Techno-Economic Modelling of Stationary Battery Storage Value Stacking at Distribution Transformers in India

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Abstract— **Distribution companies in India are facing enormous financial and energy losses. The grid of India is incorporating renewable energy technology at an exponential rate and has ambitious growth goals for the next decade. However, this grid suffers from inefficiency and unsatisfactory customer service. The project intends to study the techno-economic feasibility of deploying battery energy storage systems in the Indian grid to address the core issues experienced and foster a healthy and robust energy transition. To achieve this, basic research has been performed to understand India's grid focusing on the needs and the issues of the distribution system and companies. In parallel, a study on utility-scale battery energy storage systems was performed to validate the benefits, applications, and market matureness of these systems at grid level. Having this information, a tool has been developed to size battery systems for distribution companies. It has been developed considering the most useful and important parameters for distribution companies to visualize in order to analyse battery systems and gain a comprehensive understanding of the technical and financial impact of the installation. Finally, the tool has provided an expected result from a case study showing clear technical advantages and yearly savings, however with not financially viable results. The tool provides investment guidance as a support parameter. The technology is not at a cost level that allows distribution companies to generate profit, however, it is a rising technology that can be acquired for research purposes which will benefit the speed of market entrance and knowledge increase.**

Key Words — Battery, utility-scale, India national grid, sizing tool, transition, renewable technology.

1. INTRODUCTION

The objective of this paper is to perform a techno-economic modelling of the entire value stack of stationary Battery Energy Storage Systems (BESS) at distribution transformers in India. To complete the study, a tool will be developed. The final goal is to obtain a functional and validated tool which distribution companies (DISCOMs) in India will use as a resource to size and comprehend the techno-economic advantages of acquiring battery systems for energy storage applications at transformer level. To do so, the projects scope is to focus on the study of one application for the battery system, overload reduction in distribution transformers. Moreover, the tools outputs should be valuable, useful and aid the user understand the benefits of implementing this technology.

The methodology is represented in the project structure, which follows the chronological work performed. Research, tool design, case study, result analysis, and conclusions.

2. PROJECT BACKGROUND

2.1. IMPORTANCE OF SDG 7 FOR DEVELOPMENT

The implementation of the Sustainable Development Goals (SDGs) has proven to have a positive influence on development. The objective of SDG 7 specifically, is to ensure access to affordable, reliable, sustainable, and modern energy for all. This goal has a great impact on the majority of the 17 SDGs, more accurately, 65% of the goals to be achieved are somehow related to energy [1]. The energy goal has a direct positive impact on most of the sectors such as transport, health, or the industry. The use of sustainable, reliable, and clean technologies enables nations to grow and develop in a more robust way towards life quality, stronger health, and social and financial maturity.

2.2. ELECTRIFICATION IN DEVELOPING COUNTRIES

As previously exposed, affordable, reliable, sustainable, and modern energy is required and a key piece for the development pathway of developing and developed nations. Electrification is one of the aspects addressed by SDG 7 and the focus of this paper. Several benefits can be observed from electrification. Some of the overarching positive impacts can be seen through higher incomes, improved health care, or better quality and amount of education services available. Fig. 1 shows the advantages promoted by each set of appliances [2]. With the exponential growing interest on renewable energy technologies, emerging economies and low electrification rate countries can play a key role in the global market due to their generally high potential for renewable energy technology installation [3].

It is crucial to understand the challenges that the energy transition, especially electrification increase will bring. Three main challenges can be found. The amount of raw materials required and price fluctuation, waste management of renewable energy technologies, and the grid stability. The increased number of raw materials to be used and their treatment for manufacture, bring important challenges both for supply and disposal matters [4]. In terms of the grid stability, the integration of new generation technologies which bring variable generation or unpredictable peaks, brings voltage and frequency issues as well as overload of transmission lines and assets, and demand-generation mismatch. These factors introduce great stress to the grid lowering the efficiency, increasing supply costs, and degrading the service provided to the final customer.

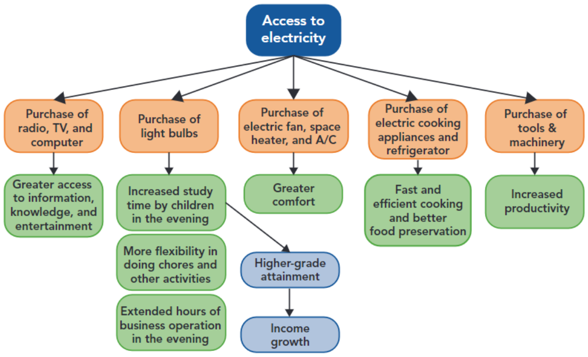

Fig. 1 Benefit pathways for household electrification

3. India and the National Grid

3.1. Energy System Background

India has made noticeable improvements regarding energy development, energy use has doubled since 2000 [5]. The major improvements withing the energy sector will be exposed as to provide the reader with the Indian energy context and latest developments. The presented topics are the focus areas addressed by SDG 7.

