ENERGY STORAGE

Analysis of thermal energy storage interventions in Andhra Pradesh

Cost-Benefit Analysis

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ANDHRA PRADESH PRIORITIES — AN INDIA CONSENSUS PRIORITIZATION PROJECT

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Short Abstract

India is expected to face a rising energy demand in future. Presently, India's energy demand is primarily being met through coal. A minor portion of the total energy demand is being met through other renewable sources viz. solar and wind. More than 30% of the total energy demand arises from the commercial building sector of India which is expected to grow with a rising urbanization in future. Hence to reduce dependence on fossil fuels like coal, energy conservation measures by means of thermal energy storage (TES) in commercial buildings can be an option. TES can help to address the gap between demand and supply of energy by peak load shaving and shifting in commercial buildings of India. The paper analyzes the nature of benefits and costs from TES applications in commercial building sector for two technological applications (with ice and hybrid salt as phase change materials respectively) in the state of Andhra Pradesh in an ex-ante situation when the technology is yet to be widely applied in commercial buildings. Indian commercial buildings have been more recently exposed to this concept of energy storage and there are only a handful of commercial building facilities that have installed such a system. A plethora of impediments and barriers exists which needs to be overcome while installing TES in the commercial building sector. These barriers include high upfront costs, challenges in sustained economic benefit generation, dearth of information and awareness, and lack of policy and institutional support. The analysis conducted in the paper shows that the benefits can be more than twice the costs in future from thermal energy storage applications in commercial buildings of Amaravati. The benefit streams will vary across technologies and would also be contingent on the discount rates used. These benefits can arise mainly from energy savings and emission reduction from reduced energy consumption leading to lesser coal consumption for electricity generation in future.

Abbreviations and Acronyms

EIA – US Energy Information Administration

Ft – Feet

Hr – Hour

HVAC- Heating, Ventilation and Air Conditioning

Kcal- Kilocalorie

Kg – Kilogram

KJ- Kilo Joules

KWh- Kilo Watt hour

KVA- Kilo Volt Ampere

L- Litres

LHTES- Latent Heat Thermal Energy Storage

Mbtu- Million British Thermal Unit

MT- Metric Ton

MW- Mega Watt

PCM- Phase Changing Material

sq. ft. – Square Feet

TR- Ton of Refrigeration

TES- Thermal Energy Storage

Extended Policy Abstract

The Problem

The energy demand in the commercial sector of India is steadily increasing owing to an economic growth spurred by a rise in service sector growth. In the commercial sector of the economy, building energy consumption is increasing rapidly and is expected to follow the same pattern in future. According to an EIA (U.S. Energy Information Administration) projection, the fastest growth in commercial building energy consumption by 2040 will occur in India. Energy consumption in commercial building sector of India is expected to increase by an average of 2.7% by 2040, which is more than twice the global average (EIA (2017); (Cabeza et al, 2002)). In India, the building sector consumes approximately about 31% of the total energy production of India. Within this, nearly 9% is consumed by commercial buildings (UNDP (2011)). India's current energy demand is primarily being met through coal with a minor portion of the total energy demand being met by other renewable sources viz. solar and wind. More than 30% of the total energy demand arising from the commercial building sector of India which is expected to grow with a rising urbanization in future. Hence to reduce dependence on fossil fuels like coal, energy conservation measures by means of thermal energy storage (TES) in commercial buildings can be an option.

To curb building energy use and final energy demand of the Indian building sector, targeted sectoral policy intervention is required. The rising energy demand in commercial buildings is accompanied by a rise in electricity use leading to a rapid increase in carbon emissions and aggravating power shortages in India. To tackle the problems arising from growing building energy use, the Indian government had issued the Energy Conservation Building Code (ECBC) in 2007. The ECBC (2007) includes several new features that include optimal use of daylight and natural ventilation and mandatory use of renewable energy among others. According to the United Nations Development Program (UNDP, 2017) code compliance in India has reached 64% by 2017. Ten states have notified ECBC and they are - Odisha, Uttarakhand, UT of Puducherry, Andhra Pradesh, Punjab, Haryana, West Bengal, Karnataka, Rajasthan and Andhra Pradesh.

Andhra Pradesh is one of the fastest-growing states of India, with demand for commercial office-space. It has increased since 2005, when the demand for office space was less than 2 million. With such a rise in building space demand which is expected to continue, energy demand is also projected to increase. Incorporating energy efficiency in new and existing buildings is thus a necessity.

The state of Andhra Pradesh adopted an Energy Conservation Building Code (ECBC) for large commercial and public buildings and major retrofits. The ECBC is expected to reportedly reduce energy consumption by as much as 40-60%, improve reliability of access to electricity, and enable consumers to save money. A recent analysis carried out Natural Resources Defense Council (NRDC) and Administrative Staff College of India (ASCI) indicate that adopting the code in Andhra Pradesh could save the amount of energy by 2030 that's needed to power 8.9 million Indian households annually over that time frame.[1]

The code has been made mandatory and effective from December 2014. It is applicable to newly constructed commercial and non-residential buildings that have a plot area of more than 1000 square meters or built up area of 2000 square meters. The code does not apply to ***factories, individual homes and multifamily residential buildings***. The code is also mandatory for multiplexes, hospitals, hotels and convention centers even if their built up area is less than or equal to 2000 square meters. The actions taken so far include new policies for promoting energy conservation measures in the state like mandatory procurement of BEE energy star rated appliances for government offices, conducting IGEA in Government buildings, Energy Conservation Act 2001 awareness workshops and waste heat recovery studies in Industries among others.

