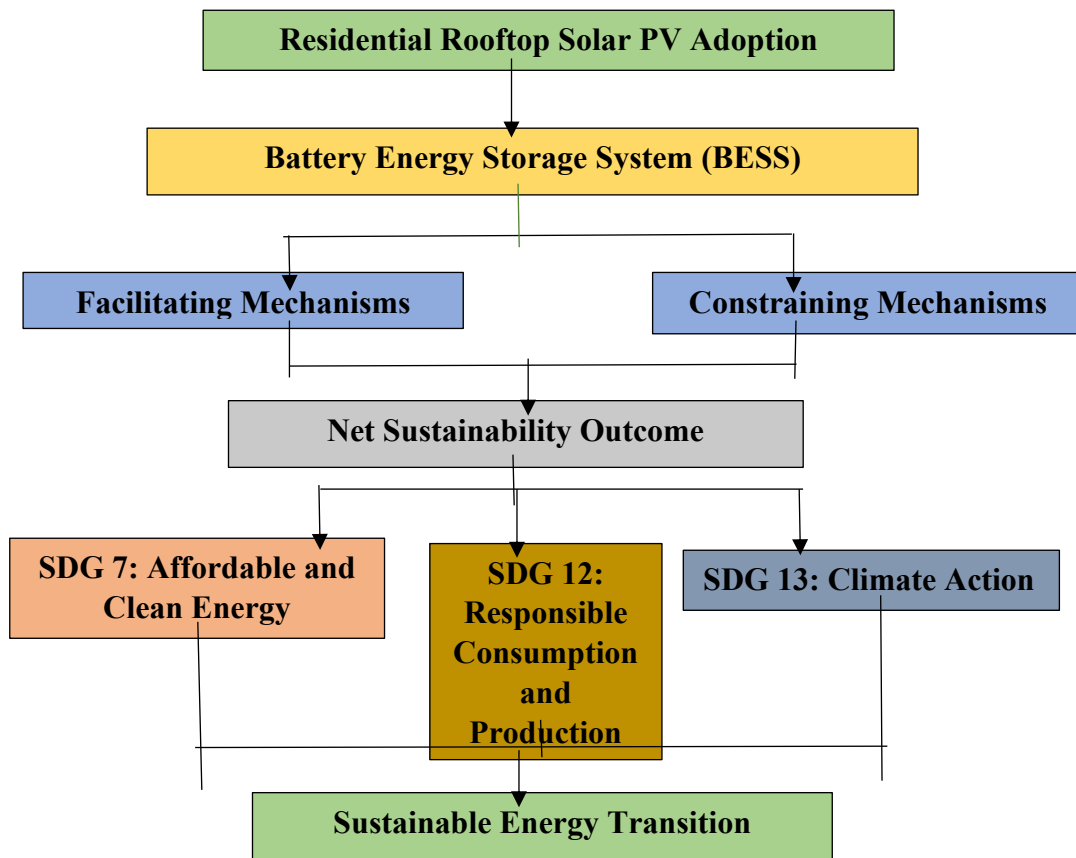


Figure 1. Solar-BESS Dual Impact Framework

2. Battery Enabled Storage Systems (Bess)

Battery storage has shown tremendous growth in past couple of years. In 2025, new battery storage capacity additions reached 108GW, noting 40% more growth than in 2024. Installed capacity is now eleven times higher than in 2021 (Global Energy Review 2026). Within the framework of its climate action goals, India has stipulated a target drawing half of its electricity from non-conventional energy resources by 2030 and to abate the emission intensity of its GDP by 45% by 2030, measured against 2005 levels. However, the inclusion of Renewable Energy into the energy mix poses a challenge for maintaining grid stability and continuous power supply. Unlike conventional energy sources such as coal, hydro and nuclear that can be stored and made readily available on demand, Renewable Energy (RE) sources such as Solar exhibit time-based fluctuations and are to be used instantly, if not then they will be lost forever. solar panels often generate electricity in excess of demand during daytime specifically around midday because of high solar irradiance, a large amount of electricity has to be exported to the grid which creates operational challenges for distribution networks including voltage fluctuations and grid power congestion. Similarly, during evening and nighttime hours there is no energy produced by solar panels because of absence of sunlight, households rely heavily on energy supplied by grid. This creates significant pressure on the power system due to which utilities have to rapidly increase their electricity supply to meet this surge in electricity demand by often relying on fossil fuel-based power plants. Such a mismatch between daytime

solar energy generation and evening energy demand creates the problem of duck curve, which graphically depicts the problem of electricity overproduction of electricity during midday and insufficient supply for quick spike in a short time in the conventional power system (Wang et al., 2019)

Energy Storage Systems (ESS) are designed to store excess energy from Renewable Energy to use it further during the period of generation deficit. National Electricity Plan (NEP) 2023 of Central Electricity Authority (CEA) forecasted the energy storage capacity requirement to be 82.37 GWh in 2026-27. This requirement is likely to move up to 411.4 GWh in year 2031-32. Further, CEA has also anticipated the requirement of energy storage to go up to 2380 GWh by the year 2047 as an implication of the addition of a larger amount of renewable energy in light of the net zero emissions targets set for 2070 (Energy Storage System (ESS) overview).