The first focus area is access to clean cooking. The Indian population with access to clean cooking was 22% in 2000 and increased to 67% in 2020 [6], [7]. The Government has worked on improving access and affordability to fuels and technology such as liquified petroleum gas and biomass cookstoves through subsidies and supporting research. The next step is to focus on rural areas. Consumer ability to pay and the distribution network must be improved to reach rural and remote areas and guarantee a stable and quality service. It is fundamental to reach those without access to bank accounts so cannot even receive the government's support in first place [8].

The next topic is energy intensity. To achieve this goal, a reduction in energy use per unit of activity is required, measured in MJ per 2017 USD PPP. In 2003 India achieved a lower value than the global average being 5.8 MJ per 2017 USD PPP in India and 6.0 MJ per 2017 USD PPP the global average. Since then, India has always been below the global average [6]. Some initiatives allowing the achievement of this goal are to introduce standards and labelling of appliances, to have codes for commercial buildings which prove energy conservation, and energy consumption requirements for energy intensive industries. The Indian Ministry of Power, through the Bureau of Energy Efficiency, is in charge of ensuring that different players follow the implemented initiatives [9].

To continue, the share of modern renewables is presented. Since 1990, India has increased the share of renewables in final total energy consumption from 10.13% to 15.93% in 2019 [6]. In 2022 the installed capacity of renewable energy was 152.36GW, meaning a 38.56% of the overall installed power capacity. India has been ranked 3rd globally for its renewable energy investments and plans for 2020. Since 2021 key private energy players have been signing important projects and investment plans. Observing this environment, the nation's goal for 2030 of achieving 60% of installed capacity from solar power seems realistic. The government has introduced organisms and laws to promote renewable energy use as well as incentives to enhance consumers and industry to purchase and utilise green energy resources [10]. There are still key challenges to be addressed such as off-taker risk, lack of infrastructure, lack of financial intermediaries, and limited understanding from investors. As seen, the challenges and the actions taken by the private and public sector match and there is a clear intention of solving these bottlenecks from the different players in the energy sector [11].

Finally, India has achieved major milestones in the sub-goal access to electricity. In 2020, 99% share of households were using electricity as a primary lighting source [6]. This relatively fast achievement was promoted by the National Electricity Policy dated 12th February 2005, which is part of the Electricity Act 2003. The core issues to be addressed to achieve 100% electrification are exposed in the policy, including: rural electrification, recovery of cost of services and targeted subsidies, technology development and research and development, energy conservation, financing programmes or protection of consumer interests and quality standards amongst others [12]. This has been an absolute success; however, work must continue. Currently, the main challenges are found in rural areas, where electrification levels are slightly below average, 95%. However, the 5% left presents major barriers. Most of the citizens in these regions do not experience reliability or service quality from the National grid or cannot afford a connection to their household.

3.2. National Grid

India's national grid has experienced a fast expansion in the last 20 years leading to many required adaptations. This section describes the national grid's current situation, including the main structure and key challenges.

It has been one interconnected system since 2013, made up of five power grids divided by geographical locations. The state-owned Power Grid Corporation of India is the owner, and the also state-owned Power System Operation Corporation oversees the operations [13]. It is one of the largest grids worldwide with 371,054 GW of installed power generation capacity reported in 2020 [14]. Important milestones have been the establishment of the Central Electricity Authority (CEA) and the State Electricity Boards through the Electricity Supply Act in 1948. After the establishment of the 5 independent regional power supply networks, in 2013 these were synchronously connected as one grid [15]. A connected grid promotes the optimal flow of power and sets ease of trading in one united market.

Fig. 2 India regional power grids. [16]

Generation capacity in the country is ruled by the use of coal. 56% of the total generation comes from coal-fired plants. Renewable technologies can be found mainly in the south, where 50% of the country's total solar installed capacity is located.

Regarding transmission and distribution of power, meeting the needs of the consumers remains to be a high priority challenge. There is enough generation capacity in the country to meet the demand, but not all this energy is able to reach the consumers. In [17] it is reported that "India's T&D losses have been over 20% of the generation, which is more than twice the world average. The ideal level of T&D losses ranges between six and eight per cent". CEA has reported an annual decrease in losses; however, this is not enough, and it is far from achieving the necessary goal to ensure customer satisfaction. Overall, the transmission sector is robust and adapting accordingly to the required changes, whereas the distribution sector presents the main bottleneck of the system.

3.3. DISTRIBUTION COMPANIES

It is clear that the Indian power sector is one of the most complex systems worldwide. The share of renewables in the energy mix has increased exponentially, energy access to all is achieved up to 99% and energy efficiency has improved at a rate better than the global average. These are remarkable achievements knowing the complexity of such a high densely populated country. All this has been backed up by strong and clear regulations that look forward to providing a well stablished base for this complex but necessary transition.