To further build on the actions taken, several steps and actions have been identified by the GHMC technical team to advance the implementation of ECBC in Andhra Pradesh that include:

- Strengthening the compliance mechanism by empaneling the pool of Third Party Assessors (TPA). TPAs are the pool of technical experts who are trained and certified by ASCI to carry out independent assessments of new commercial buildings for ECBC norms. (21)

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[1] https://www.nrdc.org/media/2014/140128

- To create market value, the state designated agency Andhra Pradesh State Renewable Energy Development Corporation will develop a label for "TS ECBC Compliant Building."(21)
- The state government will recognize and award most efficient ECBC compliant building annually on the National Energy Conservation Day in December. (21)
- In addition to immediate actions, the committee also recognized and noted the importance of scaling up ECBC to the state level. The energy department and the MA&UD will issue notifications to all ULBs across the state to comply with ECBC for all new government buildings.(21)
- To have a sustainable and effective ECBC compliance, the state government is also planning towards developing mechanisms to establish energy performance monitoring and verification system.(21)

Intervention: Thermal Energy Storage for commercial buildings

OVERVIEW

The ECBC provides minimum energy efficiency requirements for the five building systems of building envelope (walls, roof, etc.), lighting, service water heating, electrical power and Heating, Ventilation and Air Conditioning (HVAC) systems.

Heating, Ventilation and Air Conditioning (HVAC) systems are key contributors to peak loads of commercial buildings and contribute nearly 40% of the energy demand of a commercial building in India (Rajan, S. (2016)). Growing microclimatic urban temperatures, thermal comfort, consumer lifestyles have cumulatively given rise to the demand for controlled climate spaces in the last two decades in mechanically controlled commercial buildings. In Mumbai, for example, HVAC use in commercial buildings during the peak time in the afternoon contributes to over 40% of the demand, which is about 1280 MW (peak of 3200 MW) in summer and 1120 MW (peak of 2800 MW) in winter. Commercial buildings of urban centres face higher prices to meet the peak demand leading to high cost of electricity use. This could be curtailed to a large extent by moving towards efficient end-use Load Management thus making TES a lucrative option. In the commercial building segment of India, the main application of TES therefore would be in the Air Conditioning (AC) segment. This can be achieved by the following applications:

- Full Storage TES: In this application, the entire peak load is shifted to off-peak time. For example, if 100 TR-hours is the cooling requirement, TES can be used in the off-peak time to reach a capacity of 100 TR-hours and this stored energy can be used during the peak-time for cooling requirements. No power is drawn from the grid during the peak-time.
- Partial Storage TES: In this application, only partial load is shifted to off-peak time. For example, if 100 TR-hours is the cooling requirement, TES can be used in the off-peak time to reach a capacity of about 50-60 TR-hours. During the peak-time, the stored energy can be used to meet partial load while the remaining load is drawn from the grid power.

to increase the thermal storage capacity by influencing the latent heat of phase change. Thus, the nature of PCMs can affect the nature of thermal storage. Thus the two interventions are: The study examines the benefit-cost ratio for TES in commercial buildings **for two types of interventions based on phase change materials (namely ice and hybrid salt) for the state of Andhra Pradesh.** Phase change materials (PCMs) are used with TES applications

1. TES with ice as PCM
2. TES with hybrid salt as PCM

The analysis is conducted in an *ex ante* situation of a technology with future uncertainties where there is still not a wide scale application of TES technology in commercial buildings of India. For our study, we consider commercial buildings in the city of Amaravati. The detailed assumptions and the methodology of the study are hence applied in an *ex ante* context.

Implementation Considerations

Timeline: It is an ex-ante study that has been estimated for a period of 15 years.

Risks: There are certain challenges in an *ex ante* context to undertaking or implementing the technology that has been explored in this paper. These challenges relate to the widespread deployment of above thermal energy storage applications in the commercial building contexts of India. They are -

- Cost competitive energy storage technologies (including manufacturing and grid integration)

- Validated reliability & safety
- A fair regulatory environment
- Techno-economic commercial feasibility and industry acceptance.

How to measure success: Discounted benefit-cost ratio has been considered as the indicator of success for this study. For calculating the benefit-cost ratio net present value for a period of 15 years has been considered. A higher benefit cost ratio (more than one) is one of the ways of measuring the success of TES application in commercial buildings.

Quality of information: The quality of information is high as it has been backed by primary data, technological validation and is contextually relevant. The base assumptions that have been made in calculating the BCR are based on multiple stakeholder consultations, field expert views and drawing from secondary literature.

Costs and Benefits

The primary data that have been used for our model simulation are presented in the table below.

Table A: Summary Data

Building	Carpet Area(Square feet)	Heating/ AC Load(KW/day)	Building location	Commercial building type	Thermal Storage Type
1	600000	9750	Amaravati	Retail	Water
2	350000	6000	Amaravati	Retail	Water
3	250000	4000	Amaravati	Retail	Water
4	347000	24000	Amaravati	Hotel	Water
5	870000	26000	Amaravati	Office	Salt hybrid
6	580000	10000	Amaravati	Office	Salt Hybrid
7	866000	12000	Amaravati	Office	Salt Hybrid

Costs

Table- A.1 : Total cost for the intervention

Building	Capital Costs for Thermal Storage (Lakh INR)	Annual O&M Expense for Ice (Lakh INR)	Annual O&M Expense for Hybrid Salt (Lakh INR)
1	2237.54	111.88	134.25
2	1305.23	65.26	78.31
3	932.31	46.62	55.94
4	1294.04	64.70	77.64
5	3244.44	162.22	194.67
6	2162.96	108.15	129.78
7	3229.52	161.48	193.77

Breakup of direct costs

Table- A.2: Assumptions for capital cost: **

Cost of Screw Chiller	INR 15000/TR of cooling
Pump cost	INR 7500/KW
Cooling Tower	INR 5000/TR
Storage	2000 L fire water tank
Cost of Insulation	INR 0.50/L of storage
Chiller Plant Efficiency	0.8 Kw/TR
Power Factor	0.90
Savings in DG	INR 10000/KVA
Chiller Plant Cost	INR 70,000/TR
Average annual loading	0.7 of peak load
Summer days	200
Hours per day	20

** A private educational institute's building has been considered as a pilot for this purpose. The capital cost has also been optimized for carpet area.

