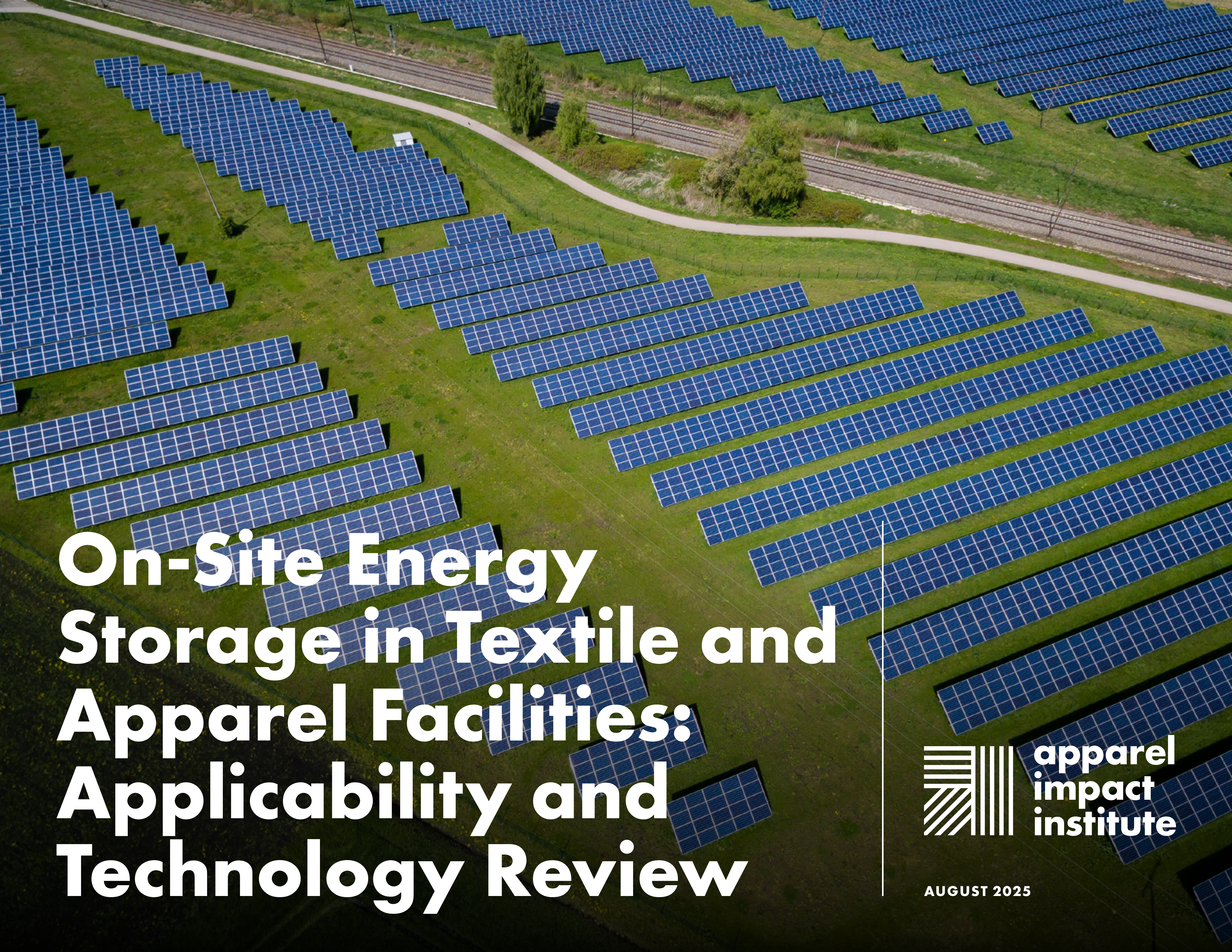


On-Site Energy Storage in Textile and Apparel Facilities: Applicability and Technology Review

apparel impact institute

AUGUST 2025

Acknowledgments

The Carbon Trust wrote this report utilizing in-house analysis based on primary sources provided by Apparel Impact Institute and an impartial analysis of secondary sources.

The Carbon Trust would like to thank everyone that has contributed their time and expertise during the preparation and completion of this report.

This report has been commissioned by Apparel Impact Institute.

Authors

Bogi Hojgaard Associate Director

Hazim Rosli Manager

James Harrington Senior Associate

Daniel Hirschowitz Associate

Natalie Tay Associate

Daphne Lim Senior Analyst

Acronyms & Abbreviations

A-CAES	*Adiabatic Compressed Air Energy Storage*
ASEAN	*Association of Southeast Asian Nations*
AUD	*Australian Dollar*
BESS	*Battery Energy Storage System*
BTM	*Behind-the-meter*
C&I	*Commercial and Industrial Sector*
CAES	*Compressed Air Energy Storage*
CAGR	*Compound Annual Growth Rate*
capex	*Capital Expenditure*
CO_2	*Carbon Dioxide*
CO_2e	*Carbon Dioxide Equivalent*
cPCMs	*Composite Phase Change Materials*
CSP	*Concentrated Solar-Thermal Power*
DERs	*Distributed Energy Resources*
DG	*Distributed Generation assets*
ESO	*Energy System Operator*
ESS	*Energy Storage System*
ETS	*Emissions Trading System*
EU	*European Union*
EV	*Electric Vehicles*
EVN	*Vietnam Electricity Group*
F&B	*Food and Beverage*
FEC	*Final Energy Consumption*
FTM	*Front-of-the-meter*
GW	*Gigawatt*
H_2	*Hydrogen*
IEA	*International Energy Agency*
IRA	*United States Inflation Reduction Act*
IRENA	*International Renewable Energy Agency*
kW	*Kilowatt*
kWh	*Kilowatt hour*
kWp	*Kilowatt peak*
SMEs	*Small and Medium Enterprises*
MW	*Megawatt*
MWh	*Megawatt hour*
NDRC	*National Development and Reform Commission*
NEA	*National Energy Administration*
O_2	*Oxygen*
OpEx	*Operating Expenditure*
PCM	*Phase Change Materials*
PPAs	*Power Purchase Agreements*
PSH	*Pumped Storage Hydropower*
RAG Analysis	*Red, Amber, Green Analysis*
RE	*Renewable Energy*
RESCOs	*Renewable Energy Companies*
Rs	*Indian Rupee*
SAIDI	*System Average Interruption Duration Index*
TES	*Thermal Energy Storage*
ToU	*Time-of-Use*
TRL	*Technology Readiness Level*
UPS	*Uninterruptible Power Supply*
USD	*United States Dollar*
VGF	*Viability Gap Funding*
VND	*Vietnamese Dong*
VPP	*Virtual Power Plant*

Contents

List of tables

Executive Summary

The deployment of distributed solar is accelerating, driven by evolving policies and regulations, innovative financing mechanisms, and shifts in corporate strategies. This growth is particularly prominent in the commercial and industrial (C&I) sector, where strong returns on investment make distributed solar an economically attractive solution for meeting on-site electricity needs. The textile and apparel industry, while in the early stages of adopting distributed solar energy, has delivered commercially viable projects. One such case is Sipani Fibres Ltd in Kolar, Karnataka, India, which successfully installed a 2.5MWp rooftop solar system, delivering estimated annual savings of approximately USD 326,000.

A strong policy environment stimulates renewable and energy storage deployment and is a key enabler of investments in onsite solar and energy storage solutions (ESS). National policies promoting the deployment of renewables support the case for energy storage solutions, as acquiring flexible assets is fundamental for balancing supply and demand in a renewable-dominated power system. Favorable policy and regulations, paired with financial incentives such as tax breaks and carbon credit schemes, can stimulate the uptake of onsite solar and ESS. This is already the case in China, where targets for 100GW of storage by 2030, supported by an emission trading system (ETS) and domestic manufacturing, have exhibited strong renewable energy deployment rates, including distributed solar. In 2022, 51.1GW of the 107GW of the newly-installed distributed solar capacity globally occurred in China. India has also seen a dramatic rise in the installed capacity of renewable technologies, guided by an ambitious national target of 500GW of renewable energy capacity by 2030, and is seeking to replicate this in the energy storage industry, targeting 74GW by 2031 through both pumped storage and battery technologies. These targets demonstrate a desire to implement clean technologies and present a strong enabling environment to catalyze investment. Conversely, weak policy directives and unambitious targets can undermine investment from the industry and, combined with the absence of competitive electricity markets and limited financial incentives, can make deployment and operation of renewable energy and energy storage assets challenging, as is the case in Indonesia and Bangladesh.

The primary driver for on-site energy storage systems (ESS) is the structure of electricity markets. In markets where ESS can participate in ancillary services and leverage time-of-use (ToU) tariffs, on-site ESS could become a revenue-generating asset. The large energy requirements in the textile and apparel manufacturing sector mean that onsite solar alone cannot meet the full electricity demand, even at peak generation, requiring ESS units to be charged from the grid. This makes ToU tariffs essential as they enable energy arbitrage, charging during off-peak hours and discharging during peak hours. Countries like China, through its National Development and Reform Commission (NDRC), and Vietnam, with its three-tier tariff structure (peak, normal, and off-peak), have enabled strong arbitrage value through wide tariff spreads. Conversely, in markets where ToU pricing is absent or the spread between the peak and off-peak rates is minimal, the economic case for ESS weakens. The limited off-peak and peak tariff differential in Bangladesh and Indonesia makes on-site ESS economically challenging.

Moreover, the presence of open ancillary service markets, allowing storage assets to participate in markets such as demand response, grid stability, and frequency reserve, further strengthens the business case for ESS. These services offer additional revenue streams that the ESS can access, enhancing the financial viability and demonstrating extra means of providing returns on investments. However, this revenue stream is not yet accessible in Indonesia, Vietnam, and Bangladesh.

In markets with a weak and/or limited electricity network, ESS can act as an uninterrupted power supply (UPS), providing a continuous supply of electricity. In the event of brownouts or blackouts, ESS can act as a generator asset to provide an uninterrupted power supply, allowing textile and apparel manufacturing sites to continue operating and delivering economic benefits. The System Average Interruption Duration Index (SAIDI) quantifies the average duration of power outages in a given country and can be used as a measure to determine the value of ESS deployment as a source of UPS. Bangladesh, with its high SAIDI and weak grid infrastructure, presents a strong case for ESS. In contrast, countries like China and Vietnam, which benefit from stable grids and low SAIDI scores, offer limited justification for ESS deployment purely as a UPS.

High capex costs are a major barrier to the deployment of ESS in textile and apparel sites in many emerging markets. In Vietnam, capex investment costs for battery energy storage systems (BESS) range from USD 360 to 420/kWh. On a power provision basis, this equates to up to VND 4,934/kWh of power generated, nearly 50% greater than the peak electricity tariff. In contrast, China – the world's largest exporter of energy storage technologies – has far more favorable capex costs at USD 126/kWh for a battery pack. This advantage has helped accelerate ESS market maturity and deployment in China. In India, Vietnam, and Indonesia for BESS, and in Bangladesh for both BESS and thermal energy storage (TES), the high capex combined with the inability to access ancillary markets and the limited revenue generation through tariff price arbitrage result in poor financial viability of on-site ESS.

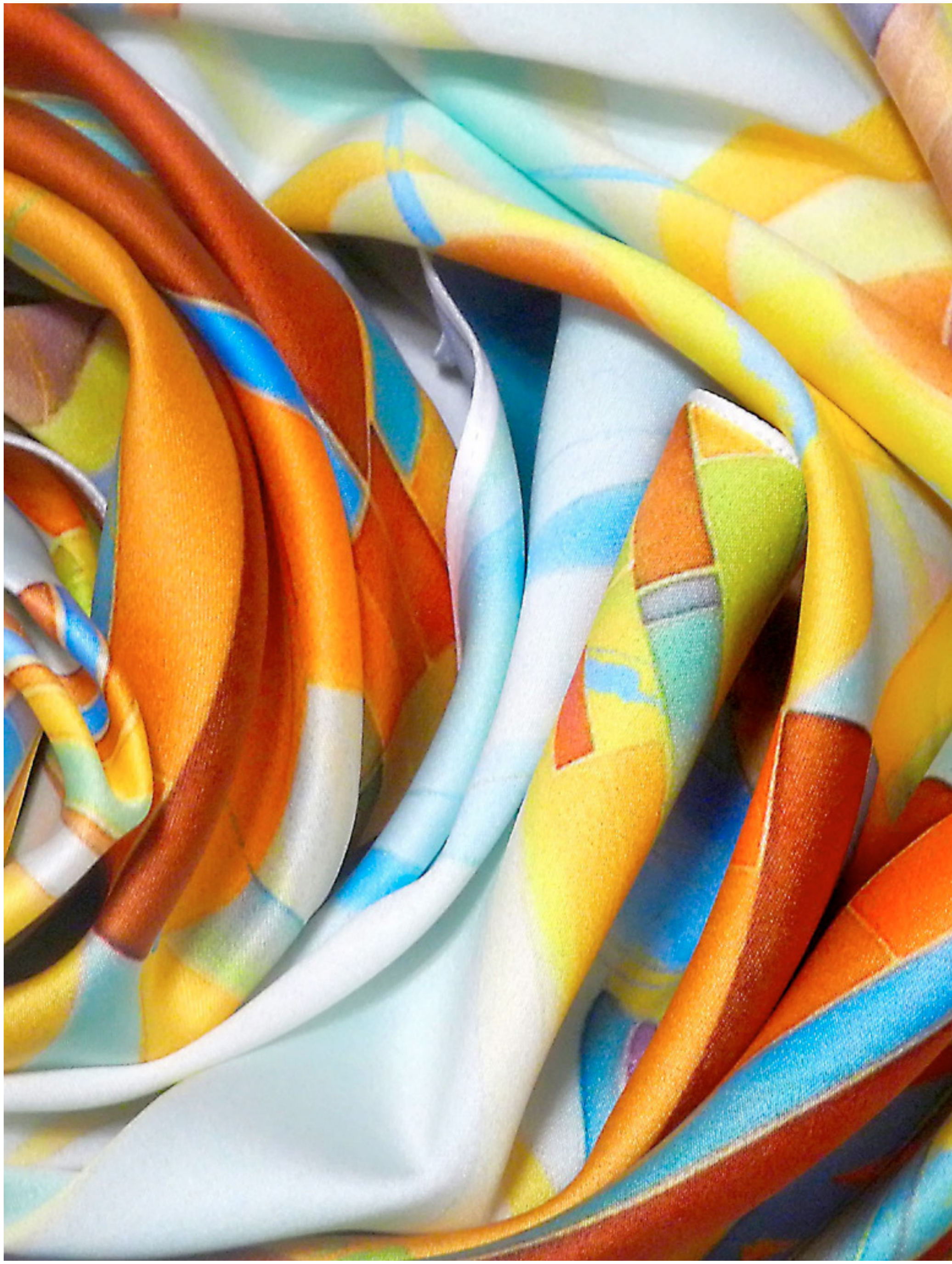
Counterfactual energy costs shape investment decisions in on-site generation and storage. In markets where existing energy sources are cheaper than grid electricity or on-site solar, the business case for alternative generation technologies is challenging. For instance, Indonesia benefits from low coal prices, as it is the world's largest coal exporter and the fourth-largest producer as of 2023. This abundance of inexpensive coal reduces the incentive for textile manufacturing owners to invest in cleaner alternatives. In contrast, Vietnam, as a net coal importer, faces higher coal costs, creating a stronger economic case for textile facilities to explore alternative energy solutions. To encourage broader adoption of clean energy technologies, especially in markets with cheap existing fuel costs, governments would need to provide incentives to guide the industry toward cleaner alternatives and make the conventional energy sources less financially attractive.