In this new section, the focus is shifted to the next challenges. India's DISCOMs are facing sever struggle to evolve in a sustainable path. Technical, operational, and financial losses are the daily protagonists of most of these companies.

There are approximately 60 distribution companies operating in India. As presented in [18], most are state-owned, and only 10% of India's population is served by private distribution licensees. Every state has at least one DISCOM, meaning 28 states and 8 union territories. The sector is shifting towards privatization. Lack of financial viability, poor planning, high costs of supply, poor supply and service quality, and non-competitive tariffs is the loop that the government is trying to stop through legal procedures and market changes to save Indian DISCOMs.

Reliability and affordability. These aspects accurately summarize the situation faced by the sector. As mentioned, the service provided is unreliable for most customers. This builds up a barrier to social and economic development, not only making customers pay for a service that does not cover the basic needs but also forcing them to invest in alternative sources of energy, which are costly and in general polluting, for example, diesel generators. In addition, tariffs in the country are not low. As mentioned in [19], "tariffs for the Indian residential sector are much higher in purchasing power parity (PPP) terms than in other developing countries". Low per capita incomes are common in the country, meaning that energy costs represent a high percentage of a household's expenditure.

DISCOMs' inability to cover their overall cost, or Average Cost of Supply (ACS), through client payments causes the financial debt circle. How is this possible? To ensure electricity access, the government requests DISCOMs to lower prices. State subsidies support this price drop. Then, the state demands additional price cuts for customers. The concept seeks long-term customer reimbursement through regulatory assets. Finally, the state requests customer-specific tariff costs. Industrial consumers will pay more than residential and commercial while The DISCOMs will earn enough from the average prices. This is known as Cross-subsidy.

If subsidies, regulatory assets, and cross subsidy perform as anticipated, the government's energy access and flexibility policies would be effective. However, the state is delayed on subsidy payments, regulatory assets from customers seldom materialize, and cross subsidy, especially due to covid, has caused serious income unbalancing. Distribution businesses are in debt and unable to improve [20].

To tackle the lack of plan efficiency, India has implemented several schemes and plans. The revamped distribution sector scheme, Saubhagya scheme, UDAY strategy, Deen Dayal Upadhyaya Gram Jyoti Yojana and The Integrated Power Development Scheme. These present different objectives focused on energy access, technical, operational, or financial aspects. The main outcome observed is that each state experiences different success rates from the schemes, so more state-based support is required. Also, the schemes have not had an overall success. The state still lacks to provide financial response on time which delays the objective achievement of the plans proposed [18].

In [18], several recommendations are proposed obtained from theoretical analysis and practical examples from existing reforms in different states. These recommendations are structured by topic; therefore, different solutions can be applied to different segments. Structural, regulatory, operational, managerial reforms, and solutions for renewable energy integration are the branches in which the solutions can be divided.

3.4. Benefits of Energy Storage Systems in Distribution networks

Multiple solutions have been proposed in the previous section, one of them focusing on renewable energy integration. The focus of this section is to provide a deeper look at the benefits of energy storage systems. The selected technology, battery systems, provide a set of applications with high benefit at utility-scale. By presenting these applications, benefits, and challenges for energy storage systems at utility-scale, the need for this report and the reasons for developing tools like the one presented in this work are highlighted.

BESS arrive in the best possible moment. Research has found several applications in which BESS can take part and exactly target the issues faced by the evolving grid. Peak shaving or load levelling is one of the most common applications where BESS can be found. Renewable energy compensation and uncertainty reduction is also a key use found in research. Moreover, BESS provide voltage and frequency control support and indirect control of line congestion, meaning that major network upgrades can be postponed. Regarding operation, batteries can behave as an energy management system by scheduling optimal power generation dispatch.

To continue, transmission and distribution congestion relief, has special consideration in this report being the objective, to support this specific use. Line overload increases the probability of network components failure and the occurrence of power interruptions as explained in [21]. This is exactly the situation currently experienced by many Indian households. Transformers in distribution lines are suffering overload due to the high demand increase and generation growth. At the same time, the lack of space to upgrade these assets triggers the sector, urban areas are densely populated and the physical space available around sub-stations is limited [19].

Overall, BESS can be seen as an energy management peak shaving (EM-PS) system providing all the above applications and mitigating high electricity prices during peak loading hours [22].

