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

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

To...

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My dad. Thanks to him I can write these words today. Not only he has made me able to study this program and complete this work, but he has also taught me how to live, grow towards my dreams, how to enjoy the things I do, and how to appreciate that there is time for everything in this life.

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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.

Keywords

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

Resumo

As empresas de distribuição de energia na Índia estão a enfrentar enormes perdas financeiras e energéticas. A rede eléctrica na Índia está a incorporar tecnologia de energia renovável a um ritmo exponencial e tem objectivos de crescimento ambiciosos para a próxima década. No entanto, esta rede sofre de ineficiências. O projecto pretende estudar a viabilidade técnico-económica da implantação de sistemas de armazenamento de energia de baterias para promover uma transição energética saudável e robusta. Primeiro, foi realizada investigação básica para compreender a rede na Índia, centrando-se nas necessidades do sistema de distribuição. Em paralelo, foi realizado um estudo sobre sistemas de armazenamento de energia em bateria para validar os benefícios, aplicações e maturação do mercado destes sistemas ao nível da rede eléctrica. Com esta informação, foi desenvolvida uma ferramenta para dimensionar sistemas de baterias para empresas de distribuição. A ferramenta foi desenvolvida considerando os parâmetros mais úteis e importantes para as empresas de distribuição usarem e analisarem os sistemas de baterias, obtendo uma compreensão abrangente do impacto técnico e financeiro da instalação. Finalmente, a ferramenta forneceu um resultado esperado de um caso de estudo mostrando claras vantagens técnicas e poupanças anuais, contudo com resultados não financeiramente viáveis. Fornece orientação de investimento como parâmetro de apoio. A tecnologia não está ainda a um nível de custos que permita gerar lucro, no entanto, está em ascensão que pode ser adquirida para fins de investigação e que beneficiará a entrada no mercado e o aumento do conhecimento.

Palavras-chave

Bateria, escala de utilização, rede nacional da Índia, ferramenta de dimensionamento, transição, tecnologia renovável.

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List of Abbreviations

ACS	Average Cost of Supply
ARR	Average Revenue Realized
AT&C	Aggregate Technical and Commercial Loss
BESS	Battery Energy Storage Systems
BRPL	BSES Rajdhani Power Ltd.
CAGR	Compound Annual Growth Rate
CEA	Central Electricity Authority
DDUGJY	Deen Dayal Upadhyaya Gram Jyoti Yojana
DER-CAM	Distributed Energy Resources Customer Adoption Model
DISCOMs	Distribution Companies
DSM	Deviation Settlement Mechanisms
EM-PS	Energy Management-Peak Shaving
EMS	Energy Management System
ESOD	Energy Storage Optimization for DISCOMs
FRP	Financial Restructuring Plan
GENCOs	Generation Companies
HT	High Tension
IPDS	Integrated Power Development Scheme
IRR	Internal Rate of Return
LBNL	Lawrence Berkley National Laboratory
LPG	Liquefied Petroleum Gas
LT	Low Tension
MDG	Millennium Development Goals
NPV	Net present Value
NREL	National Renewable Energy Laboratory
NSGM	National Smart Grid Mission
PCM	Production Cost Modelling
PPA	Power Purchase Agreement
PPP	Purchasing Power Parity
PST	Power System Toolbox
QSTS	Quasi-static time series
REMCs	Renewable Energy Management Centres
REopt	Renewable Energy Integration and Optimization
RPOs	Renewable Purchase Obligations

SCED	Security Constrained Economic Dispatch
SDG	Sustainable Development Goals
SECI	Solar Energy Corporation of India
TRANSCOs	Transmission Companies
UGVCL	Uttar Gujarat Vij Company Limited

List of Symbols

₹	Indian rupee

Chapter 1

Introduction

This chapter provides a brief overview of the work. The project objectives are clearly presented followed up by the scope and limitations, providing a clear framework. At the end of the chapter, the methodology is provided along with the work structure.

1.1 Objectives

The work presented in this paper has the objective of developing the 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 be able to use as a resource to size and comprehend the techno-economic advantages of acquiring battery systems for energy storage applications at transformer level.

1.2 Scope and Limitations

The scope of this project is to design a tool that will size BESS for a specific application, being this, reduction of overload in distribution level transformers. The project aims to validate the tool through a case study with an industrial partner, preferably a DISCOM in India interested in this emerging technology. The expected outcome is a set of technical and financial valuable parameters for the user to evaluate the possible investment in BESS and specially, understand the benefits of the implementation of the system through these outputs.

Regarding technical limitations, the tool is developed using Excel software which provides computational limitations. However, the scope of this work is to provide an initial version of the tool, therefore Excel software is an appropriate and optimal program to utilize for such development. There are also key limitations regarding data acquisition due to industrial privacy.

1.3 Methodology

The following project has been developed starting from a wide and deep literature review, analysing the Indian market and background in order to understand the environment and the need for the development of this work. The next steps have been to design the tool and develop it in Excel along with the company Pamoja and the university Instituto Superior Técnico of Lisbon, and most importantly, in partnership with the Indian distribution company UGVCL which has allowed the tool to match the needs of the final user. Finally, a case study has been performed and results have been analysed and presented.

The following report follows the methodology presented and explains each part of the development of this project in detail.

This thesis is composed of 7 chapters.

- Chapter 1 – Introduction

- Chapter 2 – Project background
- Chapter 3 – India and the National grid
- Chapter 4 – Tool development
- Chapter 5 – Case study
- Chapter 6 – Discussion
- Chapter 7 – Conclusion

Chapter 2

Project Background

This chapter provides an overview of the SDGs with special focus on SDG 7 and the importance of electrification.

2.1 Importance of SDG 7 for development

In 2015, the 17 Sustainable Development Goals (SDGs) were adopted by all the Member States of the United Nations [1]. These goals had similar scope than the previous successful agreement, the Millennium Development Goals (MDGs), but including key differences proving the will to promote a sustainable and universal development by focusing on economic growth, social inclusion, and environmental protection for all nations, developed and developing [2].

Nowadays, the SDGs are yearly tracked and have shown a positive influence on development for developing and developed nations, however, there is still much to be done and COVID-19 influence has delayed the achievement of several of the 17 goals [3].

2.1.1 SDG 7. Ensure access to affordable, reliable, sustainable, and modern energy for all.

SDG 7 is directly related to energy. More specifically, the main goal of this SDG is to ensure access to affordable, reliable, sustainable and modern energy for all [4]. This master thesis intends to address this SDG by opening a path for reliable, sustainable, and modern energy to the Indian grid consumers.

It is important to highlight the importance of the main energy goal towards the achievement of the 17 SDGs and therefore, the importance of promoting energy projects aligned with these activities and objectives. Most of the world's current key activities rely on energy, therefore, promoting access to this resource has an influence on the development and quality of many different sectors around the globe such as health, education, transport, industry, overall, activities that provide life quality and growth to society. For this reason, a study was performed by Fuso Nerini in 2020 analysing the relationship between SDG 7 and all the other goals. During the research, 169 sub-tasks were found out of the 17 goals, and it was concluded that 113 tasks were related to energy, this means 65% of the goals to be achieved are somehow related to energy. As an example, hospitals require a reliable and constant supply of energy for their activities. If this is achieved, people have access to a strong health care system with modern equipment, medicine, or reliable storage. This is the effect of not only the direct supply of energy but also from the savings generated by using clean sources that have significantly lower costs than wood, coal, or diesel [5]. By having a healthy society, citizens do not suffer from common bacteria or viruses that have proven cures and can continue with their education, professional and social lives. The same happens with the industry. Having a constant, reliable, and clean supply of energy is a need for operations to work smoothly, this way, losses in production, supply, and essential activities are avoided, costs can be reduced and having clean sources of energy avoids causing health problems to people surrounding these facilities and, of course, reduces the impact on global warming. As shown, the different sectors experience directly the impact of utilizing reliable and sustainable energy, making nations grow in more robust way towards life quality, health, and maturity.

This project aims to work aligned with the SDG 7 sub-goals and that way contribute to a chain of activities that will push development and bring life quality and growth to the communities involved in the process.

2.2 Electrification in developing countries

As mentioned in the previous section, affordable, reliable, sustainable, and modern energy is required and a key piece in the development pathway for developing and developed nations. This includes topics such as electricity, cooking technologies or energy efficiency. Electrification is a key aspect within SDG 7; therefore, this section focuses on the key advantages and potential of electrification for developing countries. By the end of the section, the importance of achieving quality supply of electricity will be presented.

2.2.1 Electrification and local development

Electrification for developing nations comes with a series of advantages, both local and global. This section focuses on the local advantages or directly for the citizens. The Inter-American Development Bank analyses the effect of electrification on development by understanding the effects on development outcomes. Other entities prefer to study this impact by focusing on consumer-surplus methods which describes the willingness of people to invest in lighting services [6]. This section focuses on the first method described.

Some of the overarching positive impacts can be seen through higher incomes, improved health care or better quality and amount of education services available. This outcomes all have a common starting point, the purchase of appliances according to [6]. After purchasing elements including light bulbs, radio, TV, laptop, fans or AC, electric cooking appliances, refrigerators, and tools and machinery, comfort is increased and easy of bringing new activities and interests to the household. For example, by purchasing a radio, TV, or laptop, the access to information is higher which can lead to new interests for the user, knowledge, and opportunities. Moreover, by having more efficient and non-polluting lighting systems, activities can be extended to night hours such as education and business, promoting higher professional opportunities and income growth. In Figure 1 a diagram describing the benefits promoted by each set of appliances is presented.

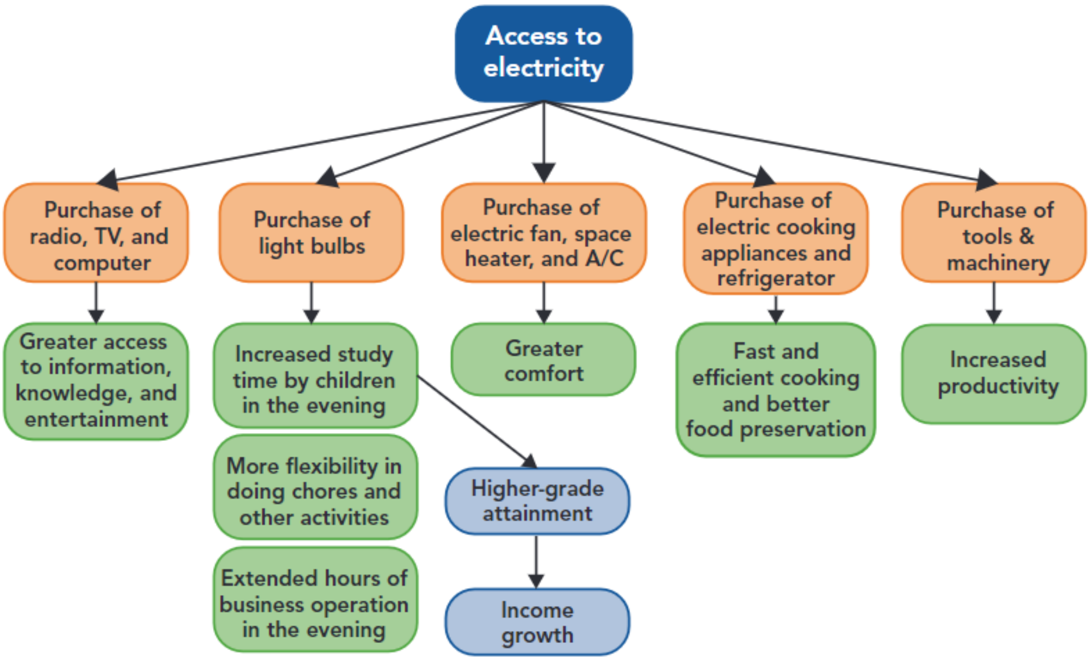

Figure 1. Benefit pathways for household electrification. [6]

2.2.2 Potential, benefits, and impacts

As mentioned in section 2.2.1, there are benefits that mean impacts in the global markets and an opportunity for developing countries to unlock their growth potential in this crucial moment for humanity. The world is implementing projects focused on renewable energy sources at an exponentially growing rate, in 2020 91% of the share of new electricity generating installed capacity was based on solar and wind projects, and 82% of the total installed capacity was renewable, an increase of 80 GW compared to 2019 [7]. This has been due to the positioning of, specially, wind power and solar photovoltaics in the market through competitive costs and high availability [8]. Now it is the moment for developing countries to enter with their power to provide the best locations with the best conditions for these technologies. Sub-Saharan Africa presents a clear advantage for solar photovoltaics with also a high costal potential for wind power [9]. This is a perfect opportunity to increase energy access in this area where electrification levels are below 20% in some of the countries such as Chad or Democratic Republic of Congo [10].

By developing renewable energy projects in these areas, local economy is expected to be benefited by promoting the participation of local teams during the project execution. Local jobs can be created during the implementation, operation, and maintenance phases of the projects. These energy sources imply a low-cost power supply that will directly benefit the local consumers.

Moreover, having renewable generation capacity, means a boost towards global markets. Once these technologies are built at large scale projects, trading with different continents will be a competitive advantage for these regions. There is a potential for activities such as synthetic fuel-based production that could be commercialized for many continents and locally to continue working towards sustainable, affordable, and, reliable energy access [8].

To achieve these key local and global changes through meeting the goal of energy access, there is a need to bring political adaptation. Strategic plans need to be brought to the table through new regulations and incentives that institutions and politics must develop and agree on. In 2019 the global investment in renewable energy capacity reached around $300 billion but only 5per cent was invested in those areas living without energy access. To achieve the 2030 and 2050 targets, tripling the investments on clean energy is needed, this means $5 trillion per year by 2030 [11].

2.2.3 Challenges

After understanding the energy access goal and the importance of electrification, it is crucial to be aware of the challenges that are to come along with this transition. There are many challenges that can be found and must be addressed by the industry along with the electrification process. Three examples are presented: Number of raw materials required and price fluctuation, waste management of renewable energy technologies, and grid stability.

The energy transition will be mineral intensive, therefore there must be an appropriate management of the origin of these resources. This also means that there will be challenges within the costs related to manufacturing, especially in a moment where inflation, price variation and economic instability are the drivers of the industry.

This leads to waste management. The increased number of metals used and the way they are processed brings an important challenge. Solar waste is estimated to produce millions of tons of waste across different nations, for example, it is estimated that the United States will have 10 million tons of solar waste by 2050 and Germany 4,3 million tons. Wind power is known to be the most difficult renewable energy waste to address due to its manufacturing characteristics, however, the market is now bringing recyclable blades to start tackling this issue [12].

Finally, the grid stability. This energy transition means including technologies that differ with the currently used methods of generation that bring along variable generation or unpredictable peaks as some of the main differences. This brings three main challenges to the grid. Frequency and voltage anomalies produced by these generation fluctuations, overload of existing transmission lines that experience difficulties matching the inflow and outflow of power specially during peak hours where the load is higher, and demand and supply mismatch. Solutions are being successfully researched and developed such as use of energy storage solutions to balance the energy flows and smart grid implementation to control and optimize the grid.

This last challenge provides the base for the project development, where grid stability challenges are tackled through the implementation of energy storage solutions.

Chapter 3

India and the National Grid

This chapter provides the status of India's energy mix, and presents the main issue addressed in this project, focusing on the national grid, specially the DISCOMs lack of sustainable business, and effectiveness to address the problem.

3.1 Energy system background

India has made noticeable improvements regarding energy development, energy use has doubled since 2000 [13]. In this chapter, the major improvements withing the energy sector will be exposed as to provide the reader with the Indian energy context and latest developments. The chapters are divided in the main areas addressed by SDG 7.

3.1.1 Access to clean cooking

According to several studies, access to clean cooking has noticeably increased in the past 20 years in India. IEA has reported an increase in access to clean cooking from 22% in 2000 to 65% in 2020 as mentioned in [14], this data based on household demand. Similarly, the World Bank reports 68% of the population in India having access to clean cooking in 2020 [15]. It is important to analyse the difference in growth between different periods. Between the year 2000 and 2005 the growth was of 6% and of 7% between 2005 and 2010. The SDG agreement was stablished in 2015, and from this point until 2020, the increase in access has been of 16% [14].

The government focused on improving access and availability of fuels and technologies such as liquefied petroleum gas (LPG), improved biomass cookstoves, biogas plants, and piped natural gas. Moreover, efforts have been made to create awareness regarding the negative effects of using traditional cookstoves and solid fuels. The main mechanisms have been to subsidise the mentioned technologies to improve their affordability and to invest in research for development to lower market prices. Some of the specific results are the current value of 4.9 million biogas plants across the country, this means an installed capacity of 9.4 MW in 2017 [16]. Currently, there are over 5 million biogas plants meaning a total installed capacity of 10.6 MW for 2021 [17]. Moreover, 85% of Indian households had access to LPG by 2020 [18].

The next step is to focus on rural areas, the main challenge to achieve this goal. In these areas, investment costs for gas or efficient stoves as well as for fuel refilling mean a barrier to achieve the full transition. Not only consumer ability to pay is a bottleneck, but the distribution network must also be improved to reach rural and remote areas and guarantee a stable and quality service. Along with this, the government is unable to track if subsidies reach the customer, this support ensures fuel refill, therefore is an important focus point. Some key challenges are to reach those who do not have access to a bank accounts so cannot even receive the government’s support in first place [19].

3.1.2 Energy intensity

Energy intensity is “measured by the quantity of energy required per unit output or activity, so that using less energy to produce a product reduces the intensity” [20]. To achieve this goal, a reduction in energy use per unit of activity is required. This is measured in MJ per 2017 USD PPP or energy demand over gross domestic product. Energy intensity in India has constantly decreased since 1991 when it reached 7.7 MJ per 2017 USD PPP. In 2003 India achieved to have an energy intensity lower 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 this date, India has always been below the global average and continued decreasing except for a slight increase in 2 points between 2007 and 2009. In 2019 the value reached was 4.3 MJ per 2017 USD PPP compared to a global average of 4.7 MJ per 2017 USD PPP [21].

The Energy Conservation Act 2001 was introduced to reduce the energy intensity in the Indian economy. In order to ensure the implementation of the act, the Bureau of Energy was introduced in 2002. Some of the key aspects and initiatives in this act that are positioning India in a promising path towards achieving the energy intensity 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 [22].

3.1.3 Share of modern renewables

Since 1990, India has increased the share of renewables in final total energy consumption from 10.13% to 15.93% in 2019 [23]. The last 8 years India has seen a constant increase in the share of renewables, the longest growth period since 1990. In 2022 the installed capacity of renewable energy was 152.36 GW, meaning a 38.56% of the overall installed power capacity [24]. The current installed capacity per technology is presented in the table below.

Table 1. Renewable energy installed capacity in India per technology in 2020. [25]

India's Renewable Energy Sources	Installed Capacity (GW)	Estimated Potential Capacity (GW)
Wind	37.5	102
Solar	33.7	750
Biomass	9.9	25
Small hydropower	4.7	20

India has ambitious goals for 2030, planning to achieve over 60% installed renewable capacity from solar power. This seems ambitious but the truth is that investment is also growing in the nation. India ranked 3rd globally in terms of its renewable energy investments and plans in 2020. Along with this, key players in the private energy sector are signing important projects and investment plans since 2021, including Tata power, Reliance Industries, GE Power India or Adani Green Energy. These are examples of energy companies with focus on different technologies such as solar or wind along with other power and industrial activities and with high importance in the Indian industrial sector [24].

Additionally, the government has introduced a set of new organisms and laws to promote the use of renewable energy. These actions include the creation of certain entities like the Solar Energy Corporation of India (SECI) which is responsible for the development of the renewable energy sector entirely. Another example is to subsidise rooftop solar installations especially in rural areas under a Rooftop Solar Programme. These changes also focus on the energy market and the industry, for example, in August 2021, new rules were stablished for the purchase and consumption of green energy. This action aims to encourage the industrial players to use renewable energy for their operations [24].

These are only some examples of what India's ambitious energy transition programme is proposing, and with this, the aim is to generate 49% of the total electricity using renewable energy also by using batteries to ensure a right penetration of these technologies to the grid [24].

There are still key challenges to be tackled 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 [25].

3.1.4 Access to electricity

India presented in 2020 99% share of households using electricity as primary source of lighting. Since the year 2000 there has been an increase in 56%. In this year, the share of households with access to electricity was of 43% [23]. The growth rate has been considerably important between the years 2015 and 2020 where the increase in electricity access was of 20%. The growth between 2000 and 2005, 2005 and 2010, and 2010 and 2015 was of 15%, 10% and 11% respectively.

This relatively fast achievement was promoted by the National Electricity Policy dated 12th February 2005. The policy was part of the Electricity Act 2003. The importance of electrifying the country for socio-economic development is stated as well as the key points to tackle such as generation, transmission, and distribution network increase. Clear objectives were stated, highlighting the willingness to achieve 100% electrification in 5 years. The achievement has arrived almost 20 years later, but the process has been steady. Moreover, the core issues to be addressed were exposed, 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 [26]. By highlighting these points, it is clear that India had a clear goal with a clear and detailed understanding of what it was required to electrify a country.

Currently, the main challenges are seen in rural areas. 99% of households have access to electricity from the grid, but these are the households in urban areas. In rural areas the electrification level is also high, 95%, but there are still key challenges to tackle to achieve the 100% objective established by the National Electricity Policy [27]. This challenge is added to the next priority tasks for India's energy sector, the reliability and affordability of electricity supply. Survey [27], presents Figure 2 in which the hours of electricity per day in every state can be observed. In dark grey, areas with supply under 18 hours per day, and light grey areas with daily supply of 20 to 21 hours. To ensure the achievement of SDG 7, not only 100% electricity access is to be achieved, but also, it must be affordable, and reliable. The study reveals the improvements in reliability since 2015. States such as Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh, and West Bengal have seen improvements in the daily hours of electricity supply. In 2015, daily power supply to rural households was around 12.5 hours, in 2018 it was 15 hours and in 2020 18.5 hours [27]. Satisfaction rates have therefore improved in grid consumers along with the daily supply increase from 23% in 2015 to 73% in 2020.

Another key aspect required to reach the 7th goal involves adding meters to promote energy tracking.

This way, DISCOMs can have access to the real energy consumption of households. Having this data will provide the real revenue to DISCOMs, which means they will be able to provide quality and reliability in their service. The challenges that DISCOMs are facing currently will be discussed in further sections.

Finally, some recommendations that can be concluded to achieve universal, affordable, and reliable electricity for all, are in first place the achievement of 100% electricity access to all households, urban and rural. Moreover, tackle those areas in which connections to the grid are too expensive for people to adopt this service even where the grid is present. Ensure that the poor households have adapted tariffs which ensure electricity use after the connection is achieved and adopt innovative solutions to achieve efficient collection of bill payments through modern metering and purchase technologies [27].

