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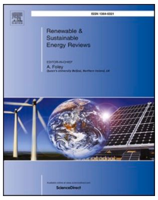

Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK

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ABSTRACT

Compressed air energy storage (CAES) is an established and evolving technology for providing large-scale, long-term electricity storage that can aid electrical power systems achieve the goal of decarbonisation. CAES facilities often utilise large underground storage caverns to ensure high capacity systems. This results in the need of locations with suitable geological features to develop a CAES plant. This paper examines recent and ongoing large-scale CAES projects and presents candidate methods of storing high pressure air using underground features. An assessment of the overall potential for CAES in India is presented by examining its geological features and locations with the greatest potential for CAES plants are determined. This is combined with an analysis of the renewable electricity generation potential in India to identify candidate areas for renewable generation and CAES integrated systems. Up to 1.05% of Indian land area is deemed suitable for CAES plant development and if fully utilised would be sufficient to meet the energy storage needs of India, however, practically a very small fraction of the total suitable land that could be developed so other competing energy storage technologies should be considered. Conversely, the UK possesses a very good potential for CAES, enough to greatly exceed necessary energy storage, owing to the abundance of salt beds not present in India. For CAES to garner serious consideration in India, aquifer storage based CAES needs to be demonstrated.

1. Introduction

As electrical power systems transition from centralised thermal power plants to distributed renewable energy sources for power generation, the balance between power supply and load demand becomes more complex. Energy storage is considered as one of the feasible solutions to aid this shift, as they provide energy buffers to detach power generation and the time of use. In 2019, the UK supplied over 30% of electrical power from renewable energy sources including wind, solar and biomass [1]. If an increasing proportion of power generation from renewable energy, in the region of 60%–70%, is to be achieved, grid scale energy storage with long term storage duration will be required to replace the role of current thermal power plants in providing flexibility services. Large scale energy storage systems allow for the storage of surplus electrical generation from renewable sources, in times of high availability but low load demand, with this stored energy supplying the grid during periods of low available generation but high demand. In addition to widespread pumped hydroelectric energy storage (PHS), compressed air energy storage (CAES) is another suitable technology for large scale and long duration energy storage.

India is projected to become the most populous country by the mid-2020s [2]. Coupled with the nation's rapid economic development, drive for electrification of rural communities and increasing urbanisation, the electricity demand of India will grow substantially in the coming decades [3]. Additionally, the government of India has set the ambitious target of providing 40% of its electricity generation from renewable sources by 2030 [4]. To achieve this goal, the rate at which renewable electricity generation technologies are being installed in India is growing each year. The UK situation is similar, being on course to achieve the target of 30% electricity generation by the end of 2020. Additionally, in 2019, the UK government established the goal of achieving net zero emissions by 2050 [5]. In recent decades, greenhouse gas emissions from the power generation sector in the UK has been reduced over 80% compared with its emission level in 1990s, however, emissions from transportation and heating sectors have not. To reduce emissions, the electrification of transportation and heating is inevitable, which will in turn require more power generation, and consequently must be supplied from renewable energy sources. Without grid scale

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long duration energy storage, it will be difficult to achieve the net zero emission goal. This paper is to examine and compare the potential capacity of CAES in India and the UK.

2. Compressed air energy storage and current technology development

CAES has been implemented at the grid level for over 40 years [6]. The complete cycle of conventional-CAES operation (diabatic-CAES, D-CAES) is comprised of two processes, the charging and discharging processes. During the charging process, electricity from the grid is used to power a motor, which drives a turbine or series of turbines, compressing air into a large underground cavern as the heat of compression is rejected to the environment [7]. Later, during the discharging process, the high pressure air from the storage cavern is mixed with gas and combusted to drive a turbine or series of turbines. This work is used to drive an electrical generator with the produced electricity supplied to the grid or consumers. Two such CAES facilities are operational at present, the Huntorf plant, in Germany, constructed in 1978, and the McIntosh plant, Alabama, USA, operational from 1991 [8]. Foley & Lobera have presented the detailed technical characteristics regarding these two operational CAES facilities [9], with the key technical parameters summarised in Table 1.

A typical configuration of conventional D-CAES systems are given in Fig. 1. The fuel input requirement in conventional CAES during the discharging phase is a necessity owing to heat that is rejected during the compression stage. This means overall efficiencies of traditional D-CAES are relatively low and is one of the main constraints of CAES as a storage option. Efficiencies of D-CAES systems can be improved significantly with the integration of recuperators, as in the McIntosh plant, in which the hot exhaust gas during the compression stage is directed to preheat the pressurised air from the cavern prior to the expansion stage [15]. This greatly reduces the thermal energy input required and results in improved efficiencies with less fuel consumption [10].

A progression of the use of recuperators is the emergence of Advanced Adiabatic CAES (AA-CAES). In AA-CAES systems, heat rejected during the compression stages is stored in a thermal energy store (TES) and used to heat the compressed air before expansion. Therefore AA-CAES systems can achieve higher system efficiencies, up to 80% expected to be achievable [16,17] with no external heat from the combustion of a fuel. TES are the limiting factor in the progression of AA-CAES because of the high temperatures that are generated during compression, which is difficult to store [18]. Thermal energy is traditionally stored in the form of sensible heat or latent heat: Sensible heat stores are a mature technology and economically attractive but latent heat technologies can store higher temperatures and achieve better system efficiencies [19]. There are examples of attempts to integrate chemical and thermochemical heat storage into CAES systems, though at present these are economically unattractive with the current state of technology [20].

Though the majority of current research is focussed on improving AA-CAES systems, a competing approach to improve round trip efficiencies of conventional CAES facilities is the development of isothermal-CAES (I-CAES) [21]. When traditional turbomachinery is employed for compressing air to high pressures, very high temperatures are achieved and as a result the air cannot be practicably stored, thus heat must be rejected cooling the air and energy is lost. Conversely heat must then be added to the system at the expansion stage to account for this. I-CAES systems aim to achieve slow compression and expansion such that these processes occur at a constant temperature. This requires continuous heat transfer during the compression and expansion stages but could result in considerably higher round trip efficiencies and additionally removes the requirement of a secondary TES. The most demonstrated methods of achieving the necessary slow expansion and compression are through the use of liquid pistons or hydraulic pumps [22,23].

CAES possesses numerous advantages over competing large scale energy storage systems, excelling in technology lifetime, energy storage duration, possessing negligible self-discharge, as well as being scalable in terms of capacities and power output. Albawab et al. compared alternative large-scale energy storage technologies across a wide range of factors to determine the overall sustainability of the competing technologies with CAES outperforming the other candidates [24]. Moreover, under current conditions in the United States market, CAES has been shown to be the most economically attractive grid-integrated energy storage technology, along with PHS, both in terms of cost per kW and cost per kWh [25].