The adoption of battery storage systems among residential prosumers is influenced by economic, technological, environmental and behavioral drivers. Early adopters of storage systems were motivated by their desire to become more and more independent of conventional grids and utilize their own produced solar electricity which is defined by many researchers as autarky. This gives them a sense of self-sufficiency. Hence, they integrated battery system along with solar systems despite them being a costly investment in the beginning (Kaps & Netessine, 2026). Environmental commitment also influences battery adoption decisions. People with strong environmental values tend to go for these systems as battery system foster households to maximize the usage of renewable energy and reduce reliance on fossil fuel-based energy (Galvin, 2021).

Increasing desire of independence from grid, continuous reduction in cost of storage systems, renewable energy penetration is expected to accelerate the deployment of BESS in residential sector. However, the impact of storage systems also depends upon their interaction with energy usage behavior of households, their lifestyle and operational characteristics. Therefore, consideration of both enabling and limiting mechanisms is imperative.

RO1: To synthesize the facilitating mechanisms through which residential BESS may mitigate the Solar Rebound Effect.

2.1 Facilitating Mechanisms

Battery enabled storage systems bolster self-sufficiency among prosumers. One of the major downsides of solar is its reliance on weather and time, leading to inconsistent and non-dispatchable energy generation that cannot keep up with varying demand. Energy storage can tackle these issues by preserving energy during surplus generation and releasing it during excess demand. The conventional energy management strategy states when excess solar generation is charged into battery storage when it is greater than the need for electricity and when demand goes beyond solar power production, the unmet demand is satisfied by the energy released from storage. Due to this, the interaction between grid and household reduces which promote self-consumption and independence from conventional grid (Bigler, 2025). A study conducted using electricity production and usage data of Texas households revealed that home energy storage system has suppressed the aggregate peak demand by 8-32% and peak power injections by 5-42% depending on the mode under which it operates. While simultaneously increasing self-consumption, it also reduces the requirement for adding new generation capacity to reliably meet peak electricity demand and would reduce the infrastructural expansion requirement to maintain distribution equipment such as substations and transformers (Fares & Webber, 2017). Another study claimed that rebound effect during the valley period (when there is no solar power generation) is due to the rise in import of electricity from the grid during that period is mainly caused due to rebound effect. Curbing the rebound effect during valley period could enhance the carbon emission reduction to 34.07 kgCO₂ per month (Qiangfei et al., 2025). Battery storage systems thus can help in mitigating solar rebound effects by maximizing self-consumption as shown in Table I.

Table 1. Facilitating Mechanisms of Residential Battery Energy Storage Systems (BESS)

Mechanism	Implications	Related SDGs
Enhanced Self-Consumption	Improves demand-supply alignment, thereby enhancing self-consumption	SDG 7, SDG 13
Grid Stability	Minimizes peak power injection into the grid while limiting peak power imports from grid.	SDG 7, SDG 13
Energy Monitoring and Feedback	Enhance energy awareness and encourage energy efficient behavior.	SDG 12

Another pathway through which storage systems may constrain solar rebound effect relates to enhanced awareness through monitoring and feedback system. Modern residential battery storage systems are equipped with digital platforms that provide information regarding solar generation, electricity consumption, grid imports, etc. empirical research on energy monitoring and feedback demonstrates that access to detailed information on electricity consumption pattern develops the habit of monitoring which in turn encourage people to adopt more energy efficient behavior. An economist supported this argument by claiming that direct feedback through monitoring and display systems can lead to early energy and carbon savings and it also lays foundation for further savings through improved energy literacy (Darby, 2006). The monitoring interface between PV systems and households can be used as a means to prevent technically-induced rebounds by identifying faults in the system so as to fix them as quickly as possible (Galvin, 2021). Another study reported that the combination of storage systems with Active Demand side Management makes the user aware of the energy demand, improves the self-use of solar produced energy, thereby usually leading to consumption reduction. Along with this, it also improves energy supply and reduce import of raw materials (Castillo-Cagigal et al., 2011).