Electrification of textile and apparel manufacturing sites using ESS would only deliver Scope 2 reductions if the grid's emissions intensity is lower than that of the existing fossil fuel source. Countries where renewable energy penetration is currently low tend to have higher grid emission intensity. In these markets, the electrification of textile and apparel facilities using ESS would not immediately reduce Scope 2 emissions. This is the case in Bangladesh, where the emission intensity of electricity from the grid averages over 300 gCO_2e/KWh higher than the emissions intensity from direct combustion of natural gas, which is the dominant fuel source in the Bangladeshi textile industry. This is also the case in the Indian, Vietnamese, and Indonesian markets, where electrification is recommended only after enough clean energy has reduced the grid's emissions intensity below that of existing fuel sources.

Operating ESS for energy price arbitrage can increase carbon emissions in markets where peak tariff coincides with periods of high solar irradiance. Energy price arbitrage strategies involve charging ESS during off-peak (often nighttime) hours and discharging during peak (daytime) hours. In China, peak tariff occurs from 2 pm to 5 pm and off-peak from 10 pm to 8 am. This would mean charging the battery at night and discharging it during the day, when solar irradiance is relatively high. As such, this could result in more expensive, but less emission-intensive grid electricity being displaced with cheaper, but more emission-intensive grid electricity.

As electricity is the most consumed energy source in tier 1 textile sites, electrochemical storage technologies are the most suitable ESS solutions. Among these, lithium-ion batteries stand out as the most mature and widely adopted option. Proven in both industrial and grid-scale applications, lithium-ion systems offer reliable backup power, operational flexibility, and uninterrupted electricity supply. As such, they are particularly well-suited for textile sites with minimal heat requirements, providing dependable and efficient means of meeting electrical energy demands.

Tier 2 sites consume a lot of thermal energy, making Thermal Energy Storage (TES) solutions appropriate. However, the majority of technologies in this class are at a much lower Technological Readiness Level. Tier 2 textile facilities rely heavily on thermal energy for their processing needs. Having thermal energy storage (TES) solutions installed could support the demand for thermal energy, potentially in a less emission-intensive manner. However, the limited commercial maturity of most TES technologies restricts the range of viable options. Many remain at early stages of development and are not yet suitable for large-scale deployment. Water-tank thermal storage stands as the most commercially viable option due to its relatively low capital expenditure (capex) and high round-trip efficiency, making it the leading choice for current applications. However, molten salt thermal energy storage is a fast-improving technological solution with a pilot project having been installed in a textile and apparel processing facility in Nantong, China.



1. Introduction

The textile and apparel sector is a significant contributor to global greenhouse gas emissions, accounting for 2% of all emissions (approximately 1.03 gigatonnes (Gt) of carbon dioxide equivalent (CO_2e)) in 2019.[1] This could rise to 1.59Gt by 2030 if no measures are taken. A large portion of these emissions can be attributed to the use of fossil fuels to support the textile and apparel manufacturing industry's thermal and electrical energy needs. To limit warming to 1.5°C, the sector must reduce emissions by 45% on an absolute basis by 2030.[2]

Renewable energy (RE) generation sources, such as solar and wind, are essential for achieving emission reduction targets in the sector and serve as a crucial foundation for electrifying the industry, as outlined in Apparel Impact Institute's Low Carbon Thermal Energy Roadmap.[3] RE assets can be connected at the grid level, but are also frequently co-located within the manufacturing sites as a local, often cost-effective, source of low-carbon electricity. The deployment of RE assets has been encouraging, with the International Renewable Energy Agency (IRENA) reporting an addition of 585GW of RE generation in 2024, bringing the total to 4,448GW, an increase of over 15% from 2023[4]. However, two key challenges remain in increasing the deployment of on-site RE:

- The variable and intermittent nature of RE technologies and
- Limited grid infrastructure, financing challenges, and market structure often hinder RE in developing economies, even though renewables are often more cost-effective than fossil-based energy sources such as coal and natural gas.

Energy storage has the potential to address both challenges in certain situations:

- Where there is excess RE generated, surplus can be stored and used during periods of low RE production and/or high energy demand.
- Energy storage has the potential to offer cost reductions by consuming stored electricity instead of grid-connected electricity. These cost reductions can be achieved through the dispatch of stored electricity and calibrated based on the differentiated electricity tariff rates in regions where time-of-use tariffs exist.
- Increased revenues can be achieved when excess stored RE-generated electricity is sold back to the grid in markets where regulations allow.

This report outlines how the implementation of on-site energy storage can help support the growth of on-site RE technologies in the textile and apparel sector.

Section 2 focuses on the state of deployment of on-site renewables, in particular on-site solar.

Section 3 focuses on the state of deployment of on-site energy storage.

Section 4 includes details on the technology options for on-site energy storage, with a focus on thermal, electrochemical, and chemical energy storage.

Section 5 presents a high-level analysis of the top 20 textile- and apparel-producing regions, outlining each's suitability for on-site energy storage.

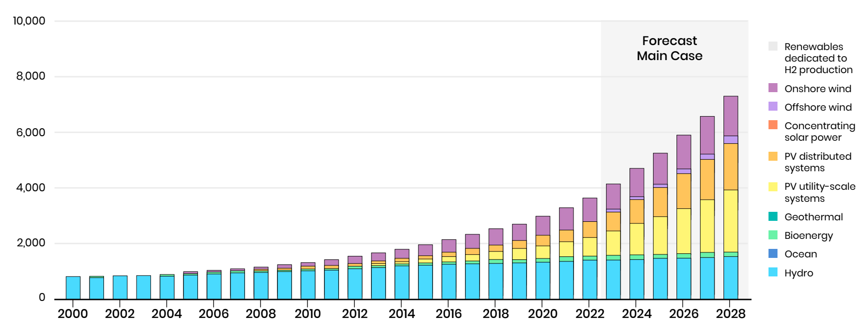
[1] Sadowski, M., L. Perkins, and E. McGarvey. 2021. "Roadmap to Net-Zero: Delivering Science-Based Targets in the Apparel Sector." Working Paper.
[2] As above
[3] Hasanbeigi, A., C. Springer, and D. Wei. 2025. "Low-Carbon Thermal Energy Roadmap for the Textile Industry."
[4] Renewable Capacity Highlights 2025

2. State of On-Site Renewables

2.1 Global trends in on-site renewables

Global renewable energy capacity increased by over 137% from 2012 to 2023 (from approximately 1,533 GW to 3,647 GW). In one of its scenarios, IEA forecasts further growth to approximately 7,284 GW in 2028.[5]

Figure 1: Historical and forecasted trend of renewable energy capacity (GW)



Clean, distributed energy resources (DERs), which are small-scale behind-the-meter (BTM) installations situated near sites of electricity use, form part of this rapid RE expansion.[6] On-site solar photovoltaic (PV) technology is a form of DER highlighted in this report due to its applicability as a source of self-generation in the Commercial and Industrial (C&I) sector and for its ability to be combined with on-site energy storage solutions to provide self-sufficient power generation. In China, the world's fastest-growing solar energy market, programs such as the 'Whole County PV' have supported significant growth in the deployment of distributed solar. This has been evidenced in 2022, when the country added over 87 GW of new solar PV capacity, with distributed solar representing 51.1 GW of the new capacity[7], demonstrating distributed solar as the primary driver of new solar installations. Notably, the C&I sector represented the greatest proportion of new distributed solar, consisting of 50.6% of the 51.1 GW of new capacity. Therefore, as the costs of fossil-based energy increase, so too is the expectation for the continued growth in solar PV deployment.[8]

[5] IEA (2024). Renewable Energy Tracker.
[6] BTM installations refer to electrical resources connected at the individual level behind the utility meter. (IRENA BTM Landscape Brief, 2019)
[7] Global Market Outlook For Solar Power 2023 - 2027 - SolarPower Europe
[8] IEA (2023). Renewable Energy Market Update

While a majority of the growth in renewables is projected to be utility-scale solar deployment, this growth is also expected to open up the market for distributed solar PV deployment.[9] Most ASEAN countries, including Indonesia, Philippines, and Vietnam, are expected to enhance regulations and infrastructure to enable greater renewables uptake in the next five years.[10] China is expected to deliver strong growth in distributed solar PV capacity, as provincial support and higher retail prices have driven rapid C&I deployment of distributed solar PV systems.[11] India is expected to improve grid access rules for distributed PV and thus show strong growth forecasts for distributed solar PV, along with utility-scale PV.[12]

Case studies in the textile and apparel industry further demonstrate the commercial value of implementing on-site solar PV systems. For example, Sipani Fibres Ltd in Kolar, Karnataka, India installed a 2.5 MWp rooftop solar system that will achieve INR 27 million (approximately USD 326,000) in annual cost savings for the manufacturing facility.[13] Edirne Giyim Sanayi, a textile company in Merkez, Turkïye has also completed a 1.61 MWp ground-mounted solar project that covers 70% of the company's electrical needs.[14]

[9] IEA Renewables 2023
[10] As above.
[11] As above.
[12] As above.
[13] Orb Energy (n.d.) 2.5 Megawatt Rooftop Solar System Sipani Fibres Limited, Bangalore, Karnataka
[14] IBC Solar (2018) IBC SOLAR Turkey commissioned PV plant for a leading Turkish textile manufacturer

2.2 Drivers of distributed solar growth

Various factors are driving the growth of on-site solar in the industrial sector. These can be broadly categorized into the following:

(1) regulatory support; (2) policy mechanisms that facilitate deployment; (3) availability of attractive financing schemes; and (4) corporate strategy.

Regulatory support enables the deployment of on-site renewables by removing barriers. This can include allowing the sale of excess electricity back to the grid and/or updating building codes to allow for the deployment of rooftop solar PV. Simplifying rules, streamlining grid access, and permitting processes are other examples of regulatory support. In Maharashtra, India, amendments to the Distribution Open Access Regulations now allow consumers with a contracted demand or sanctioned load of at least 100 kW to obtain power from renewable sources via open access.[15]

Other regulations exerting pressure on companies include the European Union (EU)'s Carbon Border Adjustment Mechanism (CBAM), which adjusts for the difference in carbon price between the EU and the country of origin. In its current implementation phase, CBAM targets high-emitting sectors, including cement, fertilizers, iron and steel, aluminum, hydrogen, and electricity. While there have been discussions aboutincluding products from more sectors, these remain unconfirmed. Nonetheless, such regulations, if applied to the textile and apparel sector, could encourage textile producers to adopt more RE systems to reduce their product carbon footprints.[16]

Secondly, **policy mechanisms**, such as net-metering schemes, capital investment subsidies, and tax breaks, have been key in driving the growth of on-site solar. These policy mechanisms often work by providing revenue opportunities (in the case of net-metering schemes), reducing the upfront cost of investment (capital investment subsidies), or smoothing a business' cash flow (tax breaks). In 2018, the state of Maharashtra in India removed the 1 MW capacity ceiling for net-metered rooftop solar projects in the textiles industry, facilitating increased deployment of on-site solar in the sector.[17] In 2023, the same State Government launched an updated 'Integrated and Sustainable Textile Policy 2023 – 2028' with capital subsidies for textile facilities to increase the environmental and economic competitiveness of the sector.

Private sector initiatives can also drive on-site solar growth through innovative business models, including novel **financing schemes**. Third-party financing or renewable energy service company (RESCO) business models shift the upfront cost of installation and implementation/operation risks away from site owners onto a specialized third-party: the RESCO.[19] The RESCO leases the rooftop from site owners and sells the electricity generated from the rooftop solar PV to the site owner at a rate lower than grid-sourced electricity tariffs. This model improves the rooftop solar business case for site owners by replacing capex with regular operational expenditure based on the electricity they consume (which will be similar to the operating expenditure incurred for consuming electricity from the grid).[20]

[15] Mercom (2023). Maharashtra announces incentives for textile units setting up solar projects
[16] European Commission (n.d.) Carbon Border Adjustment Mechanism.
[17] Mercom (2018). Maharashtra's New Textile Policy Promotes Utilization of Renewable Energy Sources
[18] Government of Maharashtra (2023). Integrated and Sustainable Textile Policy 2023 – 2028.
[19] ADBi (2021). Working Paper on India's Policies for rooftop solar
[20] As above

Additionally, tax incentives lower the installation cost for distributed solar PV systems, allowing small industrial companies to enter the market, and increasing the cost-effectiveness of distributed solar PV systems for larger companies. For example, the Indian government provides tax relief on solar energy installations through an initial accelerated depreciation rate of 40% on solar-related plants and machinery. Companies can deduct a large portion of the solar plant's cost during its early operational stage, thereby reducing taxable income and taxes.[21]

The **corporate strategies** of large multi-national corporations often acknowledge that consumers and shareholders expect the corporation to operate sustainably, exemplified by increasing sustainability reporting requirements from stock exchanges. China, the dominant textile and apparel manufacturer, has recently released sustainability reporting guidelines for its three largest stock exchanges – the Shanghai Stock Exchange, Shenzhen Stock Exchange and Beijing Stock Exchange, adding pressure and transparency demands on companies (including large listed Chinese textile companies) to disclose information on their sustainability performance and, in turn, encouraging them to better manage their energy needs and energy efficiency year-on-year.[22] For the textile and apparel manufacturing sector in other developing and emerging economies, the sustainability driver often comes from brands listed on exchanges in more advanced economies responding to increased pressure from regulation to decarbonize their own supply chain.

[21] India Briefing (2024). Understanding Accelerated Depreciation of Solar Power Assets in India.
[22] ESG Today news report

2.3 Barriers to distributed renewable deployments

A key barrier is the **high upfront installation costs**, which prevent companies, particularly small and medium enterprises (SMEs), from investing. The cost of an average 50 kWp rooftop solar system in India ranges from INR 2,050,000 to INR 3,750,000 (approximately USD 24,600–45,100).[23] SMEs, therefore, must choose between investing in solar installations or their core business. Financial institutions' perceptions of SME credit risk also hinder access to low-cost debt financing, leading to low RE deployment.[24]

The electricity demand of light industries such as textile and apparel manufacturing has grown consistently over the past five years, from 2,900 terawatt-hours (TWh) to 3,570 TWh between 2018 and 2022, underscoring the growing energy needs of the sector.[25] However, the inherent variable nature of RE (without storage) is a significant drawback for these companies as they require stable and consistent access to power. Additionally, with more renewables integrated into the grid, more investments to upgrade the grid will be required to ensure greater flexibility.

Nascent policy mechanisms, such as the lack of financial incentives (grants, subsidies, tax breaks), also hinder the development of distributed RE. **Financing challenges** in countries like Indonesia stem from limited financial institution expertise in structuring viable deals, resulting in few bankable renewable energy proposals.[26] Financial institutions in Indonesia also perceive RE projects as high risk, and there are insufficient financial de-risking instruments to address this.[27]

As such, a key solution to this challenge can be on-site energy storage systems (ESS). ESS, when deployed with distributed generation assets such as on-site solar, can serve multiple functions, which will be explored in the next section.

[23] Amplus Solar (2024). Average upfront cost of implementation
[24] Financial Express (2022). Why MSMEs are hesitant in embracing non-conventional energy sources like rooftop solar
[25] IEA (n.d.) Light Industry
[26] Energy Transition Partnership (2023). Grid & Financing Challenges for Energy Transition in Indonesia
[27] Climate Policy Initiative (2020). Enhancing Decentralized Renewable Energy Investment to Achieve Indonesia's Nationally Determined Contribution

3. State of On-Site Energy Storage

3.1 Global trends in energy storage

Global energy storage capacity growth is mainly driven by the expansion of grid-scale pumped storage hydropower (PSH), with grid-scale stationary batteries also playing a significant role. PSH installed capacity increased by 10.5 GW and reached a cumulative capacity of 175 GW in 2022, while grid-scale stationary batteries installed capacity increased by 11 GW and reached a cumulative capacity of 28 GW. [28,29]

There is limited public data on the state of deployment of behind-the-meter (BTM) stationary energy storage, which is installed at the site level behind the utility meter to serve commercial, industrial, and residential customers. Grid-scale battery storage is the dominant form of energy storage deployed currently, making up 72% of annual added capacity, while BTM application only accounts for 21% of annual added capacity.[30]

Consequently, data on the level of BTM energy storage application in light industries is lacking, and the application remains nascent.[31] The data center industry has seen considerable installation of BTM storage, approximately 12 GWh, with an estimated 4% cumulative annual growth rate (CAGR) to 2030.[32] Beyond that, selective case studies found on BTM energy storage in textile and apparel manufacturing and analogous industrial settings, such as the food and beverage industry, indicate that its application is still in its infancy.