However, aside from the relatively low efficiencies when compared to other established energy storage technologies, the greatest limitation of CAES as a large scale energy storage technology is the low energy storage density. CAES energy density is typically in the order of 3–6 Whl^{-1}, which is comparable to PHS systems, typically 1–2 Whl^{-1} [10] but is an order of magnitude smaller than existing energy storage technologies that are beginning to be implemented at the grid level, particularly electrochemical batteries possessing energy storage densities of 50–90 Whl^{-1} for Pb-Acid [26] or 200–400 Whl^{-1} for Li-Ion [27]. Owing to the low energy storage densities, large storage volumes are required to create systems with large capacities. At present, the most viable option for constructing chambers with sufficient volumes is the use of underground storage caverns. Although over-ground manufactured storage vessels can be used for the implementation of small scale CAES with very high pressures [28] or for demonstration plants, these above-ground tanks cannot currently compete with underground methods in terms of storage volumes. The use of underground storage also provides the benefits of isolation from external influences, with the only surface features being connecting valves, and much lower specific costs for storage capacity when compared to the use of above-ground tanks [29]. Therefore, the availability of suitable geographic features for the formation and locations of underground storage caverns are the major constraint to the rate of adoption of CAES as a bulk energy storage technology.

2.1. *Overview of major CAES projects*

As a long-established large-scale energy storage technology there has been continued interest in the development of CAES since its first demonstration. Consequently, there have been numerous major CAES projects, commercial or demonstrations in recent years, which are given in Table 2.

- The Norton CAES facility was a proposed CAES project of up to 2700 MW, planned to be developed in Norton, Iowa, specifically for the

Table 1
Key technical characteristics of current conventional CAES facilities.

CAES Facility	Operator	Year Operational	Deliverable Power [MW]	Discharge Time [hr]	Efficiency [%]	Pressure [bar]	Cavern Type	References
Huntorf, Germany	Uniper Kraftweke GmbH	1978	290	2	29	48–66	Two solution-mined salt caverns	[6,9–12]
McIntosh, AL, USA	Power South Energy Cooperative	1991	110	26	36	<76	Single solution-mined salt cavern	[9,12–14]

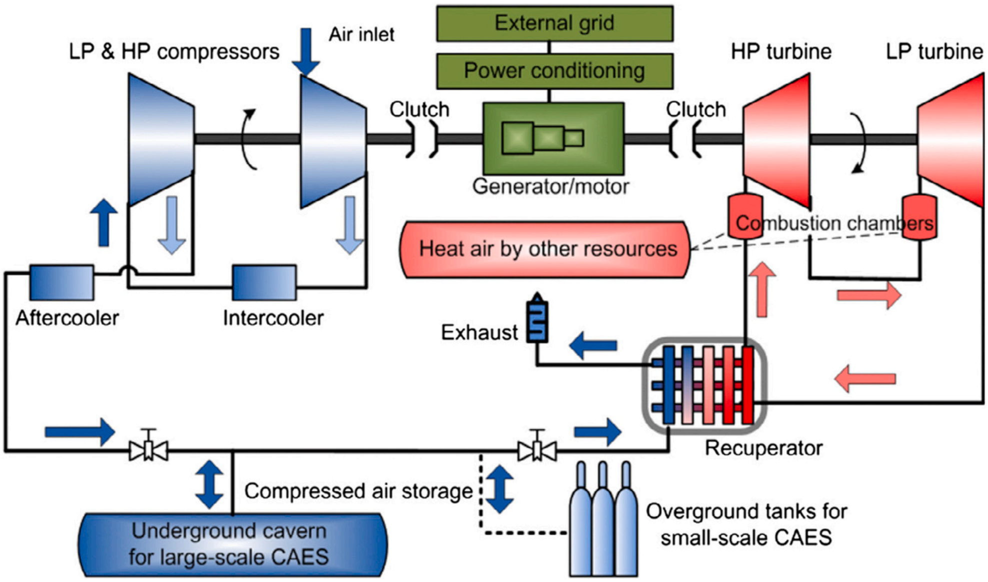

Fig. 1. CAES system configurations [8].

purpose of integrating wind power generation [30]. Initially the use of an aquifer air store was proposed but later plans were adapted into repurposing a disused limestone mine owing to overestimation of the air store size. The project suffered set-backs for a number of years and was finally discontinued in 2012. Regarding innovations, the Norton project did not advance CAES technology significantly as all planned implementations of technologies were pre-established, key lessons were learnt however, in regards to the management and economics of large scale energy storage developments [31].

- Another long planned commercial CAES project that has ultimately been abandoned, was a plant in County Antrim, Northern Ireland. The facility was again planned to utilise conventional D-CAES methods as well as employing a salt cavern as the air store. Designed to deliver 330 MW for up to 6 h, the project was awarded €90 m from EU funding, though the company, Gaelectric, went into liquidation in 2017 and no buyer was found [32] with the planning application subsequently withdrawn and no substantial developments arising from the project.
- Between 2010 and 2012, the New York State Energy Research and Development Authority (NYSERDA) aimed to achieve a 130 MW–210 MW CAES facility in upstate New York, dubbed the Seneca CAES Project. The site was deemed to be feasible because of the local salt mining operations and on-site high-pressure natural gas pipeline that could be directly used in the D-CAES plant [33]. The initial plan was comprised of 3 phases. Phase 1 involved siting, design, financials and filings. Phase 2 was to be construction and Phase 3 was to be commercial demonstration and performance reporting. However, a number of factors led to increased projected necessary investment which resulted in the project ultimately being discontinued at the end of the first phase, citing lack of economic incentive [34].
- The ADELE project, based in Staβfurt, Germany, aimed to be the first large commercial demonstration of AA-CAES technology at the grid level. As with the previous CAES projects, salt caverns were planned to be used as the underground air store, but with the addition of a large sensible heat store to capture and reinject the heat of compression. The project was designed to deliver 200 MW up to 5 h with a 70% round trip efficiency. The project was placed on hold in 2016 citing uncertain business conditions and no further updates have been published [35].
- The Bethel Energy Centre is a commissioned CAES facility in Anderson County, Texas [36] developed by APEX CAES. The project is planned to incorporate conventional D-CAES technology, utilising underground salt caverns with gas as the heat source at the expansion stage. The proposed system power is 324 MW, deliverable for up to 48 h. At the time of writing, the facility is fully permitted and construction ready and planned to be operational by 2022.
- One upcoming large-scale conventional CAES project is the Advanced Underground CAES facility from PG&E planned for San Joaquin County, California. The facility is expected to be capable of delivering 300 MW, though no estimate for total capacity is provided at this stage as the plant is going to utilise a depleted gas reservoir and capacity estimates need to be evaluated. The project is to be conducted in three stages, initially only the first stage has secured funding, which will involve determining reservoir feasibility, economic viability and environmental impacts. At the completion of phase one the project will be reassessed to determine if the project is to continue [37].