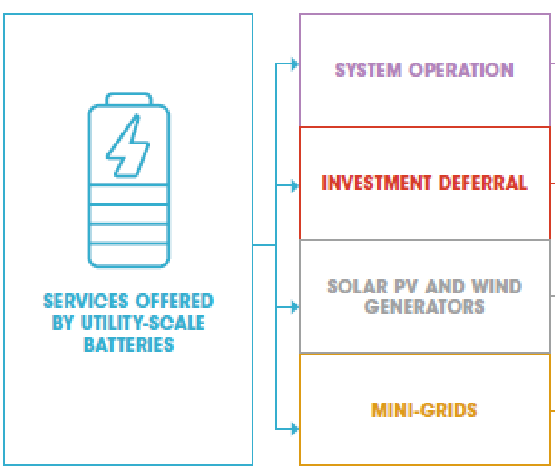

Fig. 3 Services offered by utility-scale battery storage systems. [22]

3.5. Increasing interest on BESS in India

India has the potential to become an important reference in the battery sector due to the great gap for improvement in the national grid. India can become the base case study for many countries while solving many of the core problems currently experienced.

The government not only proposes strategies and reforms which support DISCOMs directly, but also has implemented pathways to support battery storage usage and market growth. 27 GW of grid-connected battery storage are estimated to be required by 2030, and to make this possible, India's government established a National Mission on Transformative Mobility and Battery Storage in the year 2019 with the objective of making India an international and competitive battery manufacturer. Along with this, the first renewable energy auction was placed during 2020 for the development of 400 MW of generation capacity combining renewable and storage technologies [19].

Private parties have also shown their interest in the technology and have started developing case studies and research on the topic. In July 2020, a partnership between USAID and the Ministry of Power of the Government of India supported a report produced by the National Renewable Energy Laboratory (NREL) along with the collaboration of BSES Rajdhani Power Ltd. (BRPL). The four topics to be researched were: reusable framework for distribution utilities, impact of BESS on distribution system losses, minimally sizing and controlling BESS for maximum benefits, and essential and cost-effective pathways to deploy BESS [23]. The study concluded that BESS can be beneficial for the studied applications and are a better option than equipment upgrading for overloading reduction. The report had a major accomplishment which was to develop a bottom-up cost model for BESS applicable in India [23].

With a similar objective, TERI, the Energy and Resources Institute of India, launched a case study in 2018 through a pilot project with the objective, explained in [24], of reducing the stress on transformers during peak hours and reduce the peak power requirement. The article explained the challenge: "with increasing electricity consumption, the distribution transformers ger overloaded during peak load hours" [24].

This opens a window of opportunity for the BESS market in the country and a robust first step towards grid strengthening through innovative and new renewable technologies.

4. Tool development

4.1. Tool benchmark

As the need of evaluating BESS with system integration purposes increases, so does the interest in tool development for this purpose. Currently, multiple tools exist and are available free or commercially. Each tool has differentiating features as well as common ones, meaning that to obtain the most useful and realistic results, it is recommended to use a combination of them.

Overall, as mentioned in [25], "even though many tools for ESS valuation design exist, there is a lack of integrated tools that are capable of both analyzing the technical performance and valuating the economic benefit of ESSs. ESOD, the tool designed under this project, aims to fill this gap by targeting both technical and financial output calculation.

4.2. General description

The tool ESOD or Energy Storage Optimization for DISCOMs has the objective of providing DISCOMs with an approximate battery capacity to reduce the overload frequency in their substation 11 kV transformers. This application has been selected based on the previously explored possibilities for the Indian market. Battery storage based on lithium-ion technologies can avoid the investment in a new transformer by increasing the efficiency of the existing one and, therefore, increasing its lifetime. Not only this but using a battery storage system means an extra revenue through peak shaving strategies. The tool will not only provide technical outputs but also a financial analysis. The user will be able to analyse how profitable this investment can be along with other parameters that help the DISCOM to take the decision of implementing the system or not. This tool has been developed hand by hand with Indian market players such as battery manufacturers and DISCOMs in order to provide the highest value from its development.

The tool has been developed using the computer program Excel, allowing a semi-automatic computation with user-friendly interface. It is based on three types of data: inputs, process, and output data. It is divided in two sections: user, and developer. This way, the user section will be where the DISCOM operator will introduce the required data, modify parameters, and observe the results. The pages in the user section are Cover, Instructions, Input Data, Process Data, and Output Data. The developer section includes the calculation processes and include the pages Demand analysis, Battery sizing, Economic, Econ breakdown, Savings, Funding, Funding Update, All results, All economics, All Econ breakdown, All funding, All battery sizing, all savings, Feasibility projection, Econ breakdown projections, Projection results.

4.3. Introduction

Initially, the user will be guided to an instructions page. Apart from this, the user will find a specific set of instructions for every page, as to guide the actions to be taken. All the pages within the user section have a software type appearance, providing a side menu to shift through pages to allow ease of interaction. The initial instructions present the type of data in the tool: Input data, Process data, and Output data.

4.4. Input data

To start the process, the user shifts to the Input data page. The Input Data page shows the parameters the user must introduce. An instructions box is provided to guide the user through the process. The required inputs are shown in yellow and are time steps, total active power, active energy delivered into the load, the power factor, and the rating capacity of the transformer. The units of the data must also be introduced to quantify the data appropriately.