RO3: (A). To discuss the broader implications of Facilitating Mechanisms for SDG 7, 12 and 13 from Indian perspective.

2.1.1 Implications for Sustainable Development Goals (SDGS)

The enabling mechanisms discussed above reflect how residential storage systems can deliver environmental and societal advantages by enhancing self-consumption, improving grid stability, encouraging energy-conscious behavior through monitoring and feedback. These outcomes closely support several UN Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and clean energy) and SDG 13 (climate action). By allowing the integration of renewable sources like solar into the electricity system, it ensures stable and reliable energy supply. Besides, by reducing the requirement for fossil fuel backup plants, storage accelerates the decarbonization of energy systems.

From an Indian perspective, these benefits are significant as the country continuous to expand deployment of clean energy sources like rooftop solar panels in order to contribute to the targets of SDG 7 through initiatives like PM Surya Ghar Muft Bijli Yojana. However, absence of reliable storage system often limits the optimum utilization of solar energy because variable nature of renewable energy generation necessitates continued dependence on conventional energy sources. Introduction of battery storage systems can mitigate this challenge by increasing the on-site utilization of renewable energy, improving peak demand management and enhancing efficiency of distributed energy systems. In addition, BESS helps in optimizing cost by lowering exposure to volatile short-term market prices and adheres with national and state clean energy targets, including renewable consumption obligations thereby strengthening the progress towards the goal of ensuring access to clean, affordable and modern energy to all.

Beyond improving energy access and reliability, BESS are also pivotal in curtailing GHG emissions within power sector and facilitating the progress towards SDG 13. Nevertheless, these sustainability benefits are not automated. Their realization depends on consumer behavior to a large extent. Following section discusses the behavioral, economic and environmental limitations of storage systems which may restrict their ability to fully realize their contribution to sustainable development including sustainable development goals of affordable clean energy, responsible consumption and climate action.

RO2: To examine the constraining mechanisms that may amplify rebound including behavioral responses, economic barriers to adoption and environmental cost associated with it.

2.2 Constraining Mechanisms

There is no doubt that battery storage systems are a future in the world of solar energy systems as they increase the efficiency of solar systems by promoting self-consumption and reducing dependence on grids. However, it can also exacerbate the challenge of solar rebound effect. The theory of rebound effect explains that reduction in the cost of energy services owing to technological efficiency enhancement encourage increased consumption of that service thereby partially offsetting the perceived benefits of efficiency improvement. In the context of rooftop solar systems, electricity bills of prosumers get reduced due to fall in average price which persuades them to increase their electricity consumption following solar PV adoption (as shown in Table II). The integration of battery storage system may further strengthen this mechanism by decreasing the marginal cost of electricity during the period of low solar irradiance thereby stimulating electricity demand and in turn exacerbating emissions. The evidence of this increasing consumption trend post solar-storage integration was observed by (Fares & Webber, 2017) found mean increase in annual energy usage by 8% and 14% when operated under target zero mode and minimize mode respectively. They went on to say that every time a home energy storage system is charged and discharged, some energy is consumed, that is why annual energy consumption increases for every household. Similarly, (Kaps & Netessine, 2026) in their study conducted in Germany found a storage rebound effect of 4% which indicated that storage households increase their electricity consumption by 4% on average which increased the household emissions by 57 kg CO₂/ kWh/year. They also highlighted the problem of increasing grid demand variability throughout the year. This is an outcome of households becoming more reliant on their own produced energy, yet they may experience some days of low solar output and high grid dependency. So, the grid providers on average sell less energy to solar pv homeowners but simultaneously have to retain flexible capacity to ensure reliable electricity supply.

Table 2. Constraining Mechanisms of Residential Battery Energy Storage Systems (BESS)

Mechanisms	Implications	Related SDGs
Reduced electricity bill	Lower electricity bill which may further encourage higher electricity consumption	SDG12, SDG13
Moral Licensing	Strengthen the sense of environmental contribution which justify additional consumption.	SDG 12, SDG 13
Battery Efficiency Losses	Reduces the quantum of self-produced energy available for usage.	SDG 7
Adoption Cost	Limits accessibility of BESS	SDG 7
Battery induced environmental hazards	Battery production, mineral extraction and disposables create environmental concern.	SDG 13

One of the plausible explanations of the solar rebound effect has been given by moral licensing. Addition of panels in electricity system creates perception among prosumers that they can use more electricity as they have already fulfilled their responsibility towards environment and are also producing green electricity (Beppler et al., 2023b; McCarthy, 2024). Installation of storage system along with solar panels may further increase their sense of environmental responsibility by enabling greater utilization of solar energy, becoming more independent from grid and increasing self-consumption. Consequently, prosumers may view their investment in battery storage as their commitment towards environment and may feel entitled to consume more without feeling guilty. This behavior may partially offset the benefits associated with battery storage system and can lead to storage induced rebound effect. Therefore, despite improving the efficiency and utilization of solar energy residential battery storage systems, moral licensing can weaken its benefits by encouraging higher level of electricity consumption.