In contrast to the implementation of existing CAES technologies in new plants, novel CAES methods are being developed and tested:

- Hydrostor are a promising company that have demonstrated a unique type of CAES at the grid level. A commercial reference facility in Goderich, Canada became operational in 2019, rated at 1.75 MW [38]. Air is stored in a specially excavated underground cavern that can be partially flooded by a surface water reservoir. This ensures constant air pressure throughout the process as the chamber volume can vary in size through the partial flooding. Additionally, the heat of compression is captured, stored and later reinjected making the system a demonstration of adiabatic CAES. The technology is approximately 60% efficient in its current state. Additionally, Hydrostor are in the process of developing a similar plant in Strathalbyn, Australia referred to as the Angas facility. Expected to become operational by the end 2020, the Angas plant will operate with the same adiabatic, constant pressure from hydrostatic pressure balancing that the Goderich plant operates from but will differ as the plan is to repurpose a zinc mine in contrast to specifically drilling a chamber for storage. The plant is designed to deliver 5 MW for 2 h [39]. For the two projects, Hydrostor currently quotes a value of $150/kWh – $300/kWh of storage for their CAES technology [40], this is more expensive than conventional CAES systems estimated at approximate $50/kWh though is still one of the most favourable energy storage solutions in terms of cost [14].

Table 2
Major recent CAES projects.

Project Name	Location	CAES Technology	Project Purpose	Project Status	Years Active	Power [MW]	Capacity [MWh]	Efficiency [%]	Air Storage Pressure [bar]	Storage Method	Reference
Norton CAES plant	Norton, Ohio, USA	Conventional diabatic, gas fuelled	Commercial	Not realised	2001–2013	800–2700	–	–	55–110	Aquifer storage/ repurposed limestone mine	[49,50]
GAELECTRIC Northern Ireland	Islandmagee, Co Antrim, UK	Conventional diabatic, gas fuelled	Commercial	Not realised	2008–2019	200 (charge) 330 (discharge)	1980	–	–	Solution mined salt cavern	[32,51]
Seneca CAES Project	Reading, New York, USA	Conventional diabatic, gas fuelled	Demonstration	Not realised	2010–2012	130–210	2000	–	–	Solution mined salt cavern	[33,34]
SustainX Smart Grid Programme	Seabrook, New Hampshire, USA	Isothermal, innovative water-foam mixture employed to ensure constant heat transfer during compression and expansion	Demonstration	Discontinued	2013–2015	2.2 (charge) 1.65 (discharge)	1	54	12–207	Above ground pressure vessels	[41]
ADELE project	Staβfurt, Germany	Adiabatic, sensible heat store	Commercial	Discontinued	2010–2016	200	1000	70	100	Solution mined salt caverns	[32,35,52]
TICC-500	Tsinghua University, China	Adiabatic, sensible heat store	Demonstration	Active	2014 – present	0.5	0.5	33	30–110	Overground storage tank	[35,53]
Chinese Academy of Sciences, CAES demonstration plant	Bijie City, Guizhou, China	Adiabatic, sensible heat store	Demonstration	Active	2017 – present	2.8 (charge) 10 (discharge)	40	62.3	70	Overground storage tanks	[48]
Pilot scale demonstration of AA-CAES	Gotthard base tunnel, Biasca, Switzerland	Adiabatic, sensible heat/combined sensible-latent heat store	Demonstration	Active	2017 – present	0.7	–	63–74	8	Previously excavated unlined rock cavern	[43,44]
Zhongyan Jintan CAES	Jintan, Jiangsu, China	Adiabatic, sensible heat store	Commercial	Commissioned	2017 – present	50–60	200–300	–	–	Solution mined salt cavern	[46,47]
Goderich A-CAES facility	Goderich, Ontario, Canada	Adiabatic, cavern flooded and hydrostatic pressure used for isobaric storage	Commercial	Active	2019 – present	2.2 (charge) 1.75 (discharge)	7	>60	–	Specifically mined cavern	[38,40]
Apex CAES Bethel Energy Centre	Tennessee Colony, Texas, USA	Conventional diabatic, gas fuelled	Commercial	Commissioned	2019 – present	324–487	16,000	–	–	Solution mined salt cavern	[32,36]
Feicheng A-CAES	Feicheng, Shandong, China	Adiabatic, sensible heat store	Commercial	Active	2019 – present	1250 (expected)	7500	67	–	Repurposed salt and coal mine caverns	[54,55]
PG&E Advanced Underground CAES	San Joaquin County, California, USA	Conventional diabatic, gas fuelled	Commercial	Commissioned	2020 – present	300 (expected)	–	–	–	Depleted natural gas store	[32,37]
Angas A-CAES facility	Strathalbyn, South Australia, Australia	Adiabatic, cavern flooded and hydrostatic pressure used for isobaric storage	Commercial	Commissioned	2022 (expected)	5	10	>60	–	Repurposed zinc mine	[39,40]

- The only megawatt-scale demonstration of isothermal CAES in recent years has been from SustainX. The company designed and tested a 1.5 MW commercial scale prototype of a novel isothermal CAES system. The processes were based upon the compression and expansion of a foam-air mixture to facilitate fast heat transfer and maintain constant temperature throughout [41]. The system realised round trip efficiencies of 54% a significant improvement upon D-CAES. A limitation of the scalability of the prototype is that specially constructed above-ground air vessels were used as the storage medium and it is unclear whether this technology could be adapted to be integrated with larger unground storage methods. This is compounded also because SustainX has subsequently been acquired by GeneralCompression who and have divested in research in above ground CAES solutions with the future of this technology being unclear [42].
- A pilot plant for an AA-CAES system is has been demonstrated by ALACAES near Biasca, Switzerland [43]. The system uses an excavated mountain tunnel and the focus of the research is the best integration of TES with CAES to create efficient AA-CAES. Thus far, efficiencies of 63–74% have been achieved [44] although the system can only operate at low pressures in the range of 1–8 bar, the technology in this form is far from commercialisation [45].
- Construction has begun on a large-scale adiabatic CAES facility in Jintan, China. A collaboration between Tsinghua University and Zhongyan Jintan Company, the project hopes to achieve a 50 MW to 60 MW AA-CAES plant, requiring no external fuel input. The project aims to reduce solar curtailment in Jiangsu province. The facility will employ an existing salt cavern remaining for previous solution mining operations [46,47].
- A final example of an AA-CAES demonstration is by the Chinese Academy of Sciences in Bijie City, Guizhou province. A 10 MW system has been constructed by incorporating a network of above-ground storage tanks, chargeable to 70 bar, and a 22 MWh sensible heat store such that the whole system can store up to 40 MWh of electricity. At the time of writing, the system is still subject to further development [48].