4.5. Process data

The next sheet is Process Data, where key parameters are provided, financial and technical. These are provided based on research to provide ease of quick calculation, however, if the user is willing to modify these values, it is possible. In this case, the white cells are the ones that can be modified leaving the grey one’s constant. The user can decide to perform the analysis using the proposed battery system or one provided by them. The yellow cell displays a drop-down menu from which the user can select “Value predefined” or “Value custom”.

4.6. Demand analysis

To continue, before moving on to the Output Data page, it is important to introduce the developer section to understand the calculations that occur before obtaining the results. The first step is the Demand analysis page. Here, the load curve is analysed to determine the overload frequency, peak power to be covered by the system, and the total gross energy to be covered, in other words, the amount of energy that the battery system will process and therefore, avoid the transformer from processing, decreasing the overload. First, the power limit for the transformer is calculated, so from which point it is considered that the transformer is suffering overload. To continue, a count of overload is performed in the Input data. This way, if the overload limit power is surpassed, there will be a count in the column “Overload limit”. This data will be converted to a dynamic table where the number of overload moments throughout the year can be visualized summed up for one day.

The next step is to analyse the power and energy patterns. The tool enables the user to select the storage hours or discharge of the system and if the sizing must be based on the average energy profile or on the peak energy profile. This way, the tool provides 10 possibilities to the user to select from. All the configurations follow the same calculation process that is explained below. The power and energy pattern analysis will be performed through dynamic tables which processes the data automatically. These tables have the objective of finding the maximum power peaks and analysing the energy patterns in relation to them. Finding the maximum power peaks allows to know the times of the day with highest overload and determine the power to be covered by the system.

To continue, the energy analysis is performed. For this, the energy limit must be set by converting the power limit into energy using the timesteps of the data provided. The total energy required to size the battery, will be the sum of the energy found above this limit for the chosen hours.

4.7. System sizing

To continue, the battery size is calculated along with the inverter capacity. The final battery size is the total energy previously calculated divided by the depth of discharge and the roundtrip efficiency of the chosen battery system. For inverter capacity sizing, the power overload to be reduced multiplied by a sizing factor of 1,3 which considers the inverter capacity to be 25% higher than the aimed power coverage [26].

4.8. ECONOMICS

The tool has three pages of financial analysis. The "economic breakdown" enumerates all projected expenditures and revenues. Total system costs consist of EPC and Developer fees. EPC costs include lithium-ion batteries, inverters, structural BOS, electrical BOS, installation personnel and equipment, and EPC overhead. The costs of a developer consist of land, permits, connectivity, contingency, and overhead. In [27] these estimates are provided in $/kWh. The updated conversion function in Excel transfers costs to Indian Rupees. Peak shaving and asset deferral generate revenue. Avoiding the purchase of a $90,000 transformer saves deferred asset costs [28]. Peak shaving estimates include electricity purchases and sales during off-peak and peak hours. On the Process data page, the user can modify this data. Calculating earnings for storage capacity reveals the extent to which the battery system increases DISCOM's earnings.

There is also a benefit from carbon emission reductions in the grid. To satisfy peak demand, carbon-intensive technologies increase the carbon intensity of the grid. Since the battery enables the DISCOM to purchase energy during off-peak hours and sell it during peak hours, less harmful technologies must be started to address this peak.

The page Economics summarizes these costs into a profit and loss analysis and cash flow. The project lifetime is proposed in the Process data page and can be modified by the user. With this, the total system cost and the actual storage capacity, the depreciation is calculated. The operating income is calculated from the previously presented costs and revenues. The cash flow analysis presents the cost investment in fixed assets showing the total cost of the system in rupees, the operational cashflow, project cash flows, discounting factors, present value of project cashflows, and the accumulated present value of project cash. To conclude, these calculations are the base to find the net present value and the internal rate of return, key financial parameters to address the feasibility and attractiveness of a project

To finalize the economics section, the tool provides a calculation of the funding required for the project to be financially feasible. This calculation is added due to lack of market readiness; therefore, most utility-scale BESS projects will currently face negative NPV and non-attractive IRR.

4.9. OUTPUTS

To finalize the tool description, the Output page is presented. Here the user can directly visualize in a summarized way the results after the calculations have been performed. The results are split into technical and financial. The technical outputs present the total energy capacity, total inverter capacity, number of batteries, area required, reduction in overload occurrence and the power demand reduction, these two parameters supported by graphic representations. The financial outputs are the net present value, internal rate of return, savings per kWh and per year, a graph with the project cashflows, the investment required as a percentage of the CAPEX and as absolute value, the return in case of external investment, and two extra sections comparing the NPV and IRR for the 10 configurations and the investment required for the 10 configurations.