Our research identified one significant case study of on-site energy storage deployed in the textile and apparel manufacturing industry. Costa Rican textile company Proquinal installed two 40-foot MTU battery containers with a combined storage capacity of 4.3 MW and 690 solar panels over a covered parking lot with 0.255 MWp generation capacity at its Coyol de Alajuela, Costa Rica, headquarters.[33] The stored energy is delivered to its plant, which produces coated fabrics. This allowed the facility to save USD 41,000 monthly (with a payback period of 4.3 years) by charging the battery storage system from the grid in the afternoon and at night when electricity tariff rates were low and generating solar energy for self-consumption that reduced electricity drawn from the grid.[34] This also allowed the facility to avoid more than 285 tCO_2e annually, in line with the company's sustainability goals.[35]

28 IEA (n.d.) Grid-scalestorage
29 International Hydropower Association (2023) World Hydropower Outlook
30 McKinsey (2023). Enabling Renewable Energy with battery energy storage systems.
31 Light Industries: Industrial sub-sectors that are less energy intensive than heavy industrial manufacturing, including food & beverage processing, textiles, construction and mining. (IEA, n.d.)
32 US Department of Energy (2020)Energy Storage Grand Challenge: Energy Storage Market Report
33 Rolls Royce (2020). Textile company in Costa Rica produces climate-friendly energy system with MTU battery storage systems from Rolls-Royce
34 As above
35 CINDE (2020). Costa Rica Confirms Energy Storage Project by Proquinal

3.2 Drivers of on-site energy storage growth

Although the application of on-site energy storage is rare in the textile and apparel sector, some drivers of growth can be distilled from analogous sectors. Research revealed that BTM storage installation is more common in the food and beverage (F&B) sector. Many of them have done so to arbitrage grid electricity through time-of-use (ToU) tariffs. However, the combination of on-site solar plus storage remains rare.[36] Two case studies were identified. The first was the installation of a 0.336 MW rooftop solar PV system and a 0.122 MWh battery storage system by Kona Brewing Company in Kailua Kona, Hawaii.[37] The second is a 1 MW energy storage system that was installed by Algoma Orchards in Ontario, Canada.[38]

The main driver of on-site energy storage is the structure of the power markets in the location where a site operates. This specifically refers to the ability to optimize costs and generate revenue from energy storage through ToU tariffs and ancillary service markets. The existence of ToU tariffs is especially important as it enables sites to charge the on-site storage at off-peak hours when the tariff is lower and discharge the energy at peak hours when the tariff is higher. In Hawaii, where Kona Brewing Company is located, electricity tariffs are as high as USD 0.61/kWh during peak periods compared to USD 0.25/kWh during off-peak periods.[39] A similar cost structure is also in place in Ontario, where Algoma Orchards is located, with peak period electricity tariffs at USD 0.18/kWh compared to USD 0.08/kWh during off-peak periods.[40] Due to the absence of F&B examples in key manufacturing regions, examples from other locations were used.

For sites in regions that permit excess energy to be sold back to the grid, **policies and regulations** enabling further revenue generation also improve the commercial viability of on-site energy storage. Initiatives to allow 'Virtual Power Plant' (VPP)[41] are an example of such enabling regulation. Implemented in regions such as the United States, Australia, Japan, and Europe, compensation rates and mechanisms vary depending on country and context. In the United States, USD 2.00/kWh is paid to consumers for every additional kWh delivered through the Tesla – Pacific Gas and Electric Company VPP when the grid needs emergency support. Comparatively, a maximum of AUD 0.31/kWh (equivalent to USD 0.2/kWh) is delivered through the Tesla Energy Plan in Australia, with a USD 1,000 subsidy for battery energy storage systems (BESS) installation paid to end-users.[42] These initiatives can reduce upfront costs and substantially improve the business case of on-site energy storage in the industrial sector. In addition, regions with strong innovation ecosystems are also likely to help drive the implementation of novel energy storage solutions. For example, PepsiCo has teams dedicated to sourcing solutions for problems such as heat energy storage. Through engagement with startups in the Netherlands, PepsiCo has decided to

[36] The food and beverage sector has been classified as analogous to the textile and apparel sector due to the two industries' similar proportion of consumption of electricity and thermal energy, with the latter being required at similar temperature ranges.
[37] Kona Brewing Company to produce sun-powered beer through solar-plus-battery storage project with EnSync Energy and Holu Energy.
[38] Enel X (2023). Sustainable energy strategies for food and beverage manufacturers
[39] Hawaiian Electric (n,d,) Time of Use Rate History
[40] Erth Power (n.d.) Ontario ToU Pricing
[41] VPPs are a network of decentralized and distributed renewable energy sources that are aggregated, and often uses advanced software and technology to monitor, control, and coordinate the aggregated sources. This enables the VPP to respond dynamically to changes in energy demand, grid conditions, and market signals.
[42] Tesla (n.d.) Virtual Power Plant with PG&E; Tesla (n.d.) Australia Energy Plan

electrify the production of Lay's and Cheetos chips in the Netherlands, storing excess wind energy produced in the North Sea for use in cooking boilers during the day when energy costs are higher.[43,44] Heat energy is stored in Kraftblock's innovative thermal battery technology to support CO_2e emissions reduction of over 50% for the facility, with an expectation of 98% reduction in the future.[45] As above, examples in regions outside of key textile and apparel manufacturing sites were detailed due to the absence of relevant information for the sector.

Internal corporate strategy, such as meeting brands' or manufacturers' own emission reduction targets, **and regulatory pressure** to disclose sustainability efforts and climate risks, as described earlier in Section 2.2, are also drivers of on-site energy storage, as it can enable further CO_2e emissions reduction.

[43] Food Navigator Europe (2023). Electrifying crisp production: PepsiCo overcomes green energy storage issue with thermal battery tech
[44] Based on publicly available information, it appears that this Pepsico sites in Broek op Langedijk consumes renewable electricity generated from wind energy from the North Sea through the grid via market tariffs.
[45] PepsiCo (2023). How PepsiCo is investing in renewable energy solutions

3.3 Barriers to on-site energy storage deployment

Net-metering (i.e., sites are only paying the energy supplier for the 'net volume' of grid imports and site energy exports from on-site RE) is present in several markets such as India, Pakistan, Indonesia, and Vietnam.[46] This allows on-site RE generators to use the grid as a 'virtual battery' with no energy losses, removing all incentive to install an actual battery (which would incur round-trip losses and require investment)[47].

A power market structure that either does not promote cost optimization or provide revenue-generating opportunities is a barrier to on-site energy storage deployment. This specifically refers to regions where ToU tariffs are absent, such as in Bangladesh, or where the differential between the peak and off-peak tariff rates is too small to be attractive for storage. The latter is observed in the large textile-producing Indian states of Andhra Pradesh, Telangana, and Gujarat, where the difference in the tariffs between peak and non-peak hours is only up to 1 INR/kWh, (approximately USD 0.012/kWh) and, hence, considered minimal.

High costs of on-site battery storage are also a barrier. For instance, the investment cost of BESS remains high in Vietnam, ranging from USD 360 – 420/kWh for installation in one set of BESS. This is equivalent to paying VND 4,246 – 4,934/kWh of power generated, significantly higher than Vietnam Electricity Group's (EVN) maximum electricity tariff at peak periods, which is VND 3,314/kWh.[48,49] The high cost diminishes the viability of on-site energy storage. This is also seen in India, where despite battery storage costs falling to INR 10.18/kWh, it remains higher than the average industrial electricity tariff rates of INR 5 – 7/kWh.[50] As such, for manufacturers, significant cost barriers to implementing on-site renewables and storage remain. Most thermal storage solutions are still in early development stages and have not yet benefited from cost reductions due to accumulated experience that technologies like solar PV have experienced. Therefore, they largely remain too expensive, and unproven, for textile and apparel manufacturing sites.

46 Rehman, et al., (2020). The Penetration of Renewable and Sustainable Energy in Asia: A State-of-the-Art Review on Net-Metering. IEEE Access. 8. 170364-170388. 10.1109/ACCESS.2020.3022738.
47 JMK Research and Analytics (2021). India's new net metering limit risks stalling progress on rooftop solar target
48 EVNPECC3 (2023). Applying BESS for Renewable Energy Projects
49 EVN (2023). Retail Electricity Tariff
50 ETEnergyWorld (2023). Energy Storage cost at Rs 10.18 per kWh, govt plans to reduce further: Prime Minister Central Electricity Authority (2022). Electricity Tariff & Duty & Average Rates of Electricity Supply in India.

A lack of carbon pricing in a country poses a barrier, as manufacturing sites will have a weaker incentive to transition away from more carbon-intensive fossil fuels to clean energy and storage. If carbon pricing is too low to make carbon-emitting fossil fuels more expensive in the short term, companies will not prioritize on-site storage technologies. Significantly, countries that are large textile and apparel producers, such as India, Bangladesh, and Vietnam, do not price carbon. Of the large textile and apparel producing countries, only China has an emissions trading system (ETS) intended to limit emissions, although the textile and apparel sector is not currently under the scope of the ETS.[52]

Fossil fuel subsidies also hinder the implementation of energy storage, as these subsidies allow manufacturers to access lower-cost fossil fuels. Major textile-producing countries such as China and India have paid out significant fossil fuel subsidies, amounting to USD 2.2tr and USD 350bn respectively, in 2022.[53] China's coal price consequently decreased by 4.2% and coal remains the main source of electricity in India. Consequently, switching to cleaner forms of energy, such as on-site energy storage charged by renewables, becomes less attractive as there is limited cost incentive for manufacturers to benefit from.

A lack of awareness of the benefits of certain storage solutions **and risk aversion to implement more novel technologies**, such as thermal energy storage solutions, can also slow implementation.[54]

[51] OurWorldInData (2022). Which countries have put a price on carbon?
[52] International Carbon Action Partnership (n.d.) China ETS
[53] Reuters (2023). Explainer: Global fossil fuel subsidies on the rise despite calls for phase-out
[54] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.

3.4 Value of on-site energy storage

ESS can 'firm up' RE generation by storing excess energy generated during periods of high RE generation and discharging energy during periods of high energy consumption or low RE generation.[55,56] On-site ESS can be a source of 'uninterrupted power supply' (UPS) or backup power in the event of a grid outage. In the event of brownouts or blackouts, ESS acts as a generator asset, providing a continuous power supply at the installation site.[57] ESS' ability to firm capacity and as a source of uninterruptible power supply (UPS) is particularly important in countries with a high System Average Interruption Duration Index (SAIDI) score.[58]

On-site ESS can also enable cost savings by reducing imports from the grid. In regions where ToU tariffs are implemented, on-site ESS allow consumers to reduce their electricity bills by charging during 'off-peak' hours when tariffs are low and discharging during peak when tariffs are high.[59]

Co-locating storage and solar assets provides the additional benefit of optimising the kWp size of the solar installation, improving investment efficiency of solar installations, by, for example, reducing the necessary kWp size of the solar installation for a given demand load by increasing the self-consumption rate. Pairing a PV system with batteries can reduce the required size of the PV system for a given site by as much as 25%.[60]

Beyond providing site-specific benefits, on-site ESS can also provide value to the power grid, including the provision of ancillary services. ESS can inject electricity extremely fast and with higher accuracy than conventional generators to provide power system reliability services. The provision of ancillary services to the grid may comprise load shifting, frequency regulation, and reserve. By doing so, batteries can create new revenue streams for companies in regions where ancillary service markets exist.[61]

On-site ESS can reduce congestion on electricity grids by storing electricity produced when the grid is congested. This can reduce electricity losses by allowing more efficient use of the grid. This value is maximized when many ESS are aggregated using software platforms and their behaviour is coordinated.[62]

Thermal energy storage systems are particularly valuable if the conventional thermal energy generation displaced is more carbon-intensive (i.e., the fuel usually used to generate heat, such as coal, is more carbon-polluting than deriving heat from RE+ thermal energy storage systems).

As such, greater energy storage deployment could drive the business case for deploying on-site RE by providing site-level benefits to textile and apparel manufacturing facilities, in addition to wider grid-level benefits.

Even if on-site ESS is not co-located with on-site solar (e.g., if space constraints and building regulations make it challenging for sites to install them), it can still be a valuable solution. In such cases, installing on-site storage with a power purchasing agreement (PPA) to procure off-site renewable electricity could be an option.[63] An ESS with electricity drawn from the grid/off-site renewable energy source (offshore wind, for example) provides similar benefits to on-site solar-plus-storage, with the added flexibility on the choice of RE source due to absence of space constraints, which limits on-site RE to solar PV.[64]

55 NREL (2021). BTM Battery Energy Storage FAQ
56 Energy capacity firming: The ability of a technology to make up for any shortfalls in RE capacity when needed.
57 IRENA (2019). Behind-The-Meter Batteries: Innovation Landscape Brief
58 The SAIDI index is the average total duration of outages (in hours) experienced by a customer in a year.
59 NREL (2021). BTM Battery Energy Storage FAQ
60 RE-Source (2020). On-site renewable electricity and storage for corporates: business models & policy framework
61 As above.
62 As above.
63 Zeigo (2023). Can PPAs unblock access to new battery projects?
64 As above.

4. Overview of Solution Types and Technologies

This section provides an overview of the energy storage solutions by type and technology which are more applicable for light industries, such as textile and apparel, food and beverage, and production of consumer products. Technologies used for space heating or cooling in buildings (e.g. air-conditioning) or for power generation in the power sector have not been considered.

Energy storage can be classified into five main technological categories, namely:

i. **Electrochemical storage:** stores electrical energy in the form of chemical energy, which can subsequently be reconverted back to electrical energy at point of discharge, i.e. most forms of batteries. This type of energy storage involves chemical reactions to store and release energy.

ii. **Thermal energy storage (TES):** stores thermal energy by heating or cooling a storage medium. The stored energy can be subsequently discharged for heating or cooling applications.

iii. **Chemical storage:** stores energy in the form of chemical potential energy such as hydrogen, driven by chemical reactions. Stored energy is subsequently converted into other forms of energy, typically thermal or electrical energy, at point of discharge.

iv. **Mechanical storage:** stores energy in the form of mechanical potential or kinetic energy through mechanical configurations or motions of physical systems.

v. **Electrical storage:** stores energy in the form of electricity, and which is discharged to supply electricity. Examples include (super)-capacitors.

The technologies are discussed based on the following key parameters:

i. **Technology Readiness Level (TRL):** The TRL framework was introduced by the North American Space Agency (NASA) to assess the readiness of different innovations or the maturity of a specific technology on a scale of 1-9. Higher TRLs indicate greater maturity and commercialization, while lower TRLs indicate that the technology is still undergoing demonstrations or prototyping to reach commercialization. This overview will focus on technologies that are of moderate-to-high TRL (TRL 6 or higher), but also highlights lower TRL technologies that have relevance to the textile and apparel industry or industries more broadly.

ii. **Typical power (MW) and energy (MWh) output:** This indicates the range of sizes of the storage systems.

iii. **Round-trip efficiency (%):** This is the ratio of the total energy output by the system to the total energy input to the system, as measured at the point of connection. A higher round-trip efficiency is preferable as it indicates lower energy losses and a more efficient system.

iv. **Storage period:** This refers to the duration for which energy can be stored prior to effective use. It could range from hours (demand shifting) or months (seasonal storage). At the minimum, a storage period of hours-days would be preferable for the sector due to the predictable, daily cycle over which textile sites consume energy and for energy arbitrage purposes in regions where time-of-use tariffs exist.

v. **Typical capital expenditure (capex) and operating expenditure (Opex):** capex refers to the upfront investment cost of storage solutions and Opex refers to ongoing cost linked to the operations of the energy system.

vi. **Global deployment of storage (MW/MWh):** This indicates the level of adoption of storage technology worldwide (not specifically to industry use only). While TRLs of the technology may be high, global deployment may be low due to high costs and/or other lack of enabling factors and policies, thus limiting scale-up.