Collating the recent major CAES developments, it is evident that there are challenges in getting the technology to market as a commercial operation. A number of well-planned and advanced projects have been stalled and ultimately failed such as the ADELE and Norton projects. Failures are predominantly attributable to economic factors. The more promising AA-CAES technologies that are expected to become operational in the coming years are still far from the scale of conventional gas-fired CAES plants.

3. Underground compressed air energy storage and capacity analysis

3.1. Geological suitability for underground compressed air energy storage

Underground formations have long been utilised for the storage of natural gas because very large volumes and therefore storage capacities can be reached. The underground structures employed for gas storage can be adapted for several energy-carrying fluids and are increasingly being considered to use for the storage of air in large-scale CAES systems. A number of underground structures and techniques as shown in Fig. 2 can be employed for storage, with main considerations highlighted in the section.

Both commercial CAES facilities currently in operation utilise solution mined salt caverns for the air storage. Salt deposits can be multiple of kilometres thick so provide the opportunity for engineering deep, very large volume caverns. Salt cavern walls also possess moderately high strength and are usually more uniform in properties than other rock types [56], as well as maintaining a self-repairing property, where the material can flow plastically to seal fractures preventing further crack propagation [57], therefore salt caverns can remain stable for very long geological periods. Additionally, salt cavern storage requires significantly less base gas (the residual gas that must remain in the cavern upon discharging) than other mediums, particularly porous rock geologies [58]. Salt caverns are therefore best suited to the flexible operation and regular cycling that CAES plants operate under, providing higher flexibility with respect to turnover frequency with high injection and withdrawal rates [59]. Moreover, for salt caverns, exploratory work is typically lesser and therefore lower cost owing to existing knowledge of the salt structures because of prior prospecting for hydrocarbon resources [29]. A drawback of employing salt caverns is that the solution mining process is reliant on the local availability of a large amount of water for the extraction of the rock salt [60], though the obtained salt could provide an additional significant revenue stream in addition to the storage plant operation [57], provided that there exists the ability to refine the obtained brine into rock salt at a facility nearby.

In addition to salt deposits, aquifers and porous rock formations have become a standard for storing natural gas worldwide, accounting for 13% of underground natural gas storage globally [29], where the principles can be easily configured for the storage of high pressure air. An artificial gas field is formed by injecting high pressure gas into the permeable rock displacing the water and creating a variable volume gas store. A number of additional geological criteria must be met, with a suitable cap rock and surrounding rock to form a closure. Specific aquifer characteristics are also less widely known than salt formations and all of the factors result in aquifer storage being currently the most expensive form of natural gas storage available to the industry [58] and would therefore be an expensive method of underground storage in large CAES systems. Additionally, the injection of air into porous formations may change the existing cap rock properties and may impact the

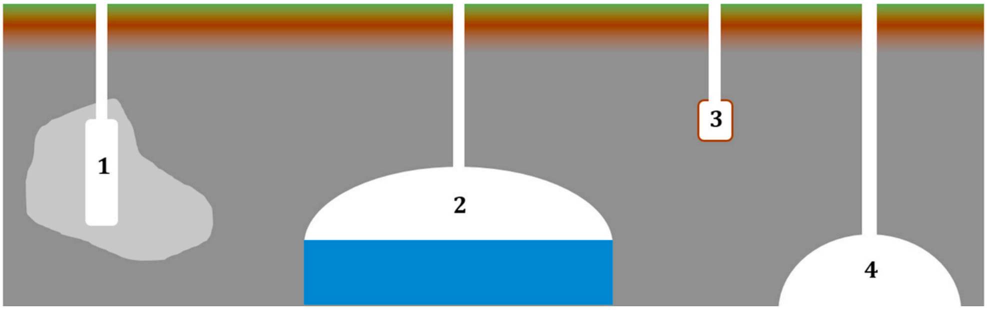

Fig. 2. Types of underground energy storage chambers. 1 - Salt cavern, typically solution mined from a salt deposit, 2 - Aquifer storage, the air is injected into a permeable rock displacing water and capped by a cap rock, 3 - Lined rock cavern, a specifically excavated chamber then lined with a material to ensure hermeticity, 4 - Depleted gas reservoir, reservoir previously used for gas tapping or storage, can be permeable or semi-permeable rock type.

operation and security of the whole system without thorough prior consideration [61]. Moreover, aquifer stores require significantly more base gas remaining after discharging further limiting the utility of this form of storage, typically between 50% and 80% cushion gas in contrast to salt caverns requiring 20% [62]. Li et al. have proposed attempting to identify locations with aquifers and a significant geothermal resource. It is suggested that this could improve the efficiency of the full system by maintaining or increasing the air temperature within the cavern, as it receives heat from the surroundings [63]. A novel well bore is suggested as the method of extracting the geothermal energy and preliminary modelling has been conducted. Determining suitable locations with this additional constraint would add complexity to the planning process however. In addition, modelling of the operation cycle of an aquifer based CAES plant has been conducted, indicating the feasibility of operating such a facility on a daily, weekly or monthly cycle [64].

A relatively new development to the underground energy storage industry is the consideration of hard rock geology lined caverns (Lined Rock Caverns – LRC). In principle, caverns can be excavated to large volumes and lined with concrete and steel to ensure no permeability. A single natural gas storage plant has demonstrated the feasibility of this type of storage in Grängesberg, Sweden with pressures or 500 bar achieved [65]. The achievable pressures could significantly exceed those of salt cavern storage, with current CAES facilities operate in the 45–80 bar range [9]. Similar storage capacities could therefore be achieved even with the smaller chamber volumes. A small scale test compressed air LRC facility has demonstrated 87 bar for the investigation of wall performance and deformation [66]. The greatest potential for LRC for CAES is therefore for locations where other geographic features are not present. Capital costs of forming caverns in hard rock geologies are currently significantly greater than in salt geologies, potentially being 15 times greater [67], though specific costs will vary each proposed location and depend heavily on the local lithological features. Zhou et al. have developed a modelling methodology for determining the degradation and damage to the cavern wall of a LRC over numerous air injection cycles [68].