Benefits

Table – B: Total benefit for the intervention

Building	Energy Saved Per Year (In MWh)	Yearly Energy Benefit (INR)	Tonnes of CO2 Equivalent Avoided	Yearly Carbon Benefits at 5% Discount Rate (INR)
1	9072	76,204,800	9,474	5,177,895
2	5292	44,452,800	5,526	3,020,439
3	3780	31,752,000	3,947	2,157,456
4	5247	44,071,776	5,479	2,994,549
5	13154	110,496,960	13,737	7,507,948
6	8770	73,664,640	9,158	5,005,299
7	13094	109,988,928	13,674	7,473,429

Breakdown of the direct social and private benefits

The direct benefits have been considered in terms of the energy and carbon emission savings. Indirect benefits could be generated in terms of long term employment generation is which if included will increase the benefit cost ratio for different discount rates in the long term. The benefits through energy and carbon emission will lead to climate change mitigation measures, reduced coal consumption, reduced emissions with concomitant health benefits. The commercial building users by means of energy savings will also save in terms of reduced energy expenses through the application of TES in the commercial buildings after the payback period (which is generally believed to be between 3 – 6 years based on the building and the local context) for the TES application is over for the commercial building.

Table-C: Summary BCR Table

Intervention	Benefit per sq ft of building carpet area	Cost per sq ft of building carpet area	BCR	Strength of Evidence
Water based thermal energy storage for commercial buildings	1,448	531	2.72	Strong
Salt Hybrid based thermal energy storage for commercial buildings	1,448	566	2.56	Strong

Based on 5% discount rate. Period of analysis is 15 years

1. Introduction

Energy is important in human lifestyle as almost every modern day activity is driven by energy. Starting from every day domestic activities such as boiling water to running an industrial plant, the avenues of energy use are limitless. The energy demand in the commercial sector of India is steadily increasing owing to a rise in economic and service sector growth. In the commercial sector, building energy consumption is increasing rapidly and is expected to follow the same pattern in future. According to an EIA (U.S. Energy Information Administration) projection, the fastest growth in commercial building energy consumption by 2040 will occur in India. Energy consumption in commercial building sector of India is expected to increase by an average of 2.7% by 2040, which is more than twice the global average (EIA (2017), Cabeza et al, (2002)). In India, the building sector consumes approximately about 31% of the total energy production of India. Within this, nearly 9% is consumed by commercial buildings (UNDP (2011))

Nearly three-quarters of this energy demand is met by fossil fuels, with coal accounting for over 70% of energy generation (EIA). However, use of fossil fuels to meet energy demands is an unsustainable option as their availability is limited. Also, toxic carbon emissions arising from use of low grade fossil fuels like poor quality coal remain a challenge for developing countries like India. India can contribute to 7% of the world's coal-related carbon dioxide emissions considering the time period of 2006 to 2030. Carbon dioxide emissions from coal combustion have been projected to total 1.3 billion metric tonne in 2030 (TERI, (2006)). Therefore, energy conservation measures in commercial building sector to reduce energy and low grade coal consumption will be an important measure in future in the context of India. Energy storage by means of thermal energy storage (TES) applications in commercial buildings of India can be a potential solution to tackle the increasing energy demands for commercial building, will be able to reduce carbon emissions as well as can contribute in solving the intermittency problem of renewable energy sources (Becherif, (2015)).

1.1 Benefit of TES

TES apart from solving the intermittency problem of renewable sources can be integrated with conventional thermal power stations for storage of excess off-peak energy for use at peak times which may also increase plant efficiency. Thermal energy storage use in buildings can improve passive temperature control (e.g., with the use of phase-change materials [PCMs]), enable demand side management/peak load shifting, reduce required peak heating and cooling loads, enable improved waste heat utilization, improve combined heat and power utilization by enabling non-coincident electric and thermal loads to be met. This can reduce the overall energy peak demand load of commercial buildings. TES, because of its ability to shift peak load also promotes energy efficiency, therefore making it a lucrative option for tackling increasing energy demands (Becherif, (2015) & Dincer, (2002)). With this background, the next section highlights the nature of materials which are currently and are envisaged to be used as phase change materials in thermal energy storage applications for commercial buildings in India.

1.2 Materials used for Thermal Energy Storage in commercial buildings

Phase Changing Materials (PCM) are best suited for use in buildings as they have latent heating and melting points close to ambient temperature, typically below the latent heat of water (333 kJ L-1) (Becherif et al, (2015). PCMs can be divided into two main families of organic and inorganic. Organic materials can be further classified into paraffin and non-paraffin such as esters, fatty acids, alcohols and glycols. Inorganic materials are subdivided into salt hydrates and metallics. Traditional PCMs such as paraffin fall well below the threshold of 333 KJ / L while hydrates have higher latent heats. Phase change materials use the latent heat of melting/solidification process to store energy thereby making them a suitable facilitator for load shifting. Hot and/or cold thermal energy storage technologies improve the ability to reduce and shift peak load from air conditioning in a commercial building.

Literature indicates that extra pumping energy related losses associated with TES systems can be within the range of 1% - 5%, which is on the higher side. Technical simulation exercises indicate that if the energy saving/supply has to be the tune of say 20 KW, then a pump of 1 KW can be required. This means a net energy savings of 19 KW will happen. It essentially translates to a – 1/20 = 5% loss in energy savings at most. This also indicates that for any TES with the proper technical optimization, the energy output to input ratio will always be greater than one leading to net energy savings even with energy consumption by pumps. In order to tackle the poor heat transfer characteristics, globally and even in India, several measures are being taken by industry players. These measures include – a) Introduction of graphite and paraffin, b) Addition of filler materials like metallic rings, capsules and finned tubes to increase thermal conductivity. These measures are currently being introduced by several industry players and on an average the energy savings are increased by 15% - 20% due to these measures.

Sustainable heating and cooling in commercial buildings using TES has gained importance because there is an increasing demand worldwide, and especially in India for heating and cooling. In such a situation, TES is important in its capacity to alleviate peak energy load and move towards a greener and more sustainable energy consumption in the near future. In the next section, a brief review of the existing literature is done before introducing the entry point of our study followed by methodology, findings, outcomes and policy conclusions.