Battery storage systems also suffer from inherent efficiency losses. For instance, (Castillo-Cagigal et al., 2011) talked about the energy losses linked with float charges which are often ignored. These losses stem from the energy required to sustain the battery operations after it is fully charged. This amount of energy does not provide any meaningful contribution in the global energy system as it cannot be effectively utilized. (McKenna et al., 2013) explained that during charging and discharging, batteries experience voltage loss. This is because batteries are usually charged at higher voltage and discharged at lower voltage. This difference in voltage results in energy losses. Furthermore, less charge can be extracted from batteries at the time of discharge as compared to what is being used to charge the batteries. This creates coulombic inefficiency which is amplified by high charging and discharging rates. Such losses can reach ₹1000/year for a 570 A h added to a 3.29 kW_{peak} PV system. This creates internal resistance and heat generation. Although Such efficiency losses do not directly contribute to solar rebound effect, they reduce the amount of self-produced energy available for usage, which weakens the economic and environmental impact expected from battery adoption.

However, adoption cost remains a critical barrier in battery adoption. Amongst various battery technologies available in the market, Lithium-ion battery (LiB) and vanadium redox flow batteries (VRFB) are the best alternatives for grid scale storage applications. The present cost of the LiBs is around INR13,600-20,000/kWh and for VRFB is around INR24,000-32,000/kWh in India. Such high upfront cost may refrain people from investing in this technology. Nevertheless, according to NITI Aayog and BNEF, the cost of LiBs and VRFBs will be reduced to INR 5500/kWh and 8700/kWh respectively by 2030 which will make them financially viable for a large number of consumers to install (Study on “Advanced Grid-scale Energy Storage Technologies”).

While Battery storage systems have undeniable ecological benefits, it also comes with an environmental cost. The mining of raw materials specifically lithium, which is a fundamental component of these batteries, frequently leads to environmental deterioration, including water depletion and pollution (Hannan et al., 2021). This extraction process poses significant ecological risks. Manufacturing process of battery is energy intensive, requiring significant amounts of energy for material processing, fabrication and assembly. Environmental concern also extends to the end-of-life disposal of batteries where complex composition of batteries and limited recycling infrastructure possess significant waste management challenges. The recycling of battery materials entails specialized processes to extract essential metals and limit waste production. However, these technologies are neither readily accessible nor economically viable. Beyond these issues, inappropriate disposal of batteries at the end of life stage can lead to the release of toxic compounds into the environment, endangering water, land and wildlife (Peter Simpa et al., 2024). Therefore, careful consideration of these effects is important.

RO3: (B). To discuss the broader implications of Constraining Mechanisms for SDG 7, 12 and 13 from Indian perspective.

2.2.1 Implications for Sustainable Development Goals (SDGS)

The limitations discussed above have important implications for the achievement of United Nations Sustainable Development Goals particularly SDG 12, SDG 13 and to some extent SDG 7. Understanding these challenges is imperative to ensure that growing deployment of storage systems leads to sustainable energy transition rather than creating new environmental and social challenges.

Although the integration of BESS promotes efficient utilization of renewable energy resources by storing surplus energy for later use, their impact on responsible consumption is influenced by consumption patterns of prosumers to a large extent. If households perceive stored electricity as abundant and inexpensive they may further raise their electricity consumption level or invest in additional electric intensive appliances as explained in theory of solar rebound effect. Such behavior combats the purpose of BESS and may prove to be a hindrance in achieving the goal of responsible consumption. It further reduces the carbon emission reduction associated with renewable energy usage thereby hampering the goal of climate benefit. Besides battery manufacturing, raw material extraction and end of life management pose significant environmental challenges that require sustainable production and recycling practices. From Indian perspective, the anticipated expansion of residential battery deployment reflects the need to improve recycling system, circular economy practices and promote responsible consumer behavior to ensure that battery storage contributes meaningfully to SDG 12 and 13.

The economic limitations associated with residential storage systems have an important implication for SDG 7. High adoption cost may restrict people from adopting storage systems. In Indian context, where renewable energy is expanding rapidly, improving the affordability of BESS through policy framework and technological improvement is essential for increasing the access of clean energy sources.