This section also allows the user to change the configuration selection. This way, the changes can be immediately observed when the configuration is changed.

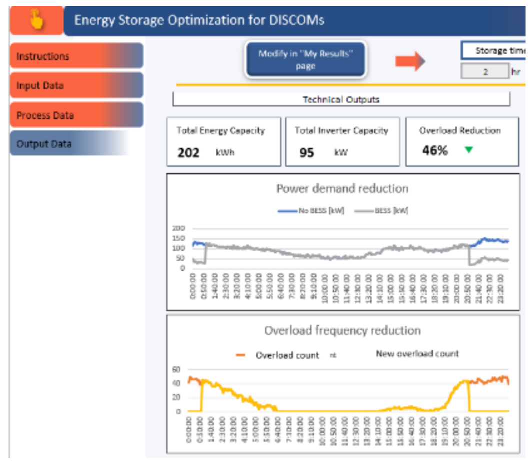

Fig. 4 Tool output display I

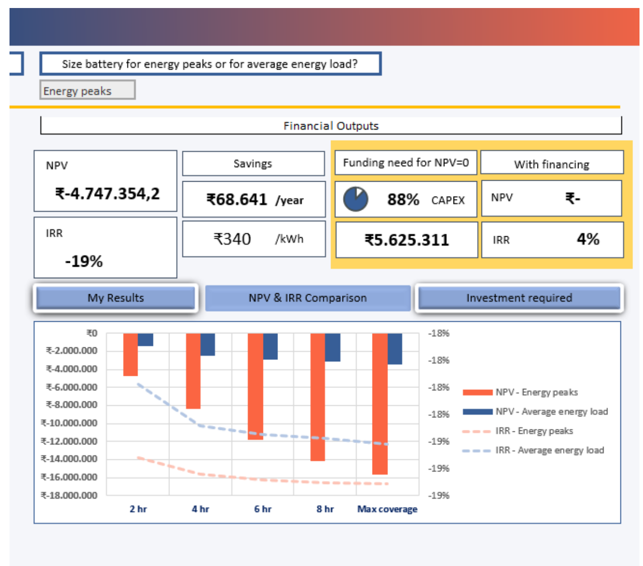

Fig. 5 Tool output display II

5. CASE STUDY

A case study is conducted to validate the tool performance. Working with an industrial partner allows the tool to provide useful results that can be analysed.

5.1. INDUSTRIAL PARTNER

UGVCL or Uttar Gujarat Vij Company Limited has provided the data to develop the case study. UGVCL is a public owned DISCOM operating in the north of Gujarat with a network of 50.000 km and over 3 million customers including industrial, residential, commercial, and agricultural [29].

5.2. DATA PROVIDED

The data set is based on a residential society for the April and May in 2019. The rating capacity is 200 kVA and data is recorded in the transformer every 5 minutes approximately. The system is a three-phase transformer. The parameters provided by the company are voltage, current, active power, active energy delivered – active energy received, active energy delivered into de load, active energy delivered + active energy received, active energy received out of the load, apparent energy delivered, apparent energy delivered + apparent energy received, apparent energy delivered – apparent energy received, apparent energy received, frequency, power factor, reactive power, current total harmonic distortion, and voltage total harmonic distortion.

5.3. PROCESS DATA

The grid carbon intensity for peak hours has been based on the coal generation plants emission factor in India of 0.95 $kgCO_2e/kWh$ [30]. The carbon intensity for off-peak hours has been defined using the emission factor of solar PV plants, being 0.24 $kgCO_2e/kWh$ [31]. The price of emissions is set to 274.7 ₹/metric tonnes CO2e [32]. Moving on to the parameters required to perform the financial analysis, the following values are stablished. The prices are averages that UGVNL provided after analysing power purchase agreements, buying trends, and tariffs for the different customers.

Economic parameters		
Parameter	**Value**	**Units**
Project lifetime	15	Years
Selling price [off-peak]	6	₹/kWh
Selling price [peak]	7,2	₹/kWh
Buying price [off-peak]	4,57	₹/kWh
Buying price [peak]	5,5	₹/kWh
Price of CO_2e emissions	274,7	₹/mTon CO_2e

Fig. 6 Economic parameters for case study development

The company showed interest in analysing the case for an 80% overload limit, so calculations were continued with this limit. Moreover, from market study, the replacement cost of the transformer is set at ₹90,000 [28].

Regarding the battery, the parameters to be considered are the nominal AC voltage, nominal ampere hour capacity, roundtrip efficiency, depth of discharge, and dimensions are established. For this case, the brand EXIDE has been selected for their large market share in India and experience with utility scale and sub-station application energy storage solutions. The inverter was selected from the brand ATESS Power.

The costs used to perform the feasibility analysis were based in kWh and shown in Fig. 7 Current component cost breakdown by system 2019 battery for utility scale. [27],[33].. The disposal cost of the battery is added as a parameter for the user to introduce, however, for this case study it was agreed to ignore this parameter.