2. Thermal Energy Storage implementation in HVAC Systems

2.1 Description of intervention

Heating, Ventilation and Air Conditioning (HVAC) systems are key contributors to peak loads of commercial buildings and contribute nearly 40% the energy demand of a commercial building in India (Rajan, S. (2016)). Growing microclimatic urban temperatures, thermal comfort, consumer lifestyles have cumulatively given rise to the demand for controlled climate spaces in the last two decades in mechanically controlled commercial buildings. In Mumbai, for example, HVAC use in commercial buildings during the peak time in the afternoon contributes to over 40% of the demand, which is about 1280 MW (peak of 3200 MW) in summer and 1120 MW (peak of 2800 MW) in winter. Commercial buildings of urban centres face higher prices to meet the peak demand leading to high cost of electricity use. This could be curtailed to a large extent by moving towards efficient end-use Load Management thus making TES a lucrative option.

In the commercial building segment of India, the main application of TES therefore would be in the Air Conditioning (AC) segment. This can be achieved by the following applications:

- **Full Storage TES:** In this application, the entire peak load is shifted to off-peak time. For example, if 100 TR-hours is the cooling requirement, TES can be used in the off-peak time to reach a capacity of 100 TR-hours and this stored energy can be used during the peak-time for cooling requirements. No power is drawn from the grid during the peak-time.
- **Partial Storage TES:** In this application, only partial load is shifted to off-peak time. For example, if 100 TR-hours is the cooling requirement, TES can be used in the off-peak time to reach a capacity of about 50-60 TR-hours. During the peak-time, the stored energy can be used to meet partial load while the remaining load is drawn from the grid power.

The entire map, particulars of the technology specific applications is outlined in the table below:

Table 1: Technology specific particulars for TES Applications

Particulars	Full Storage TES	Partial Storage TES
Required difference between Peak and Off-Peak electricity cost for economic feasibility of technology	✓✓✓✓	✓✓
Required duration of peak load for economic feasibility of technology	✓	✓✓✓
Required demand Charges for economic feasibility of technology	✓✓✓✓	✓✓
Cost of technology	✓✓✓✓	✓✓
Demand and Energy Savings	✓✓✓✓	✓✓

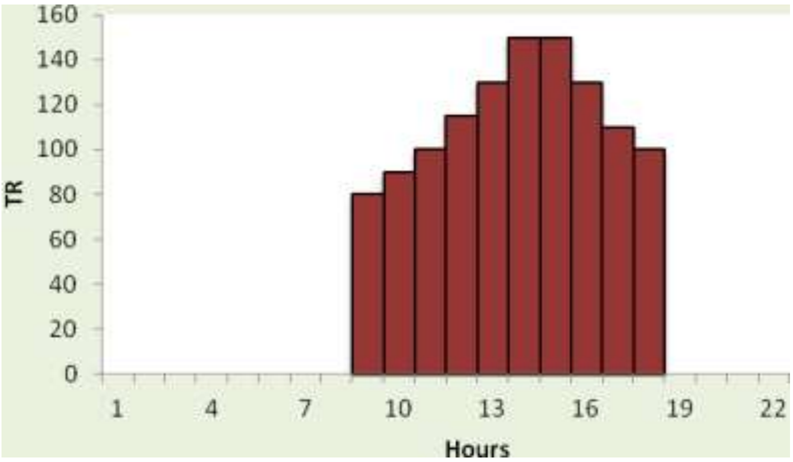
Legend:

✓: Low, ✓✓: Medium, ✓✓✓: High, ✓✓✓✓: Very High

Source: MP Ensystems' Analysis

The application of peak load shifting is illustrated further with the examples in Figure 1, Figure 2, and Figure 3. An AC load of 150 TR is considered for illustration. The total TR-hours requirement for the hypothetical commercial building establishment is 155.

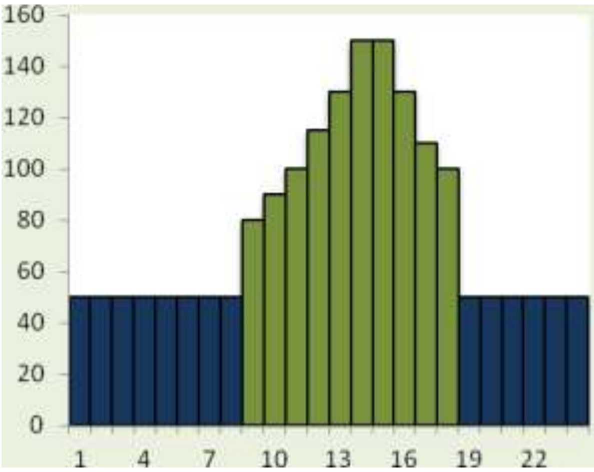
Figure 1: AC load (TR) of a typical commercial consumer (Illustration)



Source: Adapted from MP Ensystems' analysis

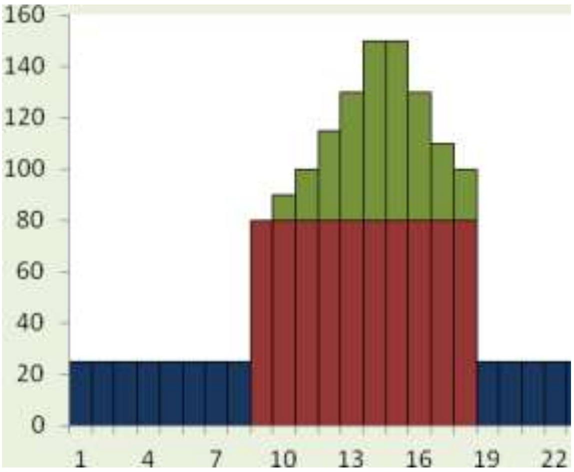
The chart above is a typical AC load (TR) for a commercial building consumer. The peak occurs for two hours from 2 PM to 3 PM. If a thermal storage is installed in the commercial building establishment to reduce the peak usage by performing thermal storage during off-peak, the load curves would pertain to the following:

Figure 2: Full Storage TES



Source: Adapted from MP Ensystems' analysis

Figure 3: Partial Storage TES



Source: Adapted from MP Ensystems' analysis

However, there are four challenges related to the widespread deployment of above thermal energy storage applications in the commercial building contexts of India. These challenges pertain to:

- Cost competitiveness of energy storage technologies (including manufacturing and grid integration)
- Validated reliability & safety
- Techno-economic commercial feasibility and industry acceptance.