Aside from utilising naturally occurring geological features, there is also great potential for the repurposing of existing underground infrastructure left as a remnant of resource extraction or natural gas stores for the storage of compressed air. At present, the most prominent method of gas storage is using depleted oil or gas reservoirs, accounting for 81% of total underground natural gas storage [29]. As these reservoirs previously contained oil or gas, the characteristics of the reservoirs, in terms of porosity and permeability, already meet the requirements for high pressure air storage [58] and it is likely that the structure and geologies of the depleted reservoirs are known owing to the surveying and prospecting prior to and during the extraction of the depleted resource. This is the method of air storage to be implemented in the planned PG&E CAES facility in San Joaquin, California [37]. The use of natural gas reservoirs can be seen as a viable candidate for the storage of compressed air particularly in Europe as the demand for natural gas is predicted to stagnate or decrease in the coming decades [69] with a number of existing reservoirs expected to be decommissioned.

In addition to the exploitation of depleted reservoirs, oil and gas wells, the reuse of disused mines has been considered for use within CAES systems and natural gas storage [70]. Many depleted coal mines possess large pre-excavated volumes therefore has the potential to significantly reduce the initial capital investment required. Additionally, closed coal mines are typically located locally to existing thermal power plants, therefore existing infrastructure could be utilised in adapting these systems into CAES facilities. The storage of natural gas and CO_2 has been demonstrated in abandoned mines, but as with depleted oil and gas reservoirs, never with a CAES system, although the previously discussed Angas CAES facility expected to be operational by 2022 aims to demonstrate the reuse of mineshafts for CAES by repurposing a disused zinc mine [39]. There are plans to adapt a network of tunnels from a previously used coal mine in northern Spain into a small-scale A-CAES pilot plant. Preliminary work has modelled the impact on the tunnels walls of cyclic loading from the injection of high pressure air and indicates that the existing infrastructure is sufficient to withstand the imposed conditions [71]. The adaptation of existing shafts in previously used coal mines do however pose the risk of the combustion of remaining coal seams with high temperatures, thus shafts would have to be adequately sealed and assessed to ensure safe operation and feasibility [29] or exploration of underground mines from differing resources.

3.2. Potential assessment for underground CAES

3.2.1. Methodology

There have been a limited number of previous attempts to assess the potential and suitability of specific locations for underground CAES storage [72–74], but these do not regard all forms of possible underground CAES technologies and have not allowed for a quantitative analysis. A methodology for assessing the geological suitability of an area for the underground CAES has been developed by Aghahosseini & Breyer [13], with three geological criteria under consideration to determine an area's suitability. Firstly, the identification of hard or porous rock geologies: with data obtained from the Global Lithological Map (GLiM) [75], four rock classifications were mapped: Mixed sedimentary, carbonate sedimentary, acid plutonic rocks and siliciclastic sedimentary, these rock types have been demonstrated to be preferred for underground gas and air storage when combined with aquifers, natural gas reservoirs or excavated to form caverns, as discussed in the previous section. Secondly, geological and mineral maps for Indian states [76] were gathered and used to identify salt deposits, in the form of halite or potash beds, and then were additionally mapped. It was found that the Indian salt reserves are concentrated in the north-west of the country, although the general availability of salt resources was very limited when compared to other world regions. Thirdly, large aquifer systems were identified and mapped. The identified aquifer systems were composed predominantly of two subsystems, the Indus Basin aquifer and the Ganges-Brahmaputra aquifer [77]. ArcGIS was used to map and process the results. Data relating to operating and disused oil and gas reservoirs and coal mines were not obtained for this analysis and focus was given to natural geological features. The mapped results of these three criteria are presented in Fig. 3.

Areas possessing at least two of these geological features were classified as being highly suitable for large scale underground CAES. In practice, it is possible that an area possessing only one of these features would be sufficient for the formation of a large storage cavern i.e. salt deposits or some hard rock geologies, however, regions with two features present would identify the most suitable areas for CAES implementation. Therefore, the final classification generates the total suitable surface area for CAES underground storage within India. Moreover, further constraints were enforced by removing urban areas, roads, railways, national parks, other restricted land for construction, areas with elevation greater than 1500 m and lakes. Furthermore, this study solely considers CAES for use in mainland India, although there are some suitable geological features present in India's island territories, their potential for the formation of CAES caverns and their integration with renewable electricity generation are not assessed here.

In addition to the determination of the overall CAES potential in India, the potential for renewable electricity generation is estimated, to assess the benefit that CAES can provide to renewable electricity generation technologies. Renewable generation can benefit from having the energy storage local to the site or entirely integrated, reducing transmission costs and losses, therefore resulting in higher round trip efficiencies. Contiguous Indian land area was divided into a grid of 1° intervals of latitude and longitude and the annual capacity factor for a power plant (both wind and solar) placed at the centre of the grid cells was calculated, this is given in (1). Data for the calculation of the Solar Annual Capacity Factor (ACF_s), was obtained from *Renewables Ninja*

Fig. 3. Left: Areas with one of the four identified geology types (Mixed sedimentary, carbonate sedimentary, acid plutonic and siliciclastic sedimentary), these areas are distributed evenly across the nation. Middle: Salt deposits mapped for India, very few salt resources available, with the largest located in the north-west of the country. Right: Large aquifer systems mapped for India, primarily covering the north composed of the Indus Basin and Ganges-Brahmaputra aquifer.

[78], which gives hourly solar data with the power output of the solar PV plant determined considering a monocrystalline solar PV module of 385 W possessing a temperature coefficient of power of −0.39% per degree Celsius [79]. The data used for the computation of the Wind Annual Capacity Factor (ACF_W) was obtained from *Soda Pro* [80] and modelled for a Suzlon S111 2.1 MW wind turbine at a hub height of 90 m [81]. This turbine was employed in the assessment as it is a large-scale Indian manufacturer and supplier of wind turbines.

$$ACF_{s,w} = \frac{E_{s,w}}{365 \times 24 \times P_{s,w}} \tag{1}$$

where $E_{s,w}$ is the annual energy generated by the assumed solar or wind plant for the centre of the grid cells and $P_{s,w}$ is the rated power of the solar or wind generation. This capacity factor is then used as a method of ranking the potential for both forms of renewable generation within India.