These technologies and their assessment against these parameters are summarized in Table 4. The actual feasibility of these technologies would depend on specific site or facility requirements (e.g. type of processes, space availability) and more in-depth feasibility assessments would need to be conducted.

Table 1: Key parameters of selected energy storage technologies/solutions[65]

Type of storage technology	Sub-Technology type	TRL	Typical power (MW) and energy (MWh) output	Round trip efficiency	Storage period	Typical capex (€/kWh unless otherwise stated)	Typical OpEx	Global deployment of storage (MW/MWh)
Thermal Energy Storage Technologies and Solutions[66]								
Sensible	Solid-state	TRL 5-9	1kW to 100MW 10kWh to GWh	>90%	Hours to months	18.4-41.4	Unknown	Likely to be low as low TRL
Sensible	Water-tank	TRL 8-9[67]	kW to 10MW kWh to 1GWh	50-90%	Hours to months	0.092-32.2	Unknown	Unknown
Latent	High temperature Composite Phase Change Materials	TRL 4	10kW to 100MW 10kWh to GWh	>90%	Hours to days	55.2-110.4	Unknown	Likely to be low as low TRL
Electrochemical Energy Storage Technologies and Solutions								
Batteries	Lithium-ion batteries	TRL 9	up to 500MW up to 1000MWh	85-89%	Up to months	600-3500/kW 350-1200/kWh	1% of capex	227-359GW by 203[68]
Chemical Energy Storage Technologies and Solutions								
Green hydrogen electrolysis and combustion	-	Moderate TRL	1-300MW (industrial hydrogen boiler[69])	18%-46%[70]	Up to months	250/kW for retrofitting boiler with a hydrogen burner[71]	3.2 (€/kW)	700MW water electrolysis capacity[72]
Biomass (Combustion via steam boiler and turbine)[73]	-	TRL 8-9	5 – 10MW 10 – 40MW	24-38% (power) 80-90% (co-generation of power and heat)	Up to months	3000–6000/kW 2300–4600/kW ***OR*** USD 600-1700/kW (retrofit for direct cofiring) [74,75]	2 – 5/MWh	140GW*[76]

[65] Unless otherwise indicated in separate footnotes, the main reference for each parameter is the European Commission, Directorate-General for Energy, Hoogland, O., Fluri, V., Kost, C. (2023). Study on energy storage, Publications Office of the European Union.
[66] Apart from capex and OpEx parameters or referenced otherwise, all other data parameters under TES are sourced from IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi
[67] EASE (2017), European Energy Storage Technology Development Roadmap
[68] Statista Research Department (2023). Global Battery Storage Capacity Needs 2030-2050. Statista.
[69] Energy.nl (2020). H2 INDUSTRIAL BOILER Technology Factsheet.
[70] Hydrogen technology faces efficiency disadvantage in power storage race. (2021). Hydrogen Technology Faces Efficiency Disadvantage in Power Storage Race | S&P Global Market Intelligence.
[71] Energy.nl (2020). H2 INDUSTRIAL BOILER Technology Factsheet.
[72] IEA (2023). Global Hydrogen Review 2023.
[73] Motola V et al., (2022) Clean Energy Technology Observatory: Bioenergy in the European Union: Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/577104, JRC130730.
[74] IEA (2020). The role of CCUS in low-carbon power systems
[75] 1 USD is equivalent to approximately 0.9 Euro
[76] Statista. (n.d.). Bioenergy capacity worldwide 2019.

Type of storage technology	Sub-Technology type	TRL	Typical power (MW) and energy (MWh) output	Round trip efficiency	Storage period	Typical capex (€/kWh unless otherwise stated)	Typical OpEx	Global deployment of storage (MW/MWh)
Mechanical Energy Storage Technologies and Solutions								
A-CAES	-	TRL 5-6	10 - 300MW 100MWh - 10GWh	>70%	Up to 10 hours	1600/kW	1% of capex	Unknown
Flywheels	-	TRL 9	1 – 20MW 5kWh – 5MWh	85 – 95%	Seconds to minutes	310/kW	1.1 – 2.9/ MWh	931MW[77]
Electrical Energy Storage Technologies and Solutions								
Supercapacitor	-	TRL 8-9[78]	up to 1kWh up to 300kW	90-95%	Seconds to minutes	87 – 2500/kW	Unknown	Unknown

4.1 Electrochemical Energy Storage

The storage of electrical energy allows the production of heat and electricity and improves the business case for using on-site renewable energy to power the site. However, charging and discharging losses of these systems can result in lower round-trip efficiencies than some TES systems such as solid-state and latent TES.

In general, they have mid to high round-trip efficiencies and appropriate storage periods. The capex of electrochemical storage solutions is significantly higher than that for TES solutions, but is lower than chemical energy storage solutions.

Batteries

Batteries are the most conventional energy storage technologies, where stored electrochemical energy is converted to electrical energy. They are comprised of at least two electrochemical cells, which use chemical reactions to generate an electric current. Batteries can be classified into primary (non-rechargeable) and secondary (rechargeable).

Lithium-ion battery technology is the predominant commercial form of rechargeable batteries with widespread application today because of its high energy and power densities compared to other commercial battery technologies (such as lead-acid batteries). They have suitable storage periods of months (1-2% self-discharge per month), 1,500 – 3,500 cycles[79], and fast response times.

These batteries are often used to store excess electricity generated by renewable energy sources and to balance the supply and demand of electricity on the grid, contributing to overall grid stability. They can additionally be used for peak shaving. While the primary function of lithium-ion batteries is not to generate industrial heat (the main energy carrier is electricity), their electrical output can be used to power electric heaters/boilers or other heat-generating devices indirectly.

77 Md Mustafizur Rahman et al., (2021). Sustainable Energy Technologies and Assessments. The development of a techno-economic model for the assessment of the cost of flywheel energy storage systems for utility-scale stationary applications.
78 REEEM (2017) Innovation Readiness Level Report: Energy Storage Technologies.
79 Cycles refers to the number of complete charges and discharges a rechargeable battery can undergo before it will no longer hold a charge.

4.2 Thermal Energy Storage

In general, TES solutions tend to be lower cost than other energy storage solutions, as seen in Table 1. The cost of the TES system typically depends on the storage material, the heat exchanger for charging and discharging the system, and the cost of space accommodating the TES system. Generally, latent and thermochemical storage in industrial usage is at a low level of development (low TRL), while sensible heat storage technologies are more mature (higher TRLs). TES technologies such as water-tank TES (sensible TES) can be used to store low-temperature heat, while sensible solid-state TES and latent technologies can store high-temperature heat of up to 1,000°C.[80]

[80] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.

Sensible heat storage

Sensible heat storage is the most common and most commercially advanced type of TES. These are systems where energy is stored by changing the temperature of a storage medium - such as rocks, water, air, or oil without a phase change. They are the lowest cost and simplest thermal storage technology.

Solid-state – Solid-state sensible TES utilizes solid materials (both natural and artificial substances) as the storage medium. These systems are typically charged overnight and have a smart control to manage the level and timing of charge/discharge processes.

Solid-state technologies have the potential to offer a cost-effective form of storage (lower capex than latent technologies) that provides both electricity and heat to industrial processes in a similar manner to cogeneration plants today. They are advantageous in their relatively shorter storage durations, and high round-trip efficiencies. However, these technologies still have relatively low TRLs (TRL 5-9) for industry use and require further research and development.

Water tank – Thermal energy stored in fluid, usually water, is the most well-developed TES technology.[81] Advantages of water tanks include high scalability, which is especially crucial for industrial applications, where large tanks up to millions of cubic meters may be needed. At the same time, water tanks may be disadvantageous in sites where space is a limiting factor. These systems typically have a short storage duration of intra-day or daily heat storage.[82] Water is also a non-toxic storage medium that is lower cost than other solid-state technologies. It is also suitable for providing low-temperature heat (up to its boiling point).[83]

While nascent, it is worth noting the growing use of water tanks in conjunction with on-site solar thermal generation to supply low-grade heat for industrial use. Water tanks with heat collected by solar thermal collectors are coming into wider use, predominantly in the textiles, mining, and food sectors. Such key markets include Austria, China, France, Germany, India, Mexico, and Spain.[84]

The main challenges in systems employing water tank storage with solar heating are control and management of the heating system. Using solar energy for industrial heating is currently limited due to varying solar irradiance across seasons and time of day. The key to managing these challenges in future systems with enhanced water tank deployment will be advanced control and metering systems (to manage generation, storage, and use of energy) and space considerations, as heat insulation of larger water tanks requires more space.[85]

[81] Sarbu I, Sebarchievici C. A Comprehensive Review of Thermal Energy Storage. Sustainability. 2018; 10(1):191. https://doi.org/10.3390/su10010191
[82] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.
[83] EASE (2017), European Energy Storage Technology Development Roadmap
[84] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.
[85] As above.

Latent heat storage

Latent heat storage refers to energy stored using phase change materials (PCM) (e.g., salts, metals, organics). In other words, these PCMs release or absorb energy with a change in physical state. An example of latent storage technologies includes high-temperature composite phase-change materials (cPCMs), whose working temperatures are defined by the melting point of PCM. High temperatures of up to 500°C can be achieved.

Compared with sensible energy storage technologies, cPCMs can provide a more compact system due to their higher energy density, which is useful when space constraints need to be considered.[86] However, salts are corrosive and have low thermal conductivity, which limits the charging/discharging rate.[87] On the other hand, metals have high thermal conductivity and hence are preferable to salts in their fast charging/ discharging rate.[88]

This could be suitable for industrial use as it can store medium- to high-grade heat. However, it has comparatively higher capex costs than TES sensible heat storage technologies, and current development is focused on material and efficiency improvements to deliver economies of scale (low TRL).[89]

Thermochemical heat storage

Chemical looping and salt hydration sorption are two examples of thermochemical heat storage systems. They have a higher energy density than sensible and latent and heat storage types, but their low TRLs of 3-4 indicate they are not presently suitable for industrial applications.

[86] Energy density refers to the maximum amount of energy accumulated per unit volume of storage unit. This depends on the maximum and minimum working temperature working conditions.
[87] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.
[88] Muhammad Anser Bashir *et al.*, 2020). High-temperature phase change materials for short-term thermal energy storage in the solar receiver: Selection and analysis
[89] IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.

4.3 Chemical Energy Storage

Chemical energy storage refers to the transformation of electrical energy into chemical energy. An advantage of chemical energy storage is that it has large storage capacities.[90] Disadvantages may include potential safety hazards associated with some chemical and physical properties, and chemicals of low volumetric energy densities require larger storage volumes which can be costly. They also generally have lower round trip efficiencies as compared to batteries (electrochemical) and TES.

Green hydrogen electrolysis and combustion

Green hydrogen can undergo direct combustion. Careful design or retrofitting of existing burner systems - or the appropriate mixing of hydrogen with existing fuels, like natural gas - is needed to ensure safe and stable combustion. The current typical volumetric limit on hydrogen in natural gas turbines and engines is 1 – 2%. This can be increased to 10 – 15% with minor retrofitting of the gas turbines.[91] Some gas turbines are even capable of burning higher mixes of natural gas-hydrogen of 50%/50% to 100% hydrogen[92]. As such, the challenge in using hydrogen as an energy source is the adaptation of existing industrial plants and the production and storage of green hydrogen in a cost-effective manner.

Biomass (combustion via steam boiler and turbine)

There are many pathways in which biomass can be converted into usable fuels, including combustion, gasification, and liquefaction. Biomass fuels can vary significantly in energy density and combustion properties. Direct biomass combustion based on a system of steam boilers and turbines is a mature, commercial technology for heat and power production (TRL 8 – 9). It is also especially applicable for industries with links to biogenic materials and, as such, there is potential for direct sourcing of biomass from facilities that handle these raw materials. However, the sustainability of these operations must be considered, and the biomass should be sustainable and not lead to increased emissions overall (i.e. agricultural waste or residues of biomass is grown sustainably, converted to energy products efficiently, and used to replace more carbon-intensive fuels).[93] It is also crucial that biomass used for energy purposes does not compete with food production. Common raw materials used in textile manufacturing, such as waste cotton stalks, could be a fuel source.[94] This can potentially reduce operating expenditure related to transport if the relevant facilities are near each other. Other considerations include the need for added treatment to ensure the biomass is appropriately processed for efficient combustion and energy generation.

Further, the systems can be highly efficient if there is cogeneration of power and heat. Existing coal boilers can be retrofitted to co-fire biomass, which would further reduce costs for the manufacturing facility as it reduces the need for investment in new equipment. This includes replacement with new mills and burners suitable for biomass fuels. The overall capex of the system is likely to be relatively high compared to other storage types.

90 National Energy Technology Laboratory (2021). Chemical Energy Storage.
91 IRENA (2019), Innovation landscape brief: Renewable Power-to-Hydrogen, International Renewable Energy Agency, Abu Dhabi.
92 GE (2022) Hydrogen Overview.
93 IEA Bioenergy (2024). Bioenergy, a sustainable solution
94 Pandirwar et al., (2023). Physical, Chemical, Thermal, and Mechanical Properties of Cotton Stalk: An Industrial Multi-purpose Cotton By-product. Journal of Agricultural Engineering. 60. 188-204. 10.52151/jae2023602.1807.

4.4 Other Mechanical and Electrical Energy Storage

Lastly, there are mechanical and electrical energy storage technologies. These are less applicable to industry use of process heat due to their very short storage durations, and more suited for transportation, grid services, and power generation.

Mechanical - Adiabatic Compressed Air Energy Storage (A-CAES)[95]

A-CAES refers to energy storage in the form of high-pressure compressed air in a geological underground void. This compressed air is used to generate power in a turbine while simultaneously recovering the heat from the thermal storage. It has a storage duration of up to 10 hours and a moderate response time. These systems are in the process of demonstration and are not commercially available yet.

Flywheels

Flywheels are composed of rotating mass that stores kinetic energy. They usually offer high-power low-energy outputs and provide durability up to 100,000 cycles. Flywheels are well placed for fast frequency response but suffer high idle losses and can therefore only be used for very short-term storage (seconds to minutes), which is too short for the textile industry. They are suitable for transportation (electric and hybrid vehicles, trains, ferries, etc), and contribute to grid stability.

Electrical - Supercapacitors

Supercapacitors store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte. These devices are suitable for high-power uses and are used widely in hybrid buses and other automotive applications, back-up power applications.[96] However, their typically extremely limited storage capacity (typically <1MWh) means that they are not suitable for energy management for textile manufacturers.

[95] Choudhury, S (2021). Flywheel energy storage systems: A critical review on technologies, applications, and future prospects. Int Trans Electr Energ Syst. 2021; 31(9):e13024. https://doi.org/10.1002/2050-7038.13024

[96] EASE (2017), European Energy Storage Technology Development Roadmap

4.5 Summary

Five main types of energy storage solutions were reviewed. In general, apart from water-tank TES, all other TES solutions have low TRL and hence are not yet ready for commercialization. The benefits of water tank TES are its lower capex compared to all other energy storage types and relatively high round-trip efficiencies. Further, they have storage periods of hours to months, appropriate for peak shaving and resiliency purposes for sites in the textile and apparel industry. Solid-state sensible thermal storage has similar suitable characteristics, and while it may potentially be an option in the medium term (see Table 5), it has yet to reach full commercialization.[97]

Table 2: Timeframe for thermal energy storage solutions to commercialize

Type of thermal energy storage technology	Sub-Technology type	IRENA (2020)	Systemiq (2024)[98,99]
Sensible	Solid-state	5 – 10 years	By 2030
Latent	cPCMs	At least 10 years	By 2030

Biomass may potentially be a suitable option for the textile industry, especially when waste biomass is sustainably sourced from Tier 3 facilities and Tier 4 raw material production sites readily and cheaply. It is an established technology, and where existing boilers (e.g., coal boilers) can be retrofitted, this presents a cheaper option than the installation of new boilers. However, retrofitting might still be more expensive than other solution types, and physical biomass storage requires large amounts of space on-site.