Our study intervenes at the fourth point of technoeconomic commercial feasibility leading to a discount rate sensitive classical benefit cost analysis. To conduct sensitivity of benefit cost ratio to different discount rates we essentially calculate a cost stream and a benefit stream for each commercial building. Then we find out the ratio of benefit to cost for different discount rates to investigate how feasible TES using PCM is in commercial buildings in the Indian context in future. The analysis is conducted in an *ex-ante* situation of a technology with future uncertainties where there is still not a wide scale application of TES technology in commercial buildings of India. For our study, we consider commercial buildings in the city of Amaravati of the state Andhra Pradesh. The detailed assumptions and the methodology of the study is hence applied in an *ex ante* context and highlighted in the next section.

2.2 Data

The primary data that has been used for our model simulations have been presented in the table below.

Table 2: Description of the Data

Building	Carpet Area (Square Feet)	Heating/AC Load (KW/day)	Building Location	Building Type
1	600000	9750	Amaravati	Retail
2	350000	6000	Amaravati	Retail
3	250000	4000	Amaravati	Retail
4	347000	24000	Amaravati	Hotel
5	870000	26000	Amaravati	Office
6	580000	10000	Amaravati	Office
7	866000	12000	Amaravati	Office

2.3 Literature Review

Literature with regards to LHTES (Latent Heat Thermal Energy Storage) deals with research and development of heat storing potential of PCM, application for energy storage purposes and technoeconomic interventions and systems modeling of thermal energy storage applications (Abhat 1983; Kim & Norford 2017. Early work in the domain of LHTES was mostly focusing on R&D (research and development) of PCM and their storage applications. Across the world, R&D has been carried out for nearly all PCMs including organic and inorganic heat storage materials classified as paraffins, fatty acids, inorganic salt hydrates and eutectic compounds (Abhat, 1983); (Anisur et al, 2013); (Beerbaum & Weinrebe, 2000); (Cabeza et al, 2003);(Chiu Martin & Setterwall, 2009); (De Gracia & Cabeza, 2015); (Dincer, 2002); (Haghshenaskashani & Pasdarshahri, 2009); (Hamdan & Elwerr, 1996); (Hasnain, 1998); (Khan,Rasul, & Khan, 2004); (Py, Olives & Mauran, 2001); (Xiao,Feng, & Gong, 2002);(Yang, 2017) ; (Zalba,Marın, Cabeza & Mehling, 2003); (Zhou, Zhao & Tian, 2012).

De Gracia et al. 2015 highlights that Thermal Energy Storage (TES) is important in its capacity to shave peak load and for increasing efficiency in HVAC systems. Advantages of TES in an energy system are seen through an increase in overall efficiency and reliability, better economics, reduced investments and running costs and less pollution of environment and less CO_2 emissions (Dincer 2002, De Gracia et al, 2015). TES can be achieved through three methods, namely sensible, latent and thermochemical storage methods (De Gracia et. al, 2015). Of these three, latent heat storage is becoming increasingly popular because of its ability to minimize the gap between peak and off-peak loads of electricity demands. PCM absorb or release a large amount of heat while changing phase from solid to liquid or vice-versa. When this characteristic of PCM is utilized it can be employed effectively for energy conservation in commercial buildings (Kim et al, 2014). Due to the capacity to store energy, phase change materials can also reduce the cooling load of air conditioning during summer season by means of cooling at night (Zhou et al, 2012). Through its ability to shave off-peak load LHTES helps save operative costs of building (Zhang et al, 2007). In sum, LHTES can promote energy conservation with thermal comfort suiting to the climatic specificities of a place (Zhou et al, 2012).

Ibrahim & Ilinca, 2013 suggests that TES has high heat cycle efficiency (70% - 90%) and can prove particularly beneficial for commercial buildings and renewable energy storage. LHTES can be economically viable in commercial building applications Sun et. al, 2014 along with promoting thermal comfort and energy conservation. Haghshenaskashani & Pasdarshahri, 2009 have shown through a simulation model, that depending on the quality of PCM maximum entering heat flux to building can be reduced about 32.8% for real applications for the city of Tehran in Iran. Mandilaras, 2013 have demonstrated, that under adopted conditions (unoccupied homes and no energy systems), the decrement factor reduces by 30-40% due to implementation of PCM for a Mediterranean residential building. Kim et al, 2014 have demonstrated reduced energy consumption for Korean residential buildings through thermal energy storage applications. Sun et.al, 2013 have demonstrated through an energy and economic analysis that building enclosures with phase change materials boards (PCMB) can save energy through using a natural cold source and reduction in electricity consumption by air conditioning system. This has been proven to be true for five different regions of China.

An important criterion for any new technology for a developing country like India is its commercial viability. Commercial viability can be tested through technoeconomic simulations and analysis. A number of technoeconomic analysis has been carried out with regard to LHTES. Khan et. al, 2004 carried out a techno-economic analysis for energy-conservation opportunity in an institutional building by means of application of LHTES. Yan et al, 2014 undertook techno-economical and social evaluation methodologies for energy storage systems for commercial buildings and demonstrated the commercial viability of the technology. Becherif et. al, 2015 explored the possibilities of an efficient hydrogen production and storage technology, and the impact of policy on its development by means of a comprehensive techno/socio/economic study of long term hydrogen based storage systems in electrical networks applicable to different types of buildings.

Enhancement of energy efficiency is a key reason for promotion of TES in commercial buildings. It is expected that an increase of energy efficiency will lead to a cost-effective pathway for reducing green house gas emission (Parameswaran et. al, 2012). Benefits from carbon emission reduction due to TES installations in buildings are relatively unexplored and there is scanty literature in that domain for Indian context. For developed countries there exists some literature. Anisur et. al, 2013 have emphasized the opportunities and scope for energy savings and greenhouse-gas emissions reduction with the implementation of PCM in TES systems. Darkwa, 2000 has carried out a mathematical evaluation of phase change wall systems for reducing energy consumption in buildings and CO_2 emissions in the UK. Hence, from literature it emerges that technoeconomic simulation leading to a discount rate specific classical benefit cost analysis that looks into the feasibility of TES using phase changing materials in commercial building is scarce in the Indian Context. This research and analysis does the task of bridging this gap.