The available area suitable for underground CAES was additionally compartmentalised into the same 1° by 1° grid cells. The cell areas suitable for CAES were then min-max normalised to rank the locations in terms for CAES suitability availability, as were the capacity factors for solar and wind generation. The three normalised factors are then multiplied together to provide a CAES-solar integration potential score

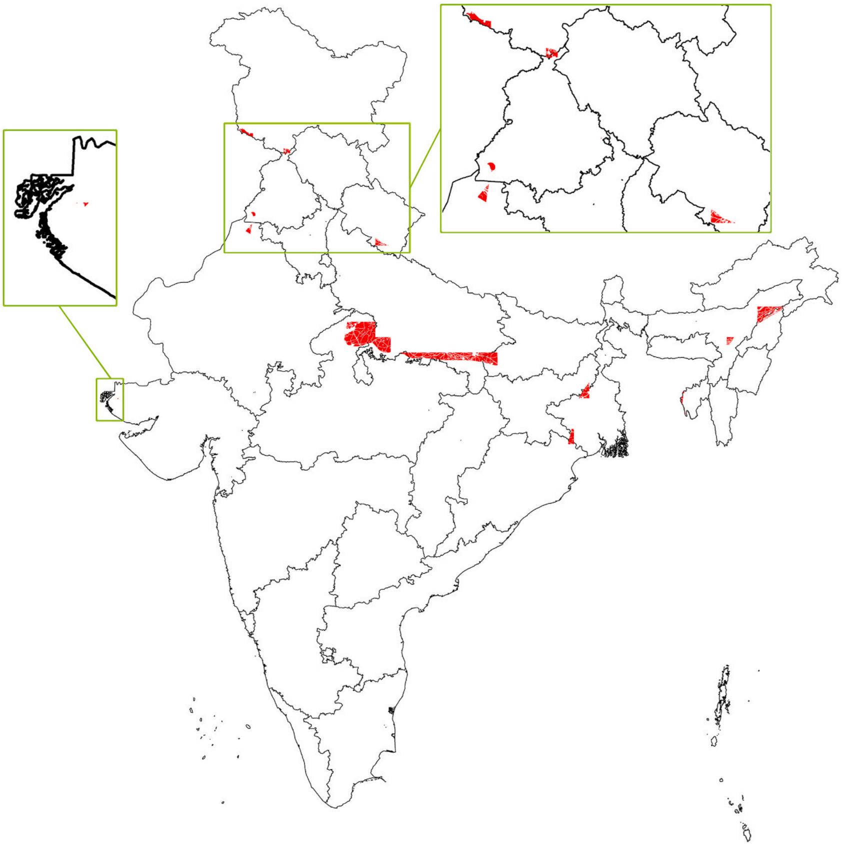

Fig. 4. Identified areas most suitable for underground CAES in India.

($CAES_{SIS}$), CAES-wind integration potential score ($CAES_{WIS}$) and overall CAES-renewable integration potential score ($CAES_{RIS}$) as in (2), (3) and (4). These scores are between 0 and 1 and can be used for a direct comparison.

$$CAES_{SIS} = AF_{CAES} \times ACF_s \tag{2}$$

$$CAES_{WIS} = AF_{CAES} \times ACF_w \tag{3}$$

$$CAES_{RIS} = AF_{CAES} \times ACF_s \times ACF_w \tag{4}$$

3.2.2. *Feasible CAES storage capacity in India*

Applying the methodology presented in Section 3.2.1, the regions suitable for underground CAES in India are identified and presented in Fig. 4. Total land area with the geological potential for underground CAES is determined to be 34,400 km^2, with the greatest density of CAES suitability across central-northern states of Madhya Pradesh and Uttar Pradesh. A small area of CAES suitable land is identified in the west of Gujarat and additional clusters of land in Jammu & Kashmir and Punjab. There is some suitability for CAES in the east of the country in West Bengal and Assam.

The total land area of India is approximately 3.29×10^6 km^2, therefore this analysis concludes that 1.05% of land would be deemed suitable for the installation of a large scale CAES facility. Taking assumptions that all of the determined CAES suitable land could accommodate CAES plants with similar energy density characteristics to the Huntorf and McIntosh plants and a constant energy storage density (regardless of the implementable storage type at a particular location), an estimate for the total capacity of CAES in India can be determined. The number of possible caverns is calculated from determining the amount of Huntorf caverns that would fit in the total above ground surface area deemed suitable for CAES. Note the Huntorf storage facility is comprised of two storage caverns, but parameters are only taken for one of these for this analysis. With the number of possible caverns determined an estimate of an upper limit of the cavern volumes can be given. Results are contained in Table 3.

Total electricity demand in India is estimated at 10^9 MWh annually [82], therefore the total underground CAES energy storage capacity potential stands at approximately 10 times greater than annual demand if all available land were utilised for this underground storage of air. Thus, although it can be concluded that there is sufficient geological resource to meet India's energy storage requirements, it is highly unlikely that CAES alone will be a sufficient technology in its current form. Utilisation of all potential land is likely to be very small (much less than 1% of available) thus a variety of differing energy storage systems should be examined for the Indian situation. India's suitable land area for CAES also ranks very low when compared to other nations [13] predominantly owing to the lack of availability of salt deposits. As such it is very unlikely that sufficient CAES plants can be constructed at an economically viable price to totally meet India's energy storage requirements, unless there are substantial advancements and demonstrated CAES facilities utilising storage mediums other than salt caverns.

Fig. 5 displays the distributions of the potential for solar and wind generation across India. When considering electricity generation from solar, there is greatest potential in the north-west of the country across the states of Rajasthan and Punjab. For wind generation, the highest potentials are in the western states of Gujarat and Rajasthan and across the south-central states of Karnataka and Maharashtra. In general, there is not good coincidence between areas of both high solar and wind potential, though Gujrat and some areas of Rajasthan do show promise of high levels of generation from both renewable resources.

Table 3
Total CAES capacity in India.

Constant	Value		
Total suitable area for CAES	34,400	km^2	
Huntorf cavern surface area occupied	0.00125	km^2	[13]
Number of possible caverns	2.75×10^7		
Volume of Huntorf cavern	141,000	m^3	[84]
Total available volume for CAES caverns	3.88×10^{12}	m^3	
CAES energy storage density	0.003	MWh·m^{-3}	[85]
Total potential for CAES in India	11.6×10^9	MWh	

Of the 357 grid cells that India has been divided into, 31 contain suitable geographic criteria for underground CAES development. These are ranked in Table 4 along with the normalised factors for wind and solar generation. From the analysis, the states of Madhya Pradesh and Uttar Pradesh are identified as the locations where renewable generation could most benefit from integration with CAES owing to the good renewable potential and wide availability of CAES suitable land. Further detailed investigation should be conducted with a focus on these two states to determining the viability of underground CAES systems in these regions.

The state of Gujarat possesses very good solar and wind power generation potential but possesses minimal geological potential for the construction of underground CAES, therefore in this area particularly renewables should be developed and integrated with more appropriate energy storage technologies.