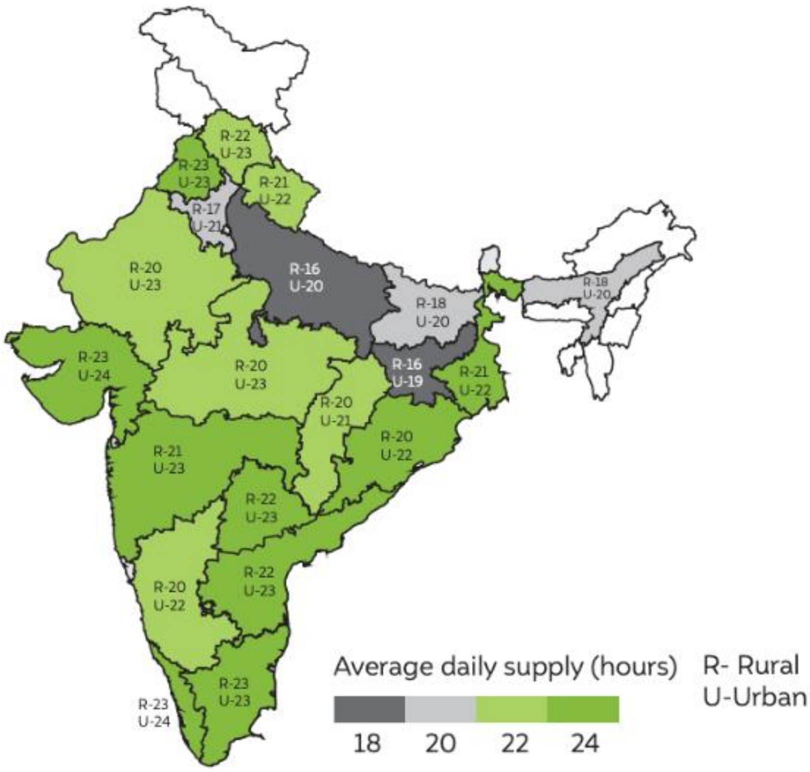

Figure 2. Hours per day received by state separated by rural and urban areas. [27]

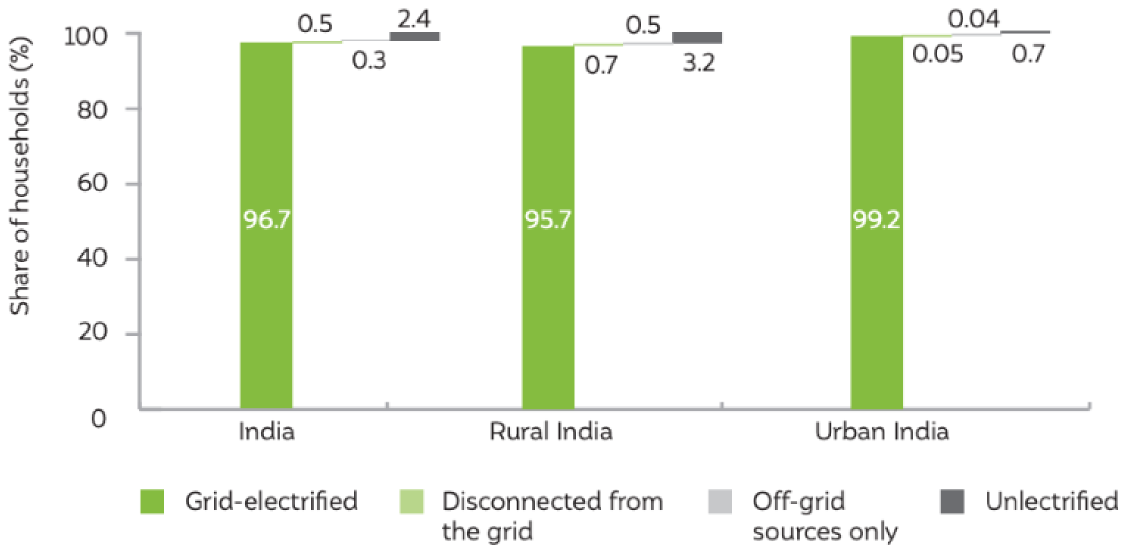

Figure 3. Household electrification level in India. [27]

3.2 National grid

After understanding the growth in India's electricity use, it is the moment to introduce and comprehend the backbone that makes it possible. India's national grid has experienced a fast expansion in the last 20 years that has led to many required adaptations. This section aims to describe the national grids' path and current situation, including the main structure and key challenges to be addressed to ensure a service based on quality and reliability.

3.2.1 Structure

India's National Grid has been one interconnected system since 2013. It is made up of five power grids divided by geographical locations. These are the Northern region, Northeastern region, Western region, Southern region, and Eastern region. The state-owned Power Grid Corporation of India is the owner of the grid, and the also state-owned Power System Operation Corporation oversees the operations. Power Grid Corporation develops key activities that ensure the implementation of innovative changes and improvements to the grid as well as establishing new connections within India and with external countries that increase the robustness and quality in operations of the system [28]. It is one of the largest grids worldwide with 371,054 GW of installed power generation capacity reported in 2020 [29].

Figure 4. India regional power grids. [30]

Important milestones for the development of the Indian National Grid have been, as a first step, 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 [31]. Having one national connected grid aims to promote the optimal flow of power resources to high load regions as well as to establish easy trading in one united electricity market. It is important to note that all regions have enough capacity to meet their demand needs, however, lower demand areas transmit electricity to high demand areas periodically. An example of these power shifts is from the Eastern region to the Western and Southern regions, both having high industrial and agricultural loads that produce peaks that the Eastern region can back up. Figure 5 aims to illustrate the demand variation between regions to understand the need of the regions experiencing daily peaks [30].

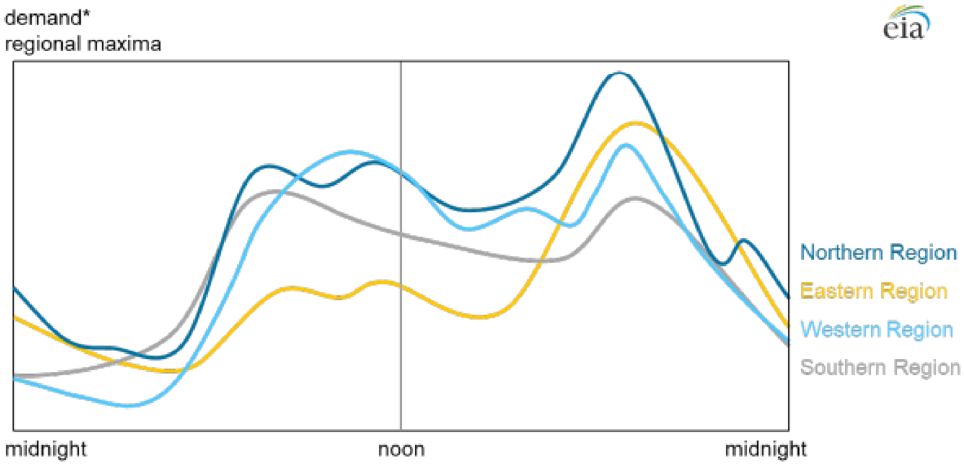

Figure 5. Daily demand shift per region. [30]

Generation capacity in the country, as seen in Table 2, is dominated by the use of coal, followed by water reservoirs for hydropower plants. The major generating capacity is found in the Western Region. Here, 37% of the country's coal-fired generating capacity is found, along with 44% of the natural gas-fired generating capacity. Regarding new renewable technologies, the Southern region has more than 50% of the country's total installed solar capacity [30].

Table 2. India generating capacity by region, 2018 (MW). [30]

Region	Coal	Gas	Diesel	Nuclear	Hydro	Wind	Solar	Other	Total
Northern Region	51,940	5,781	-	1,620	19,808	4,300	5,823	4,508	93,780
Western Region	74,348	10,806	-	1,840	7,448	13,387	6,169	3,566	117,564
Southern Region	46,182	6,473	562	3,320	11,775	17,935	15,491	5,335	107,072
Eastern Region	27,463	-	100	-	4,942	-	660	800	33,965
Northeastern Region	770	1,775	36	-	1,427	-	38	300	4,346
Total	200,703	24,835	698	6,780	45,399	35,622	28,181	14,510	356,727
Percent share	56%	7%	0%	2%	13%	10%	8%	4%	100%

Regarding transmission and distribution of the power, meeting the needs of the consumers remains to be a challenge of high priority to be tackled by the Indian system. There is enough generation capacity in the country to meet the demand, however, not all this energy is able to reach the consumers. In [32] it was reported that "India's T&D losses have been over 20% of generation, which is more than twice the world average. The ideal level of T&D losses ranges between six and eight per cent." The CEA has reported an annual decrease in losses; however, this is not enough and is far from achieving the necessary goal for ensuring customer satisfaction. This authority stated that the "latest report October states that in 2020 the T&D losses had declined to 20.66% in 2018-19, from 21.04% in 2017-18, and 21.42% in 2016-17" [32]. This challenge is indeed the one tackled through this thesis proposal. The effect of this phenomena and the problems observed within the Indian electricity market and its distribution companies will be further explained in section 3.3 Distribution companies.

3.2.2 Transmission

This trading and electricity flow is possible due to the inter-regional transmission capacity. By the end of 2019, 94,850 MW of transmission capacity were reported and this number is estimated to reach 118,050 MW by the end of 2022 [33]. Growth in interregional capacity has increased exponentially, observing a difference of 58.050 MW between 2015 and 2016 and a difference of 102,050 MW between 2019 and 2020. This represented 425,770 ckt. Km in 2020 [34]. The nominal system voltages recorded in the Indian transmission lines are 765, 400, 220, 132 and, 110 kV. India's 2030 renewable energy installed capacity target of 450 GW requires rapid transmission network growth. For this, key actions that are already being taken by the different actors such as utilities, are, the addition of high voltage direct current technologies, flexible AC transmission systems, digital substations, advanced measurement units, and static synchronous compensators [34].

Private sector is gaining strength in ownership of transmission lines segments. 7.5% of the total length is owned by this sector while 54.1% and 38.4% are owned by the state sector and the central sector respectively. Regarding alternating current substations, the total capacity was reported as 947,263 MA and the HVDC substation capacity as 25,500 MW in 2020. From the total AC substation capacity, the private sector owns 3.8% but growing at a fast rate of 38% Compound Annual Growth Rate (CAGR) in the past 7 years. The private sector has secured 35 out of 50 projects awarded in the first half of 2020. The interest in transmission projects from private sector players is attracting state utilities to participate and create favourable regulation for project development. To continue, an important factor that has provided support in avoiding line congestion, has been the increase in interregional transfer capacity which grew from 33,950 MW in 2014 to 102050 MW in 2020 [34].

Important challenges faced by transmission players (TRANSCOS) are mainly due to Covid-19 which forcefully stopped the development of new projects. Nevertheless, the sector is already starting to move forward with the private and state sector mobilising resources. The process is slow but the number of projects already under development account for 86,000 ckt. Km of lines and 314,875 MVA substation capacity [34].

Moreover, the Indian Government has established several plans and strategies to ensure a robust development of the transmission network. Some include international cooperation such as the SAARC Framework Agreement on Energy Cooperation or the Memorandum of Understanding for establishment of the BIMSTEC Grid Interconnection [35]. International cooperation plans aim to provide ease of trading and network expansion amongst the involved nations. For example, the SAARC or South Asian Association for Regional Cooperation promotes support between 8 countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri-Lanka. Two examples of national action plans include the National Electricity Plan II and the Green Energy Corridors. The first one aims to analyse the current situation in the transmission infrastructure and detect future needs [36]. The second one, aims to provide a healthy transmission network growth proportional to the renewable capacity installation. This way, renewable energy addition into the system will be done under a robust transmission infrastructure which provides optimal use of green sources and avoiding damage to the National Grid [37].

3.2.3 Distribution

Distribution lines are those connecting the transmission network with the end customer. There main type of distribution lines are High Tension (HT) and Low Tension (LT) but Middle Tension or voltage can also be found. The first type supplies electricity to industrial customers, and the second, to residential and commercial customers. Since these lines are connected to the transmission lines, the greatest voltage found in the lines is 66 kV. The range of voltage available at this level is broad: 66 kV, 33 kV, 22 kV, 11 kV, 400 V and 230 V. Also Including 6.6 kV, 3.3 kV, and 2.2 kV [38].

The distribution network is the last step to arrive to the customer and where the cash is exchanged. Customers pay bills to the distribution companies, and these will then pay back to the transmission and generation companies. Every piece is key in this process to enable the financial fluidity of the system, but the distribution network has the responsibility of billing the right amount of electricity to its customers to cover the expenses of all the chain.

One of the basic schemes presented to enhance the distribution network development and updating is the Integrated Power Development Scheme (IPDS). Three basic objectives are presented focusing on urban areas. To strengthen the sub-transmission and distribution networks, include metering in distribution transformers, feeders, and consumer levels, and enable IT for the distribution sector while strengthening the network [39]. Moreover, there are plans to focus on the financial side of this segment such as the Guidelines for Financial Restructuring Plan (FRP), the Standard Bidding Document for Distribution Franchisees. The first one, published in 2012, aims to provide an action plan for distribution companies and the government in order to ensure the long-term viability of the DISCOMs [40]. The second one, aims to call the private sector to participate in the management of distribution of electricity. This was implemented in 2012 by the Ministry of Power at the moment, Sushilkumar Shinde after observing the effectiveness in loss reduction for the distribution sector in the states of Maharashtra and Uttar Pradesh, where this business model was implemented [41].

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 dominate the daily activities of the majority of these businesses The Electricity market is aware of this, and as a result, numerous action plans and new tactics have been implemented across the nation to address the most significant barrier to the growth of this sector. This section aims to present the current situation of Indian DISCOMs in detail, clarify the main reasons for the struggle present today, and mention current and future paths proposed to move forward towards a well stablished electricity market.

3.3.1 Status of DISCOMs

There are approximately 60 distribution companies operating in India. As presented in [42], 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.

Privatization has been one of the first steps in order to improve the current situation faced by these players. Starting in 2003, the Electricity Act aimed to give the first step to the free market. This Act gave choice to bulk consumers with consumption over 1 MW to choose their supplier, however, conditions in the Act made the swich unfeasible for many. An extra charge was required to be paid to the DISCOM that was going to be left [43]. Also, it opened delicensing of generation and independent regulators at the state and central level [42]. The latest action plan was announced under the Electricity Amendment Bill in 2021. Now, the customer is not part of a specific sector or has a set power consumption, it is open to all customers of the Indian grid. De-licensing the electricity distribution business and bringing in competition are the key goals to provide the customer the power to choose their supplier [43].

The need for privatization comes from the vast number of losses generated every year by DISCOMs. In 2021, the losses generated by DISCOMs was estimated to be ₹ 90,000 crore (1031,32 €). This amount of debt introduces the sector in a loop of loss. DISCOMs cannot pay generators on time and cannot invest in new infrastructure which enables high quality power supply and the transition to renewable energy [42]. This brings in the next challenge, operations. The average overall Aggregate Technical and Commercial Loss (AT&C) in India is 25,54% in 2021 being the world's average of 6-10%. India has enough generation capacity to fulfil the demand, however, 66% of customers in rural areas and 40% in rural areas still face outages once a day [27]. AT&C losses are keeping this energy from reaching the end customer and causing power outages even when there is enough capacity.

Reliability and affordability. These aspects accurately summarize the situation faced by DISCOMs. As mentioned, the service provided is unreliable for most of the customers. This builds up a barrier to social and economic development, not only making the customers pay for a service that does not cover the basic needs but also forcing the users 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 [13], "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.

In summary, DISCOMs in India are facing lack of financial viability, poor planning, high costs of supply, poor supply and service quality, and non-competitive tariffs. A loop that the government is trying to stop through legal procedures and market changes that will be further presented after defining the source of the problem.

3.3.2 Source of the problem

DISCOMs' inability to repay the total cost or Average Cost of Supply (ACS) through customer payments is the primary mismatch that causes the financial debt loop. How is this even possible?

The government asks DISCOMs to reduce the price for customers to make sure people access electricity. This price reduction is covered by the state through subsidies. Then, more reduction in price is demanded by the state for customers. The proposal aims to get this amount back from the customers on the long term through regulatory assets. Finally, the state asks to provide different tariff prices depending on the type of customer. This way, industrial customers will pay higher rates than residential and commercial. The average price obtained from the different segments will result in a feasible amount of income for the DISCOM. This is called cross subsidy.

The government seems to be implementing strategies which allow citizens access energy and provide flexibility for a range of activities within varied customer segments, however, this would be true if the subsidies, regulatory assets, and cross subsidy worked as planned. Currently this is not the case. The state runs behind on subsidy payments, regulatory assets from customers never arrive and cross subsidy, especially due to covid, has produced critical unbalancing on the expected income. This last method was probably the least probable to fail, but covid-19 brought a demand decrease challenge, making industrial production decrease along with the demand for electricity, meaning drastically lower income for DISCOMs. All this sums up to the current high cash-crunch for distribution companies, covered in debt and hopeless to provide an improved, quality, reliable, and affordable service [44].

3.3.3 Implemented schemes

Promising strategies as the ones presented cannot provide support if all the involved parties do not meet the payment timings and expected demand.

In 2022, the Central State announced a revamped distribution sector scheme. Within five years, the scheme aims to provide assistance for infrastructure creation, including pre-paid smart metering and feeder separation, upgrading of systems and all tied to financial improvements [42].

In 2017, the Saubhagya scheme aimed for network strengthening. It had noticeable success in universal electricity access, especially for off-grid rural users. What is yet to be achieved is the tariff realisation for these new customers. This challenge means an important impact in DISCOM losses since they again do not receive the real cost for the operations back from the users.

The UDAY strategy approved in 2015 was a proposed action plan to support DISCOMs and release them from high debt. The objectives mentioned were financial turnaround, operational improvement, reduction of cost of power generation, development of renewable technology, and energy efficiency and conservation. Targeted activities focused on feeder metering, smart metering, AT&C losses, and elimination of ACS-ARR gap. Average Revenue Realized (ARR) represents the difference between the DISCOM’s costs and the revenue from the customer. Achievements were expected to be met latest by 2019. The process started by buying 75% of debt to the distribution companies, then convert it to bonds and finally sell them. In 2020, objectives were not met since it was observed that the ARR and the ACS gap was even higher than initially reported. Further, AT&C losses remained at 20%, being the objective to achieve 15% by 2019.

Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) scheme, implemented in 2015, targets rural areas. The objectives are to strengthen the sub-transmission and distribution infrastructure, increase feeder separation between rural and agriculture, and increase metering in rural areas.

The Integrated Power Development Scheme (IPDS) has similar goals to the previous scheme and was launched in 2014. It focuses on improvement of the sub-transmission and distribution network, metering of distribution transformers, feeders, and consumers, and IT enablement for all urban regions. These two schemes aim to finance projects to up to 90% of the costs under conditions including timely completion and reduction in AT&C losses [42].

Some bottlenecks which challenge the way forward include the cost of transmission being fixed, long-term PPAs signed with generation companies, and a volatile income revenue model. This has been proven from 2015 to 2020 where the schemes have not been as successful as expected. As previously indicated, a delay in funding from the federal and state governments is a serious obstacle to the improvement of the situation, as the majority of programs rely on government funding. Following is a state-by-state breakdown of the improvement in DISCOMs' profitability after the implementation of the schemes, as shown in [42].

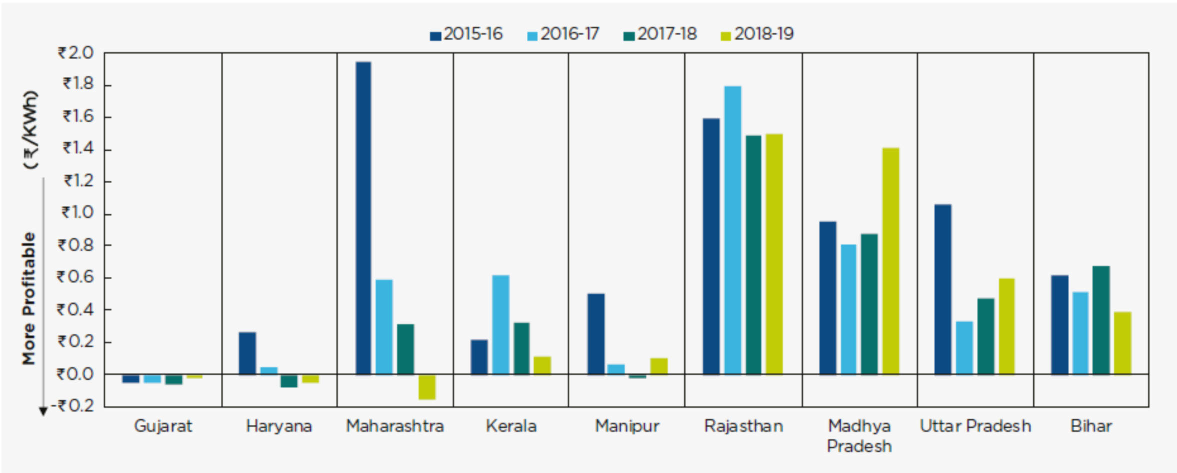

Figure 6. ACS-ARR Gap performance of selected states during UDAY period. [42]

Having an equal scheme for all the country does not represent an equal outcome for all states. Figure 6 shows how Haryana, Maharashtra, and Kerala show the best results after the implementation of the schemes. This is due to different states having their own schemes addressing the same challenges as the state ones but reenforcing the financial support to strengthen the grid connections, feeder separation and other specific capex grants [42]. State focused schemes are a great advantage due to the high geographic and consumer diversity in the country. As mentioned in [42], “a geographically big state such as Rajasthan, with highly rural population, struggles ensuring better performance by DISCOMs”.

Finally, to show how these schemes have affected the state of DISCOMs through the last decades, Figure 7 illustrates the profitability of DISCOMs through the years of implementation of the different plans. The higher the values, the lower the profitability for the DISCOM. The graph shows the variation in the difference between ACS and ARR. Since the start of the IPDS and UDAY schemes India's DISCOMs saw a profit increase since 2015 until 2017, however a rebound has been faced since 2018 proving the lack of success for the sector.