2.4 Calculation of the Costs and Benefits

First a research design table is presented followed by a detailed methodology that has been adopted for model building, estimation and simulation.

3. Research Design

Table -3: Research Design Summary

Research Type	Research Design
Primary (P)	Observational. Interview was conducted across 7 data points in Andhra Pradesh across the district of Amaravati. For building the model on which the data simulation was performed, observation and estimations of an educational institution that has already integrated TES in its HVAC systems have been used.
Secondary(S)	Non- Systematic review method. The review method was used to summarize and synthesize existing literature on TES and its application so as to find out the gaps in the sector, where the study described in this paper can intervene.

4. Detailed Methodology:

The methodology has two basic components – a) Secondary Data Analysis and b) Primary Data Analysis through field survey. As a part of the secondary data analysis, technoeconomic data is collected validated from various stakeholders leading to a technoeconomic simulation. The results of the technoeconomic simulation have led to the formation of some parameters of costs which have been applied in the benefit cost ratio calculations for every discount rate by constructing a financial simulation model. Further, data and parameters have been validated through a case study analysis of the model. This has been backed up by the primary data of seven commercial buildings of Amaravati. The load profile, capital costs and benefit streams of these buildings have been gathered to use as an input in the model for coming up with a discount rate specific benefit cost ratio for every chosen commercial building of Amaravati. The commercial buildings considered are from hotel, tourism and health sector in Amaravati from the state of Andhra Pradesh. With this methodological outline, the assumptions are described below:

The basic model input assumptions of the model are outlined below:

Assumptions:

- **Input parameters**: The input parameters of the model include existing technological parameters and other space optimization related measures for a commercial building. The benefits in terms of energy savings and carbon emission reduction benefits have been considered. The technical conversion numbers have emerged for economic feasibility calculation only after conducting a technical simulation and feasibility analysis. Based on the technical feasibility criteria, the cost conversion numbers have been arrived along with certain optimum storage capacity, fixed and variable costs for certain space utilization.

- **Pattern of load consumption and associated assumptions in a typical commercial building:** Before, the field data from the seven commercial buildings are collected and simulated, a test case analysis is done for a pilot commercial building to finalise on the technical and financial input parameters for simulation and for finalisation of the technical economic and financial model. This developed model is thereafter used for the classical benefit cost ratio calculation for different discount rates. Some of the assumptions of the test case analysis are detailed out below:

Test Case Assumptions:

- **Load:** Average load of the test case/pilot commercial building is everyday around 4000 Kwh. The building also has solar charged battery options for meeting electrical load at night. The solar generation reaches a peak of close to 30 Kwh on a bright shining day around 12 pm in the noon. The solar generation peak drops from 5.00 PM. Beyond that point, the load of the building does not drop to a large extent because of residential facilities within the commercial complex.
- **Space:** Existing duct based air pump heating system can also be used for the thermal energy storage options. For installation of solar thermal storage, space is a constraint in the test case building. This is true in the Indian context, as for most commercial type of space operations; the building has already used its space or has to struggle for optimising space in a growing urbanisation context of India.
- **Distribution of loads:** The tariff paid by the building is around INR 9/ kWh for power purchase from the grid. Most of the generation as of now is not sufficient to give it back to the grid as it will be used mostly for self consumption and surplus won't be generated. For generating surplus, a minimum space is required to generate the storage. The peak bill for the building goes to INR 12 - 14 lakhs during the summer months till October. From November onwards, the bills drop to INR 8 - 10 lakhs. The building has been using VRV systems for AC load. Thermal energy storage system is

being envisaged to be implemented for reducing close to 30% - 50% of the peak load demand of the office complex.

Once the test case is run, the technical parameters are finalized and the capital costs and other expenses for the TES application in a commercial building is finalised. The assumptions of the capital cost after finalisation of the technical parameters is outlined below:

Table-4: Assumptions for capital cost: ** (After test case finalization)

Cost of Screw Chiller	INR 15000/TR of cooling
Pump cost	INR 7500/KW
Cooling Tower	INR 5000/TR
Storage	2000 L fire water tank
Cost of Insulation	INR 0.50/L of storage
Chiller Plant Efficiency	0.8 Kw/TR
Power Factor	0.90
Savings in DG	INR 10000/KVA
Chiller Plant Cost	INR 70,000/TR
Average annual loading	0.7 of peak load
Summer days	200
Hours per day	20

** A private educational institute's building has been considered as a pilot for this purpose

- Assumption for engineering simulation. Based on engineering simulation, optimised carpet area catering to per TR of AC load from a building has been obtained. The conversion factor 200 square feet per TR has been used. In order to obtain this conversion factor, a commercial building with an optimised AC load of 500 has been considered.

5. Costs

For calculating the discounted cost we have taken into account capital cost and O&M cost. Capital costs are considered to be same for both technologies in this analysis as based on the test case parameters comes to an average cost of INR 368 per sq ft. O&M cost is assumed to be 5% of capital costs for ice TES and 6% for salt hybrid TES. With development of the technology in future, O&M costs might decrease at an increasing rate. However, uncertainty of such a situation compels a consideration of constant yearly O&M cost for the fifteen year period. Capital Costs and yearly O&M Costs for each building are presented below.

Table: 5: Description of Costs

Building	Capital Costs for Thermal Storage (Lakh INR)	Annual O&M Expense for Ice (Lakh INR)	Annual O&M Expense for Hybrid Salt (Lakh INR)
1	2237.54	111.88	134.25
2	1305.23	65.26	78.31
3	932.31	46.62	55.94
4	1294.04	64.70	77.64
5	3244.44	162.22	194.67
6	2162.96	108.15	129.78
7	3229.52	161.48	193.77

6. Benefits

Two separate benefits have been considered, namely energy saving benefits and carbon avoided benefits. Energy savings benefits make up the vast majority of the benefits.