Current Component Cost Breakdown by System ($2019)	
Utility Scale	
Model Component	**$/kWh**
Lithium-ion Battery	192
Battery Central Inverter	15
Structural BOS	13
Electrical BOS	35
Install Labor & Equip	19
EPC Overhead	10
Sale Tax	16
∑ EPC Cost	**300**
Land acquisition	0
Permitting fee	1
Interconnection fee	8
Contingency	9
Developer overhead	7
EPC/developer net profit	16
∑ Developer cost	**41**
∑ Total system cost	**341**

Fig. 7 Current component cost breakdown by system 2019 battery for utility scale. [27],[33].

5.4. RESULTS

TABLE I TECHNICAL RESULTS SUMMARY

Technical results	
Parameter	**Value**
Overload limit power	80 kW
Overload limit energy	7 kWh
Gross energy for storage sizing	255.31 kWh
Actual storage capacity	355 kWh
Inverter size	95 kW
Total units	2
Total area	2 m^2

TABLE II FINANCIAL RESULTS - CAPEX AND OPEX

Financial results - CAPEX and OPEX	
Parameter	**Value**
Total system cost	₹ 9,864,617.3
CAPEX – EPC cost	₹ 8,677,909.3
CAPEX – Developer cost	₹ 1,186,708.0
OPEX – O&M	₹ 246,615.43/ year

TABLE III FINANCIAL RESULTS - VARIABLE SAVINGS

Financial results – Variable savings	
Parameter	**Value**
Peak shaving revenue	₹ 340,398.3/ year
Carbon emission savings	₹ 68.98/ year

TABLE IV FINANCIAL RESULTS - NPV AND IRR

Financial results – NPV and IRR	
Parameter	**Value**
NPV	₹ -8,387,604
IRR	-19%

TABLE V FINANCIAL RESULTS - FUNDING REQUIRED

Financial results – Funding required	
Parameter	**Value**
Funding required	88% of CAPEX
Funding required	₹ 9,864,617
Expected IRR for NPV = 0	4%

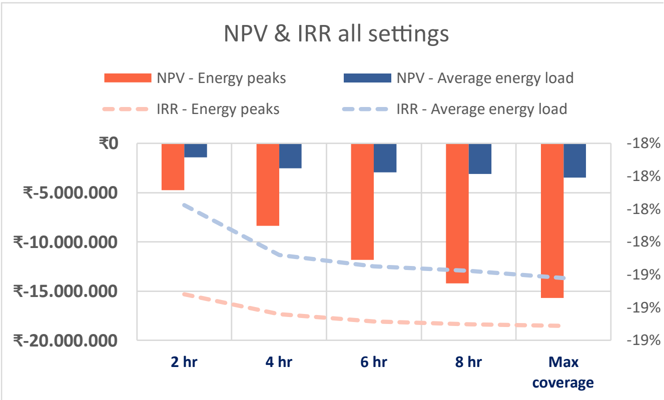

Fig. 8 All hour's financial results - NPV and IRR comparison

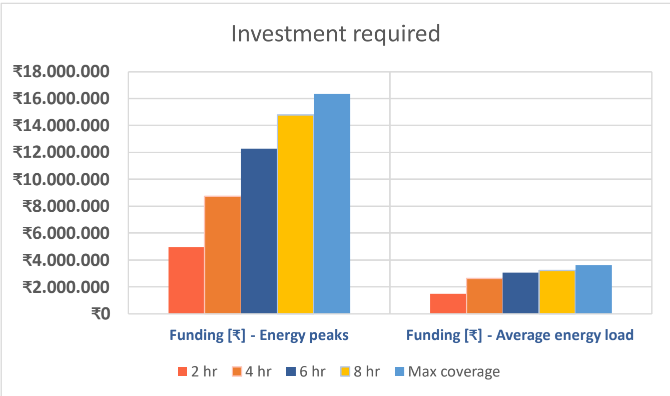

Fig. 9 All hour's financial results - Investment required

6. DISCUSSION

6.1. EVALUATION OF RESULTS

The BESS allows the transformer to reduce overload occurrence in 46%, almost half of the occurrence. Moreover, the maximum power peak experienced by the transformer is reduced meaning that during the discharge period of the battery, from 21:00:00 to 01:00:00, the maximum peak observed is of 57.41 kW instead of 152.41 kW. Also, financially, the system integration does provide a yearly revenue through peak shaving activities of ₹12,369. Observing these results, BESS integration is a success.

On the other hand, the results presented, show a financially unattractive investment. A negative NPV of ₹-8,387,604 and a return in investment of -19% is a reason to set a "no go" for this investment. One reason for this can be the fact that this data is only representative of two months of one year, therefore the demand curve is not representative or realistic to size the BESS. However, the main reason found for these results is the market readiness of BESS for utility scale applications.