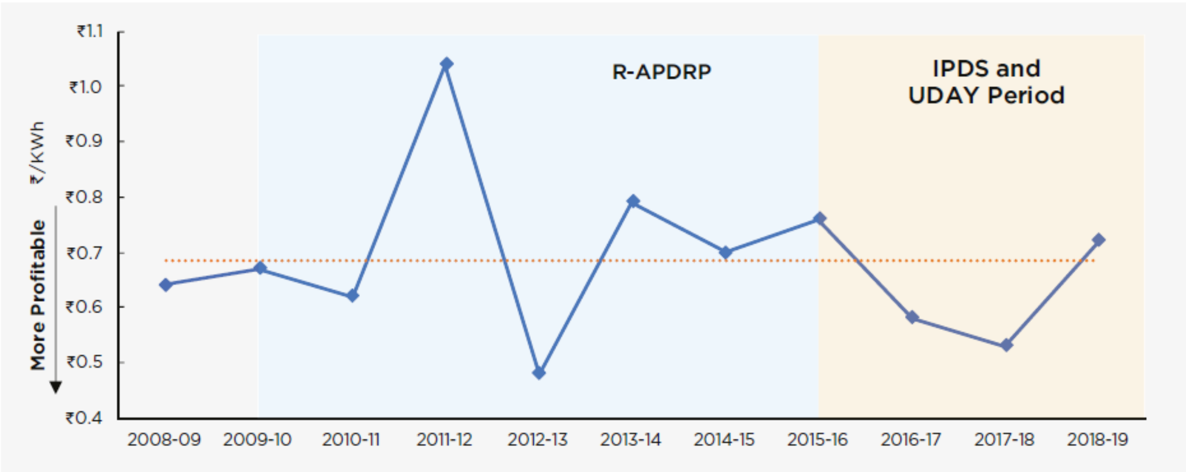

Figure 7. India's ACS-ARR Gap journey. [42]

3.3.4 Pathways for improvement

Several recommendations are presented in [42] obtained from theoretical analysis and practical examples from existing reforms in different states. These recommendations are structured by topic; hence, 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.

3.3.4.1 Structural reforms

Structural reforms are based on ownership models, vertical, and horizontal unbundling.

Three ownership models are present in India: state, licensee, and franchisee model. Shifting ownership models towards private structures will promote competition and free market behaviour in the distribution sector. This aims to provide the customer with decision possibilities regarding their tariffs. A World Bank study has proven that having a restructured governance in state owned DISCOMs, enabled a successful turnaround which improved long-term decision-making, proving that the aim is not to dissolve state ownership but promote a balance that enables private sector participation as well as public [42]. The distribution franchisee model allows private entities to perform specific activities in state-owned DISCOMs without having the ownership. Private entities can be attracted due to the ease of operational and management action leading to fast reduction in technical and commercial losses. On the other side, the licensee model, makes the private entity owner and operator of the DISCOM. This would be more interesting in urban areas with highly populated regions and a variety of customers [42].

Vertical unbundling involves the "functional independence of generation, transmission, and distribution" [41, p 24] entities, whereas horizontal unbundling can happen within each segment of the chain by bringing in entities to propose different offers [45]. Not only customers will be positively affected by this strategy, but the players will have the ability to choose their partners to have the best portfolio. In terms of horizontality, the main attraction is the significant increase in operational and financial efficiencies that DISCOMs are expected to experience "by enabling flexibility in short-term power procurement through power markets" as mentioned in [41, p 24].

3.3.4.2 Regulatory reforms

Regulatory reforms, on the other hand, focuses on the regulation side of the problem.

The CERC and SERCs have been established to introduce a higher governance quality in the power sector. The next step is for these entities to "implement adequate transparency measures or create frameworks for meaningful public input to the regulatory process" points out [42].

In parallel, tariff setting is a priority focus for India's government. Low tariffs do not cover DISCOMs costs. This will be probably one of the most challenging aspects, low-paying customers do not have the ability to increase their spendings by much more than the current rates, however, some states have been successful in setting up tariffs and meeting cost level. Delhi and Gujarat are examples of these. Three basic principles have been implemented by these states: Differentiating fixed and variable tariffs to reflect fixed and variable costs, quarterly tariff adjustments, and simplify the tariff structure through customer category reduction.

DBT or Direct Benefit Transfer is another regulatory reform proposed. The government plans to transfer subsidies provided to DISCOMs to the customers. This way, customers will directly be subsidized and will receive money in their bank accounts to pay for the electricity bills. Subsidising customers has been a successful practice in India for matters such as LPG consumption, therefore, it is a tested model in the country that can bring a change for the distribution company profits. There are associated benefits since the subsidies are better targeted, and losses can be reduced in the process. Moreover, a behavioural change is promoted. The whole system is digitalized, and customers increase their social inclusion by opening bank accounts to receive the money transfer. However, there are risks that cannot be underrated such as over estimation of cash, proper customer identification, and delaying payments [46].

3.3.4.3 Operational reforms

Operational reforms are the next targeted focus area. Technical and policy-based solutions can be found under the operational side of the reform.

Power procurement cost optimisation is the first proposed aspect to change. "80% of the expense of the DISCOMs" [41, p 31] come from this cost due to long-term Power Purchase Agreements (PPAs) that force DISCOMs to pay fixed costs based on incorrect estimates of power demand, leading to the loop mentioned before where high cost of power brings insufficient capital to incest in infrastructure and, in consequence, payment delays to GENCOs. The tendency must shift towards short-term power procurement contracts. An example of this is how the state of Andhra Pradesh saved ₹2,342 crore by introducing this market change [42].

The next targeted area within the operational reforms, is metering and billing. Keeping track of consumption is the backbone of the problem. With data availability both customers and DISCOMs are benefited, losses can be precisely accounted, core week points can be detected, and reforms can be implemented based on this information. India has a billing efficiency of 83%, this can be highly improved in the following years. The National Smart Grid Mission (NSGM), established by the Government of India in 2015 and in operation since 2016 has the goal of accelerating the Smart Grid deployment in the country by bringing awareness to all the parties involved in the grid system, from GENCOs, to customers [47]. A variety of projects have been implemented to prove and provide information in what smart metering can do and what are the benefits. Some of these projects include peak load management, power quality management, and outage management.

To continue, upgrading the distribution infrastructure is the next key challenge and need for the whole system to see the effects of all the different reforms the success of the sector. If the infrastructure is not improved, customers will continue experiencing outages, no matter how optimized the market is or how efficient the billing mechanisms and tariffs are. Some of the most critical points are cables which can be installed underground near to urban areas to avoid theft, high voltage and low-voltage cables can be used to avoid direct hooking. Transformer loads can be analysed to adapt the connected load and avoid overloading and therefore increase the equipment's lifetime and achieve optimal working conditions [42].

3.3.4.4 Renewable energy integration

Due to the current situation DISCOMs are facing, especially regarding long-term PPAs, it is hard for DISCOMs to work with new renewable energy generation plants. This is a challenge, but there are alternative pathways that can be taken to adequately introduce renewable solutions in the equation while DISCOMs achieve the contractual readiness.

Regional interconnection and balancing will provide benefits for the whole nation while reaching the goal of 50% of the power generation capacity being met by renewables. Strategies like the Green Energy Corridor are already strengthening the transmission capacity and system while renewable energy management centres (REMCs) are stablished to provide high quality forecasting of renewables. Coordination between government and companies to make proper use of these new organism and infrastructure can provide technical and managerial improvements for DISCOMs.

Renewable purchase obligations or RPOs are a policy that makes obtaining a share of electricity from renewable sources a requisite for DISCOMs and energy producers. In 2018, this requirement was raised from 17% to 22% [42].

Renewable energy forecasting errors are translated into Deviation Settlement Mechanisms (DSM) for DISCOMs as a penalty. Introducing advanced forecasting into the system will reduce this cost from DISCOMS. Not only this, but the grid reliability and stability will be improved “while allowing for a more cost-optimum economic dispatch of the other generators in the fleet” [41, p. 42].

Finally, decentralized renewable energy is becoming increasingly appealing to governments around the world, giving economic, social, and long-term benefits.

India's installed capacity for rooftop solar electricity is below the desired level. The objective for 2022 was set on 40 GW and only 15% of this has been achieved, however, the legal and financial environment in the country shows a positive pathway for this technology. This technology can mean T&D loss reduction, peak-load management improvement, and power-procurement optimisation for DISCOMs; therefore, they are being encouraged by the government to promote customers to instal solar power on their rooftops.

Minigrids can address several matters currently concerning DISCOMs. India is almost fully electrified, however, the quality of the service provided is poor due to low reliability and consistency. Minigrids are a combination of renewable solutions, for example solar panels and batteries set up near an off-grid area to stablish a grid. The size of the system and closeness to the customer, minimises T&D losses, and means a cost-effective solution for both customer and DISCOMs. The customer can enjoy highly adapted tariffs while the DISCOM avoids high costs from expanding the grid until remote rural areas. Not only economic and environmental aspects are tackled, having high quality and reliable electricity access under adapted tariffs enables village citizens with lower financial means to see a positive impact in their development, promoting business creation, education, health, and safety [42].

Finally, energy storage, as the protagonist of this report, is the next increasingly explored technology to provide support to DISCOMs and the grid in India and worldwide. Energy storage can be found in different forms such as pumped hydro-storage, batteries, flywheels, supercapacitors, and green hydrogen. The three last technologies are not so currently implemented and in early stage, so the focus relies on the two first mentioned solutions. Pumped hydro-storage, as mentioned by the U.S. department of energy in [48],

> “Is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine. The system also requires power as it pumps water back into the upper reservoir (recharge). PSH acts similarly to a giant battery because it can store power and then release it when needed.”

This service is efficient and can provide services such as frequency and voltage regulation, and black start facility [42].

Batteries are an exponentially growing market able to be used to support many activities. For the grid, batteries can change the game and provide a key service becoming one of the main grid assets. Batteries can be made from different materials and can be presented in different settings, individually, in packs or in modules. Applications where batteries can take part are peak shifting, cost-optimization for the power market, voltage regulation, frequency regulation, and transformer overload management amongst others. Batteries can provide multiple services during their lifetime becoming more cost-effective. During a same day, while the main service is not being provided, a secondary action can be taken in order to optimise the use of the system [42]. This technology has awakened interest in this transition moment for the electricity market. Renewable energy integration is not an easy task for the current grid setting present in the world. Batteries may address several gaps, including reducing energy loss by transferring energy produced by solar panels during peak hours to night and high demand hours, resulting in increased market flexibility and cost savings. The technology arrives in the perfect moment for the Indian national grid. DISCOMs are facing decline while the government is pushing an exponential renewable energy integration plan in a very short time range. The country needs to strengthen the grid as soon as possible and with high quality results to provide citizens the services required and support the development of the nation.

3.3.4.5 Managerial reforms

Managerial reforms come last at this recommendation set. These are seen as the head and complementary reform to the previously proposed solution pathways. As stated in [42],

> "Effective reforms are typically a result of stable leadership and vision sustained over time. Good leadership endures shifts in political leanings, navigates technological hype cycles, and holds the line over time to deliver its vision through persistence and dedication to transformation. […] Transformation is enabled by innovation, and decision-makers across the ecosystem must be open to new ideas and processes, and ways of doing business."

Managerial quality also needs close customer contact to take decisions based on the final client satisfaction. As a result, some jurisdictions have already established call centres to facilitate close connection and support. In the same way, employees that are aligned with the corporations vision, mission and feel motivated and engaged by it will provide improved DISCOMs performance by enhancing active mindsets aiming for the company's improvement [42].

3.4 Benefits of Energy Storage Systems in Distribution Networks

Multiple solutions have been proposed in the previous section. The focus of this section is to provide a deeper look at the benefits of one of these proposals, energy storage systems. The chosen technology, battery systems, offers a variety of applications with substantial utility-scale benefits. By presenting these applications, benefits, and even challenges for energy storage systems, the need for this report and the reasons for developing tools like the one presented in this work are highlighted.

3.4.1 System definition

Battery energy storage can be defined from the point of view of the grid operators as a technology that allows system operators and utilities to store energy for later use. This stored energy comes from the grid or power plants and will be discharged during another moment depending on the application [49]. Lithium-ion battery systems are the most frequently used for grid-scale applications. This technology has evolved exponentially going through technical innovation, improved manufacturing capacity, and therefore, experienced steep price decline. From 2010 to 2016 a reduction of 70% in price was reported [49]. Projections show and studied in [50] that by 2025 capital costs for the technology will decline by 14 to 38%. Figure 8 presented by [49] presents the different types of chemistries and the installed capacity evolution from 2008 to 2017 clearly highlighting the major presence of lithium-ion batteries in the market.

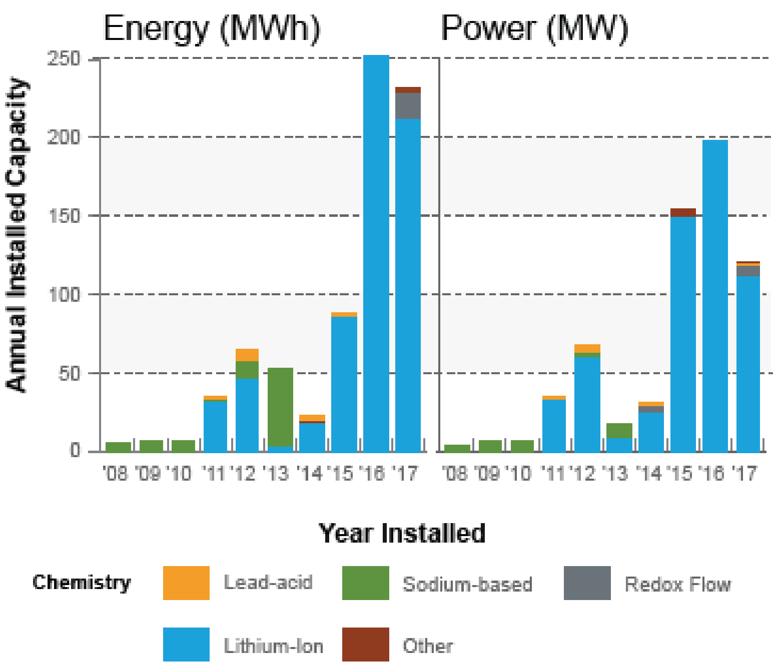

Figure 8. U.S. utility-scale battery storage capacity by chemistry (2008-2017). [49].

Battery energy storage systems (BESS) are gaining importance in the power system. There is a need for system flexibility and reliability coming from the increasing presence of renewables in the grids worldwide. Combining this with the rapid cost decline shows the need for this technology to be implemented even at faster rates. Policymakers, regulators, and utilities have seen the opportunity that BESS will provide. Therefore, policies and roadmaps are being developed to “jump-start BESS deployment” [49].

The grid, as mentioned in the previous section, is experiencing challenges due to the rapid energy transition. The power system must constantly evolve to meet the expectations regarding reliable electricity supply [51]. Lack of adaptation and innovation is the motor that brings in challenges within demand-side management, maintenance of power quality standards, renewable energy deployment, and meeting reliability requirements [52].

3.4.2 Applications and benefits

BESS arrive in the best possible moment. Research has found several applications that BESS can take part in that can 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 [52], [53], [54]. Renewable energy compensation and uncertainty reduction is also a key use found in research. It has been proven that the reliability of renewable energies can increase since the energy produced during generation peak hours can be stored and utilized during peak demand hours, which, at the end of the day, is translated to reduction of the system's losses [51], [52], [53]. Moreover, BESS provide voltage and frequency control support and indirect control of line congestion, meaning that major network upgrades can be postponed, delaying capital cost investments on transmission lines upgrading and other electrical equipment [52], [53], [54], [55]. Regarding operation, batteries can behave as a management system by scheduling optimal power generation dispatch which again, allows operational flexibility for renewable technologies, increasing its reliability and finally delivering power quality [52], [54], [56]. Figure 9 summarizes the different sets of applications in sub sections depending on the scope and objective of the final use.

To continue, transmission and distribution congestion relief, as one of the mentioned applications, 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 [51]. This is exactly the situation currently experienced by many Indian households. Other ways of tackling this challenge are to combine the following: add capacitor banks to compensate reactive power, use higher harmonic filters, replace power transformers, and increase the cross-sections of power lines used [51]. The attractiveness of BESS comes in due to the high cost of other equipment mentioned and lack of space near urban areas to increase infrastructure such as distribution transformers. India, as a fast-developing country with high populated regions, faces this challenge closely. 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 [13]. In this case, depending on the demand to be covered, and therefore the size of the BESS, it could provide a solution, or another alternative should be found.

Overall, BESS can be seen as an energy management peak shaving (EM-PS) system providing the above applications and mitigating high electricity prices during peak loading hours [54]. One of the major discoveries shows how a battery used for more than one application simultaneously, results in a more attractive financial feasibility [50]. This way, when the battery is not performing one of the activities, it can perform a second one. Using batteries in such way improves the IRR of the project analysed [57].

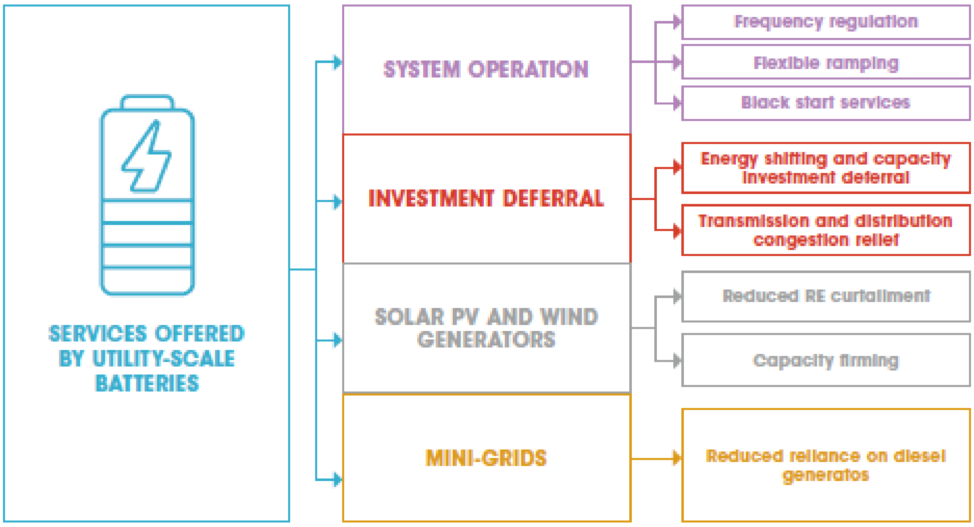

Figure 9. Services offered by utility-scale battery storage systems. [54]

3.5 Increasing interest on BESS in India

India has the potential to become an important reference in the battery sector due to the gap for improvement available 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 [13].

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). This report had the objective of

> "analyze the impact that EVs could have on its service territory and to understand the benefits that could be had from installing battery energy storage systems (BESS)" since "one of the most essential institutions in India's power sector are the distribution utilities […] managing the electric grid, and their ability to evolve with the changing needs of their customers is important to catalyze modernization."

As mentioned in [58]. The report also mentioned the four topics to be researched: 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 [58]. To obtain the cost-benefit analyses focused on the application of load-levelling on transformers, BRPL installed BESS at distribution transformers. Algorithms for battery sizing are based on avoiding transformer overload, therefore, the load over 70% of the rated capacity in overloaded transformers is to be absorbed by the battery. The study concluded that BESS can be beneficial for the studied applications and are a better option than equipment upgrading for overloading reduction. The document had a major accomplishment which was to develop a bottom-up cost model for BESS applicable for India [58].

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 [59], 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" [59].

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.

Chapter 4

Tool development

This section presents the tool Energy Storage Optimization for DISCOMS (ESOD). The layout, presentation, and calculation processes are explained in detail.

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.

This software can be divided in two main categories, software tools in power systems and energy storage valuation and design tools. The first group is mainly intended “to value energy storage’s technical contributions to the grid” [60]. The second group focuses on “techno-economic analyses of ESSs” divided in two topics, ESS valuation and system design [60]. Examples of well-known tools found in the first group are Power System Toolbox (PST) which is MATLAB-based, PowerWorld, CYME, OpenDSS, Quasi-static time series (QSTS), Production Cost Modeling (PCM), Security Constrained Economic Dispatch (SCED), PLEXOS by Energy Exemplar, PROMOD by Hitachi ABB, amongst others. For the second group, valuation tools are QuESt, StorageVET, energytoobase, BatSIMM. Within the design tools, MASCORE, MDTm DER-CAM REopt, or Homer can be found [60].

The main difference that can be observed between all the software in the market is the main objective. Some of these tools will have high capability for system design and present technical aspects and barriers, however, leaving out key financial parameters. The opposite characteristics will be found in the rest of the tools. For example, Renewable Energy Integration and Optimization (REopt), developed by NREL, will “optimize the integration and operation of energy system for buildings, campuses, communities, and microgrids” [60]. Whereas Distributed Energy Resources Customer Adoption Model (DER-CAM), developed by Lawrence Berkley National Laboratory (LBNL), aims “to find the optimal investments on new DERs for buildings or microgrids” [60]. A clear example of the different technical and financial point of view as well as the final BESS application.

Overall, as mentioned in [60], “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 tool 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 a technical output 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.

4.3 Tool structure

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. All the sections will be further explained in the following sections.

Different type of cells and buttons can be found along the tool. Table A 2 explains the colour and style code for the main ones.

4.3.1 Cover and Instructions

The cover is styled image to set the design of the tool and introduce the user to the system.

Next, the “Instructions” page can be found. Here, the user will find a brief introduction to the type of data that the tool works with as well as how this data should be used, modified, and manipulated. In this page, there is a side menu introduced to simulate a software interface, offering a familiar visual structure to the tool, and providing easy shift between tabs. The set of instructions can be observed in Figure 11 as the user will visualize them.

Figure 10. ESOD cover page

Welcome to ESOD, the Tool that will provide your company with the battery storage capacity that fits your needs.

This tool is based on three types of data: Inputs, process, and output data.

1. The user will have to provide the required input data in the specified format: load parameters, financial parameters. The different sections provide a specific set of instructions.

2. The tool will use this data along with the processing data to show a set of outputs. These outputs include: Battery capacity (kWh), loss reduction, savings, NPV, IRR, funding required...

You can also provide your specific processing data if you want to perform a more detailed and customized analysis by accessing the "Process Data" section and modifying the data with your available information. For example: battery specifications.

Figure 11. ESOD instructions provided to user

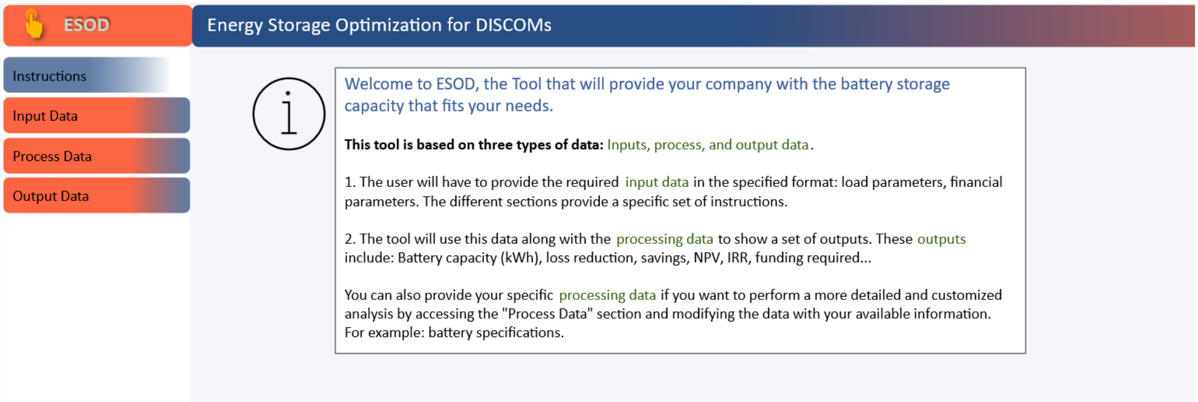

Figure 12. ESOD instructions page

4.3.2 Load inputs and process data

To perform the techno-economic analysis, transformer data is to be introduced in the tool by the user. The Input Data page shows the parameters that the tool requires to process the data. An instructions box is provided to guide the user through the input process.