As stated previously, it has been assumed that the TES system runs for an optimum of 6 hours and can avoid 60% of the energy requirement of the peak load capacity. The kWh saved per year has been multiplied by the average cost of energy from the grid, Rs. 8.4 per kWh. Based on engineering simulations applied to specific building conditions, the energy saving in kWh and INR from storage is estimated below for each building.

Yearly energy benefit measure, obtained in MWh, has been multiplied by a constant of 1.03, which is the conversion factor between MWh and tonnes of CO2 equivalent. This gives the amount by which emission has been reduced due to LHTES integration in the building system.

Each tonne of carbon equivalent saved is valued at the social cost of carbon based on literature review. For this study, SSC for the four discount rates has been obtained from Tol (2018) and GoI (2017), and they are valued as follows:

- 3% discount rate SSC= $25.3/ton CO2 at 2010 $
- 5% discount rate SSC= $7.60/ton CO2 at 2010 $
- 8% discount rate SSC= $7.39/ton CO2 at 2010 $
- 10% discount rate SSC= $4.11/ton CO2 at 2010 $

Table 6: Energy and Cost Benefits

Building	Energy Saved Per Year (In MWh)	Yearly Energy Benefit (INR)	Tonnes of CO2 Equivalent Avoided	Yearly Carbon Benefits at 5% Discount Rate (INR)
1	9072	76,204,800	9,474	5,177,895
2	5292	44,452,800	5,526	3,020,439
3	3780	31,752,000	3,947	2,157,456
4	5247	44,071,776	5,479	2,994,549
5	13154	110,496,960	13,737	7,507,948
6	8770	73,664,640	9,158	5,005,299
7	13094	109,988,928	13,674	7,473,429

Costs and benefits are discounted over a period of 15 years, the expected life of the TES using four different discount rates 3%, 5%, 8% and 10%. Carbon benefits are summed instead of discounted, since the discounting is embedded in the social cost of carbon value applied.

Discussion of omitted benefits and limitations to the calculation

There are other considerations which could lead to obtaining further energy and carbon benefits of TES installation. The first is through the consideration of waste heat. If the energy required for TES is sourced from waste heat, input energy costs are zero and benefits are higher.

However, the problem with this estimation is that a uniform standardization measure is required. Waste heat usage will depend on the nature of the commercial building and the temperature of the waste heat. Only after knowing that for commercial buildings for every climatic condition can this potential benefit be calculated. For large industry it might be easier to estimate. However, for a commercial building without standardization in the input temperature parameter, the context will differ across buildings in various climatic conditions. Due to this differential it has not been considered.

An additional way of sourcing energy for TES, is from the grid itself during off-peak hours. However, for this method one needs a round trip efficiency number which needs to be calculated beforehand. For our test case, we have done a simulation of round trip efficiency and the figures range from 0.4 – 0.6. The obtained efficiency figures are very building specific and a standardized assumption in an ex-ante situation is not wise. Owing to that, this approach to benefit calculation has also been avoided.

Another important assumption while calculating the benefit stream is consideration of depreciation as a tax benefit which can be claimed by users for tax savings. However, this is only relevant for financial and private cost-benefit analyses. In economic cost-benefit analysis, as presented here, taxes are a transfer and can be suitably ignored.

While considering the reduction in carbon-emissions, the possible benefits from integration of renewable energy in the entire network has been ignored. This is because, India, at present is facing a major issue of the grid- locking along with an intermittency problem, which needs to be addressed before significant co –benefits from storage arise. In an ex-ante situation of a technology which is not even commercially applied in commercial buildings such an assumption of renewable energy integration might produce results with little resemblance to reality.

Another bone of contention in this study is the extent to which carbon benefits accrue, given the benefit and cost stream calculation assumptions. It can be argued that carbon benefits will not be significant until and unless there is waste energy utilization. This is because when TES is not powered by waste energy, overall energy consumption might increase, and hence contribute to increase in carbon emissions. At this juncture, a test simulation and standardization for various commercial buildings needs to be done before coming up with a conclusive statement on this.

7. Results, Interpretation and Analysis

Table 7: Summary Table: Building Specific Benefit Cost Ratio

Building Number	Intervention	Intervention Subtype	Discount Rate	Benefit (Lakh INR)	Cost (Lakh INR)	BCR	Quality of Evidence
BCR(For Building 1)	TES	Water	3%	11682.82	3399.33	3.44	Strong
			5%	8686.48	3185.69	2.73	
			8%	7277.96	2925.82	2.49	
			10%	6216.22	2783.37	2.23	
BCR(For Building 2)	TES	Water	3%	6814.98	1982.94	3.44	Strong
			5%	5067.11	1858.32	2.73	
			8%	4245.47	1706.73	2.49	
			10%	3626.13	1623.63	2.23	
BCR(For Building 3)	TES	Water	3%	4867.84	1416.39	3.44	Strong
			5%	3619.37	1327.37	2.73	
			8%	3032.48	1219.09	2.49	
			10%	2590.09	1159.74	2.23	
BCR(For Building 4)	TES	Water	3%	6756.56	1965.95	3.44	Strong
			5%	5023.68	1842.39	2.73	
			8%	4209.09	1692.10	2.49	
			10%	3595.05	1609.71	2.23	
BCR(For Building 5)	TES	Salt Hybrid	3%	16940.09	5284.85	3.21	Strong
			5%	12595.40	4925.11	2.56	
			8%	10553.04	4490.10	2.35	
			10%	9013.52	4253.16	2.12	
BCR(For Building 6)	TES	Salt Hybrid	3%	11293.39	3523.24	3.21	Strong
			5%	8396.93	3283.41	2.56	
			8%	7035.36	2993.40	2.35	
			10%	6009.01	2835.44	2.12	
BCR(For Building 7)	TES	Salt Hybrid	3%	16862.20	5260.55	3.21	Strong
			5%	12537.49	4902.47	2.56	
			8%	10504.52	4469.46	2.35	
			10%	8972.08	4233.61	2.12	

From the above table 3 it can be seen that the BCR values are significant and above 2 for all the buildings for both types of interventions. It is evident that the benefit is double the cost and they differ for two different technological options (Water and Salt Hybrid). The higher value of the ratio makes a strong case for TES integration in commercial buildings of Andhra Pradesh (in Amravati) in future. The outcomes of this exercise are indicated in Table 6 of next section.