In summary, presently, water tank (thermal) energy storage and lithium-ion batteries are likely to be the most suitable recommended technologies for the textile and apparel sector, followed by solid-state thermal energy storage and biomass combustion. However, as technologies mature and become lower cost, more types of storage technologies may become viable for the sector.

[97] It would benefit from investments supporting its further innovation and commercialization.
[98] Systemiq (2024). Catalysing The Global Opportunity For Electrothermal Energy Storage.
[99] According Systemiq, thermal storage solutions are expected to be applied to industrial processes with temperatures needs of up to 400°C by 2030 (which includes the textile and apparels sector's needs).

5. Hight-Level Analysis of the Suitability of On-Site Energy Storage in Key Textile and Apparel Manufacturing Regions

Twenty garment-producing regions, chosen based on their share of apparel emissions, were considered as part of this work. However, due to the lack of available apparel-specific sector emissions data in Cambodia, Ethiopia, Myanmar, Sri Lanka, and Germany, these were excluded from Table 2. They are included in summary Table 3.

5.1 Methodology

Countries' overall suitability for on-site / energy storage deployment was assessed against the following five categories:

Revenue opportunities: To be a viable economic proposition, energy storage assets must have a means of making a return on capital invested. Many storage assets, such as BESS, can stack multiple revenue streams. The state of ToU tariffs, ancillary services, and system average interruption disruption index (SAIDI) are assessed under this category.

Policy environment – renewables: A supportive policy environment for renewables generally supports the case for energy storage. As variable RE sources gain traction, the grid needs flexibility to manage their fluctuations and ensure stable power delivery through the provision of ancillary services. Policies promoting renewables create a demand for flexibility, which in turn drives the development and deployment of storage solutions, along with associated markets and policy frameworks. The availability of grants, subsidies and tax breaks, regulatory frameworks, and market access was qualitatively assessed at a high level. Renewables as a portion of final energy consumption (FEC) targets are expressed as a percentage.

Policy environment – energy storage: A sound energy storage policy environment acts as a catalyst, lowers risks, creates stable markets for energy storage services, and fosters technological advancements. The combination of drivers ultimately makes energy storage a more attractive and economically viable option for businesses to deploy. Without such policies, the path to widespread adoption becomes significantly more challenging and uncertain. The availability of grants, subsidies and tax breaks, coherent regulatory frameworks, and market access were qualitatively assessed.

Energy system indicators: While the policy environment serves as an indication of how easy it may be to invest in energy storage within a given region, there are some energy system metrics that provide a closer-to-real-time picture of how successful those policies have been in driving the deployment of renewable energy and energy storage. The deployment of RE and energy storage was quantitatively assessed.

Additional market indicators: In addition to the elements described in the above bullets, other important market indicators of a region's suitability for energy storage investment were assessed. These are the average cost of industrial electricity, battery storage capital cost, and energy storage compound annual growth rates, which were quantitatively and qualitatively assessed.

Specific thermal energy storage factors were not analyzed, as even more advanced energy markets (such as the UK) lack a coherent set of policies that relate specifically to thermal energy and thermal energy storage. Therefore, these were excluded from the RAG analysis of the 20 countries. It is also worth noting that many of the considerations that relate to energy storage generally, (e.g. TOU tariffs) also relate to thermal energy storage, particularly when the thermal storage is essentially a vector change (e.g. using power to produce heat).

Table 3 summarizes the indicators used in each category and their respective scoring rubric.

Table 3: Indicators and Scoring Rubric of Red, Amber, Green (RAG) Analysis

METRIC	RED	AMBER	GREEN
Revenue Opportunities			
State of Time-of-Use (ToU) Tariffs • A type of electricity pricing that charges customers different rates based on when they use electricity. • This means electricity costs more during peak demand periods, typically evenings and weekdays, and is cheaper during off-peak times, like late nights and weekends. • ToU tariffs are crucial to the economic viability of energy storage as they allow the asset to earn revenue through energy arbitrage and facilitate cost reduction through peak charge avoidance.	Not implemented – no ToU tariffs exist	Nascent – some projects exploring ToU tariffs Regional – ToUs present in some states, but not all	Implemented – ToU tariffs are implemented in the market
State of Ancillary Services • Ancillary Services are the functions that ensure electricity flows smoothly and reliably, from generators to consumers, without compromising grid stability. These are typically procured through markets run by a region's energy system operator (ESO). • Energy storage can earn revenue by providing these services (e.g. Frequency management) where such markets exist.	Not implemented – no markets for ancillary services exist	Nascent – some ancillary service markets exist	Established – there are markets for a large range of operability services
System Average Interruption Duration Index (SAIDI) • Interruptions in the supply of electricity are very costly for manufacturing facilities. SAIDI describes the number of hours per year the average energy user suffers disconnection from the electricity grid or a lack of supply. • The value of deploying energy storage increases with the frequency and duration of interruptions and the costs associated with facility downtime. • NB: There is no single source that covers all the countries under investigation. The sources used are from different websites, reports, and databases, and they may have different definitions, methodologies, and years of measurement for SAIDI. • As grid conditions vary substantially within transmission and distribution networks, site-specific information should always be obtained before conducting a techno-economic assessment.	0 to 1.9 hours	2 to 4.9 hours	Established – there are markets for a large range of operability services

METRIC	RED	AMBER	GREEN
Policy Environment – Renewables			
Renewable Energy as a % of Final Energy Consumption Targets – 2030 and 2050 • The percentage of renewable energy sources in the final FEC targets of a country or region. Regions with ambitious near-term (2030) FEC targets will need to deploy significant volumes of energy storage over the next few years to balance supply and demand while assuring system operability. The more challenging the FEC target in the longer term (2050), the greater the utility of energy storage, increasing the rationale for energy storage. • FEC targets are subject to variation over time, and recent policy changes may not be included. Much of the data comes from IRENAs (2020) Global Renewables Outlook: Energy Transformation 2050[100] – the most recent dataset that allowed comparison between different countries.	0 - 39% (2030) 0 - 49% (2050)	40 - 49% (2030) 50 - 74% (2050)	50%+ (2030) 75%+ (2050)
Policy Environment – Renewables • Regions with policies that promote renewables will have inherent intermittency in their systems that energy storage systems can help balance – increasing the rationale for energy storage (including BESS). These can be (i) Grant, Subsidies and Tax Breaks; (ii) Regulatory Framework; and (iii) Market Access. • Policy environment was assessed at a high level. There may be new and/or local policy initiatives that were not	Poor	Average	Good

[100] IRENA (2020) Global Renewables Outlook: Energy transformation 2050

METRIC	RED	AMBER	GREEN
Policy Environment – Energy Storage			
Grants, Subsidies, and Taxes • Grants, subsidies, and tax breaks offer crucial financial support, bridging gaps between upfront costs and future profit, making energy storage projects more commercially attractive for businesses.	Poor	Average	Good
Regulatory Framework • Regulatory frameworks define the rules that govern energy system operation and include rules around asset licensing and ownership, market access, tariff structures, etc. Clear and concise rules de-risk investments by providing certainty.	Poor	Average	Good
Market Access • Open and fair market access is essential for facilitating both in-front-of and behind-the-meter energy storage, allowing storage to compete in multiple markets, maximising earning potential. Restricted or limited access, conversely, limits revenue streams and weakens the business case for storage.	Poor	Average	Good
Energy System Indicators			
Deployment of Renewable Energy (MW) and Energy Storage (MWh) • As more variable sources of RE are deployed, their inherent intermittency creates demand for storage for grid stability. RE policy deployment (MW) and energy storage deployment (MWh) provide a retrospective view on how successful policy environments have been in driving investment and deployment. • Data on energy storage deployment were not available in some regions.	**RE**: 0 to 50 GW **Storage:** 0 to 500 GWh	**RE**: 50 to 100 GW **Storage:** 500 to 1,000GWh	**RE**: 100+GW **Storage:** 1,000+GWh

METRIC	RED	AMBER	GREEN
Additional Market Indicators			
Average Cost of Counterfactual Energy Sources (Electricity and Coal) • High energy prices increase the rationale for investing in on-site renewables and storage. Self-generated power can offer both cost savings and independence from (potentially volatile) grid prices. Integrating further storage optimizes self-consumption, giving greater certainty in a high-cost, fluctuating energy market. • In many key garment-producing regions, much of the energy (particularly thermal energy) comes from on-site fuel sources such as coal. Understanding these counterfactual costs is essential for building an economic case for onsite renewables and storage.	Low	Average	High
Battery Storage Capital Expenditure (capex) • Higher capital costs increase the revenues an energy storage asset must obtain to achieve an acceptable return on investment. Countries with strong domestic supply chains typically have lower capital costs. • capex was assessed quantitatively (USD/MW or USD/MWh), but is expressed qualitatively due the substantial variability between datasets. Battery storage is not the only energy storage technology studied, but serves as a good benchmark for assessing storage costs more generally. • Where capital costs are unavailable, capex was estimated based on the size of the domestic market, domestic expertise, and policy environment. capex costs vary significantly across geographies.	High	Average	Low
Energy Storage Compound Annual Growth Rate (CAGR) • A high CAGR signifies a rapidly expanding market, offering potential for high returns as well as suggesting rising demand for energy storage solutions, driven by factors like renewable energy integration, grid modernization, and increasing focus on energy security. This translates to potential for low-cost project finance, higher capacity utilization, and faster cost recovery for investors. Here, retrospective battery storage CAGR in each region from 2015-2020 is considered. As there is significant variability in the CAGR rates, only qualitative results are provided.	Low	Average	High

5.2 Results

A breakdown of the categories analyzed can be found in Section 4.1. An overall score was reached qualitatively through engagement with experts in the Carbon Trust, with significant emphasis placed on revenue opportunities and the policy environment for energy storage.

Table 4: RAG analysis of the suitability of different textile and garment producing regions for on-site energy storage

			REVENUE OPPORTUNITIES			POLICY ENVIRONMENT							ENERGY SYSTEM		MARKET INDICATORS				
						RENEWABLES			STORAGE										
Region	Textiles and Clothing (% of Value Added in Manufacturing)	Share of Apparel Emissions (%)	State of ToU Tariffs	State of Ancillary Service Market	SAIDI (hours)	Policy Environment	RE as % of FTC targets (2030)	RE as % of FTC targets (2050)	Grants, subsidiaries, tax breaks	Regulatory framework	Market Access	Overall Score	Renewable Energy Deployment (MS)	Energy Storage Deployment (MWh)	Average Cost of Industrial Electricity ($/MWh)	Average Coal Prices	Battery Storage capex	Energy Storage Retrospective CAGR (2015-2020)	Overall Sutability for On-site Energy Storage (RAG)
China	10.0	30.2	Implemented	Nascent	0.9	Average	25%	80%	Good	Average	Good	Good	895,000	2,500,000	Low	Medium	Low	Very high	High
India	9.0	10.9	Regional	Nascent	3.7	Average	40%	60%	Average	Average	Good	Average	136,000	500,000	Medium	Medium	Moderate	Moderate	Moderate
Bangladesh	57.0	6.9	Not implemented	Not implemented	6.1	Poor	20%	43%	Poor	Poor	Average	Poor	6,000	bw/ no data	High	High	High	Low	Low
Vietnam	15.0	6.1	Implemented	Not implemented	21	Average	32%	44%	Average	Poor	Average	Average	17,000	bw/ no data	Medium	High	High	Low	Low
Indonesia	11.0	5.8	Not implemented	Not implemented	28	Poor	23%	31%	Average	Poor	Average	Average	10,000	bw/ no data	Low	Low	High	Moderate	Low
Pakistan	30.0	4.7	Regional	Nascent	89.6	Poor	30%	60%	Poor	Poor	Poor	Poor	9,000	bw/ no data	High	High	High	Very low	Low
Turkey	15.0	4.7	Implemented	Established	44.7	Average	30%	50%	Average	Average	Average	Average	49,000	bw/ no data	High	High	High	Very low	Moderate
South Korea	3.0	3.5	Implemented	Established	0.0	Average	20%	35%	Good	Good	Good	Good	17,000	1,000,000	High	High	Low	Moderate	High
United States	1.0	1.7	Regional	Established	1.3	Good	50%	80%	Good	Average	Good	Good	292,000	1,200,000	Low	Low	Low	High	High
Taiwan	Limited data	2.1	Implemented	Established	0.2	Poor	20%	50%	Average	Average	Good	Average	7,000	bw/ no data	High	High	Low	Low	Moderate
Japan	2.0	1.9	Implemented	Established	0.0	Average	24%	50%	Good	Good	Good	Good	93,000	3,000,000	High	High	Low	Moderate	High
Brazil	5.0	1.0	Implemented	Not implemented	6.6	Good	45%	60%	Average	Poor	Average	Average	178,000	bw/ no data	Medium	High	High	Low	Moderate
Mexico	2.0	0.7	Implemented	Not implemented	0.6	Average	35%	50%	Poor	Poor	Average	Poor	30,000	bw/ no data	Medium	High	High	Very low	Low
Egypt	8.0	0.4	Implemented	Not implemented	2.0	Poor	42%	60%	Poor	Poor	Average	Poor	8,000	bw/ no data	Low	High	High	Very low	Low
Thailand	6.0	0.4	Implemented	Not implemented	0.4	Average	30%	37%	Average	Poor	Average	Average	12,000	bw/ no data	Medium	High	High	Moderate	Low

Table 5: Summary of results in Table 4

High	China, South Korea, United States, Japan, Germany
Moderate	India, Turkey, Taiwan, Brazil
Low	Bangladesh, Vietnam, Indonesia, Pakistan, Mexico, Egypt, Thailand, Cambodia, Ethiopia, Myanmar, Sri Lanka

Key apparel sector emitters

According to data provided by Aii, China (30.2%), India (10.9%), Bangladesh (6.9%) and Vietnam (6.1%) are the regions with the highest share of global apparel sector emissions. Respectively, these countries account for 41.3%, 8.9%, 7.7%, and 8.7% of the number of facilities worldwide. While, apart from China, these locations score poorly in the assessment for attractiveness of near-term investment in energy storage, developing regional roadmaps for these areas could yield the greatest results for medium- to long-term apparel sector emissions.

Financial analysis

To better analyze the value of energy storage technologies in the textile industry, a financial analysis was carried out. This analysis evaluated the economic viability of integrating energy storage solutions in the most carbon-intensive textile markets focused on in this report.

For the analysis, two tiers of sites were investigated: **Tier 1 sites**, where the manufacture and assembly of final products takes place, and **Tier 2 sites**, where the production of the fabrics and materials used by Tier 1 suppliers takes place.

Tier 1 sites primarily consume electricity, making **battery energy storage systems (BESS)** the optimal energy storage solution. In contrast, **Tier 2** sites have greater thermal energy requirements due to fabric dyeing and wet processing, justifying consideration of thermal energy storage.

Two financing models were considered to evaluate the sites: the RESCO model and the capex model. In the capex model, costs for developing and installing the technology are covered upfront, ensuring ownership is transferred to the consumer upon investment. The subsequent sections discuss the results from the financial analysis using the capex model.