The required inputs are shown in yellow and are time, total active power, active energy delivered into the load, the power factor, and the rating capacity of the transformer. Units must also be introduced to quantify the data appropriately. Moreover, the timesteps are to be decided by the user, the tool will adapt to the data provided. In this page, there are two calculations taking place that the user will be able to observe, the overload count and the actual energy delivered into the load, these are shown with white titles. The overload count will be explained further in the section Demand analysis. The energy delivered into the load is calculated using equation (1). This equation includes a condition to exclude data errors that produce big jumps in the energy delivery.

$$Energy\ Delivered\ into\ Load = Active\ Energy\ Delivered\ into\ Load_{t+1} - Active\ Energy\ Delivered\ into\ Load_{t} \quad (1)$$

Where t is the active energy in a specific time frame.

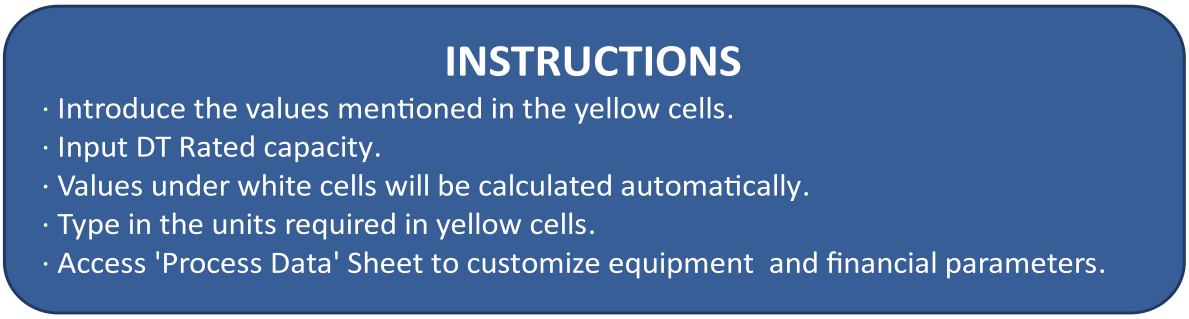

Figure 13. ESOD instructions in input data page

Energy Storage Optimization for DISCOMs

Instructions

Input Data

Process Data

Output Data

INSTRUCTIONS

- Introduce the values mentioned in the yellow cells.
- Input DT Rated capacity.
- Values under white cells will be calculated automatically.
- Type in the units required in yellow cells.
- Access 'Process Data' Sheet to customize equipment and financial parameters.

Load

DT Rated Capacity [KVA]	100	
Time step	5	sec

Time	Total Active Power (kW)	Active Energy Delivered into Load (kWh)	Power Factor [-]	Energy Delivered into Load	Overload count
0:00	116,22	124200,12	0,98	10,13	1
0:05	118,25	124210,25	0,98	10,39	1
0:10	117,55	124220,64	0,98	8,95	1
0:15	113,63	124229,59	0,98	10	1
0:20	116,91	124239,59	0,98	9,35	1
0:25	107,39	124248,94	0,98	9,73	1
0:30	113,79	124258,67	0,98	9,01	1
0:35	113,56	124267,68	0,98	9,96	1
0:40	115,18	124277,64	0,98	10,22	1
0:45	109,81	124287,86	0,98	10,05	1
0:50	109,81	124297,91	0,98	9,05	1
0:55	114,12	124306,96	0,98	9,94	1
1:00	118,46	124316,9	0,98	10,73	1
1:05	112,86	124327,63	0,98	21,58	1
1:20	110,77	124349,21	0,98	9,61	1
1:25	108,34	124358,82	0,98	8,4	1
1:30	105,94	124367,22	0,98	9,46	1
1:35	105,3	124376,68	0,98	9,01	1
1:40	102,74	124385,69	0,98	8,7	1
1:45	93,92	124394,39	0,98	9,18	1
1:50	110,42	124403,57	0,98	8	1
1:55	102.39	124411.57	0.98	9.03	1

Figure 14. ESOD input data page

The next sheet is Process Data, here, some key parameters are provided, both financial and technical. These based on research to provide the user ease of quick calculation; however, these may be modified. In this case, the white cells are the ones that can be modified, leaving the grey one's constant. The parameters provided are shown in the figures below.

INSTRUCTIONS

- Only white and yellow cells may be modified.
- Select options from yellow cells.
- If "Value custom" is selected, insert data in white cells under title "Value custom".

Figure 15. ESOD instructions in process data page

Parameter	Custom	Predef	Value predefine	Units
Battery cost		137	137	₹/kWh
Disposal cost		2	2	₹/x
O&M cost		2	2	₹/x
Battery lifetime		2	2	Years

Figure 16. ESOD process data parameters

Grid parameters

Parameter	Value	Units
Peak carbon intensity	0,95	$kgCO_2e/kWh$
Off-peak carbon intensity	0,24	$kgCO_2e/kWh$

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_2

Transformer

Parameter	Value	Units
Overload limit	0,8	%
Replacement cost	₹90.000,00	

Figure 17. ESOD process data parameters

Battery specifications

Parameter	Value custom	Value predefined	Value predefined	Units
Nominal AC voltage		2	2	V
Nominal capacity	250	400	400	kWh
Nominal capacity	90	200	200	Ah
Roundtrip eficiency	0,85	0,9	0,9	%
Storage time	4	0	0	hr
Maximum charge rate	2	0	0	A/Ah
Maximum charge current	2	0	0	A
Maximum discharge current	2	0	0	A
Operating temperature	2	0	0	°C
Depth of discharge	0,7	0,9	0,9	%
Number of cycles	5000	0	0	
Dimensions of battery pack				
Lenght	2	0	0	m
Width	2	0	0	m
Height	0	0	0	m
Weight	0	0	0	kg
Dimensions of inverter				
Length	0	0	0	m
Width	0	0	0	m
Height	0	0	0	m
Weight	2	0	0	kg

Figure 18. ESOD process data parameters

As shown in Figure 18, 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”. The tool will operate the calculations based on the text in the yellow cell. In this page an instructions box is also provided to guide the user.

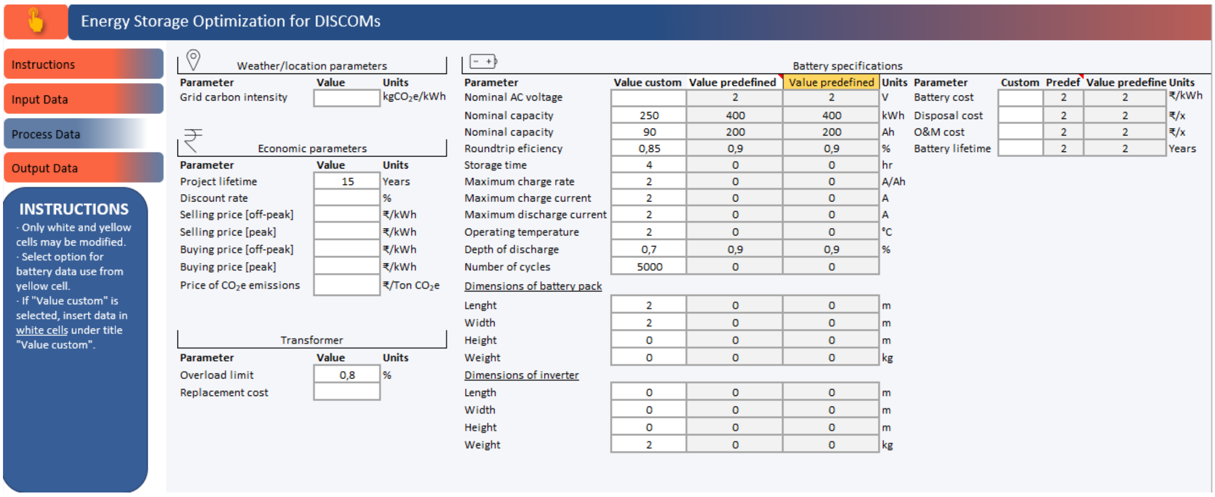

Figure 19. ESOD process data page

4.3.3 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.

The process starts by calculating the power limit for the transformer, so from which point it is considered that the transformer is suffering overload. In Figure 17, in the Process data sheet, the overload limit in percentage is provided and the user can modify it for their case. Therefore, with this parameter and the rating capacity of the transformer from the Input data sheet, the limit can be calculated.

$$Overload\ limit\ [kVA] = Rated\ capacity\ [kVA] * Overload\ limit[\%] \qquad (2)$$

The limit is obtained in kVA and the amount of overload experienced by the transformer must be calculated in kW. For this, the average power factor is calculated based on the power factor data provided in the Input data sheet. If the average power factor is above 0.93 it is assumed that the apparent power in kVA is equal to the active power in kW, therefore the overload limit in kVA will be equal to the overload limit in kW. 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 one placed in the column “Overload limit” mentioned in section 4.3.2.

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. Figure 20 represents this information with a set of example data.

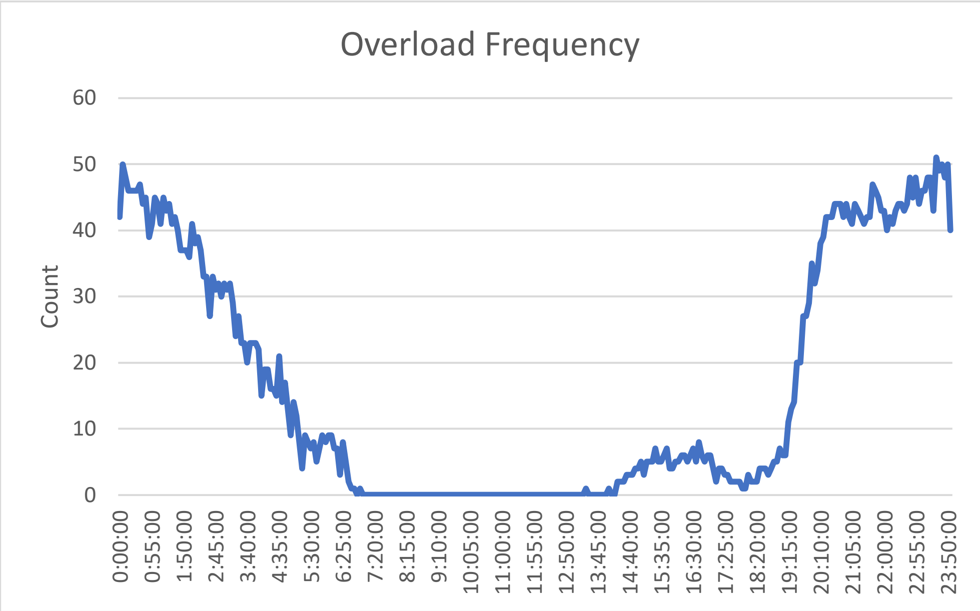

Figure 20. Overload frequency. Overload count experienced per period annually

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. The available hours for selection are 2, 4, 6, 8, and maximum overload coverage. This way, the tool provides 10 possibilities to the user to select from. The selection lists are available in the Output page. In the Demand analysis page, all these 10 configurations are calculated. Specifically, the parameter that is calculated for all scenarios is the gross energy storage required to size the system. All the configurations follow the same calculation process that is explained below. The two differences are, the number of hours considered to obtain the final energy amount, and the base load being, or the maximum recorded in period or the average, both parameters defined by the user. This provides the user the option of visualizing the different sizing possibilities with the different financial results, being able to take the most suitable decision for the project.

The power and energy pattern analysis will be performed through dynamic tables which processes the data automatically, however, this is the step that requires the tool developer or expert to perform the final manual steps to allow the system to calculate the final gross power and energy. The step to be performed is simply to find the highest overload occurrence and add the highest energy segments for each configuration.

The dynamic 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. Usually, the highest peaks will match the highest overload periods, therefore both the frequency and intensity of overload experienced by the transformer can be reduced. Once the power curve is analysed, the developer can detect the energy peaks matching the power overload periods. For this, the energy limit must be set.

$$Energy\ limit\ [kWh] = Power\ limit[kW] * \frac{Time\ steps\ [minutes]}{60\ [\frac{minutes}{hour}]} \tag{3}$$

The energy above the limit for the selected number of hours will be calculated by the tool using (4). After this, the total amount of energy to be covered by the system is calculated using (5).

$$\begin{gathered} Energy\ for\ storage\ sizing_t[kWh] = \\ Maximum\ energy\ over\ Energy\ limit_t\ [kWh] - Energy\ limit\ [kWh] \end{gathered} \tag{4}$$

$$\begin{gathered} Total\ gross\ energy\ for\ storage\ sizing[kWh] = \\ \Sigma Energy\ for\ storage\ sizing_t\ [\text{kWh}] \end{gathered} \tag{5}$$

The process will be presented with examples and graphic support in section 5.

The page includes a final calculation conducted after the system has been sized. This is the comparison of overload frequency before and after the system is in place along with a power curve comparison. This provides added value to the user by showing how much overload is avoided and how much power the transformer avoids processing. These results are displayed in the Output page.

As shown in Figure 21, the developer section is visualized in a traditional Excel view. The demand analysis page is divided in outputs, process data and simple calculations in the left, overload frequency comparison, the calculation section, and the dynamic tables to the right of the page along with graphs to guide the developer.

Total capacity to be covered by storage		
ENERGY OUTPUT:		
145,59	kWh	
PEAK POWER:		
72,41	kW	
Energy output options		
Energy peaks		
2hr	145,59	kWh
4hr	255,31	kWh
6hr	358,53	kWh
8hr	430,54	kWh
Max coverage	475,96	kWh
Average energy load		
2hr	45,34	kWh
4hr	78,53	kWh
6hr	90,65	kWh
8hr	96,03	kWh
Max coverage	107,51	kWh

Initial data	
Rating capacity	
100	kVA
Overload	
0,8	
Overload limit	
80	kVA
	kW
7	kWh
Average PF	
0,944	

	Before BESS		After BESS
Time from data	**Loading over limit capacity**	**New Max Power**	**New overload count**
		128,11	
	Total power cov	95	kW
0:00	1	21,22	0
0:05	1	23,25	0
0:10	1	22,55	0
0:15	1	18,63	0
0:20	1	21,91	0
0:25	1	12,39	0
0:30	1	18,79	0
0:35	1	18,56	0
0:40	1	20,18	0
0:45	1	14,81	0
0:50	1	14,81	0
0:55	1	19,12	0
1:00	1	118,46	1
1:05	1	112,86	1
1:20	1	110,77	1
1:25	1	108,34	1
1:30	1	105,94	1
1:35	1	105,3	1

Calculation process for capacity stablishing							
	#	kWh	kWh	kWh	kWh	kWh	kWh
Time	**Overload count**	**Máx. de Energy Delivered into Load**	**Energy when overload**	**Energy peaks - 4 hr**	**Promedio de Energy Delivered into Load**	**Energy when overload**	**Average energy load - 4 hr**
		2407,67	475,96	255,31	1597,19	107,51	78,53
0:00:00	42	10,13	3,46	3,46	8,64	1,97	1,97
0:05:00	50	11,37	4,70	4,70	8,72	2,06	2,06
0:10:00	48	11,42	4,75	4,75	8,09	1,43	1,43
0:15:00	46	10,7	4,03	4,03	8,01	1,35	1,35
0:20:00	46	10,6	3,93	3,93	8,42	1,75	1,75
0:25:00	46	11,95	5,28	5,28	8,44	1,77	1,77
0:30:00	46	11,36	4,69	4,69	8,22	1,55	1,55
0:35:00	47	10,32	3,65	3,65	7,95	1,28	1,28
0:40:00	44	14,21	7,54	7,54	8,30	1,64	1,64
0:45:00	45	10,68	4,01	4,01	8,29	1,62	1,62
0:50:00	39	10,56	3,89	3,89	7,99	1,32	1,32
0:55:00	41	17,34	10,67	10,67	8,02	1,35	1,35
1:00:00	45	10,73	4,06		7,92	1,26	
1:05:00	44	21,58	14,91		8,19	1,52	
1:10:00	41	9,8	3,13		7,71	1,05	
1:15:00	45	9,97	3,30		7,71	1,04	
1:20:00	43	9,75	3,08		7,62	0,95	
1:25:00	44	10,19	3,52		7,69	1,02	

Figure 21. ESOD demand analysis page, section 1: Outputs, simple calculation, overload frequency comparison, calculation table

Total capacity to be covered by storage		
ENERGY OUTPUT:		
255,31	kWh	
PEAK POWER:		
72,41	kW	
Total power covered		
95	kW	
Energy output options		
Energy peaks		
2hr	145,59	kWh
4hr	255,31	kWh
6hr	358,53	kWh
8hr	430,54	kWh
Max coverage	475,96	kWh
Average energy load		
2hr	45,34	kWh
4hr	78,53	kWh
6hr	90,65	kWh
8hr	96,03	kWh
Max coverage	107,51	kWh

Initial data	
Rating capacity	
100	kVA
Overload	
0,8	
Overload limit	
80	kVA
	kW
7	kWh
Average PF	
0,944	

Figure 22. ESOD demand analysis page, section 1: Power and energy gross outputs for selected configuration, energy gross output for all system configurations, overload limit calculation, power factor average calculation,

	Before BESS		After BESS
Time from data	**Loading over limit capacity**	**New Max Power**	**New overload count**
0:00	1	116,22	1

Figure 23. ESOD demand analysis page, section 1: Overload frequency comparison

Calculation process for capacity stablishing							
	#	kWh	kWh	kWh	kWh	kWh	kWh
Time	**Overload count**	**Máx. de Energy Delivered into Load**	**Energy when overload**	**Energy peaks - 4 hr**	**Promedio de Energy Delivered into Load**	**Energy when overload**	**Average energy load - 4 hr**
		2407,67	475,96	255,31	1597,19	107,51	78,53
0:00:00	42	10,13	3,46	3,46	8,64	1,97	1,97
0:05:00	50	11,37	4,70	4,70	8,72	2,06	2,06

Figure 24. ESOD demand analysis page, section 1: Calculation table

Energy dynamic table data source			Reduction percentage	46%	2496	4642
	Promedio de Energy Delivered into Load2	Máx. de Energy Delivered into Load	Etiquetas de fila	Máx. de New Max Power	Suma de New overload count	Suma de Loading over limit capacity
0:00:00	8,64	10,13	0:00:00	49,31	0	42
0:05:00	8,72	11,37	0:05:00	33,75	0	50

Figure 25. ESOD demand analysis page, section 2: dynamic tables I

Graph combine				
Etiquetas de fila	No BESS [kW]	No BESS overload count	BESS [kW]	BESS overload count
0:00:00	116,22	42	49,31	0
0:05:00	128,75	50	33,75	0

Figure 26. ESOD demand analysis page, section 2: dynamic tables II

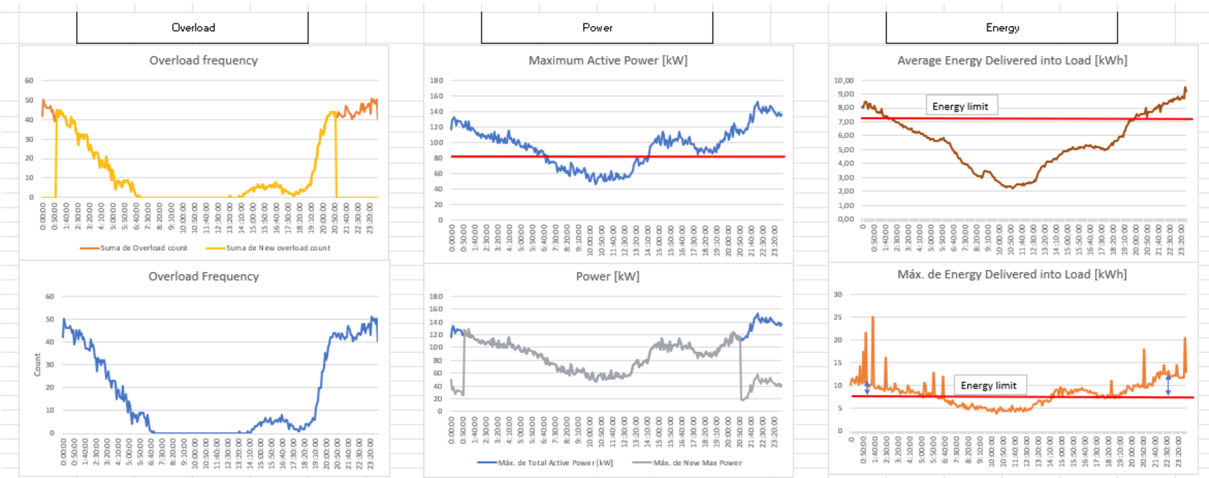

Figure 27. ESOD demand analysis page, section 3: graphs

4.3.4 Battery sizing

The Battery sizing page obtains the net power and energy to be covered by the system from the Demand analysis page. From the Process data page, information on the battery and inverter packs is collected, the user would have defined if the system should use the predefined system or the one introduced. After this, the battery and inverter sizing process take place.