Table 8: Outcomes of Interventions

Intervention Outcomes	Potential Outcome Explanation	BCR (for Water)	BCR (for Salt Hybrid)
Energy Savings/ Cost Savings	TES can help in potentially reducing the energy consumption and hence can save the cost associated with energy consumption significantly both in the short (within next 6 years) and long run (beyond next 6 years) through peak load shaving and a balanced utilisation of energy in peak and off peak hours	Significant	Significant
Environmental outcomes	The reduced energy consumption that potentially arises out of TES installation is also associated with the potential to concomitantly reduce GHG emissions especially CO2 from commercial buildings.	Significant	Significant
Increased economic activity and growth	With growing urbanisation in an emerging economy like India the future growth of commercial buildings could potentially lead to a high demand for energy and could have serious repercussions on GHG emissions due to higher usage of electricity in meeting the AC load. Thus the demand for TES applications could also increase accordingly and more so in the light of the energy conservation and saving and also due to increased demand for certified green buildings under Smart City Mission in India (http://smartcities.gov.in/content/). The rise in demand for TES applications could in turn raise the demand for skilled labour for installation, fabrication, welding purposes and maintenance activities associated with - 1) the manufacturing of the technology; 2) its installation in commercial buildings; and 3) periodic maintenance. The rise in demand for skilled labour can lead to more job creation, potential increase in the wage levels, and can potentially improve the quality of life. As the economies in scale in applications of TES gets progressively achieved the cost is also expected to come down and the demand for these skill based activities pertaining to TES would increase and could very well be recognised as a part of the skill based activity under National Skill India Mission (http://nationalskillindiamission.in/). However, these are expected to happen more as indirect benefits owing to the application of TES technology in commercial buildings in India.	Significant	Significant

The above outcome immediately hints towards certain policy conclusions which can be drawn from potential future TES applications in commercial buildings of India and in the state of Andhra Pradesh.

7.1 Assessment of Quality of Evidence

The quality of evidence is high and is contextually relevant. The base assumptions that have been made in calculating the BCR are based on multiple stakeholder consultations, field expert views and drawing from secondary literature. As already mentioned before, purposive sampling has been considered for estimating the BCR. The sample buildings and baseline cost and benefit figures pertaining to each intervention type for those buildings have been decided in consultation with thermal engineers, designers, project developers and policy makers. The validation of base case is also done with typical case studies of a commercial building in hotel, hospital, educational institute and commercial complex. Research questions aimed at isolating cause and effect (i.e. what is happening) are answered using quantitative observational studies often relying on data from engineering simulations. In other words, the body of evidence is diverse and validated with stakeholders.

8. Policy conclusions

Higher benefits arising from energy savings and carbon emission reductions in comparison to the costs in the commercial buildings of Andhra Pradesh highlight the need to internalize the application of TES technologies in the policy space dealing with sustainable habitat within India. To start with, as a part of Smart City and Sustainable Habitat Mission of the government, the future potential importance of TES installation in commercial buildings needs to be recognised. Then, TES application can be mentioned as a part of amended National Building Codes which can then be implemented in the state building codes. For implementation of new building codes which have internalized TES applications, the municipal by laws of the cities need to change. In order to implement these codes at the commercial building level of a state, the state level nodal agencies have to work in unison with the national nodal agencies. For instance, the central policy determining the national building codes related to energy efficiency measures in a commercial building is being designed by the Bureau of Energy Efficiency (BEE) under the purview of Ministry of Power. Once the amendment in building codes for introduction of TES in commercial buildings is done, BEE will have to work with the state nodal agencies and other relevant ministries like

Ministry of Urban Development, Ministry of New and Renewable Energy and Ministry of Environment, Forest and Climate Change to actually implement new commercial building codes of commercial buildings in India at a state level. Finally, the implementation will be done at a state level through state level nodal departments. Moreover as a part of Skill India Mission, potential usage of thermal energy storage in commercial buildings for future can be given a recognition owing to its potential of generating indirect job benefits. The potential higher benefits from energy savings and carbon emission reduction in comparison to the costs incurred in commercial buildings of the state of Andhra Pradesh also fits to the mitigation commitment of India as per the Nationally Determined Contribution (NDC) as agreed and ratified after the Paris Climate Agreement. The energy savings and carbon benefits from potential future applications of thermal energy storage in commercial buildings of a large state of India like Andhra Pradesh will only facilitate in achieving the 33% - 35% emission reduction international commitment of India by 2030. On an average, when 30% - 40% of the total energy consumption of India comes from commercial building, TES technology application in commercial buildings through definite policy directions, institutional mechanisms can be a policy winner in the long run.

As a parting note, it should be mentioned that this work is limited in its intervention capacity to not have dealt with the scope that TES provides for energy arbitrage or waste energy use. TES applications by means of peak demand management can yield significant savings through energy arbitrage or usage of waste energy. Targeted policies that address these possibilities through designing a suitable financial solution can act as an impetus for wider mainstream use of TES, among others. However, this is a complete separate area of work and dedicated research work needs to be undertaken to this effect.

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As a new state, Andhra Pradesh faces a bright future, but it is still experiencing many acute social and economic development challenges. It has made great strides in creating a positive environment for business, and was recently ranked 2nd in India for ease of doing business. Yet, progress needs to be much faster if it is to achieve its ambitions of becoming the leading state in India in terms of social development and economic growth. With limited resources and time, it is crucial that focus is informed by what will do the most good for each rupee spent. The Andhra Pradesh Priorities project as part of the larger India Consensus – a partnership between Tata Trusts and the Copenhagen Consensus Center, will work with stakeholders across the state to identify, analyze, rank and disseminate the best solutions for the state. We will engage people and institutions from all parts of society, through newspapers, radio and TV, along with NGOs, decision makers, sector experts and businesses to propose the most relevant solutions to these challenges. We will commission some of the best economists in India, Andhra Pradesh, and the world to calculate the social, environmental and economic costs and benefits of these proposals

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