The financial analysis was conducted based on data and plant size for a specific Tier 1 and Tier 2 site, whereas the archetypal consumption profile for both tiers was derived across multiple sites. As a result, the findings provide indicative insights applicable to most Tier 1 and **Tier 2 sites** within each market. The **selected technology** modelled for **Tier 2 sites** is the **5MWh Shanghai Electric molten salt energy storage solution (MSESS)**. This is due to its successful deployment in the Rudong Knitit facility in China, proving its application as an ESS for Tier 2 textile sites.

Alongside the financial analysis, a sensitivity assessment was carried out to examine the **peak/off-peak tariff spreads** and **initial capex costs** within the model. These were identified as the most influential factors affecting the model's results and overall site economics. Given their impact, variations in these criteria were further explored, with the outcomes for each market and site tier combination outlined in the country analysis below.

China – High suitability

Along with being responsible for almost a third of global apparel sector emissions[101], China has also been an excellent location to invest in energy storage over the last decade, represented by the high battery storage CAGR.

Advantages:

- **Energy storage capex:** China has relatively lower capital costs for battery packs at USD 126/kWh; approximately 10 to 20% lower than those in the USA and EU, respectively.[102] This is in large part due to its strong domestic supply chains for battery materials and components, reducing the dependence on imports and transportation costs. China is the world's largest exporter of energy storage technologies, with two companies (CATL and BYD) holding over 50% of the market share in energy storage battery shipment volume.[103]
- **System-wide ToU tariffs:** The National Development and Reform Commission (NDRC) issued a policy in 2023 requiring local governments to implement ToU tariffs for almost all retail customers, including industrial users.[104]
- **Policy Environment for storage:** China's battery storage policy landscape is a mix of ambitious targets and top-down directives. Driven by climate goals and grid integration needs, the central government aims for 100GW of storage by 2030, supported by the "New Energy Storage Development Implementation Plan".[105] This plan incentivizes cost reductions, technology development, and regional deployment, with provinces exceeding central targets.

Challenges:

- **Low-cost electricity:** China has relatively low electricity prices.[106] This reduces the value energy storage technologies can have in avoiding high prices by increasing self-consumption from renewable technologies.
- **Low SAIDI:** China's grid, while carbon-intensive, is relatively stable. This reduces the rationale of using energy storage as a supply of back-up power.[107]

[101] Based on data provided by Aii
[102] According to BloombergNEF (2023), average price of lithium-ion batteries in China cost USD126/kWh, while those in US and Europe were 11% and 20% higher.
[103] InfoLink Consulting (2022). Battery Shipment Ranking
[104] Lantau group (2021). Chinese Power Sector Reforms
[105] China Briefing (2022) China's Energy Storage Sector: Policies and Investment Opportunities
[106] GlobalPetrolPrices (2023) Electricity prices around the world
[107] World Bank (2019) System Average Interruption Duration Index

Financial analysis - China

Tier 1 sites

Large tariff spreads offer value from energy price arbitrage, proving a positive business case for ESS in Tier 1 sites in China. This is despite the absence of excess solar to load shift.

capex: ~USD 599,200	IRR: 17%
Opex: ~ USD 16,240/year	Payback period: ~ 6.6 years

- **The BESS capex (USD/kWh):** The BESS capex significantly improved site economics. A 5% increase in BESS capex, decreased the project 20-year NPV by 0.6%. The impact of the indicator on IRR is non-linear as a 50% decrease to the capex cost, from USD 200/kWh to USD 100/kWh, increased the IRR by 14%, whereas a 50% increase demonstrated a smaller effect, decreasing the IRR by 7%.
- **The impact of peak/off-peak tariff spreads (USD/kWh):** High tariff spreads of around USD 0.15/kWh showed significant savings when operating energy price arbitrage, with the analysis demonstrating that a stand-alone BESS could generate an IRR of around 16%, representing annual savings exceeding 20% of the initial capex investment. Additionally, a 10% increase in the peak/off-peak tariff differential resulted in a 1% increase in the project IRR.

Tier 2 sites

MSESS installation can generate significant financial savings by utilizing energy price arbitrage on peak/off-peak tariff spreads, despite the absence of excess solar to load shift.

capex: USD 2.06 million	IRR: 24%
Opex: USD 58,000/year	Payback period: ~ 5 years

- **The MSESS capex (USD/kWh):** At lower USD/kWh values, changes to the MSESS capex cost yielded greater reductions to project IRR than increasing the peak/off-peak tariff spreads. This is due to the lack of fixed costs in the model. There is a negative non-linear relationship between project IRR and capex cost. Increasing the capex from USD 90 to 135/kWh decreased the IRR from 25% to approximately 18% whereas an increase to USD 180/kWh decreased the IRR to approximately 14%.
- **The impact of peak/off peak tariff spreads (USD/kWh):** The large spread between the peak and off-peak tariff price in China results in high returns for the solar + MSESS system, with energy price arbitrage exhibiting annual savings exceeding 24% of the relative MSESS capex investment, contributing to a payback period of approximately 5 years. The system is also highly sensitive to changes in the tariff spread; a 50% reduction yielded a negative project NPV, whereas a 20% increase yielded an IRR of around 20%.

Impact on grid-related GHG emissions

The immediate impact of implementing ESS in textile sites across China could lead to an increase in grid-related GHG emissions. This is because peak tariff hours are charged from 14:00 to 17:00, representing times with greater generation from solar energy, and therefore, periods with a lower expected grid emission intensity. Conversely, off-peak tariff hours are charged from 22:00 to 08:00, representing the hours with much lower penetration of solar energy and subsequent highest generation from fossil fuels, correlating to the hours in which the emission factor of the Chinese grid is likely to be at its highest.

After the short term, ESS has the potential to significantly reduce greenhouse gas (GHG) emissions. This is driven by the rapid expansion of solar and wind energy in China's power sector. Current predictions estimate that these technologies could comprise 32% of the energy mix by 2030 and 78% by 2050, a substantial increase from just 14% in 2022[108]. As a result, the emissions intensity of China's power grid is expected to decline from the current 614gCO_2e/kWh to approximately 515gCO_2e/kWh by 2030 and to between 144 and 239gCO_2e/kWh by 2050.[109] Both projections fall well below the emission intensity range of power generated from direct coal combustion, which is between 568 and 606 gCO_2e/kWh.[110]

[108] Study on life-cycle carbon emission factors of electricity in China, International Journal of Low-Carbon Technologies.
[109] Decarbonisation of China's regional power grid by 2050 in the government development planning scenario, Environmental Impact Assessment Review.
[110] The authors assumed a 60% boiler efficiency for the combustion of coal to produce thermal energy.

Recommendations

1. **Textile and apparel manufacturing sites, especially Tier 2 sites, are recommended to electrify their operations in the immediate term.** While the immediate impact of installing thermal storage on a site's Scope 2 emissions may be unclear, further increases in renewable energy penetration and consequent reductions in the emissions intensity of China's grid will enable sites to experience reductions in their Scope 2 emissions before 2030. Electrification of textile sites, especially tier 2 sites, should therefore be a higher priority than investments in MSESS.

2. Due to the current grid emissions intensity being above the range from coal-fired generation, and the use of price arbitrage to shift consumption to periods of low generation from renewable sources, onsite **BESS and MSESS do not currently enable significant reductions in Scope 2 emissions** in China. Although they are currently commercially viable, in the absence of offsite PPAs from clean energy sources, their **implementation is not recommended until after 2030** – the period when the penetration of renewable energy is expected to have increased significantly.

India – Moderate suitability

India has moderate potential for energy storage investment. Growing renewable energy, declining battery costs, and nascent supportive government policies indicate increasing potential, while there is a high degree of regional policy variability, with some regions lagging behind others.

Advantages:

- **Ambitious renewable deployment targets:** India's aggressive push for 500GW of renewable energy capacity by 2030, while crucial for climate goals, necessitates significant investments to ensure a stable grid.[111] This creates opportunities for battery storage deployment as efficient storage solutions will become key to managing the variable nature of solar and wind power.
- **Regional ToU tariff implementation:** India has introduced guidelines to promote the adoption of ToU tariffs across all states as part of efforts to integrate increasing shares of solar and wind power in the national electricity system. However, implementation effectiveness varies by state, depending on the local regulatory framework and the availability of smart metering technology. States such as Gujarat, Maharashtra, Andra Pradesh, and Ladakh are more advanced in this regard. In 2023, the Government announced plans that this is set to change with the Ministry of Power scheduled to introduce ToU tariffs nationwide from 2024/2025, with prices varying between normal, solar, and peak demand hours.[112] Implementation of this is still awaiting confirmation.

Challenges:

- **Nascent and regional policy environment:** India's policies in relation to energy storage show ambition, but implementation remains highly regional due to differentiated policy implementation between states. India's energy policy framework largely excludes support for energy storage from key programs and initiatives, and the lack of energy storage policy guidelines and supporting programs present a barrier for investment. Conversely, some states such as Gujarat, Maharashtra, Andhra Pradesh, and Ladakh have taken steps to promote energy storage with specific policies and ancillary services. India also has some initiatives to advance energy storage in the country, such as the National Mission on Transformative Mobility and Battery Storage, the National Energy Storage Mission, and the India Energy Storage Alliance.[113,114,115] Therefore, while the ambition and planning of national policies aimed at driving uptake of ESS is present, full-scale adoption of these policies across all states presents a challenge to the development of the industry on a national level.

111 CitiGroup (2023) India Clean Energy: Progress & Policy
112 Reuters (2023) India to extend time-of-use electricity tariffs
113 Government of India (2022) National Mission on Transformative Mobility and Battery Storage
114 Ministry of New and Renewable Energy (2018) National Energy Storage Mission
115 IESA (2024) Energy Storage Association in India - IESA

Financial analysis – India

Tier 1 sites

Without the ability to load shift, BESS cannot increase solar self-consumption, restricting revenues to energy price arbitrage. Additionally, the low peak/off-peak tariff spread is insufficient to drive the investment case for BESS.

capex: USD 1,150,000	IRR: -7%
Opex: USD 29,600/year	Payback period: Does not pay back

The BESS capex (USD/kWh): Solar PV is unable to cover an average Tier 1 site's energy demand even at peak solar output, requiring the battery to charge from the grid instead. As a result, the BESS generates annual savings of only approximately USD 54,700 – less than 5% of the initial capex investment. This represents close to twice the annual Opex payments, resulting in the inability to provide a payback on the asset over a 20-year period. The sensitivity analysis showed the high impact of this indicator: a 5% reduction in battery capex led to an 8.3% increase in project NPV. Reducing capex costs by 56% to USD 200/kWh, to align with investment costs in China, would increase the IRR from -7% to 3.6%.

The impact of peak/off-peak tariff spreads (USD/kWh): The peak pricing period spans a total of seven hours, with peak tariff rates standing on average 1.47 times the off-peak rates. Given the generally low tariff rates in India, a 5% reduction in the peak/off-peak tariff spread would lead to a net reduction in project NPV of 1.8%. Additionally, for the project to achieve an IRR over 3%, the spread price differential would need to increase by 240% from USD 0.030/kWh to USD 0.102/kWh, an amount which is considered unlikely to materialize in the short term.

Tier 2 sites

As in the case with BESS, the limited revenue, driven by a small peak/off-peak tariff spread, is unable to drive the investment case for MSESS.

capex: USD 1,870,000	IRR: 5%
Opex: USD 45,460/year	Payback period: 19 years

The MSESS capex (USD/kWh): Solar PV is unable to cover the average Tier 2 site's energy demand at peak solar output, requiring the thermal battery to charge from the grid instead. As a result, the solar and MSESS generate annual savings of USD 208,700 – just over 11% of the capex investment costs or over 4 times the annual Opex costs, which presents a payback period of 19 years. The relationship between this indicator and the project IRR is close to linear. As capex increases from USD 125/kWh to USD 170/kWh, the IRR falls to 0%. Whereas decreases to the capex to USD 80/kWh returns an IRR of approximately 11%.

The impact of peak/off-peak tariff spreads (USD/kWh): This factor is essential to the MSESS business case as there is no excess solar for the MSESS to capture, restricting revenues to energy price arbitrage, which is driven by the difference in peak/off-peak tariff prices. The sensitivity analysis on the tariff spread price displayed a near-linear effect on project IRR, and increasing the spread by around USD 0.02/kWh improves project IRR by approximately 5%.

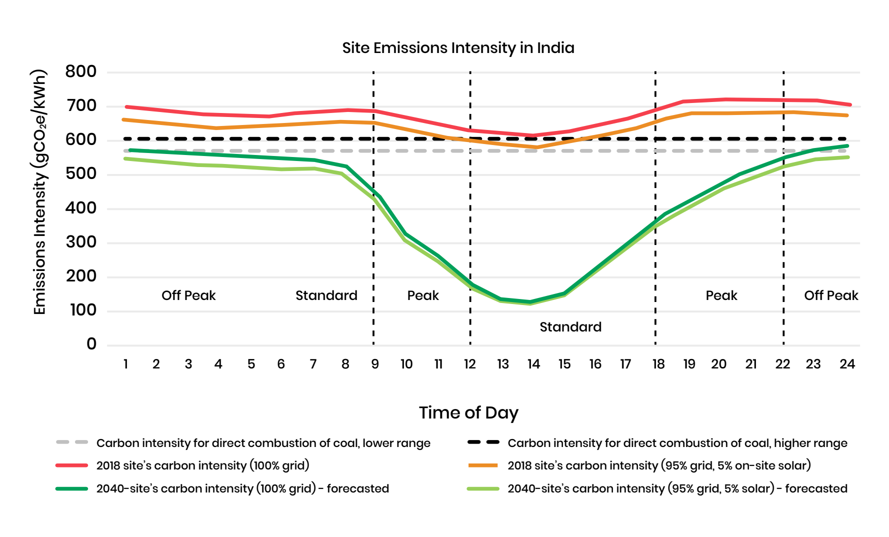
Impact on grid-related GHG emissions

The 2018 grid emissions intensity in India ranged from 613gCO_2e/kWh to 718gCO_2e/kWh, higher than the emissions intensity range of direct coal combustion (568 – 606 gCO_2e/kWh). Furthermore, the peak tariff applies at times with the greatest levels of solar energy penetration and hence the lowest grid emission intensity. In contrast to the off-peak tariff, which occurs at night and during times with the lowest solar energy generation and highest grid emissions intensity, therefore, using energy price arbitrage could result in displacing less emission-intensive grid electricity with more emission-intensive grid electricity.

Immediate electrification of textile facilities in India would result in higher Scope 2 emissions for the generation of thermal energy. This is because the ESS would be charged directly from the grid, which is currently more emissions-intensive than from direct coal combustion.

In the medium term, direct electrification using solar and ESS, combined with an energy price arbitrage strategy, has the potential to reduce Scope 2 emissions. As solar integration within the Indian grid expands, the grid's emissions intensity is expected to decline, reaching an estimated range of 131 gCO_2e/kWh to 579 gCO_2e/kWh by 2040, with variations driven by the prevalence of solar in the day (see figure 2), bringing the emissions intensity below direct coal combustion.

Figure 2: A comparison of the hourly grid emissions intensity in India (in 2018 and forecasted to 2040) overlaid against the emissions intensity of direct coal combustion, with varying reliance on the grid for electricity in India.



Recommendations

1. **Indian textile and apparel manufacturing sites, especially Tier 2 sites, are recommended to electrify their operations in the medium term.** India's grid is expected to become less emissions-intensive than direct coal combustion in the medium term. Therefore, electrifying operations in advance could allow for reduced Scope 2 emissions once the Indian grid becomes less carbon-intensive.