3.2.3. *Feasible CAES storage capacity in the UK*

The availability of CAES suitable features in the UK is substantially different to that of India. The UK is a much smaller country by area and population and possesses a wide abundance of salt deposits these can be observed in Fig. 6. The Cheshire Basin in north-west England contains numerous large salt beds. Historically, caverns have been formed from these beds and used to storage natural gas, and because of the wide availability and previous usage, much attention has been directed at adapting this geological resource for CAES. If all of the existing salt caverns present in the Cheshire Basin were converted to the storage of air then 725 GWh of capacity would be achieved, 26 times greater than the UK's current pumped hydro capacity [86]. Taking all the salt beds present in the Cheshire Basin as a whole, it has been estimated that it is abundant enough to form up to 100 caverns, providing capacity for 2.53 TWh of storage with an output power of up to 40 TW [87], this would greatly exceed daily average demand of the UK grid. It will almost certainly be cheaper to repurpose the existing gas facilities to CAES storage as the UK decarbonises than it will to construct new salt caverns. In addition to the use of salt caverns for CAES, there exists great potential for the UK's saline aquifer resources to be employed. There is sufficient capacity for 96 TWh using the saline aquifers [88], although these will prove more difficult to harness and their use relies upon less established technologies than salt deposit storage. In the near future, it is recommended that the salt deposits should therefore be targeted for the development of CAES in the UK, prioritising existing infrastructure from previous gas stores.

4. Concluding remarks

Compressed air energy storage is a large-scale energy storage technology that will assist in the implementation of renewable energy in future electrical networks, with excellent storage duration, capacity and power. The reliance of CAES on underground formations for storage is a major limitation to the rate of adoption of the technology. Several candidate methods for using underground formations for CAES have been discussed and can be drawn from specially constructed features to the repurposing of existing infrastructure. Presently salt caverns show the most promise as these have been demonstrated for use in gas and CAES storage and are abundant in many locations. An assessment of the potential for underground compressed air energy storage has been conducted for India by collating geological characteristics local to each region and integrating the potential for renewable electricity generation. India has great potential for solar generation, particularly in the northwest of the country and a lesser potential for wind generation. The

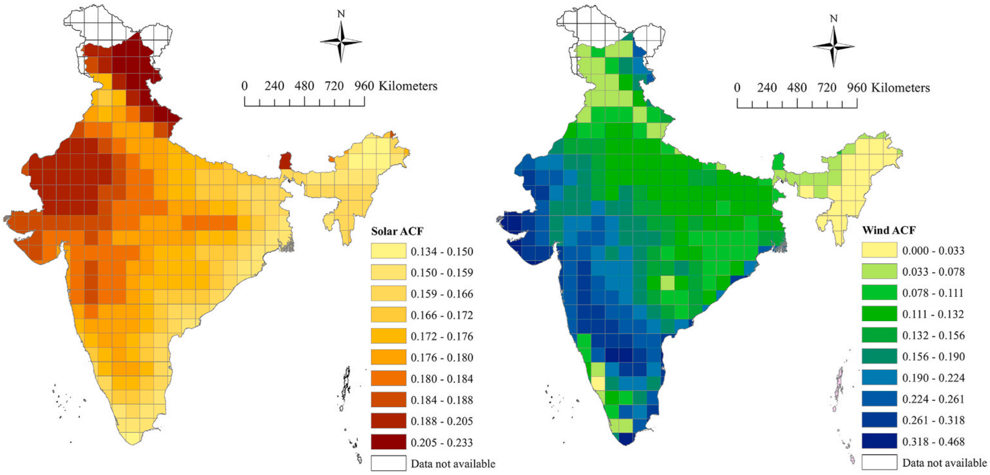

Fig. 5. Left: Solar capacity factor distribution for India. Right: Wind capacity factor distribution for India [83].

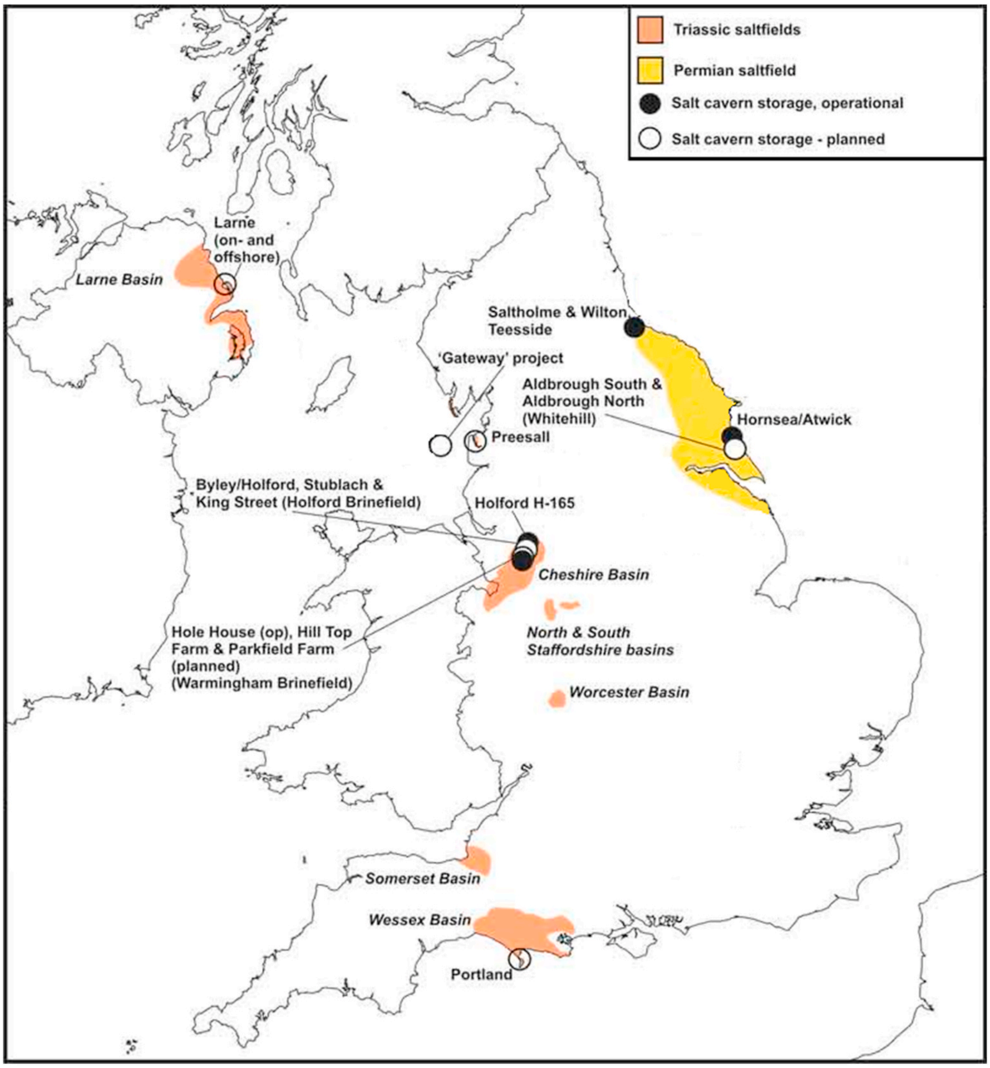

Fig. 6. UK salt deposits. Operational and planned natural gas storage sites that have the potential to be converted to CAES storage [89].