The battery sizing considers two key factors, depth of discharge and roundtrip efficiency of the provided system. By adding these parameters to the gross energy, the actual storage capacity required by the system is calculated.

$$Actual\ storage\ capacity\ [kWh] = \frac{Total\ gross\ energy\ for\ storage\ sizing}{Roundtrip\ efficiency\ [\%] * Depth\ of\ Discharge\ [\%]} \quad (6)$$

The inverter size sets the maximum power that the battery will deliver. The maximum power recorded in the demand analysis minus the overload limit is used to determine the size since by covering this peak, the overload is reduced. Using this value plus a correction factor to count inverter efficiency losses, the inverter size is obtained. It is recommended to use an inverter with 25% bigger capacity than the maximum capacity aimed for the system, therefore for this case a correction factor of 1,3 is used [61].

$$Inverter\ capacity\ [kW] = Gross\ power[kW] * 1{,}3 \quad (7)$$

Finally, the number of packs is calculated. For this the ampere hour capacity to be covered is calculated and compared with the system capacity to propose the total number of packs required to cover the energy range. Therefore, the energy to be covered will be compared to the voltage and depth of discharge of the proposed battery pack.

$$Ampere\ hour\ requirement\ [Ah] = \frac{Actual\ storage\ capacity\ [kWh]}{Nominal\ AC\ voltage\ of\ battery\ pack\ [Volts] *\ Depth\ of\ discharge\ [\%]} \quad (8)$$

The total ampere hour requirement can be then compared with the nominal capacity of the battery to know the number of packs that will achieve this capacity.

$$Number\ of\ packs\ required\ in\ parallel\ connection\ [Units] = \frac{Ampere\ hour\ requirement\ [Ah]}{Nominal\ capacity\ battery\ pack\ [Ah]} \quad (9)$$

Area can be a bottleneck for the installation of a battery system in a substation, therefore the area required by this system is also provided. The DISCOM can be able to estimate if this area is available in their substation or can analyse how much this land acquisition can cost.

$$Area\ required\ [m^2] = Width\ of\ battery\ pack\ [m] * Length\ of\ battery\ pack[m] * battery\ pack\ units +\ Inverter\ length\ [m]\ *\ Inverter\ width\ [m] \quad (10)$$

Battery system sizing		
Parameter	**Value**	**Units**
Storage capacity required gross (without efficiency)	145,59	kWh
Storage capacity required net (with DOD)	181,99	kWh
Storage capacity required with battery efficiency	202	kWh
[illegible]	[illegible]	
Inverter capacity required	95	kW
Ah required	126,38	Ah
Number of packs required in parallel connection	1	Units
Area required	2	m_2

Battery specifications					
Parameter	**Value Calculation**	**Units**	**Parameter**	**Value for calculation**	**Units**
Nominal AC voltage	2	V	Battery cost	27819	$/kWh
Nominal capacity	400	kWh	Replacement cost	0	$/x
Nominal capacity	200	Ah	Operation & maintenance cost	695,47	$/x
Roundtrip eficiency	0,9	%	Battery lifetime	15	Years
Depth of discharge	0,8	%			
Storage time	2	hr			
Dimensions of battery pack					
Lenght	0,730	m	**Size battery for energy peaks or for average energy load?**		
Width	0,468	m	Energy peaks		
Height	0,212	m			
Weight	101	kg			
Dimensions of inverter					
Length	0,8	m			
Width	1,2	m			
Height	1,9	m			
Weight	948	kg			

Figure 28. ESOD battery sizing page

4.3.5 Economics

The financial analysis is split in three pages in the tool. The page “Econ breakdown” provides all the costs and revenues expected. Costs are divided in the EPC costs and the Developer costs adding up to the total system costs. The EPC costs are the lithium-ion battery, inverter, structural BOS, electrical BOS, install labour and equipment, and EPC overhead. The Developer costs are the land acquisition, permitting fee, interconnection fee, contingency, and developer overhead. These values are provided in $/kWh in NREL [62]. The costs are converter into Indian Rupees using the updated conversion rate function provided by Excel. In terms of revenue, two sections which are peak shaving, and savings by asset deferral. Savings on asset deferral are based on avoiding the purchase of a new transformer, for this a ₹90.000 (1031,32 €) transformer is considered [63]. For peak shaving calculations, buying and selling electricity prices at off-peak and peak hours is required. This data is provided but it can also be modified in the Process data page. The result is shown in Econ breakdown page and the calculation is performed in the Savings page. To know how much the earnings increase for the DISCOM compared to not having the battery system, the earnings are calculated for the provided storage capacity.

Moreover, the saving due to carbon reduction in the grid is used as a positive revenue for the DISCOM. During peak hours, the grid carbon intensity is higher due to the use of carbon intensive technology to handle the high demands. Since the battery allows the DISCOM to buy energy during off-peak hours and sell it during the peak hour, less polluting technologies are to be started in order to tackle this peak.

$$Earnings\ before\ battery\ \left[₹/_{year}\right] = (Selling\ peak - Buying\ peak)\left[₹/_{year}\right] * Actual\ storage\ capacity\ [kWh] * 365\ [days] \tag{11}$$

$$Earnings\ after\ battery\ \left[₹/_{year}\right] = (Selling\ peak - Buying\ peak)\left[₹/_{year}\right] * Actual\ storage\ capacity\ [kWh] * 365\ [days] * \text{ Roundtrip efficiency } [\%] \tag{12}$$

$$Earnings\ increase\ \left[₹/_{year}\right] = Earnings\ before\ battery\ \left[₹/_{year}\right] - Earnings\ after\ battery\ \left[₹/_{year}\right] \tag{13}$$

$$Earnings\ increase\ [\%] = \frac{Earnings\ after\ battery\ \left[₹/_{year}\right] - Earnings\ before\ battery\ \left[₹/_{year}\right]}{Earnings\ before\ battery\ \left[₹/_{year}\right]} * 100 \tag{14}$$

$$Carbon\ emission\ savings\ \left[₹/_{year}\right] = Grid\ intensity\ peak\ hours - Grid\ intensity\ offpeak\ hour\ \left[{}^{kgCO_{2e}}/_{kWh}\right] * Average\ carbon\ pricing\ \left[₹/_{kgCO_{2e}}\right] * \left[\frac{1}{1000}\right] * Actual\ energy\ storage\ capacity\ [kWh] \tag{15}$$

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.

$$Depreciation\ [₹] = \frac{Total\ system\ cost\ [₹]}{Project\ lifetime\ [years]} \tag{16}$$

The operating income is calculated from the previously presented costs and revenues.

$$Operating\ income\ [₹] = \Sigma Revenue + Savings - \Sigma CAPEX\ Costs - \Sigma OPEX\ Costs\ [₹] \quad (17)$$

$$Taxes\ [₹] = Operating\ income\ [₹] * Tax\ rate\ [\%] \quad (18)$$

$$Net\ operating\ income\ [₹] = Operating\ income\ [₹] - Taxes\ [₹] \quad (19)$$

Investments		
Total system cost	₹ 9.272.999,9	
CAPEX - EPC cost	₹ 8.157.463,2	
CAPEX - Developer cost	₹ 1.115.536,8	
System lifetime	15	years
Financial parameters		
Project lifetime	15	
Operating costs	2,5%	
IRC Rate	25%	
Risk-free rate	1%	
Debt spread	4,0%	
Systematic risk coefficient (ßCP)	3,00	
Business risk (ßA)	1,50	
Market risk premium	4,0%	
% D	50%	
K_D	**5,0%**	
% CP	50%	
K_{CP}	**13,00%**	
WACC	**8,38%**	

Figure 29. ESOD economics page. Financial parameters and investments

Year	
Saving on asset deferral	
Peak shaving revenue	
Carbon emissions savings	
OPEX - O&M	
Disposal cost	
Depreciation	
Operating income	₹
Taxes	₹
Net operating income	₹

Figure 30. ESOD economics page. Profit and loss analysis

The cash flow analysis presents the investment cost 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. The equations are presented below.

$$Operational\ cash\ flow\ [₹] = Net\ Operating\ income\ [₹] + Depreciation\ [₹] \quad (20)$$

$$
\begin{aligned}
&Project\ cash\ flow\ [₹] \\
&\qquad = Cost\ invetstment\ in\ fixed\ assets\ [₹] \\
&\qquad + Operational\ cash\ flow\ [₹]
\end{aligned} \tag{21}
$$

$$
Discounting\ factor\ [-] = \frac{1}{(1 + WACC)^{year}} \tag{22}
$$

$$
\begin{aligned}
&Present\ value\ of\ project\ cash\ flows\ [₹] \\
&\qquad = Project\ cash\ flow\ [₹] * Discounting\ factor\ [-]
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
&Accumulated\ present\ value\ of\ project\ cash\ [₹] \\
&\qquad = Present\ value\ of\ project\ cash\ flows^{year-1}\ [₹] \\
&\qquad + Present\ value\ of\ project\ cash\ flow^{year}\ [₹]
\end{aligned} \tag{24}
$$

	0	1	
Cost investment in fixed assets - EPC	₹ -2.474.294,5	₹ -2.474.294,5	
Cost investment in fixed assets - Developer	₹ -338.360,9	₹ -338.360,9	
Operational cash flow	₹ -	₹ 284.151,9	₹
Project cash flows	₹ -2.812.655,4	₹ -2.528.503,5	₹
Discounting factors	*1,0000*	*0,9227*	
Present value of project cash flows	₹ -2.812.655,4	₹ -2.333.105,9	₹
Accumulated present value of project cash	₹ -2.812.655,4	₹ -5.145.761,3	₹

Figure 31. ESOD economics page. Cash flows

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. The internal rate of return is calculated using the function provided by Excel with this objective.

$$
Net\ present\ value\ [₹] = \Sigma Present\ value\ of\ project\ cash\ flows\ [₹] \tag{25}
$$

NPV	₹ -25.930.557,6
IRR	-7%

Figure 32. ESOD economics page. Feasibility financial parameters

The values provided in the previous figures are example references and not a finalized case.

Investments		
Total system cost	₹ 5.625.310,9	
CAPEX - EPC cost	₹ 4.948.589,1	
CAPEX - Developer cost	₹ 676.721,8	
System lifetime	15	years

Financial parameters	
Project lifetime	15
Operating costs	2,5%
IRC Rate	25%
Risk-free rate	1%
Debt spread	4,0%
Systematic risk coefficient (ßCP)	3,00
Business risk (ßA)	1,50
Market risk premium	4,0%
% D	50%
K_D	**5,0%**
% CP	50%
K_{CP}	**13,00%**
WACC	**8,38%**

Cashflow			
Year	0	1	2
Saving on asset deferral		₹ 90.000,00	
Peak shaving revenue		₹ 194.112,56	₹ 194.112,56
Carbon emissions savings		₹ 39,34	₹ 39,34
OPEX - O&M			₹ 140.632,77
Disposal cost			
Depreciation		₹ 375.020,72	₹ 375.020,72
Operating income	₹ -	₹ -90.868,83	₹ -321.501,60
Taxes	₹ -	₹ -	₹ -
Net operating income	₹ -	₹ -90.868,83	₹ -321.501,60
	0	1	2
Cost investment in fixed assets - EPC	₹ -2.474.294,5	₹ -2.474.294,5	
Cost investment in fixed assets - Developer	₹ -338.360,9	₹ -338.360,9	
Operational cash flow	₹ -	₹ 284.151,9	₹ 53.519,1
Project cash flows	₹ -2.812.655,4	₹ -2.528.503,5	₹ 53.519,1
Discounting factors	*1,0000*	*0,9227*	*0,8514*
Present value of project cash flows	₹ -2.812.655,4	₹ -2.333.105,9	₹ 45.567,0
Accumulated present value of project cash	₹ -2.812.655,4	₹ -5.145.761,3	₹ -5.100.194,3
NPV	₹ -4.747.354,2		
IRR	-19%		

Figure 33. ESOD economics page

	Utility Scale				Rupee conversion
COSTS	**Model Component**	**$/kWh**	**₹/kWh**	**₹**	₹ 81,51
Lithium-ion Battery	Lithium-ion Battery	**192**	₹ 15.653,91	₹ 3.165.394,60	
Inverter	Battery Central Inverter	**15**	₹ 1.210,35	₹ 244.747,00	
Structural BOS	Structural BOS	**13**	₹ 1.066,89	₹ 215.737,79	
Electrical BOS	Electrical BOS	**35**	₹ 2.891,24	₹ 584.640,54	
Install labor & equipment	Install Labor & Equip	**19**	₹ 1.578,28	₹ 319.146,57	
EPC overhead	EPC Overhead	**10**	₹ 791,62	₹ 160.075,20	
	Sale Tax	**16**	₹ 1.280,08	₹ 258.847,36	
	∑ EPC Cost	**300**	₹ **24.472,39**	₹ **4.948.589,07**	
Land adquisition	Land acquisition	**0**	₹ -	₹ -	
Permitting fee	Permitting fee	**1**	₹ 99,28	₹ 20.075,31	
Interconnection fee	Interconnection fee	**8**	₹ 621,81	₹ 125.737,09	
Contingency	Contingency	**9**	₹ 761,81	₹ 154.046,35	
Developer overhead	Developer overhead	**7**	₹ 539,00	₹ 108.991,09	
	EPC/developer net profit	**16**	₹ 1.324,71	₹ 267.871,95	
	∑ Developer cost	**41**	₹ **3.346,61**	₹ **676.721,78**	
	∑ Total system cost	**341**	₹ **27.819,00**	₹ **5.625.310,86**	
	O&M Costs		₹ 695,47		
			₹/mt CO2 e	**₹/kWh**	**₹**
Carbon pricing	3.37 USD per mt CO_2e	3,37	₹ 274,69	₹ 0,19	₹ 39,34
REVENUE	with focus only on overload it is hard to find a revenue				
Peak shaving	₹ 194.112,56				
Savings of avoiding a new transformer	₹ 90.000,00				

Figure 34. ESOD econ breakdown page

Process data		
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
Energy in battery	355	kWh
Economic loss	100%	%
Peak hour selling price increase		
Base tariff	420	
Increase peak hour	82	
Increase	20%	

Savings annual - Peak shaving		
Earnings before battery		
₹	220.029,30	year
₹	620,50	INR/kWh
Earning after battery		
₹	340.398,27	year
₹	959,95	INR/kWh
Savings		
₹	120.369	Year
₹	340	INR/kWh
Earnings increase		
	55%	

Figure 35. ESOD savings page

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 lack of readiness of the market for this technology, therefore, utility-scale BESS projects currently, most of the projects will encounter negative NPV and non-attractive IRR. This topic will be further discussed in the sections Discussion and Conclusion. This page has the same structure as Figure 33 but with an additional cell showing a percentage, the CAPEX is multiplied by this percentage and, through automatic data tables, the appropriate percentage to make the NPV zero is found. Therefore, this percentage of the CAPEX is to be covered by external investment or funding.

Investments			
Total system cost	₹	5.625.310,9	
CAPEX - EPC cost	₹	4.948.589,1	
CAPEX - Developer cost	₹	676.721,8	
System lifetime		15	years
Financing iteration	₹	3.656.452,1	CAPEX %
CAPEX - EPC cost	₹	3.216.582,9	0,650
CAPEX - Developer cost	₹	439.869,2	

Figure 36. ESOD funding. In purple CAPEX % calculated

In Figure 36, the top 3 values are the original total CAPEX and EPC and developer costs. Below this, the new CAPEX is visualised affected by the applied percentage.

CAPEX covered		**NPV**		**Required funding**
	₹	**-2.854.570,1**		₹ 5.625.311
10%	₹	119.804,9	12,2%	12,2%
20%	₹	-420.990,5	0,0%	88%
30%	₹	-961.786,0	0,0%	
40%	₹	-1.502.581,5	0,0%	
50%	₹	-2.043.376,9	0,0%	
60%	₹	-2.584.172,4	0,0%	
70%	₹	-3.124.967,8	0,0%	
80%	₹	-3.665.763,3	0,0%	
90%	₹	-4.206.558,7	0,0%	
100%	₹	-4.747.354,2	0,0%	

Figure 37. ESOD funding: data table iterating for percentage of CAPEX to be covered

The tool provides a new page with 10 financial studies to obtain the NPV, IRR, and funding required for all the cases following the structure shown in Figure 33. The following section provides the display of this information for the user.

4.3.6 Outputs

To finalize the tool description, the Output page is presented. This page is found in the user section as seen by the layout. 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 in the yellow boxes represented in the upper section of Figure 38.

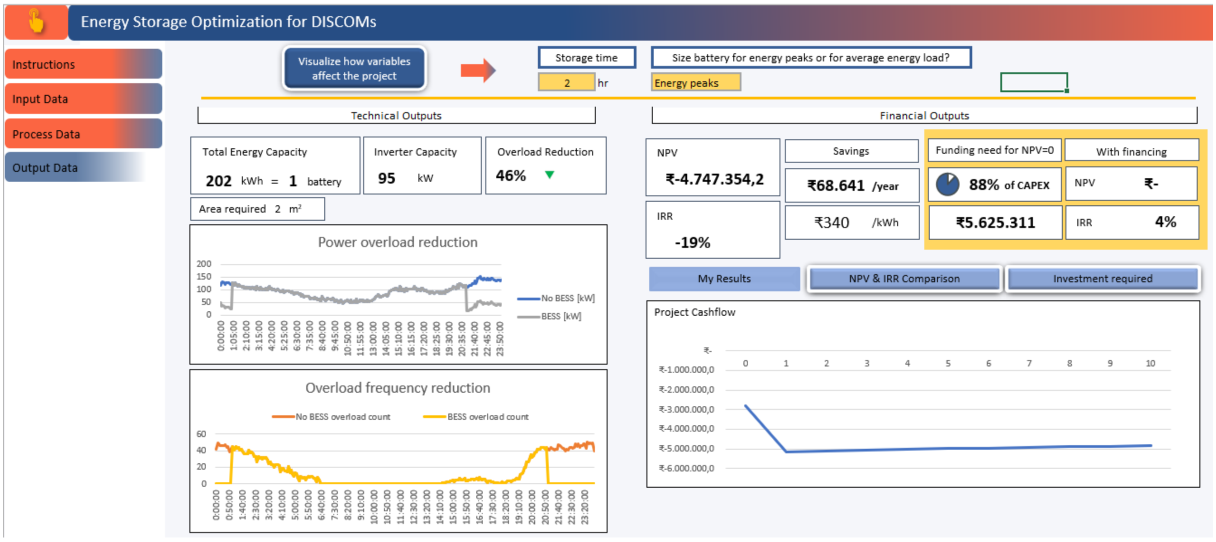

Figure 38. ESOD output page I

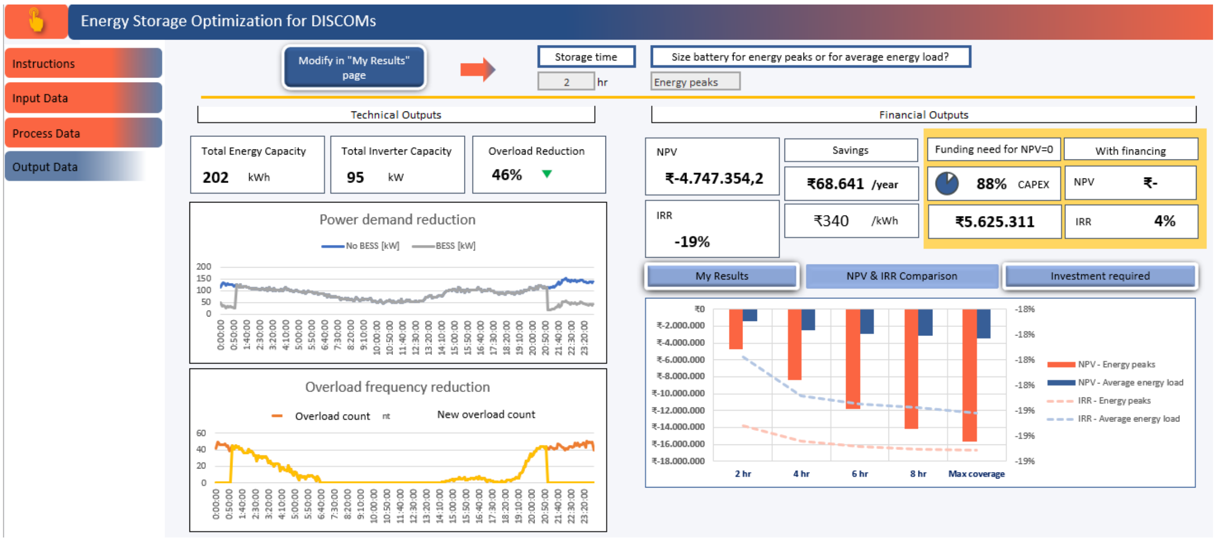

Figure 39. ESOD output page II

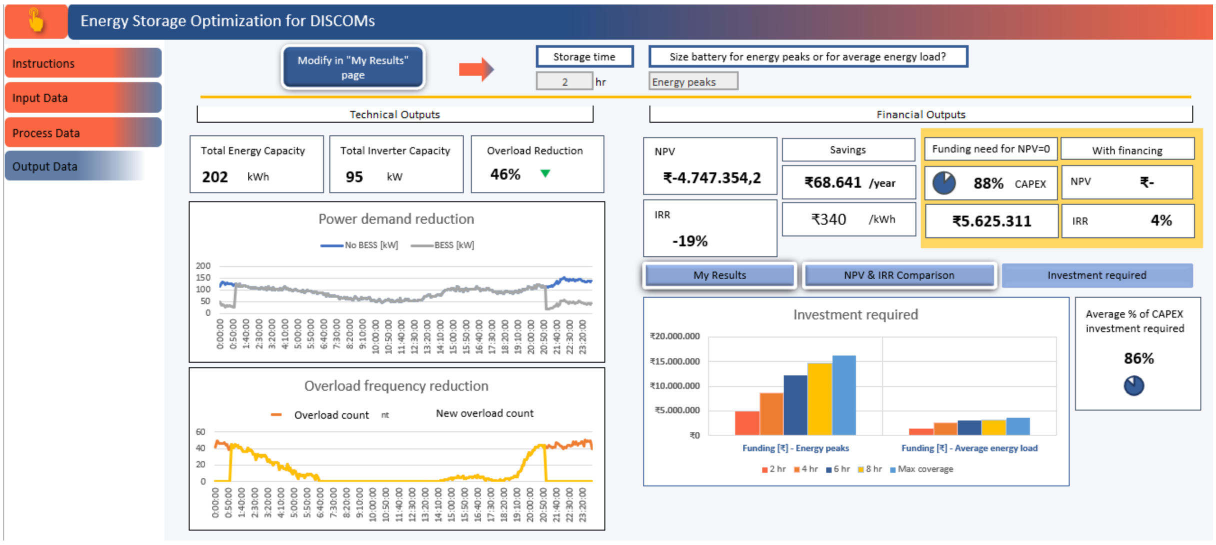

Figure 40. ESOD output page III

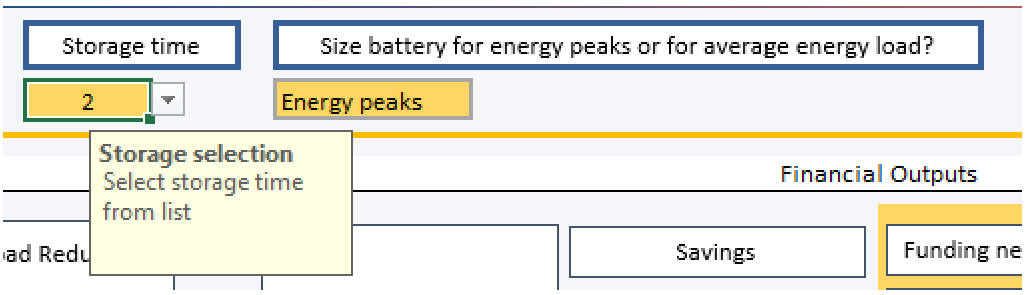

Figure 41. ESOD output page selection panel

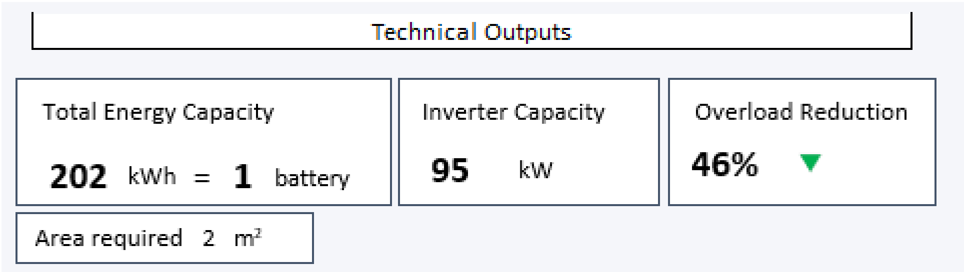

Figure 42. ESOD outputs page technical results display

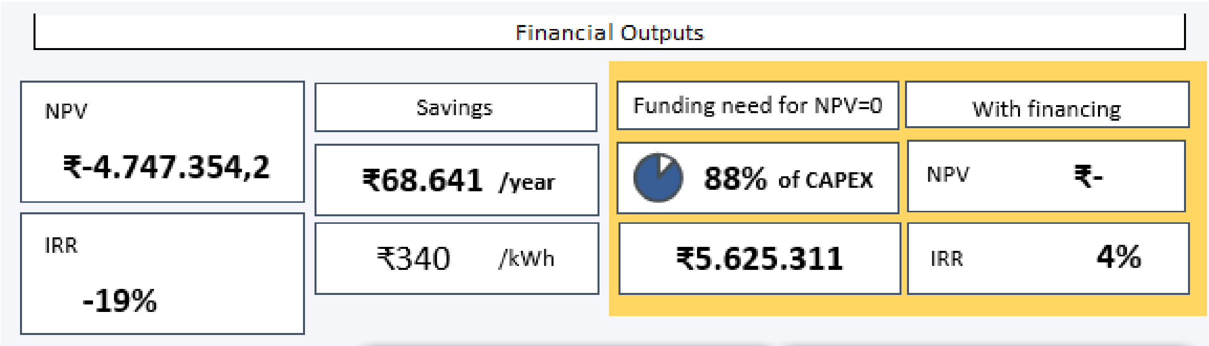

Figure 43. ESOD outputs page financial results display

Chapter 5

Case study

This chapter present a real case study performed in partnership with an Indian DISCOM. The chapter aims to present the key calculation processes and has the main objective of showing the results obtained by the tool. After obtaining these results, interviews were conducted with industry experts and discussion was held with UGVCL to validate the values obtained.