The large-scale battery storage market growth has clear potential to support renewables penetration in the grid and allow a robust energy transition, with applications detected at all the levels in the electric chain, from generation to consumption. However, there are many barriers limiting the growth of the market such as high upfront costs [22].

It is important to highlight that different key enabling factors have to come together to provide access to an increased deployment of this systems in the world's markets [22]. The three points presented in Irena's study are reduction of investment costs to reduce the viability economic gap, create valuable regulatory frameworks for energy storage and, establish pilot projects to understand, evaluate, and learn from the technology's behaviour [22].

Studies have proven that to make this technology attractive in the present market environments, the BESS should be installed for different applications, this way, it can generate revenue streams from a variety of sources including "cost-based and market-based" services, so avoiding costs to the utility, and providing competitive price participation in the market [34].

7. CONCLUSIONS

Paraphrasing the introduction, the current thesis intended to perform the techno-economic modelling of the entire value stack of stationary Battery Energy Storage Systems at distribution transformers in India. To complete the study, a tool was to be developed to meet the needs of Indian DISCOMs. The final goal was to obtain a functional tool which distribution companies in India will be able to use as a resource to size and see the techno-economic advantages of acquiring battery systems for energy storage applications at transformer level.

The conclusions can be divided in two sections, the tool and the results obtained. In first place, the tool succeeds to provide useful outputs for the user. A variety of technical and financial parameters are provided for specific user cases. These outputs include energy storage capacity, maximum power covered, overload occurrence reduction, NPV, IRR, savings, investment required and a comparison of NPV, IRR and investment needs for a variety of system configurations. Overall, parameters that help the DISCOM understand the available possibilities, and provide alternative options of comparison.

Moreover, the tool provides a user-friendly interface to allow a semi-autonomous analysis performance with clear outputs supported by visual graphic elements. The tool has been validated through interviews with industry and academia experts in the field. Key interviews were held with the company AmpereHour, a battery provider in India, KTH, the Swedish university in Stockholm, Fundacions Valencia, the organization in charge of bringing innovation to the port of Valencia, Vision Mechatronics, a battery provider in India with expert consultants in the battery sector, UGVCL, the partner DISCOM that provided data for the case study development, and Pamoja Cleantech, energy access company. The value of the outputs provided by the tool was recognized and discussed through interviews.

Moving on to the numerical results, the key takeaway is the lack of market readiness for BESS at utility-scale. For the load data provided, none of the system configurations studied provided a profitable or financially viable project. However, the overload reduction of 46% with only 4 hours of discharge shows the potential of BESS for this application when combined with a peak shaving strategy to provide revenue. Thinking in terms of present markets, the clear conclusion is that BESS large-scale systems must be used to provide multiple services in markets with tariffs that differ among power levels and benefit DISCOMs from providing higher quality electricity supply to the grid.

The main takeaway for the DISCOM would be to find external funding to implement the BESS and install a system based on average energy load sizing. It would be interesting for the company to obtain funding and install the system since this provides the ability of studying the BESS and being able to learn from its behaviour. After the initial investment, after a set time of research period, the next step can be to analyse the different transformers owned by the DISCOM and use the tool to evaluate the attractive sites to implement a second system or more, depending on the market in the area, available technologies, and possible applications. BESS at utility-scale do not only provide benefits for the grid, but these systems are also energy transition enablers, robust technologies with great storage potential with the ability to respond to charge and discharge need in short periods of time and able to adapt to different environments, applications, and needs. Combined with sensors and energy management systems (EMS), system owners can regularly adapt the behaviour of the batteries to the needs as well as track the charge and discharge curves to understand, learn and readapt the technology during its lifetime.

Batteries will be the core of the future grids in the world, therefore research, development, enabling policies, and markets must continue looking into this direction to allow a fast-paced integration of utility-scale BESS.

The main future developments revolve around making the tool more sophisticated, accurate, and with a greater scope.

In first place, to develop the tool further into an updated version, it is recommended to add the use of a coding software such as Python. Here, the whole calculation process will be introduced into the coding language keeping the interface in Excel. This way, the calculation times and capacity increase noticeably. Moreover, the whole calculation process can be automatised and allow total user independence when using the tool.

Second, the tool has the potential to include several applications to analyse. The current version includes the case in which the BESS is utilized to assess asset deferral and peak shaving applications. In future versions, it is recommended to add as many applications as possible which can include voltage regulation, frequency regulation, or renewable integration assessments amongst others. The user should be able to select the application or combination of applications to be assessed and therefore observe the optimum combination for the specific case study.

Third, the tool should include a catalogue of available battery storage systems for the user to select from. Not only the tool should include different lithium-ion batteries but also different chemistries such as lead-acid. At the moment the tool presents one lithium-ion proposed system.

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