total land area suitable for underground air storage has been evaluated to be 34,400 km^2 or approximately 1.05% of total land area. It is suggested that this resource is sufficient to meet India's electricity storage requirements solely with CAES though this scenario is highly unlikely as only a very minor fraction of this land could practicably be used. The regions of Madhya Pradesh and Uttar Pradesh have been identified as the areas with the greatest potential for the development of CAES technologies to support renewable generation. To improve the assessment, details pertaining to the gas reservoirs and stores for India should be obtained and integrated with the analysis, as should large mines be identified, as both features can be repurposed for underground CAES. Moreover, the differences in energy storage density of the varying underground energy storage methods can be factored into the analysis, as CAES systems utilising different geological formations do not operate with the same characteristics. The identification of candidate locations with the highlighted regions can be undertaken to assess the suitability and the feasibility of a plant can be investigated. The lack of salt caverns in India is likely to be a major constraint in the development of CAES in India until the technology has been proven with a different air storage medium. The UK situation for CAES is widely different with large salt deposits with sufficient capacity to meet energy demand if fully utilised.

CRediT authorship contribution statement

Marcus King: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Writing - original draft. **Anjali Jain:** Investigation, Formal analysis, Resources, Writing - review & editing. **Rohit Bhakar:** Writing - review & editing, Supervision. **Jyotirmay Mathur:** Writing - review & editing, Supervision. **Jihong Wang:** Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 4
Results of analysis of CAES and renewable electricity integration in India (by 1° grid cells)

State	Local Latitude [°N]	Local Longitude [°E]	CAES Suitable Area [km^2]	Annual Capacity Factor (Solar)	Annual Capacity Factor (Wind)	Normalised Area Factor	Normalised Solar Factor	Normalised Wind Factor	Solar-CAES Factor	Wind-CAES Factor	Potential Factor
Madhya Pradesh	26.5	78.5	4974.9	0.193	0.090	1.00	0.94	0.18	0.935	0.185	0.173
Uttar Pradesh	25.5	78.5	4139.7	0.194	0.105	0.83	0.94	0.22	0.780	0.179	0.168
Uttar Pradesh	25.5	79.5	3809.4	0.189	0.094	0.77	0.91	0.19	0.700	0.148	0.136
Uttar Pradesh	25.5	83.5	3597.6	0.182	0.094	0.72	0.88	0.19	0.637	0.140	0.123
Uttar Pradesh	25.5	82.5	2599.2	0.183	0.098	0.52	0.88	0.20	0.462	0.105	0.093
Uttar Pradesh	25.5	81.5	2678.0	0.185	0.091	0.54	0.90	0.19	0.483	0.101	0.090
Uttar Pradesh	25.5	80.5	1680.7	0.186	0.091	0.34	0.90	0.19	0.304	0.063	0.057
West Bengal	23.5	87.5	928.3	0.175	0.088	0.19	0.85	0.18	0.158	0.034	0.028
Jharkhand	22.5	86.5	1090.8	0.174	0.068	0.22	0.84	0.14	0.185	0.031	0.026
Madhya Pradesh	25.5	77.5	448.4	0.197	0.131	0.09	0.95	0.27	0.085	0.024	0.023
Uttarakhand	29.5	79.5	568.6	0.204	0.068	0.11	0.99	0.14	0.081	0.016	0.016
Uttar Pradesh	26.5	79.5	442.6	0.189	0.090	0.09	0.92	0.18	0.113	0.016	0.015
Jharkhand	24.5	87.5	419.5	0.177	0.087	0.08	0.85	0.18	0.072	0.015	0.013
Rajasthan	29.5	74.5	370.6	0.197	0.073	0.07	0.95	0.15	0.071	0.011	0.011
Jammu and Kashmir	32.5	75.5	394.0	0.193	0.052	0.08	0.93	0.11	0.074	0.008	0.008
Punjab	33.5	73.8	323.7	0.202	0.056	0.06	0.98	0.11	0.041	0.008	0.007
Rajasthan	26.5	77.5	186.0	0.194	0.100	0.04	0.94	0.21	0.035	0.008	0.007
Jharkhand	24.5	83.5	229.3	0.186	0.082	0.05	0.90	0.17	0.063	0.007	0.007
Jammu and Kashmir	32.8	74.7	303.7	0.193	0.040	0.06	0.94	0.08	0.057	0.005	0.005
Punjab	30.5	74.5	228.1	0.191	0.051	0.05	0.93	0.10	0.042	0.005	0.004
Gujarat	23.6	68.7	12.2	0.201	0.487	0.00	0.97	1.00	0.002	0.002	0.002
Tripura	23.6	91.6	242.0	0.176	0.018	0.05	0.85	0.04	0.041	0.002	0.002
Rajasthan	29.4	73.6	38.3	0.198	0.083	0.01	0.96	0.17	0.475	0.001	0.001
Nagaland	26.5	94.5	2814.6	0.173	0.001	0.57	0.84	0.00	0.007	0.001	0.001
Jammu and Kashmir	33.5	74.5	7.5	0.207	0.069	0.00	1.00	0.14	0.019	0.000	0.000
Assam	27.5	94.5	126.0	0.160	0.003	0.02	0.78	0.01	0.001	0.000	0.000
Meghalaya	25.5	92.5	23.9	0.182	0.008	0.00	0.88	0.02	0.004	0.000	0.000
Nagaland	25.5	93.5	476.9	0.185	0.000	0.10	0.90	0.00	0.086	0.000	0.000
Assam	27.5	95.5	36.1	0.163	0.000	0.01	0.79	0.00	0.033	0.000	0.000
Punjab	30.5	76.5	2.1	0.192	0.081	0.00	0.93	0.17	0.005	0.000	0.000
Jammu and Kashmir	33.0	73.9	31.5	0.000	0.000	0.01	0.00	0.00	0.000	0.000	0.000
Nagaland	26.7	95.2	203.0	0.169	0.000	0.04	0.82	0.00	0.000	0.000	0.000

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