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. The case study not only allows numerical results to be analysed but also provides an advantage regarding tool design. During the case study development, the industrial partner was able to provide insights regarding interesting, expected outputs, which type of data could be provided and in which format, current used technologies by the market, and insights on the general layout. One of the key objectives is to develop a useful tool, therefore, sharing the product with the industry allows the project outcome to achieve to this objective.

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 of different categories including industrial, residential, commercial, and agricultural. The vision is to be World Class Electricity Utility aiming to tackle social and economic development with the mission of Consumer Satisfaction through Service Excellence [64].

As mentioned in the company profile [64]

> "The Main Object to be pursued in terms of the Memorandum of Association of the Company is: To undertake the electricity sub-transmission distribution and retail supply in the State of Gujarat or outside the State and for this purpose to plan, acquire, establish, construct, erect, lay, operate, run, manage, maintain, enlarge, alter, renovate, modernize, work and use a power system network in all its aspects and also to carry on the business of purchasing, selling, importing, exporting, wheeling, trading of electrical energy, including formulation of tariff, billing and collection thereof and then to study, investigate, collect information and data, review operations, plan, research, design and prepare project reports, diagnose operational difficulties and weaknesses and advise on the remedial measures to improve and modernize existing sub transmission and supply lines and sub-stations."

The group has extended experience since its commercial operation start in April 2005. Moreover, UGVCL is a pioneer in special design transformers and owns the first National Accreditation Board for Testing and Calibration Laboratories among State DISCOMs called the Hi-Tech Testing Laboratory [64].

5.2 Data provided

The data set provided by UGVCL is based on a residential society for the summer months of April and May in 2019. The transformer analysed has a rating capacity of 200 kVA and data is recorded every 5 minutes approximately, some timesteps are of 15 minutes due to reading delays. The system is a three-phase transformer, therefore every parameter is provided for the three phases except for frequency that is provided as for the whole system. 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 Assumptions and data used for calculations

Key parameters must be set to perform the analysis. These and key assumptions are stablished through research and conversation with the DISCOM.

The main assumption was to change the provided rating of the transformer from 200 kVA to 100 kVA. Since the effectiveness of the tool wants to be analysed, the company proposed this change because the transformer data provided did not suffer overload during this period. By reducing the capacity, the tool can recognize overload.

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 [65]. The carbon intensity for off-peak hours has been defined using the emission factor of solar PV plants, being 0.24 kgCO_2e/kWh [66]. The price of emissions is set to 274.7 ₹/metric tonnes CO_2e (3.15 €/ metric tonnes CO_2e) [67]. 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

Figure 44. Economic parameters for case study development

Moving on to the transformer data, the overload limit is established at 80% of the rated capacity after analysing the overload occurrence for 70%, 80%, and 90%. The company showed interest in analysing in depth the case for an 80% limit therefore the calculations were continued with this limit. Moreover, from market study, the replacement cost of the transformer is set at ₹90,000 [63].

Transformer		
Parameter	**Value**	**Units**
Overload limit	0,8	%
Replacement cost	₹ 90.000,00	

Figure 45. Transformer data for case study

An inverter was found to match the power requirements of the analysis. For the objective of the tool the only parameter required are the dimensions of an existing inverter to calculate the area required by the total system. The brand ATESS Power was selected for this. Regarding the battery, more parameters are to be considered and provided by the tool. The nominal voltage, nominal ampere hour capacity, roundtrip efficiency, depth of discharge, number of cycles 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.

Parameter	**Value Calculation**	**Units**
Nominal voltage	8	V
Nominal capacity	400	kWh
Nominal capacity	200	Ah
Roundtrip eficiency	0,9	%
Depth of discharge	0,8	%
Storage time	4	hr
Dimensions of battery pack		
Lenght	0,730	m
Width	0,468	m
Height	0,212	m
Weight	101	kg
Dimensions of inverter		
Length	0,8	m
Width	1,2	m
Height	1,9	m
Weight	948	kg

Figure 46. Data provided from reference systems to develop case study. [68],[69].

The costs used to perform the feasibility analysis were based in kWh and shown in Figure 47. 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**

Figure 47. Current component cost breakdown by system 2019 battery for utility scale. [50],[70].

5.4 Data analysis and results

This section provides the steps taken to complete the data analysis and result calculation.

5.4.1 Demand analysis and battery sizing

Once all the process data and inputs have been stablished together with the DISCOM, the tool automatically obtains the overload frequency for the two-month period provided, and the energy delivered into the load considering a data treating code to avoid negative values or bigger than 400 kWh. Following (2) the overload limit is calculated as follows.

$$Overload\ limit\ [kVA] = 100\ kVA * 80\ \% = 80\ kVA \tag{26}$$

For this case, the overload limit is 80 kVA or 80 kW. The power factor is calculated as the average power factor obtained from the data provided. The value obtained is 0.94 which, as defined in the tool structure, is negligible and therefore the overload limit in terms of active power equals overload limit in terms of apparent power.

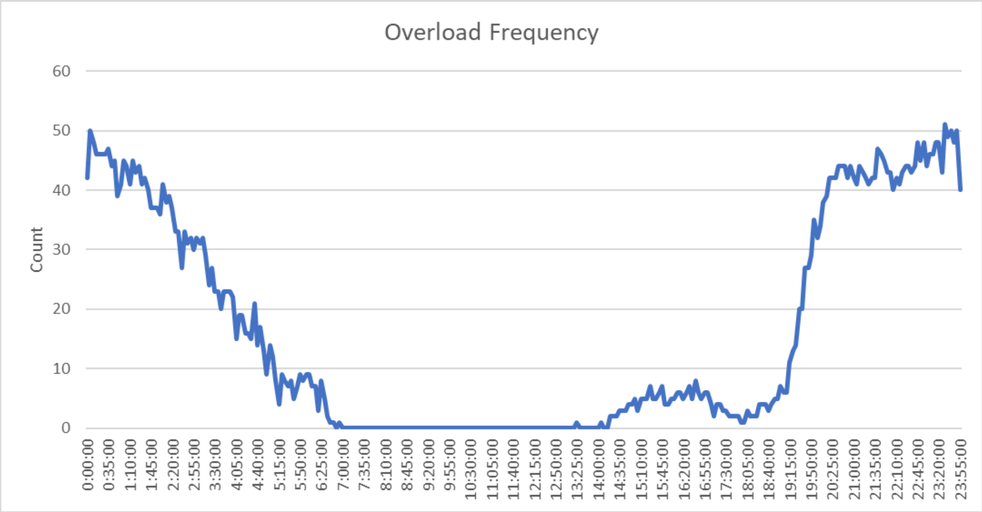

Figure 48. Overload count for case study

The data is counted for the two months and represented in one day sum. For example, all the times in which transformer experiences overload at 18:00:00 throughout the year will be added and shown in the time 18:00:00. The overload count shows the seasonal effect in the data. There is a long peak from 20:00:00 until 2:00:00. April and May are summer months in India, and it is common for residential customers to utilize air conditioner solutions during the night to allow sleep under high temperature conditions.

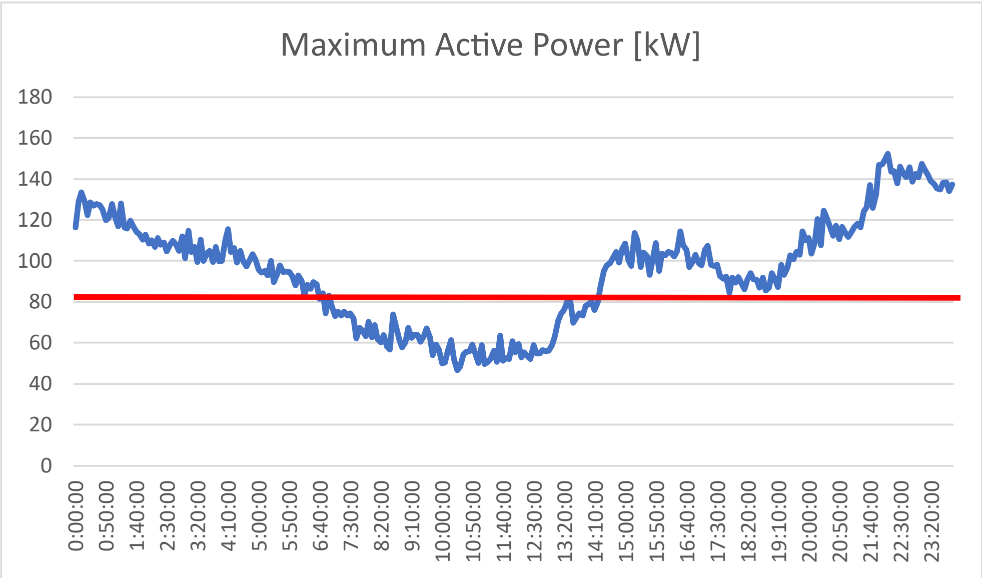

Figure 49. Maximum active power for case study [kW]

As observed in the power pattern, the maximum power levels match the highest overload occurrence moments, therefore, it is concluded that the highest peaks occur the highest number of times. The red line shows the overload limit positioned at 80% of the rated capacity.

It is important to calculate the overload limit in energy units to obtain an accurate battery sizing. Following (3), the energy limit is calculated.

$$Energy\ limit\ [kWh] = 80\ kW * \frac{5\ minutes}{60\frac{minutes}{hour}} = 7\ kWh \quad (27)$$

With this value, the energy delivered into the load above the overload limit can be visualized directly in using energy data. As presented previously, the user can select to perform the study for maximum energy peaks or for the average energy values. For the current case, the user selected a 4-hour discharge system to be sized considering energy peaks. Figure 50 shows the maximum energy delivered into the load showing the energy over the overload limit. In Figure 51 the average energy delivered into the load is represented. The second figure is not used for this case study but is shown as an example of the possible difference between the maximum and average data.

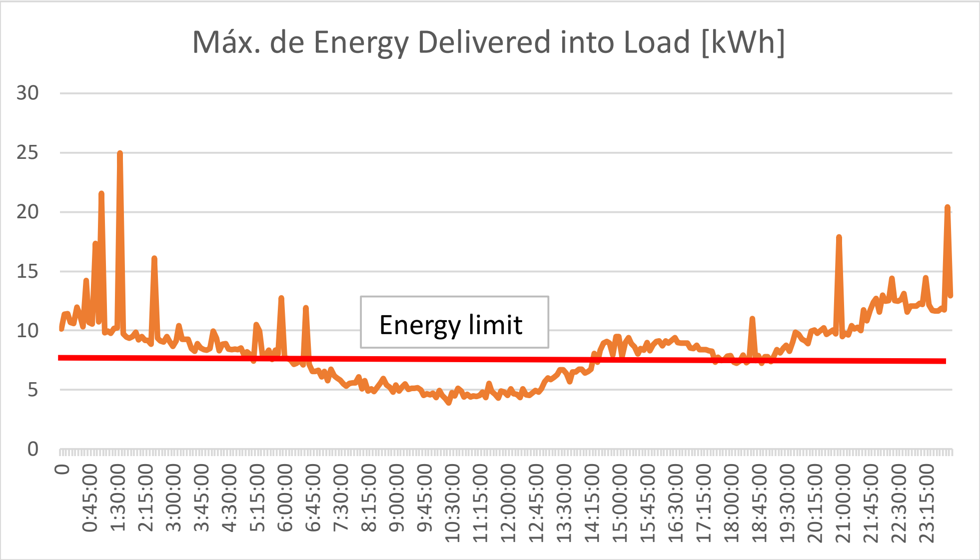

Figure 50. Maximum energy delivered into the load per hour with energy limit in red

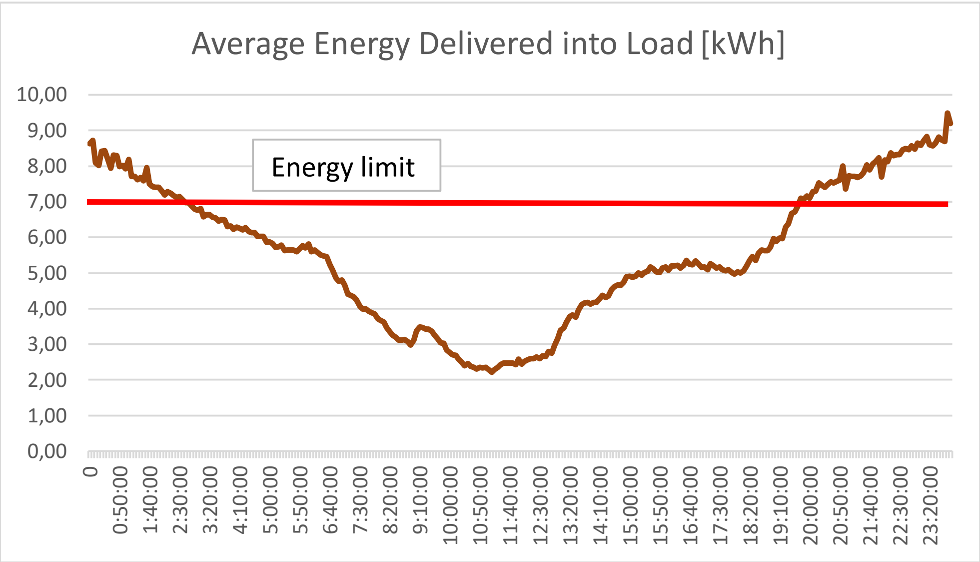

Figure 51. Average energy delivered into the load per hour with energy limit in red

The user selected 4 hours of storage for the system, therefore the developer calculates the total amount of energy to be covered during the 4 hours with highest overload occurrence. The highest occurrence matches the highest energy peaks. The energy to be stored is the amount observed between the red energy limit line and the orange line representing the maximum energy peaks. In Figure 52 the blue arrows point out the segment.

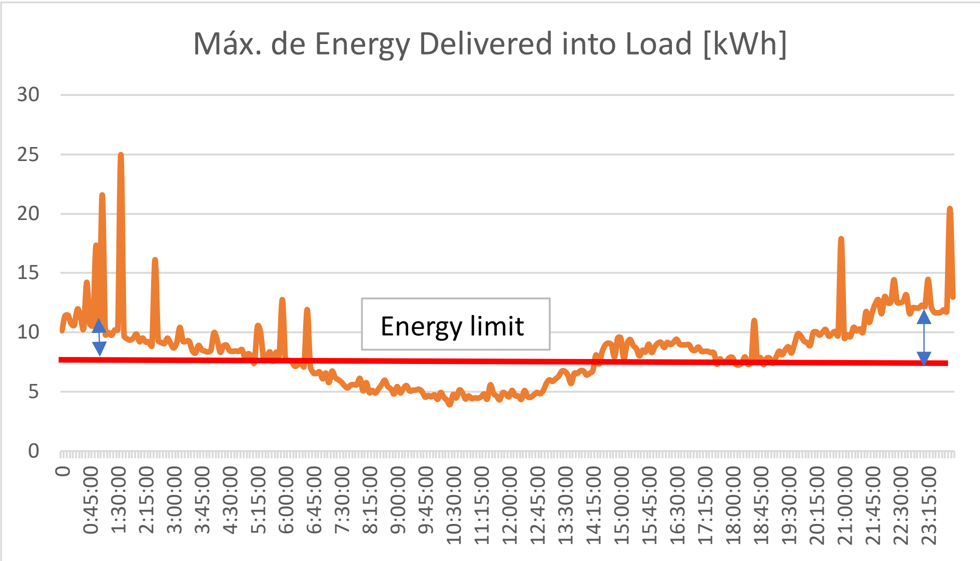

Figure 52. Energy segments for storage sizing

In order to complete this calculation and know the amount of energy the storage system should be sized for, for every timestep, the overload limit is subtracted from the peak energy when the amount of energy is over 7 kWh, therefore, only the amount of energy over 7 kWh will be considered for the total energy calculation.

$$Energy\ for\ storage\ sizing_t = Maximum\ energy\ over\ 7\ kWh_t\ \ [kWh] - 7\ kWh \tag{28}$$

Finally, the total energy to be considered to size the system is the sum of the energy calculated for every timestep. In this case, the obtained value is shown below. For the proposed case, the highest energy peaks for a 4-hour period were found between 21:00:00 and 01:00:00. The most optimum range is detected by the developer, which will adapt the energy calculation for the different users.

$$Total\ gross\ energy\ for\ storage\ sizing = \Sigma Energy\ for\ storage\ sizing_t = 255.31\ kWh \tag{29}$$

Once the total gross energy for storage sizing is determined, the tool automatically performs the rest of the calculations. First, the battery system is sized by including the depth of discharge and efficiency to the previously obtained energy value. This new energy amount is the actual storage capacity as shown in (6).

$$Actual\ storage\ capacity\ [kWh] = \frac{255.31\ kWh}{80\ \% * 90\ \%} = 355\ kWh \tag{30}$$

Following, the inverter is sized. From Figure 49, the maximum peak is observed at 152 kW. To size the inverter, the power below the limit must be subtracted, in order to know the amount of power the system must be able to cover to avoid overload.

$$Inverter\ capacity\ [kW] = 152.41\ kW - 80\ kW * 1{,}3 = 95\ kW \qquad (31)$$

The units required for UGVCL are 2.

$$\text{Ampere hour requirement [Ampere} - \text{Hour]} = \frac{355\ kWh}{2\ \text{V} *\ 80\ \%} = 221.63\ Ah \qquad (32)$$

$$Number\ of\ packs\ required\ in\ parallel\ connection\ [Units] = \frac{221.63\ Ah}{200\ Ah} = 2\ units \qquad (33)$$

$$Area\ required\ [m^2] = 0.468\ m * 0.730\ m * 2 +\ 0.8\ m\ * 1.2\ m = 2\ m^2 \qquad (34)$$

Table 3. Technical results summary

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

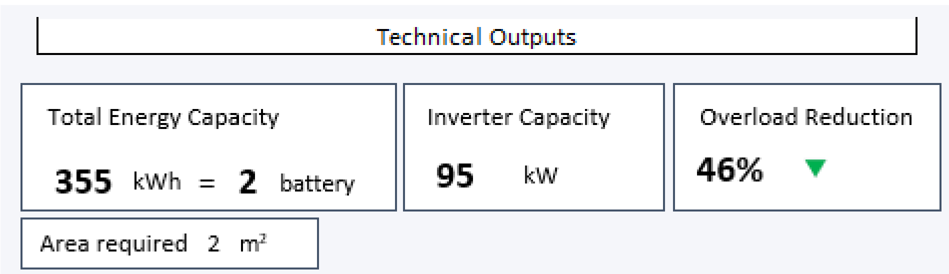

Figure 53. Technical results - Tool display

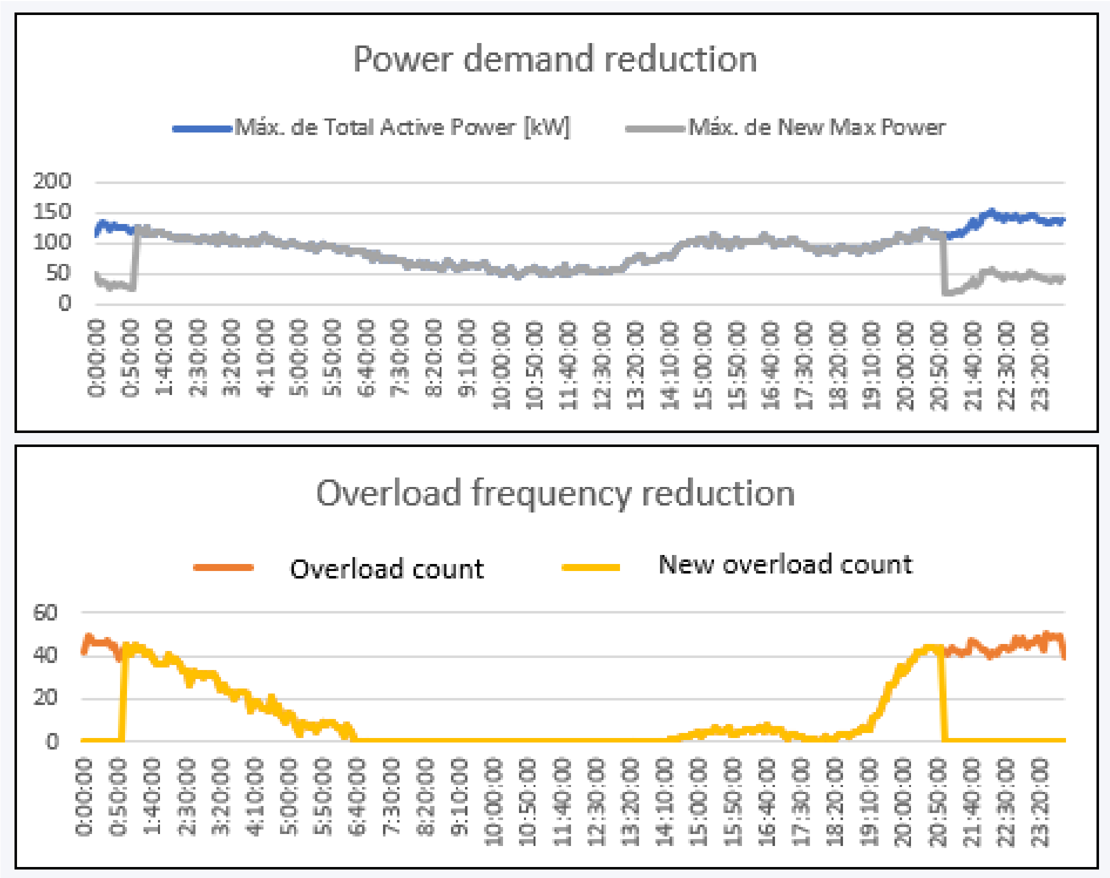

Figure 54. Technical graphic results - Tool display

5.4.2 Financial results

The costs, savings and financial results are presented in the following table following the equations in the section Economics and the data found in the section Assumptions and data used for calculations.