3. Discussion

This review presents an extensive overview of the role of Battery energy storage systems in influencing solar rebound effect by combining technical, economical, behavioral and environmental aspects. Unlike prior literature available in domain which primarily focused on technical performance, environmental impacts and economic feasibility, this study reveals that sustainability outcomes of BESS cannot be understood through analyzing these dimensions independently. Instead, residential storage system should be considered as socio-technical system wherein overall impact on sustainable energy transition is determined by interaction of technological aspects interact with consumer behavior, economic suitability and policy framework.

Present work advances the understanding of dual role of BESS on solar rebound effect. As shown in Figure I. Battery storage possesses the potential to both mitigate and amplify solar rebound effect. On one hand, it improves utilization of solar energy, by increasing self-consumption, enhancing stability of grid and more efficient integration of renewable energy into electricity system. On the other hand, behavioral responses such as increased electricity consumption owing to reduced energy cost and greater availability of self-generated power, together with moral licensing, efficiency losses associated with the internal system of batteries, high adoption cost and environmental constraints may offset the benefits associated with storage systems. This indicates that performance of residential BESS should be assessed from a broader socio-economic perspective that encompasses prosumers behavior, economic feasibility, environmental effects rather than solely evaluating it on the basis of technical efficiency.

Viewed through the lens of Sustainability Development Goals, influence of BESS extends across multiple SDGs particularly SDG 7, SDG 12 and SDG 13 which are closely interconnected. Maximizing the progress towards these goals requires adoption of a holistic approach with regard to storage systems that combine technological innovation with responsible consumer behavior, circular economy activities and supportive policy interventions. These findings are specifically relevant for India where expedited uptake of renewable energy particularly solar energy is expected to increase the requirement for battery storage systems. Improving affordability of battery storage, strengthening recycling infrastructure and consumer awareness will therefore be essential for success of long term sustainable development goals.

Therefore, degree of the success of storage systems in mitigating solar rebound effect and promoting environmental sustainability does not solely depend upon technical performance, rather Consumer Social Responsibility (CNSR) plays a major role in shaping the sustainable energy outcomes. According to (Soni & Dawar, 2018) Adoption of green products, although an important element of consumer social responsibility, does not entirely capture the scope of consumers' commitment towards environment and society. It extends to the reduction in consumption level as well as judicious resource use. Consumers must immediately pay attention to

their consumption patterns, alter their lifestyle and behave in a way that promotes social welfare and improve environmental health. Consumers exhibiting sense of environmental and social responsibility may act in a manner that would promote conservation objectives. Whereas, consumers with lower degrees of social responsibility would get motivated to further raise their consumption level without thinking about its impact on environment. In the context of impact of BESS on solar rebound effect and environment, CNSR may act as a deciding factor that decides whether the integration of battery storage systems would actually reduce electricity consumption and carbon emissions.

4. Conclusion

Several Initiatives taken to promote solar PV technology in India specifically among residential sector led to its widespread deployment. However, fluctuating nature of solar energy generation necessitated integration of a reliable system to meet the temporal mismatch between electricity generation and household demand, thereby ensuring a stable electricity supply during peak demand and during low solar production. While BESS would facilitate greater usage of solar energy, reduce conventional grid dependency, carbon footprint in atmosphere thereby contributing to green economy which it surely does, its overall success depends not merely on technological performance, but also on prosumers behavior. Prosumers' behavior can either lead to mitigation of challenges associated with renewable energy or exacerbate the issue. Behavioral responses associated with increased availability of self-generated energy and lower perceived cost can offset a portion of anticipated ecological gains through storage rebound effect. Further, environmental cost associated with extraction of raw material, manufacturing, use and end of life disposal of batteries remain a significant challenge that requires careful consideration. Therefore, all these dimensions should be considered while assessing the overall impact of BESS on Sustainable energy transition.

Surmounting these challenges requires a comprehensive approach that combines technological innovation with behavioral and policy interventions. Since a significant portion of the storage induced rebound effect arise from behavioral responses, strategies aimed at influencing consumer interventions are important. Educational campaigns should be organized at various levels to make people aware of the implications of excessive usage of electricity despite using renewable energy. A sense of environmental and social responsibility should also be inculcated through CNSR programs so as to make people utilize solar system energy in a sustainable manner rather than treating lower-cost electricity as a justification for higher consumption. At policy level, incentive schemes should be framed in a way that rewards efficient use of electricity rather than merely supporting technology adoption. From an environmental perspective, battery recycling, sustainable mineral sourcing, and the development of low-impact storage technologies can help minimize the lifecycle environmental burdens associated with battery deployment.

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Sakshi Jajoo: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft.

Mamta Soni: Conceptualization, Supervision, Validation, Writing – review & editing.

Conflicts of Interest

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