2. **Tier 2 sites in India should consider investing in on-site MSESS to discharge stored thermal demand during peak hours when the grid emissions intensity is lower than during the off-peak hours.** On-site MSESS can reduce a site's Scope 2 emissions. However, it is no-ted that a 5% IRR over a 20-year period can be considered as too low a return for some sites. Therefore, sites are recommended to continually monitor the capex of on-site MSESS.[116]

3. While on-site BESS can support reductions in Scope 2 emissions in the medium term, an IRR of -7% indicates that it is not yet commercially viable. Further reductions in BESS capex are needed for it be considered. **Sites should monitor the capex of on-site BESS through to the medium term.**

[116] The capex for MSESS used in this analysis is that for China due to the lack of publicly available data for India. Readers should note that the IRR for on-site MSESS could be lower than the 5% stated in this roadmap due to differing capex.

Bangladesh – Low (near-term) suitability

The Bangladesh textile industry accounts for 57% of total national manufacturing in 2020, the highest share in the world.[117] Deployment of energy storage in Bangladesh faces several challenges for prospective investors.

Advantages:

- **High SAIDI[118] :** This indicates there is a role for energy storage to act as a source of low-carbon back-up power in periods of system outage. The value will depend on the revenue lost per blackout hour, along with the costs of counterfactual back-up power sources (e.g., diesel generators).

Challenges:

- **Low ToU tariffs peak/off-peak differential:** Bangladesh implements ToU tariffs. The current price difference of USD 0.027/kWh between peak and off-peak rates represents 25% of the relative peak price. This limited variation restricts the potential revenues generated from energy storage through energy price arbitrage.
- **No open ancillary service markets:** Bangladesh has not implemented ancillary services, a key revenue stream for energy storage in most developed power systems.
- **Lack of policy environment for renewables and storage:** Low renewable and battery deployment targets, the absence of competitive and transparent electricity markets, and lack of regulatory frameworks/ tax breaks/incentives for renewable energy and energy storage make profitable deployment and operation challenging.
- **High battery storage capex:** High upfront cost and limited availability of battery storage systems make energy storage economics challenging.
- **Prevalent use of captive fossil-based assets for electricity:** The unreliable nature of Bangladesh's power grid has led most industrial and manufacturing plants to not rely on the grid for electricity, but to have their own captive fossil-based power generation assets. Sites might, therefore, be unable to benefit from cost savings from energy price arbitrage.

117 World Bank (2020) Textiles and clothing (% of value added in manufacturing)
118 Dhaka Tribune (2021) Power sector in Bangladesh: Surplus generation doesn't mean disruptions gone

Financial analysis - Bangladesh

Tier 1 sites

With no excess solar to load shift, revenues are limited to energy price arbitrage, which itself is a poor source of revenue due to low peak/off-peak tariff spread.

capex: USD 1,900,000	IRR: N/A
Opex: USD 48,000/year	Payback period: Does not payback

The BESS capex (USD/kWh): Solar PV is unable to cover the average Tier 1 site's energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the BESS generates annual savings of approximately USD 40,000 USD – just 2% of the initial capex investment. This represents savings of just less than the annual Opex costs, indicating that BESS is not a viable investment. Additionally, to achieve a positive IRR of around 0.1%, the capex would need to reduce by around 80% from USD 699/kWh to approximately USD 150/kWh.

The impact of peak/off-peak tariff spreads (USD/kWh): The current low tariff rates prevent the ability of the system to become profitable, and increasing the difference between the peak and off-peak tariff spreads would need to occur to promote the business case for BESS. The model predicts that the spread price differential would need to increase by approximately 600% from USD 0.027/kWh to USD 0.192/kWh to achieve a positive project IRR.

Tier 2 sites

Tier 2 energy demand exceeds the capacity of on-site solar generation, causing the MSESS to rely on grid charging. This prevents revenue from selling excess solar energy back to the grid. The financial viability of the system hinges on energy price arbitrage, but the current peak/off-peak tariff spreads are insufficient to justify the investment case.

capEx: USD 1,940,000	IRR: 3%
OpEx: USD 55,000/year	Payback period: Does not pay back

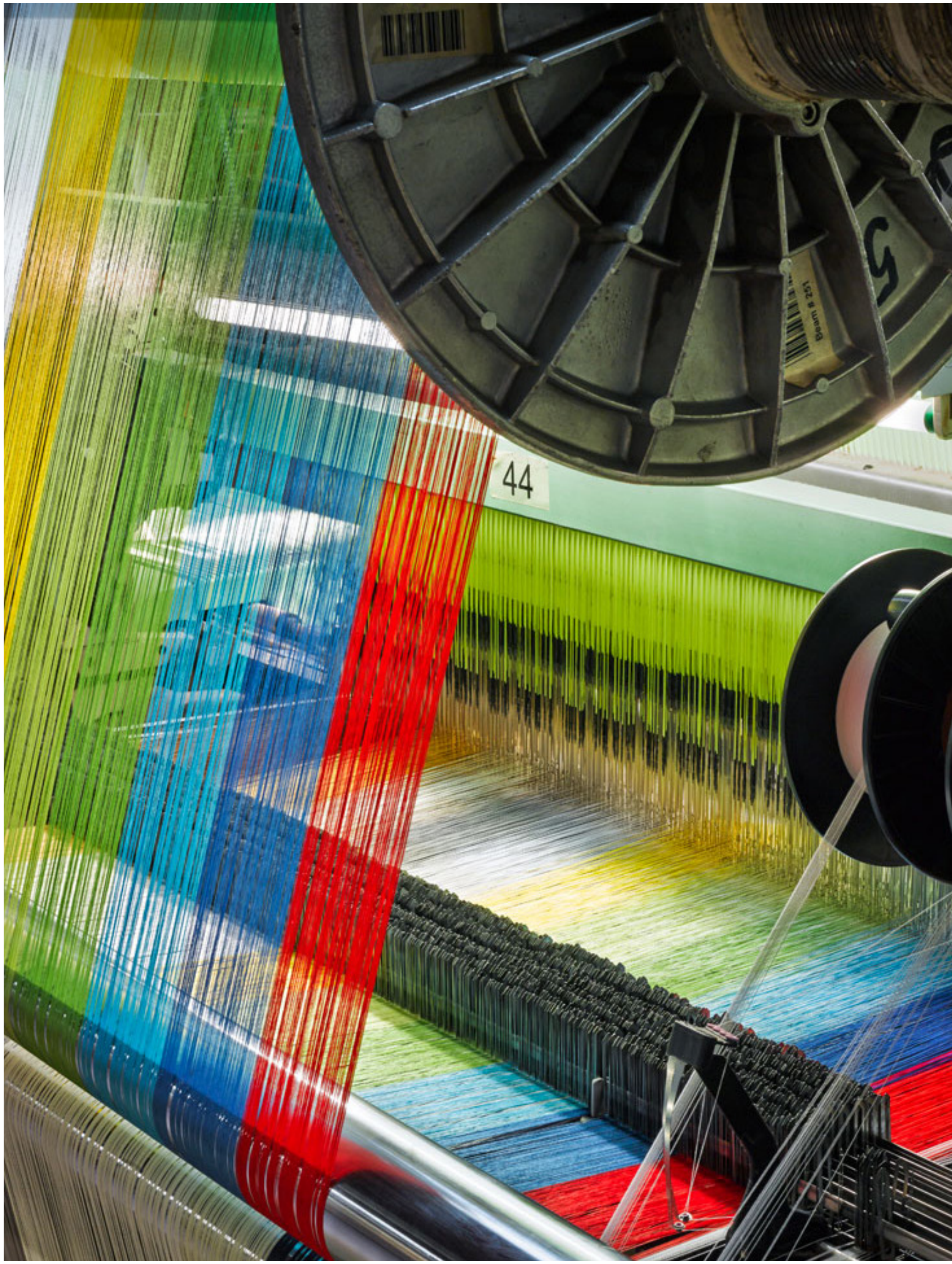
The MSESS capex (USD/kWh): Solar PV is unable to cover the average Tier 2 site's energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the solar and MSESS generate annual savings of over USD 189,000 from energy price arbitrage, equivalent to 10% of the capex investment costs and representing over 3 times the annual Opex costs. These savings are insufficient in providing a payback over a 20-year period on the investment. The capex of the MSESS is the most sensitive input affecting the outcome of the financial analysis.

The impact of peak/off-peak tariff spreads (USD/kWh): This factor is essential to the MSESS business case as there is no excess solar for the asset charge from, restricting revenues to energy price arbitrage, driven by the value of tariff spreads. The correlation between the tariff spread price and the project IRR is near linear, and increasing the delta by USD 0.1/kWh improves the IRR by approximately 14%.

Impact on grid-related GHG emissions

Immediate electrification of textile facilities in Bangladesh would result in higher Scope 2 emissions than through continued use of natural gas combustion, which is currently the main supply source of electricity and thermal generation in Bangladesh's textile industry. This is because the current grid emissions intensity in Bangladesh (691 gCO_2e/kWh) is greater than the emissions intensity of direct natural gas combustion (336 – 402 gCO_2e/kWh). Therefore, electrifying with ESS and changing the source of supply to grid electricity would substitute less emission-intensive electricity generated from natural gas combustion to replace with more emission-intensive grid electricity.

The grid's emissions intensity would need to reduce below natural gas levels for Scope 2 emissions savings to occur. Bangladesh has outlined its renewable energy goals in the Mujib Prosperity Plan, which states that by 2030, 30% of energy consumption should come from renewable energy sources. Therefore, integrating the electrification of sites with the addition of renewables into the national energy system may provide significant benefits and reduce greenhouse gas emissions compared to current levels.

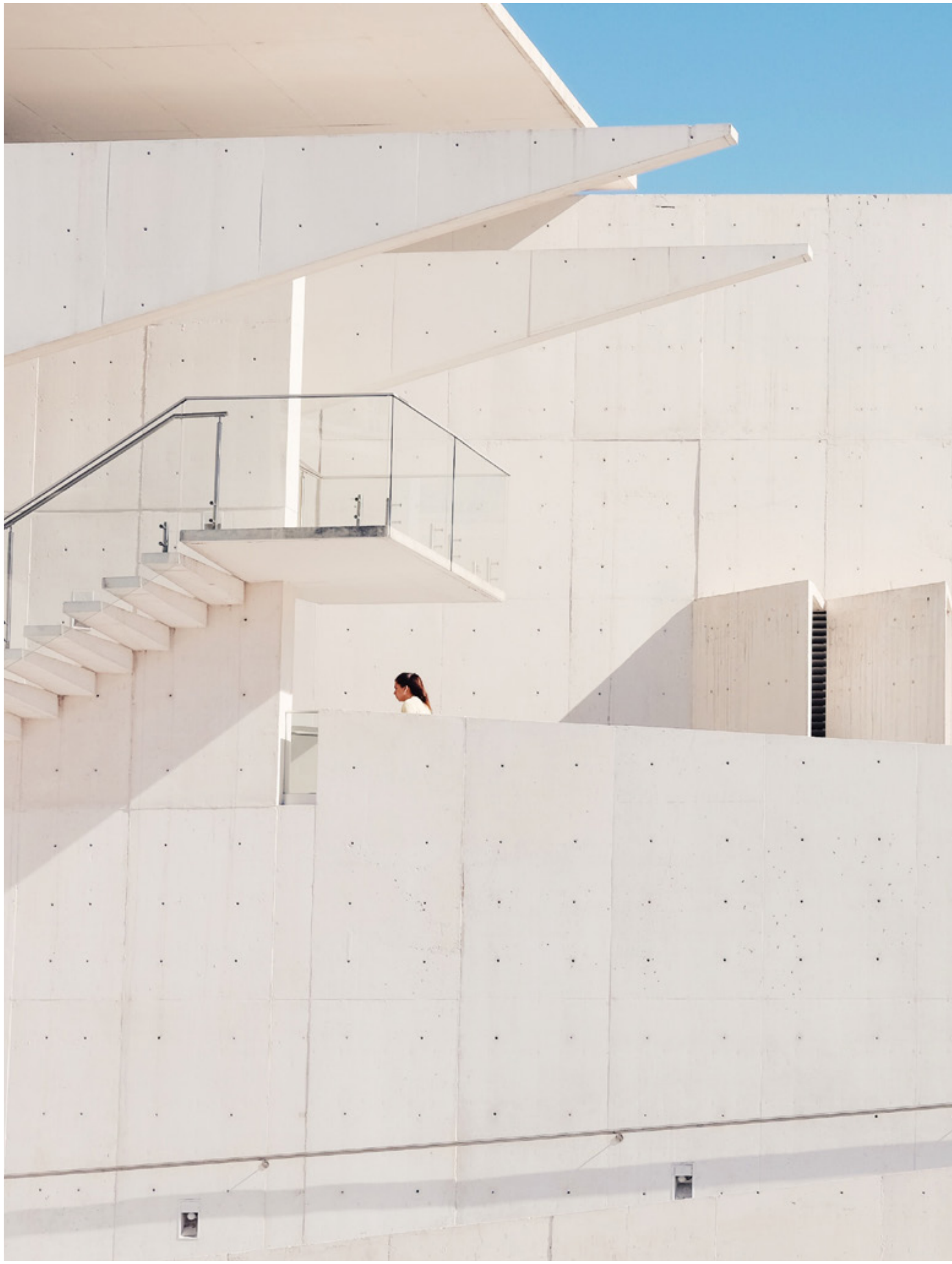


Recommendations

1. **Electrification is not recommended in the short term, as it is neither commercially viable nor does it contribute to emissions reduction.** Bangladesh's grid emissions intensity is much higher than that from the direct combustion of gas, and that is likely to remain in the short term. Therefore, electrification in the short term is not recommended, as it would lead to higher Scope 2 emissions for both Tier 1 and Tier 2 sites.

2. Investing in on-site **BESS for energy price arbitrage is not recommended**, as it is neither commercially viable nor does it contribute to emissions reduction.

3. While the IRR for on-site MSESS is positive (3%), **it is recommended that sites monitor the capex of MSESS further to ascertain its future commercial viability**. The capex of MSESS must drop further for it to be economically viable and to deliver the required return on investment needed to justify the implementation across Tier 2 sites.



Vietnam – Low (near-term) suitability

Over the past few years, Vietnam has been improving its policy framework in relation to renewables and storage, but significant challenges remain for energy storage developers and operators.

Advantages:

- **ToU tariffs implemented for industrial consumers:** In Vietnam, industrial customers with high energy use are subject to three-rate pricing, which varies depending on peak, normal, and off-peak hours.[119]
- **Optimistic energy storage policy developments:** While the policy framework for energy storage in Vietnam remains relatively weak, there are several incentives that support renewable energy projects, including energy storage. For instance, corporate income tax (CIT) incentives provide discounts depending on the location and nature of the project.[120]
- **High coal prices:** The cost of coal in Vietnam is high (USD 104/tonne), because the country is a net importer and faces a domestic market shortage.[121] Vietnam primarily imports coal from Indonesia, Australia, and Russia, which contributes to the import cost and the exchange rate risk. These elevated costs, which also impact electricity prices, enhance the value of storage, thereby promoting increased self-consumption.

Challenges:

- **No open ancillary service markets:** Vietnam currently lacks open ancillary service markets, but it is working on developing them as part of its electricity market reform. Currently, the National Load Dispatch Center (NLDC) is responsible for system and market operation, and it procures ancillary services from generators and transmission service providers directly, through contracts or regulations.[122]
- **Low SAIDI:** Vietnam's grid is fairly stable in urban and industrial areas, meaning the frequency and duration of power outages is typically low.[123] This can reduce the value of energy storage, serving as a source of backup power.
- H**igh battery storage capex:** The capex of battery storage systems is elevated due to several factors, including limited domestic manufacturing capacity and expertise in battery storage technologies. Most of the components and equipment must be imported from other countries, which adds to the transportation and installation costs. These challenges make battery storage projects more costly and risky than in other countries with high battery storage deployment.