Table 4. Financial results - CAPEX and OPEX

Parameter	**Value**	**Value (1 INR = 0.011 €)*[1]**
Total system cost	₹ 9,864,617.3	113,039.61 €
CAPEX – EPC cost	₹ 8,677,909.3	99,441.01 €
CAPEX – Developer cost	₹ 1,186,708.0	13,598.60 €

[1] All conversions from INR to Euros have been processed using the conversion 1 INR = 0.011 €. [71]

OPEX – O&M	₹ 246,615.43/ year	2,825.99 €/year

Table 5. Financial results - Variable savings

Parameter	**Value**	**Value**
Peak shaving revenue	₹ 340,398.3/ year	3,900.66 €
Carbon emission savings	₹ 69.16/ year	0.79 €

Table 6. Financial results - NPV and IRR

Parameter	**Value**	**Value**
NPV	₹ -8,387,604	-96,114 €
IRR	-19%	

Table 7. Financial results - Funding required

Parameter	**Value**	**Value**
Funding required	88% of CAPEX	
Funding required	₹ 9,864,617	113,039€
Expected IRR for NPV = 0	4%	

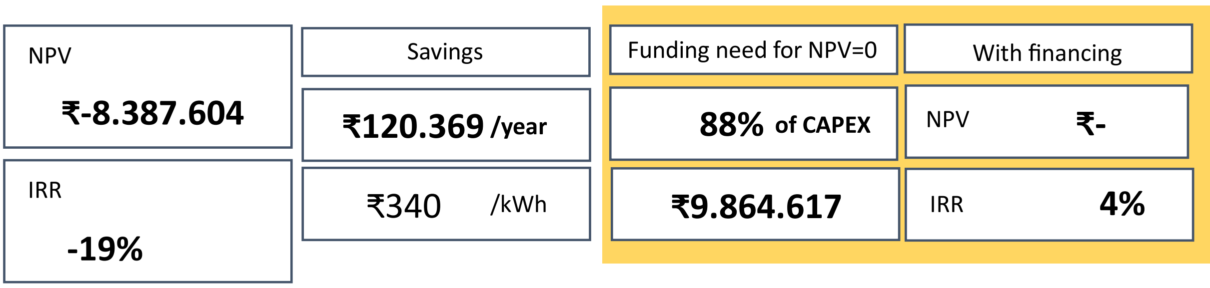

Figure 55. Financial results - Tool display

5.5 Results for all storage hours and energy loads

Finally, to conclude the results section for this case study, the key results for the 10 possible storage time combinations is presented.

Table 8. Energy peaks all hour's storage and financial results

	Energy peaks				
	2 hr	**4 hr**	**6 hr**	**8 hr**	**Max coverage**
Actual storage capacity [kWh]	202,21	354,60	497,97	597,98	661,07
NPV [₹]	₹-4,747,354	₹-8,387,605	₹-11,812,334	₹-14,201,389	₹-15,708,451
	-54,400 €	-96,114 €	-135,358 €	-162,735 €	-180,004 €
IRR [%]	-19%	-19%	-19%	-19%	-19%
Funding [₹]	₹4,938,160	₹8,724,719	₹12,287,095	₹14,772,171	₹16,339,804
Funding [%]	87.8%	88.4%	88.4%	88.8%	88.9%

Table 9. Average energy load all hour's storage and financial results

	Average energy load				
	2 hr	**4 hr**	**6 hr**	**8 hr**	**Max coverage**
Actual storage capacity [kWh]	62.98	109.08	125.91	133.39	149.33
NPV [₹]	₹-1,429,129	₹-2,522,594	₹-2,924,707	₹-3,103,336	₹-3,484,215
	-16,297 €	-28,767 €	-33,352 €	-35,389 €	-39,733 €
IRR [%]	-18%	-18%	-18%	-18%	-19%
Funding [₹]	₹1,486,568	₹2,623,982	₹3,042,257	₹3,228,065	₹3,624,252
	16,952 €	29,923 €	34,693 €	36,812 €	41,330 €
Funding [%]	84.9%	86.5%	86.9%	87.0%	87.2%

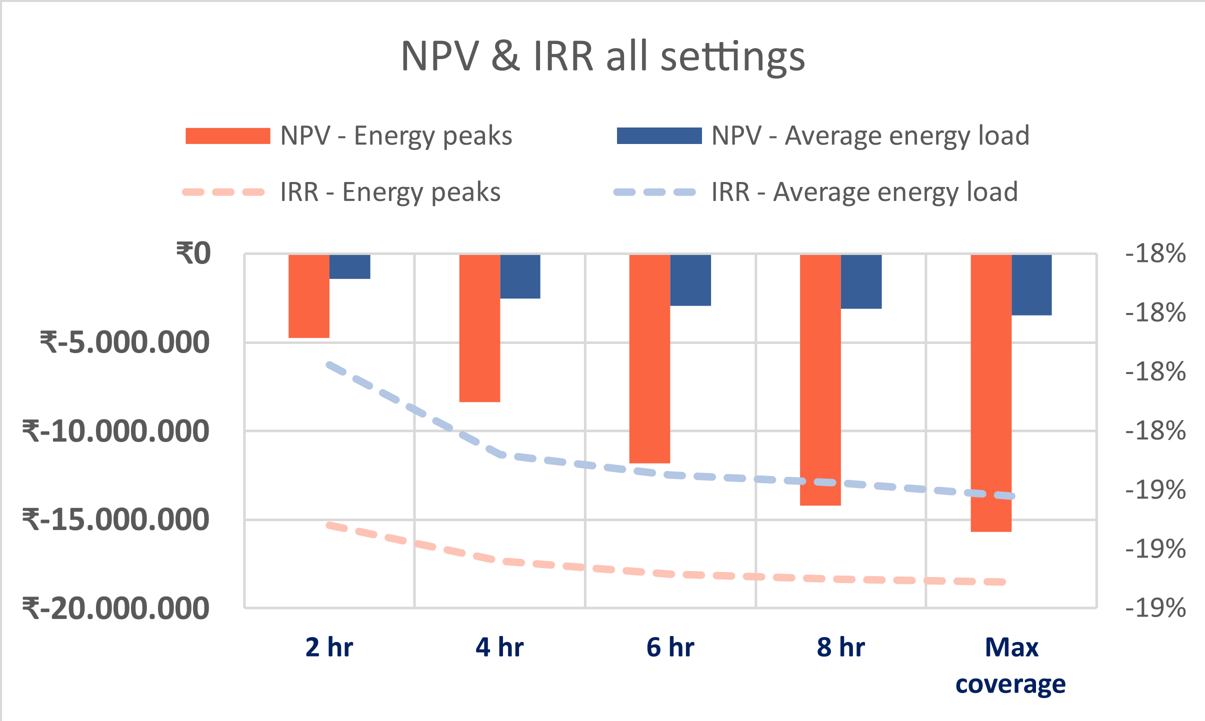

Figure 56. All hour's financial results - NPV and IRR comparison

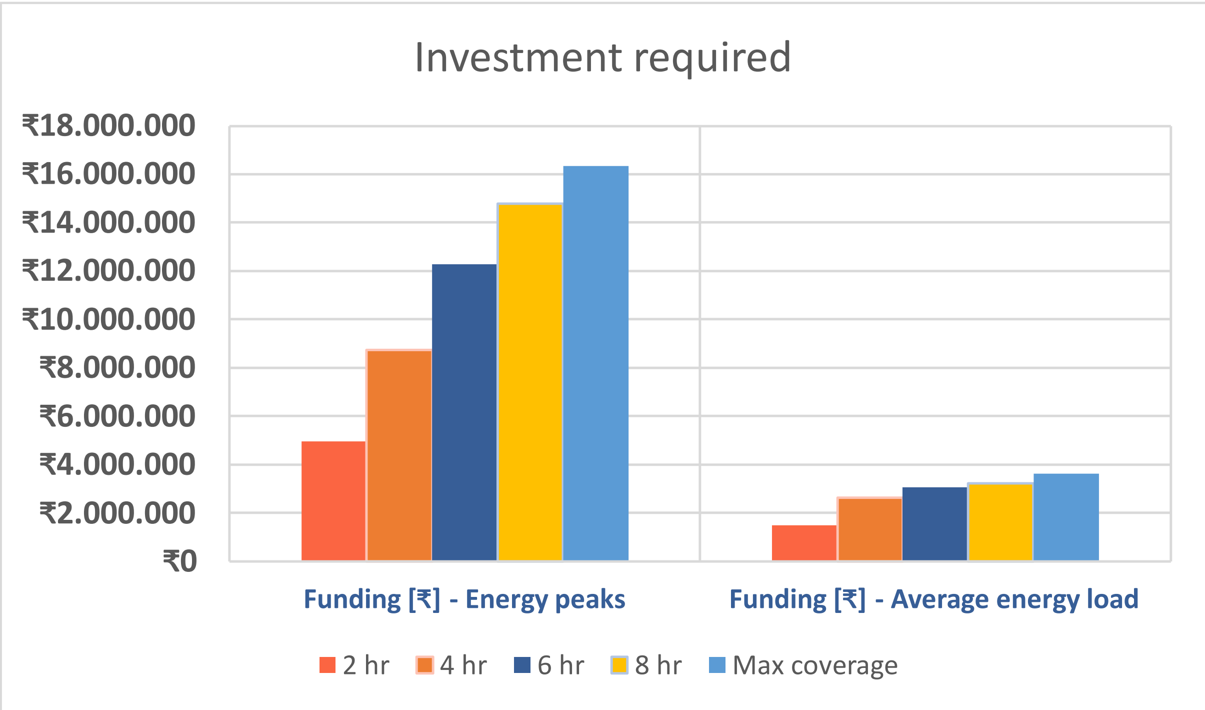

Figure 57. All hour's financial results - Investment required

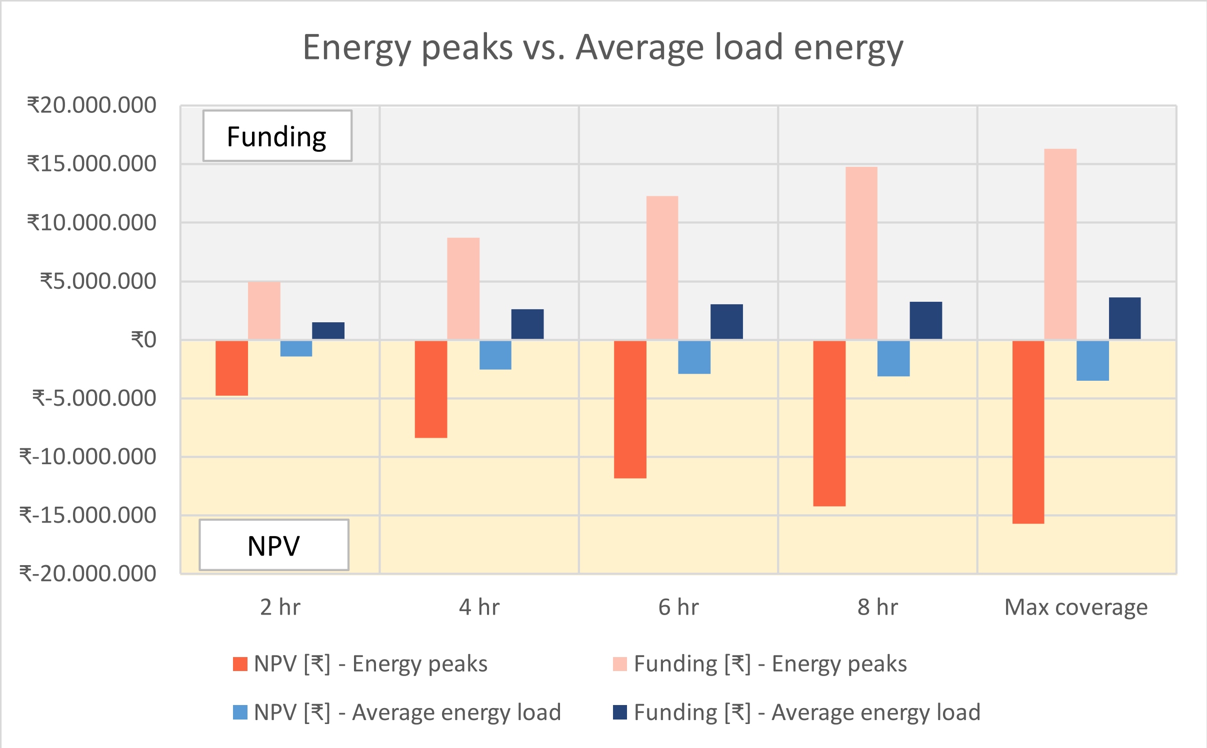

Figure 58. Comparison energy peak vs average load sizing results

Chapter 6

Discussion

This chapter comments on the results presented in the previous chapter.

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 previously, 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.

As shown in Figure 56 and Figure 58, for the 10 proposed energy storage sizes, the NPV is negative as well as the return on investment that remains at an average of -19%. Sizing for average energy load is closer to being financially feasible providing a maximum negative NPV with a maximum coverage storage of ₹-3,484,132 compared to the maximum negative NPV for energy peak sizing with the same storage time system of ₹-15,708,083. This is almost 5-time lower NPV. Given this case study, it is more interesting to leave out the energy peak occurrence points and tackle the average energy load in order to have an optimized system that will most likely provide revenue with a much lower investment cost. Note that this revenue will only be observed in the case of lower investment costs.

Figure 57 shows the investment that the DISCOM will required to make the system NPV zero considering the current market costs per kWh. As expected, these investment requirements are proportional to the NPV of the different configurations. Knowing that the investment required for the highest storage capacity configuration for average energy load configuration is ₹3,624,166, it is possible to say that these projects could easily be implemented with financial support and start deploying the technology for this sizing configurations to tackle overload and peak shaving applications. However, this amount is still around 90% of the CAPEX, therefore the DISCOM may face challenges to find funding for such a great percentage of the project upfront costs. Once more, this situation comes down to the lack of market readiness for utility-scale application BESS.

The large-scale battery storage market growth is considered with a fast amount of 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, as mentioned in Irena [54],

> "Utility-scale battery storage technologies have high upfront costs. Further, since utility-scale battery storage is an emerging technology, key stakeholders such as governments, regulators, system operators, generators and financiers are not completely aware of its benefits and case studies. As a consequence, they have not fully updated planning, valuation, procurement and interconnection processes to accommodate this new asset class. […] Also, regulatory constraints, due to regulation not taking this technology into account, further limit the revenue streams and deployment of utility-scale batteries."

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 [54]. 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 [54].

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 [72].

6.2 Cost projection scenarios and sensitivity analysis

After analysing and understanding the presented results, it is concluded that one of the ley barriers for BESS utility-scale deployment are investment costs. For this reason, this section is presented. This section aims to analyse the system proposed for the case study, 4 hours discharge for peak energy, over a period of time using cost projections proposed by NREL from 2019 to 2050. By performing this analysis, the study aims to provide information on when the DISCOM could invest on this project without requiring external funding and show the NPV and IRR expected for these years. The data used to perform the financial projection is based on the cost per kWh for an a 60 Mwe system considering an average of storage times from 2 to 10 hours of discharge [70]. Tables Table A 3, Table A 4, and Table A 5, show the cost projections for the three different proposed scenarios, moderate, advanced, and conservative.

Considering the demand curve provided for this study, cost projections for different scenarios from [50] with data in Cost estimation for utility-scale BESS and using the tool ESOD, the NPV and IRR are calculated for all the estimated costs.

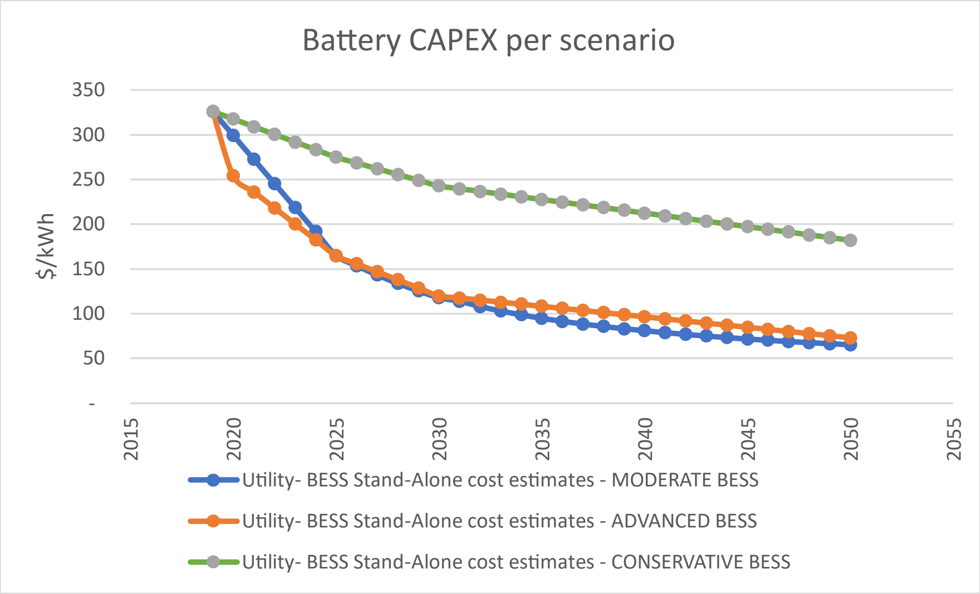

Figure 59. CAPEX projection per scenario. Graph generated from data in [70].

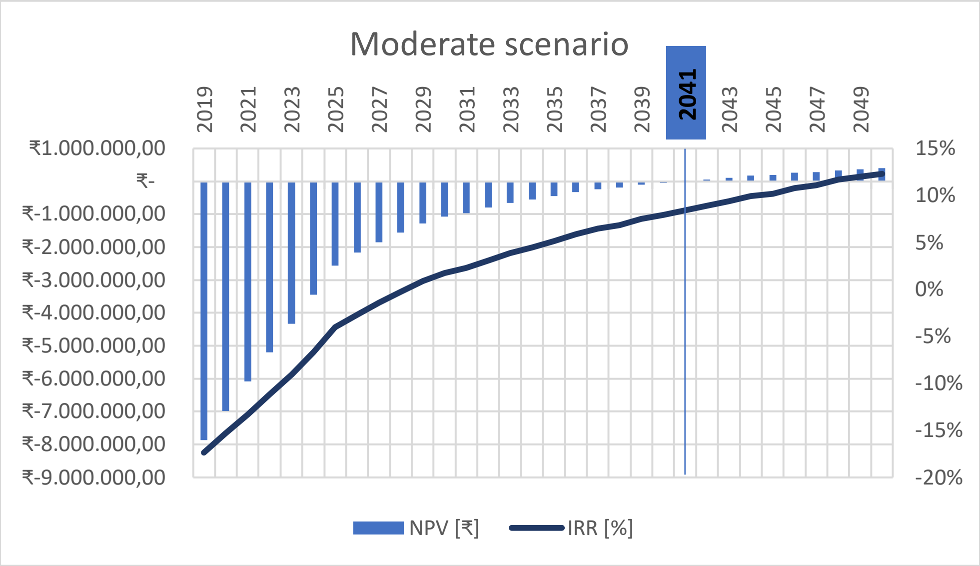

Figure 60. NPV and IRR per year for moderate scenario.

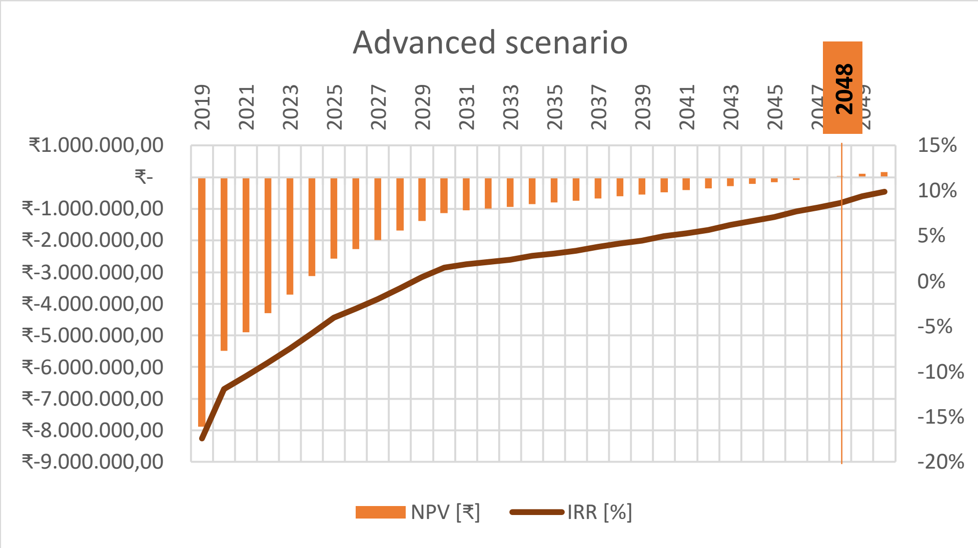

Figure 61. NPV and IRR per year for advanced scenario.

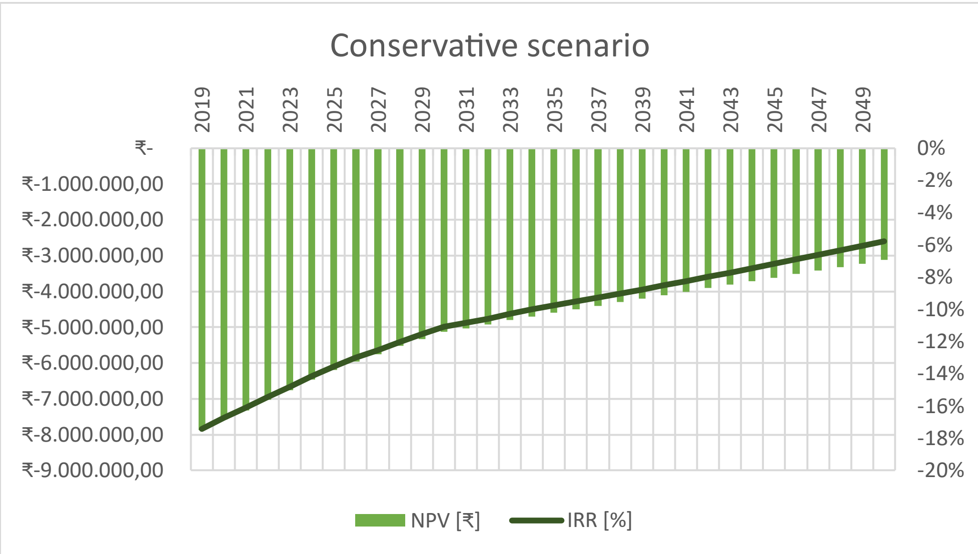

Figure 62. NPV and IRR per year for conservative scenario.

From Figure 60 and Figure 61 it is concluded that for the moderate and advanced scenario, in years 2041 and 2043 respectively, UGVCL could be able to invest in the proposed system obtaining an NPV of ₹3,110 and ₹30,903 respectively with a return of 8% and 9% respectively. However, if projections vary as estimated in the conservative scenario, costs would not be low enough before 2050 to achieve an interesting financial return from the project.

To continue, a sensitivity analysis has been conducted to analyse the actual storage size affects the overload presence.

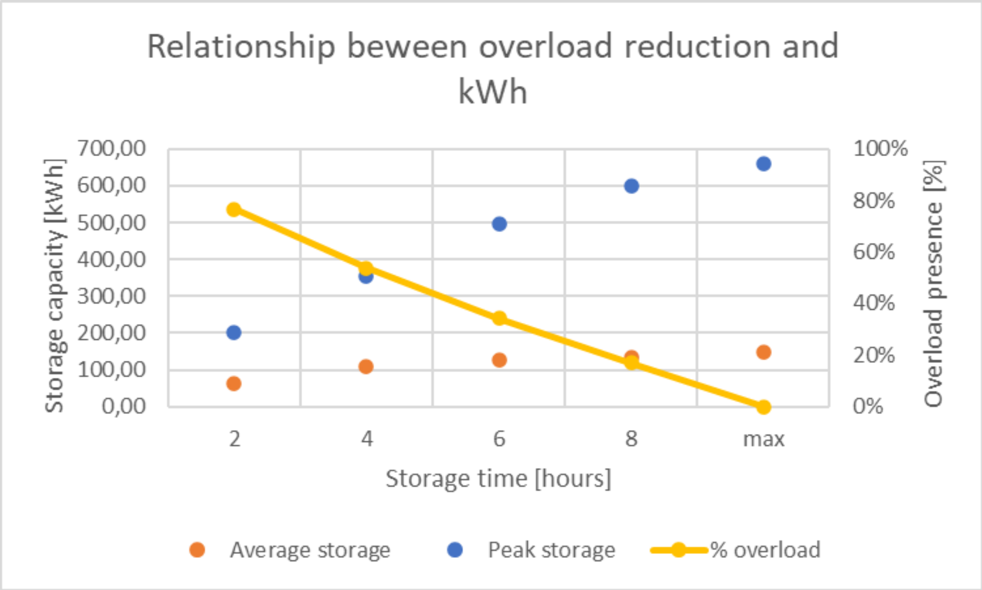

Figure 63. Sensitivity analysis. Overload vs energy storage

The orange and blue dots show the energy storage for average storage and peak storage sizing respectively, considering every storage time represented along the horizontal axis. The yellow line shows the overload experienced by the transformer at every level. As expected, since the sizing is done focusing on the overload segments, a higher storage capacity, means a lower overload experienced by the transformer. However, as seen in Figure 56, a higher energy storage capacity, requires a higher investment cost and lower NPVs. Knowing these factors, the user has to be able to prioritize the objective of the project since a total overload coverage will mean a higher negative impact, and the need of higher external investment.

Finally, a second sensitivity analysis is presented to observe the effect on the project's profitability for a set of energy price differences. This study compares different NPV and IRR results while varying the gap between selling price at peak hours and buying it at off-peak hours. India is suffering the consequences of the low quality of electricity supply and the fast-growing demands. In March 2022 the purchase price of electricity was recorded to be over double the price in March 2021 [73]. Moreover, already in 2020, Indians were "paying three to four times the cost of generating electricity", the "highest power tariff in much of South Asia even as India's power generating cost is the lowest in among 12 countries" as mentioned in [74]. Therefore, this is a necessary analysis to understand the effect of price variation to the project in the current volatile markets.

Figure 64 shows a positive NPV when the price gap is above 12 ₹/kWh. In terms of IRR, a positive return can be observed with 7 ₹/kWh difference. 7 ₹/kWh to 12 ₹/kWh are not common average values found throughout the year in India, therefore, a yearly average revenue would not consider such peaks. In 2022 a peak of 8.32 ₹/kWh was registered during a specific period of March, as mentioned previously from [73], but the average values recorded since 2020 are of 4 ₹/kWh [75]. These results prove that a strong variation in price is not enough to make the project viable under current price conditions.

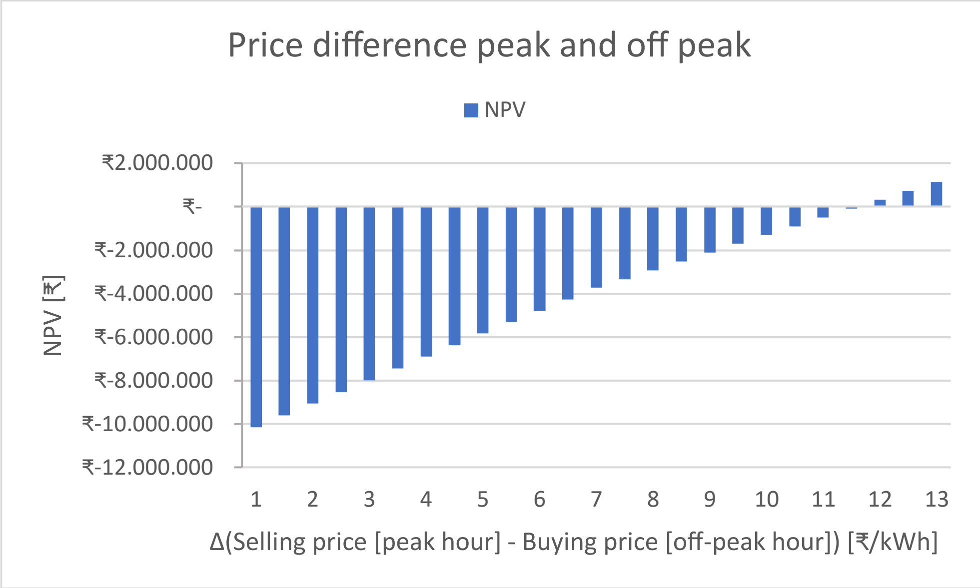

Figure 64. Sensitivity analysis. NPV vs price difference variation between off-peak and peak hours

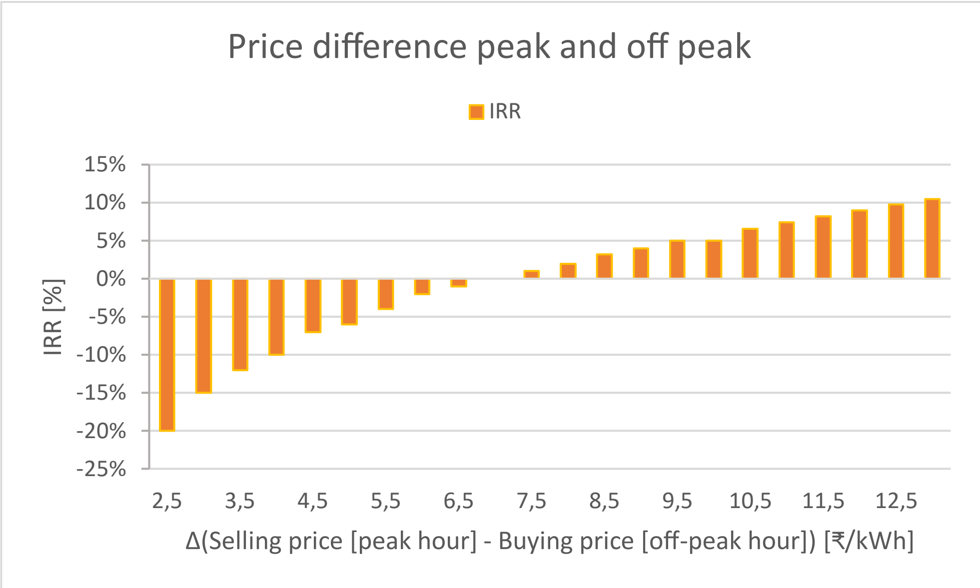

Figure 65. Sensitivity analysis. IRR vs price difference variation between off-peak and peak hours

Chapter 7

Conclusion

This chapter summarises the conclusions, intending to focus on conclusions for the tool development and the case study performed and points out the next steps to be performed in order to improve the presented work and tackle the present limitations as well as increase the scope of work.

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 ESOD 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.

Observing these factors, the ESOD tool can be an important asset in the Indian DISCOM sector improvement. The main advantage is the ability to bring a new debate to the table, where companies can analyse solutions that can be directly implemented without the need of the government or external entities. This can represent a step forward towards solving the distribution sector pain points. These companies require immediate solutions that can provide real benefits and the use of storage technologies is clearly one of the alternatives to continue studying and analysing for the next years.

To continue with the tool's conclusions, the main limitations must be highlighted. By using Excel, it was decided to avoid using coding language. This language is available in this software, however, for this initial tool design it was decided to leave out a coding structure. This means that the tool requires interaction from the developer in order to provide the full output results in the display page by selecting the peak hours of energy overload from the treated data. In the next section, a solution for this barrier is presented.

Moving on to the numerical results, as mentioned previously, 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 bust 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 DISCOM 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 this 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. As mentioned in Benefits of Energy Storage Systems in Distribution Networks, BESS at utility-scale do not only provide benefits for the grid of application, these systems are 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 have to 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 can 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 the user to be fully independent when using the tool, meaning the only task would be to input data and analyse the results obtained from 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. This will provide the user with valuable insights since the market currently lacks tools which can provide a full range of application analysis for both technical and financial aspects, an integrated software [60].

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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Annexe 1

Relevant information

This annexe provides major data analysed and used throughout the project development.

A.1 Current costs for utility-scale BESS in 2019

This section presents the estimated cost breakdown for a battery system at utility scale in 2019. The costs have been used to calculate the financial parameters in the tool.

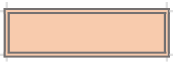
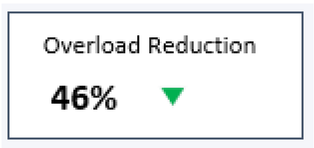
Table A 1. Current Component Cost Breakdown by System ($2019). [50],[70]

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**

A.2 ESOD layout

Table A 2. Cell types: Style and meaning

Image	**Description**	**Type**
	Red and blue gradient	Buttons. Allow the user to shift from one page to another in the User section.
	Blue and white gradient	Current page. Shows the user the currently visualized page.
	Blue box and white text	Guiding information. Provides guiding information such as instructions or explanations.
	Bottom and side lines	Titles
	Grey border	Data provided by the tool which the user may modify.
	Grey fill and grey border	Data provided by the tool which may not be modified by the user.
	Light yellow fill and black border	Inputs. The user may type an input or select from a list.
	Dark yellow fill and double black border	Input titles for Input page.
	Light salmon fill and double grey border	Output values for developer page.
	Light blue fill, white border, and shade	Button. Allows the user to visualize different sets of outputs.
	Blue border	Results presentation.

A.3 Cost estimation for utility-scale BESS

The following section provides the cost estimation performed from 2019 until 2050 for battery systems at utility scale for three scenarios, moderate, conservative and advanced for both CAPEX and OPEX based on power and energy units.

Table A 3. Utility-scale BESS stand-alone cost estimates - Moderate scenario. [50],[70]

Generated 2020/10/27						
		Utility- BESS Stand-Alone cost estimates - MODERATE BESS Assume 2019 60-MWe AC-Coupled Systems 2-10 hours of storage duration				
		year	batt_capex_per_kWh	batt_capex_per_kW	batt_om_per_kw	batt_om_per_kwh
		2019	326	250	2.5% of total capital costs	-
		2020	299	268	2.5% of total capital costs	-
		2021	272	284	2.5% of total capital costs	-
		2022	245	301	2.5% of total capital costs	-
		2023	219	318	2.5% of total capital costs	-
		2024	192	334	2.5% of total capital costs	-
		2025	165	351	2.5% of total capital costs	-

		2026	153	360	2.5% of total capital costs	-
		2027	143	363	2.5% of total capital costs	-
		2028	134	363	2.5% of total capital costs	-
		2029	125	359	2.5% of total capital costs	-
		2030	118	352	2.5% of total capital costs	-
		2031	114	357	2.5% of total capital costs	-
		2032	108	370	2.5% of total capital costs	-
		2033	103	380	2.5% of total capital costs	-
		2034	99	387	2.5% of total capital costs	-
		2035	95	392	2.5% of total capital costs	-
		2036	91	395	2.5% of total capital costs	-
		2037	88	397	2.5% of total capital costs	-
		2038	86	398	2.5% of total capital costs	-
		2039	83	398	2.5% of total capital costs	-

		2040	81	396	2.5% of total capital costs	-
		2041	79	395	2.5% of total capital costs	-
		2042	77	392	2.5% of total capital costs	-
		2043	75	389	2.5% of total capital costs	-
		2044	73	386	2.5% of total capital costs	-
		2045	72	382	2.5% of total capital costs	-
		2046	70	378	2.5% of total capital costs	-
		2047	69	373	2.5% of total capital costs	-
		2048	67	368	2.5% of total capital costs	-
		2049	66	362	2.5% of total capital costs	-
		2050	65	356	2.5% of total capital costs	-

Table A 4. Utility-scale BESS stand-alone cost estimates - Advanced scenario. [50],[70]

Generated 2020/10/27						
		Utility- BESS Stand-Alone cost estimates - ADVANCED BESS Assume 2019 60-MWe AC-Coupled Systems 2-10 hours of storage duration				
		year	batt_capex_per_kWh	batt_capex_per_kW	batt_om_per_kw	batt_om_per_kwh

		2019	326	250	2.5% of total capital costs	-
		2020	254	195	2.5% of total capital costs	-
		2021	236	181	2.5% of total capital costs	-
		2022	218	168	2.5% of total capital costs	-
		2023	200	154	2.5% of total capital costs	-
		2024	182	140	2.5% of total capital costs	-
		2025	165	126	2.5% of total capital costs	-
		2026	156	120	2.5% of total capital costs	-
		2027	147	113	2.5% of total capital costs	-
		2028	138	106	2.5% of total capital costs	-
		2029	129	99	2.5% of total capital costs	-
		2030	120	92	2.5% of total capital costs	-
		2031	117	90	2.5% of total capital costs	-
		2032	115	88	2.5% of total capital costs	-
		2033	113	87	2.5% of total capital	-

					costs	
		2034	110	85	2.5% of total capital costs	-
		2035	108	83	2.5% of total capital costs	-
		2036	106	81	2.5% of total capital costs	-
		2037	103	79	2.5% of total capital costs	-
		2038	101	78	2.5% of total capital costs	-
		2039	99	76	2.5% of total capital costs	-
		2040	96	74	2.5% of total capital costs	-
		2041	94	72	2.5% of total capital costs	-
		2042	92	70	2.5% of total capital costs	-
		2043	89	69	2.5% of total capital costs	-
		2044	87	67	2.5% of total capital costs	-
		2045	85	65	2.5% of total capital costs	-
		2046	82	63	2.5% of total capital costs	-
		2047	80	61	2.5% of total capital costs	-

		2048	78	60	2.5% of total capital costs	-
		2049	75	58	2.5% of total capital costs	-
		2050	73	56	2.5% of total capital costs	-

Table A 5. Utility-scale BESS stand-alone cost estimates - Conservative scenario. [50],[70]

Utility- BESS Stand-Alone cost estimates - CONSERVATIVE BESS Assume 2019 60-MWe AC-Coupled Systems 2-10 hours of storage duration				
year	batt_capex_per_kWh	batt_capex_per_kW	batt_om_per_kw	batt_om_per_kwh
2019	326	250	2.5% of total capital costs	-
2020	317	244	2.5% of total capital costs	-
2021	309	237	2.5% of total capital costs	-
2022	300	231	2.5% of total capital costs	-
2023	292	224	2.5% of total capital costs	-
2024	283	218	2.5% of total capital costs	-
2025	275	211	2.5% of total capital costs	-
2026	268	206	2.5% of total capital costs	-
2027	262	201	2.5% of total capital	-

			costs	
2028	255	196	2.5% of total capital costs	-
2029	249	191	2.5% of total capital costs	-
2030	243	186	2.5% of total capital costs	-
2031	240	184	2.5% of total capital costs	-
2032	237	182	2.5% of total capital costs	-
2033	233	179	2.5% of total capital costs	-
2034	230	177	2.5% of total capital costs	-
2035	227	175	2.5% of total capital costs	-
2036	224	172	2.5% of total capital costs	-
2037	221	170	2.5% of total capital costs	-
2038	218	168	2.5% of total capital costs	-
2039	215	165	2.5% of total capital costs	-
2040	212	163	2.5% of total capital costs	-
2041	209	161	2.5% of total capital costs	-

2042	206	158	2.5% of total capital costs	-
2043	203	156	2.5% of total capital costs	-
2044	200	154	2.5% of total capital costs	-
2045	197	151	2.5% of total capital costs	-
2046	194	149	2.5% of total capital costs	-
2047	191	147	2.5% of total capital costs	-
2048	188	144	2.5% of total capital costs	-
2049	185	142	2.5% of total capital costs	-
2050	182	140	2.5% of total capital costs	-

A.4 Projections of NPV and IRR based on cost projections per scenario

The following section presents the NPV and IRR results obtained by introducing the energy cost projections in the ESOD tool.

Table A 6. Financial projection results utility-scale BESS. Moderate scenario.

	Utility- BESS Stand-Alone cost estimates - MODERATE BESS	**NPV**	**IRR**
year	batt_capex_per_kWh	NPV [₹]	IRR [%]

2019	326	₹ -7.881.261,69	-17%
2020	299	₹ -6.985.708,93	-15%
2021	272	₹ -6.090.156,18	-13%
2022	245	₹ -5.194.603,42	-11%
2023	219	₹ -4.334.174,75	-9%
2024	192	₹ -3.450.623,42	-7%
2025	165	₹ -2.567.072,10	-4%
2026	153	₹ -2.174.382,62	-3%
2027	143	₹ -1.847.141,39	-1%
2028	134	₹ -1.552.624,28	0%
2029	125	₹ -1.275.381,32	1%
2030	118	₹ -1.080.828,20	2%
2031	114	₹ -969.654,99	2%
2032	108	₹ -802.895,18	3%
2033	103	₹ -663.928,67	4%
2034	99	₹ -552.755,46	4%
2035	95	₹ -441.582,25	5%
2036	91	₹ -330.409,04	6%
2037	88	₹ -247.029,13	6%
2038	86	₹ -191.442,53	7%
2039	83	₹ -108.062,62	7%
2040	81	₹ -52.476,02	8%
2041	79	₹ 3.110,59	8%

2042	77	₹ 58.697,19	9%
2043	75	₹ 114.283,80	9%
2044	73	₹ 169.870,40	10%
2045	72	₹ 197.663,70	10%
2046	70	₹ 253.250,31	11%
2047	69	₹ 281.043,61	11%
2048	67	₹ 336.630,21	12%
2049	66	₹ 364.423,52	12%
2050	65	₹ 392.216,82	12%

Table A 7. Financial projection results utility-scale BESS. Advanced scenario.

	Utility- BESS Stand-Alone cost estimates - ADVANCED BESS	**NPV**	**IRR**
year	batt_capex_per_kWh	NPV [₹]	IRR [%]
2019	326	₹ -7.881.261,69	-17%
2020	254	₹ -5.493.121,01	-12%
2021	236	₹ -4.896.085,84	-11%
2022	218	₹ -4.301.450,63	-9%
2023	200	₹ -3.712.416,41	-7%
2024	182	₹ -3.123.382,19	-6%
2025	165	₹ -2.567.072,10	-4%
2026	156	₹ -2.272.554,99	-3%
2027	147	₹ -1.978.037,88	-2%

2028	138	₹ -1.683.520,77	-1%
2029	129	₹ -1.389.003,67	0%
2030	120	₹ -1.136.414,81	1%
2031	117	₹ -1.053.034,90	2%
2032	115	₹ -997.448,30	2%
2033	113	₹ -941.861,69	2%
2034	110	₹ -858.481,78	3%
2035	108	₹ -802.895,18	3%
2036	106	₹ -747.308,58	3%
2037	103	₹ -663.928,67	4%
2038	101	₹ -608.342,06	4%
2039	99	₹ -552.755,46	4%
2040	96	₹ -469.375,55	5%
2041	94	₹ -413.788,95	5%
2042	92	₹ -358.202,34	6%
2043	89	₹ -274.822,44	6%
2044	87	₹ -219.235,83	7%
2045	85	₹ -163.649,23	7%
2046	82	₹ -80.269,32	8%
2047	80	₹ -24.682,72	8%
2048	78	₹ 30.903,89	9%
2049	75	₹ 114.283,80	9%
2050	73	₹ 169.870,40	10%

Table A 8. Financial projection results utility-scale BESS. Conservative scenario.

	Utility- BESS Stand-Alone cost estimates - CONSERVATIVE BESS	**NPV**	**IRR**
year	batt_capex_per_kWh	NPV [₹]	IRR [%]
2019	326	₹ -7.881.261,69	-17%
2020	317	₹ -7.582.744,10	-17%
2021	309	₹ -7.317.395,14	-16%
2022	300	₹ -7.018.877,55	-15%
2023	292	₹ -6.753.528,59	-15%
2024	283	₹ -6.455.011,00	-14%
2025	275	₹ -6.189.662,04	-14%
2026	268	₹ -5.957.481,69	-13%
2027	262	₹ -5.758.469,97	-13%
2028	255	₹ -5.526.289,63	-12%
2029	249	₹ -5.327.277,90	-12%
2030	243	₹ -5.128.266,18	-11%
2031	240	₹ -5.028.760,32	-11%
2032	237	₹ -4.929.254,46	-11%
2033	233	₹ -4.796.579,97	-10%
2034	230	₹ -4.697.074,11	-10%
2035	227	₹ -4.597.568,25	-10%
2036	224	₹ -4.498.062,39	-10%
2037	221	₹ -4.399.623,00	-9%

2038	218	₹ -4.301.450,63	-9%
2039	215	₹ -4.203.278,26	-9%
2040	212	₹ -4.105.105,89	-9%
2041	209	₹ -4.006.933,52	-8%
2042	206	₹ -3.908.761,15	-8%
2043	203	₹ -3.810.588,78	-8%
2044	200	₹ -3.712.416,41	-7%
2045	197	₹ -3.614.244,04	-7%
2046	194	₹ -3.516.071,67	-7%
2047	191	₹ -3.417.899,30	-7%
2048	188	₹ -3.319.726,93	-6%
2049	185	₹ -3.221.554,56	-6%
2050	182	₹ -3.123.382,19	-6%