119 Vietnam Electricity (2023) Tariffs
120 Grant Thornton (2020) Tax Incentives for Renewable Energy in Vietnam
121 S&P Global Commodity Insights (2022) Coal costs in Vietnam
122 EVNNLDC (2020) role of National Load Dispatch Center in 2020
123 World Bank (2019) SAIDI ratings

Financial analysis – Vietnam

Tier 1 sites

Energy price arbitrage offers the only mechanism for revenue generation, due to demand outstripping on-site solar supply, and a lack of ancillary markets. This predicates investment on the value of peak/off-peak tariff spreads, which at present do not provide a strong enough financial incentive.

capex: USD 929,000	IRR: -3%
Opex: USD 24,000/year	Payback period: Does not pay back

The BESS capex (USD/kWh): Solar PV is unable to cover the average Tier 1 site's energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the BESS generates annual savings of approximately USD 58,600, which is just over 6% of the initial capex investment and equivalent to approximately 2.5 times the annual Opex costs. These costs, combined with limited revenues, prevent the asset from paying back on its investment within its operating life. Sensitivities on the impact of capex within the model show a 5% capex decrease, leading to an 11% increase in NPV. To achieve a positive IRR of 3%, capex would need a 39% reduction, from USD 488/kWh to approximately USD 300/kWh.

The impact of peak/off-peak tariff spreads (USD/kWh): Increasing the peak/off-peak tariff spread improves the business case for BESS in tier 1 sites. To achieve a positive project IRR of 3%, the price differential would need to increase by 71% from USD 0.076/kWh to USD 0.13/kWh..

Tier 2 sites

As with Tier 1 sites, energy price arbitrage provides the only mechanism to pay back on investment costs of MSESS. However, minimal variations in peak/off-peak tariff values, which drive the basis for energy price arbitrage, do not offer a strong financial basis to justify the investment.

capex: USD 1,660,000	IRR: 11%
OpEx: USD 48,000/year	Payback period: ~ 10 years

The MSESS capex (USD/kWh): Solar PV is unable to cover average tier 2 sites' energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the solar and MSESS generate annual savings of USD 255,000 – 15% of the capex investment costs, which is over 5 times the annual Opex costs. As a result, payback on the initial investment could be achieved in 10 years. Thermal storage capex values interact in a non-linear manner on both IRR and NPV. As capex decreases, the resulting impact on IRR and NPV is amplified, leading to progressively larger gains.

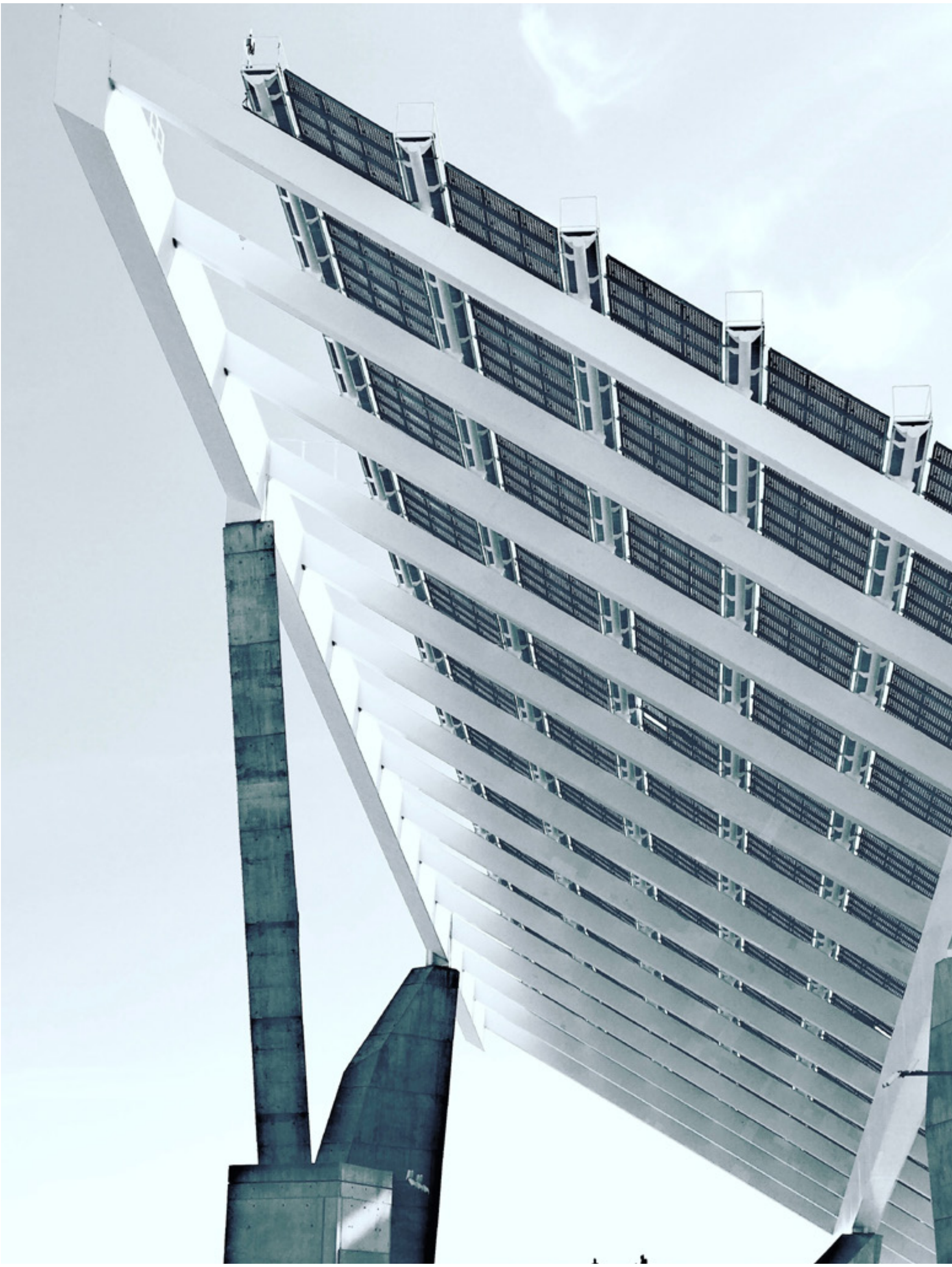
The impact of peak/off-peak tariff spreads (USD/kWh): As the solar array is not large enough to generate excess solar energy to load shift, arbitraging the peak/off-peak tariff differential is the only source of revenue for the MSESS. Consequently, changes to this indicator have a significant impact on the overall economics of the system. The larger the tariff spread, the greater the NPV and IRR of the system.

Impact on grid-related GHG emissions

The immediate electrification of textile facilities in Vietnam could lead to lower Scope 2 emissions compared to the continued use of coal combustion. This is because the current grid emissions intensity in Vietnam (472 gCO_2e/kWh) is lower than the emissions intensity range of direct coal combustion (568 – 606 gCO_2e/kWh).

However, operating based on an energy price arbitrage principle and charging during off-peak hours (22:00 to 04:00) corresponds to the times solar irradiance is at its lowest and fossil fuel-based generation is at its highest. Then the GHG emissions of the system could be greater, as it would be substituting less emissions-intensive electricity with cheaper, but more emissions-intensive electricity.

In the longer term, direct electrification with solar and ESS and operating on an energy price arbitrage policy could lead to a reduction in Scope 2 emissions. This is because the grid emissions intensity is projected to decrease to around 390 gCO_2e/kWh in 2030 and 308 gCO_2e/kWh in 2040, creating greater differences against the emission intensity from direct coal combustion.



Recommendations

1. **Vietnamese textile and apparel manufacturing sites, especially Tier 2, are recommended to electrify their operations in the short term.** Sites can benefit from reduced Scope 2 emissions with electrification in the immediate term. This is because the current grid emission intensity is lower than direct coal combustion, providing immediate savings in greenhouse gas emissions. Further increases in renewable energy penetration and consequent reductions in grid emissions intensity would enable sites to experience further reductions in Scope 2 emissions. Electrification of sites in Vietnam, especially Tier 2 sites, should come before investments in MSESS.

2. Although on-site MSESS energy price arbitrage does not currently produce reductions in Scope 2 emissions, its good commercial viability and the projected increase in the penetration of renewable energy in the Vietnamese grid suggest that on-site MSESS could support a site's decarbonization. **Sites should consider implementing on-site MSESS in the medium term.**

3. On-site BESS is neither commercially viable nor does it enable reductions in Scope 2 emissions. Further reductions in the BESS capex and increased renewable energy penetrations are needed before it should be considered. **Tier 1 sites should therefore monitor the capex of on-site BESS in the medium term before implementation.**

Indonesia – Very low (short term) suitability

Advantages:

- **Ambition to supply EV batteries:** Indonesia has an ambition to become a battery exporter by 2030, leveraging its abundant nickel reserves and offering incentives for foreign investment. Key investments include South Korean participation in the country's first EV battery plant and an investment in nickel processing led by Chinese battery material producer, GEM.[124] As the battery industry scales, this should drive down locally produced battery capex costs over time.

Challenges:

- **Existing ToU tariffs are not well-designed: Existing tariffs are divided into two categories:** simple or flat tariff charging schemes for residential users, and dual tariff charging schemes for large commercial and industrial users. The latter appears to be only charged for those connected to the Java-Bali grid. There have been proposals to introduce ToU tariffs for industrial customers in Indonesia to reduce peak demand and increase investments in energy efficiency. One proposal suggested that the tariff for industrial customers could be divided into three periods, incentivising industrial customers to shift their load to off-peak hours to save costs.[125] Additionally, the state-owned utility PLN conducted a study analysing ToU tariffs as a means of providing better cost reflectivity compared to the existing electricity tariff schemes.[126] However, no changes have been implemented in response to these studies.
- **No ancillary service market:** Indonesia still does not have a functioning ancillary service market for electricity. The country's power market operates under a single-buyer model, where the state-owned utility PLN is the sole buyer and operator of transmission, distribution, and retail businesses, as well as the operator of most major power plants.[127]
- **Poor policy environment for renewables and storage:** Indonesia has unambitious targets for renewable power generation, reducing the role storage can play in securing system operability.[128] The policy environment for storage is also nascent, with most initiatives focused on developing production capabilities for EVs, rather than focusing on commissioning and operating assets domestically.[129]
- **Cheap coal:** The cost of coal in Indonesia is low, evidenced by Indonesia being the largest exporter and the fourth largest coal producer in the world in 2023.[130] Where coal boilers are used for thermal power in manufacturing facilities, theirs low cost will make energy storage technologies less attractive.

124 CSIS (2022) Indonesia's Battery Industrial Strategy
125 Yuniarto et al (2023) Customer behaviour towards energy usage with time of use tariff: a systematic literature review
126 IAEE FullPaper - Electricity tariff cost reflectivity and time of use tariff in java-bali system.docx
127 Indonesia Investments (2024) Perusahaan Listrik Negara - PLN
128 Indonesia to abandon 23% renewable energy target, The Jakarta Post
129 Indonesia's battery industrial strategy
130 Coal Exports Statistics 2023 - TradeImeX Blog | Global Trade market information

Financial analysis - Indonesia

Tier 1 sites

Due to energy demand requirements, the BESS system would need to be charged from the grid, linking the profitability of the system to the value of the peak/off-peak tariff spreads, which do not currently present a strong enough incentive to overcome the high capex investment costs.

capex: USD 1,350,000	IRR over a 20-year period: -23%
Opex: USD 34,900/year	Payback period: Does not pay back

The BESS capex (USD/kWh): Solar PV is unable to cover the average Tier 1 site's energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the BESS generates annual savings of approximately USD 36,800 – a little over 2.5% of the initial capex investment. These annual savings are very close to the annual OpEx payments, therefore demonstrating the inability of the asset to pay back on its investment. The model was most sensitive to changes in this indicator, with a 5% reduction in the capex providing a 6% increase in NPV. Moreover, to achieve a positive IRR of around 3%, the initial capex would need to reduce by 80% from USD 488/kWh to USD 100/kWh.

The impact of peak/off-peak tariff spreads (USD/kWh): The current low tariff rates prevent the BESS from demonstrating profitability. Increasing the difference between peak and off-peak tariff spread price would need to occur to promote the business case for BESS. The model shows that large changes to the spread price are required to generate a positive business case, with an increase of 300% from the current USD 0.032/kWh to USD 0.132/kWh, achieving a positive IRR at just 0.1%.

Tier 2 sites

As with Tier 1 sites, the ESS would be charged from the grid, limiting revenues to energy price arbitrage. Therefore, to justify the investment cost, the peak/off-peak tariff spread would need to provide enough value to generate revenues, and this is currently not the case.

capex: USD 1,880,000	IRR: 1%
OpEx: USD 53,000/year	Payback period: Beyond 20 years

The MSESS capex (USD/kWh): Solar PV is unable to cover the average Tier 2 site's energy demand at peak solar output, requiring the battery to charge from the grid instead. As a result, the solar and MSESS generate annual savings of approximately USD 161,800 – under 9% of the capex investment costs and around 3 times the annual Opex costs, resulting in a payback time in excess of 20 years. The project is most sensitive to changes in capex as the MSESS' energy output is several times larger than the solar arrays. An 8% increase in the capex cost to USD 120/kWh would result in a negative project IRR.

The impact of peak/off-peak tariff spreads (USD/kWh): As the solar array is not large enough to generate excess solar energy to load shift, the peak/off-peak tariff delta is the only source of revenue for the MSESS. The relationship of the tariff spread to project IRR is non-linear, with increases in the spread price showing increases to the IRR, but at a decreasing rate.

Impact on grid-related GHG emissions

Immediate electrification of textile facilities in Indonesia would result in higher Scope 2 emissions compared to maintaining power through direct coal combustion. This is because the current grid emissions intensity in Indonesia (829 gCO_2e/kWh) is greater than the emissions intensity range of direct coal combustion (568 – 606 gCO_2e/kWh). Therefore, electrifying sites in the short term would displace less emission-intensive thermal energy generated from direct coal combustion with more emission-intensive thermal energy generated from the grid power.

In the long term, electrification of the textile industry is not expected to yield greenhouse gas savings. Current projections indicate that the share of renewable energy in Indonesia's power generation mix will increase to 28% by 2038, up from 19% in 2021. While this trend signals progress, it remains uncertain whether the shift will be substantial enough to lower the grid emissions intensity below that of direct coal combustion.

Recommendations

1. Electrification is not recommended in the short term as it is neither commercially viable nor does it contribute to a site's emissions reduction. While electrification is a key vehicle to decarbonizing a site's operations in other regions, Indonesia's grid emissions intensity is very much higher than that from the direct combustion of coal, and projections show that it is likely to remain this way until the medium term. Therefore, electrification will lead to higher Scope 2 emissions for Indonesian textile sites and is not recommended until Indonesia's grid is less emissions-intensive than direct coal combustion.

2. Investing in on-site BESS and MSESS is not recommended before the medium term, as they do not enable reductions in Scope 2 emissions, nor are they commercially viable. Furthermore, it is unclear if the challenging regulatory environment will improve in the medium term to permit any significant changes to this scenario.

Apparel Impact Institute (Aii) is a 501(c)(3) global nonprofit organization dedicated to identifying, funding, scaling, and measuring the apparel and footwear industry's proven environmental impact solutions. Aii works with over 50 brands and retailers who are leading the sector's global decarbonization efforts, including Target, PVH, Lululemon, and H&M Group.

Aii is calling for a US$250M Fashion Climate Fund to leverage a first-of-itskind collaborative funding model between philanthropy and corporate entities. It is designed to catalyze climate action by funding and scaling solutions for decarbonization, and marked to unlock a total of US$2B in blended capital, to meet the industry's goal to halve carbon emissions by 2030.

Most recently, Aii has updated its widely credited 2021 "Roadmap to Net Zero," a report and guide calling for the system-wide collaboration needed to reduce GHG emissions in the apparel and footwear industry by 45% at minimum by 2030 and to zero by 2050. To learn more about Aii, visit apparxselimpact.org.

apparel impact institute