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UTILIZATION OF COMPRESSED AIR ENERGY STORAGE THROUGH RENEWABLE ENERGY SOURCES

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Abstract- **Renewable energy such as wind, solar, tidal, and wave only produces electricity intermittently and with low power and energy density, thus, non-dispatch able and difficult to use at large scales as the modern society requires. That is why many renewable energy technologies are lacking the economies of scale, which reduces their competitiveness and delays the transition to a low carbon economy. Therefore, economic solutions to bulk energy storage are urgently needed in order for renewable energy to take a significant share in the total energy mix. Most energy storage systems are expensive, either in terms of energy losses incurred in storing and retrieving the energy. For example, batteries are costly, fly wheels are suitable for short duration storage only. The compressed air energy storage system(CAES), besides pumped-hydro, is the only conceivable technology able to provide the very large scale energy storage deliverability above 100MW in single unit sizes while free from adverse environmental effects of pumped-hydro. Hence, CAES has recently received lots of attention and it has been recently proposed that large scale solar-CAES and wind-CAES deployment can enable renewable energy to compete against coal-fired electricity generation. In CAES, a source energy is stored in the form of highly pressurized air in underground rock caverns and the compressed air is released through turbines to generate electricity when needed.**

Keywords— Compression, pumped hydro, Caravans, Off-peak load, Spinning Reserve, Thermal energy storage.

I. INTRODUCTION

As global warming and climate change continue to increase and make themselves known not only by their consequences but increased awareness, the interest for sustainable solutions grows rapidly. The concept of "sustainable development" is a multifaceted term, used by many and in just as many contexts. Many definitions of sustainable development are derived from the Brundtland report, which states that to make development sustainable humans need to "ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987) but this can be interpreted in many ways. While its vague definition is by some deemed problematic, the general consensus is still that sustainable development is of the greatest importance for the future of the human race and needs to be a top priority (Kuhlman and Farrington, 2010)[1].

One of the most important drivers of development is energy, which is necessary for growth on both an individual and global level (IPCC, 2016) and also part of the UN's sustainability goals (UN, 2016). In many parts of the world there is an abundance of energy, as society has spent both time and resources in developing the techniques of harnessing energy from sources such as oil, coal and nuclear materials. With the growing climate changes it has been made obvious that the traditional ways of energy production will no longer be able to sustain the world in ways that do not risk radically changing the global ecosystem. Furthermore, the UN sustainability goals specify that energy should be both clean and affordable, a criterion that is not fulfilled by the use of fossil fuels (Stockholm Resilience Centre, 2018). Renewable energies in many forms are being developed, but just as fossil energies have a problem fulfilling the "clean" part of "clean and affordable energy", renewables have a problem fulfilling the "affordable" part. Within this affordability spectrum falls the problematic fluctuating properties of many renewable energies as the main sources (such as sun, wind and waves) are not constant in their supply but vary with time.

The technological concept of compressed air energy storage (CAES) is more than 40 years old. Compressed Air Energy Storage (CAES) was seriously investigated in the 1970s as a means to provide load following and to meet peak demand while maintaining constant capacity factor in the nuclear power industry. Compressed Air Energy Storage (CAES) technology has been commercially available since the late 1970s. One commercial demonstration CAES plant has been operating successfully for over 24 years, and another has been operating successfully for 11 years. In addition, many other CAES plants have been investigated via siting, economic feasibility, or design studies (EPRI, 2002).

This project is based upon the storage of the compressed air into the air cylinders or the Rock caravans, the compressed air will be stored through the compressor that supply the compressed air to the storage. The compressed air will be flows through the turbine with the help of the pipe, the turbine is placed in a closed container and it has the inlet and outlet of the container and through the inlet we are placing a nozzle that can inject the high pressured air into the turbine case and the nozzle is placed where the compressed air hit directly to the turbine blades that tends to rotate the turbine.

The Architecture is built with the various individual components those are:-1.Solar energy, 2.Compressor, 3.Inlet valve, 4. Air storage tank, 5.Outlet valve, 6.Turbine, 7.shaft, 8.DC generator, 9.Output DC, 10.Load.

III. Working and Block Diagram

Working: - The basic functioning of Compressed Air Energy Storage (CAES) is explained in below Figure, while the introduction image above shows an artist's rendering of a CAES plant integrated with a solar power farm. Essentially, the term compressed air energy storage outlines the basic functioning of the technology. In times of excess electricity on the grid (for instance due to the high power delivery at times when demand is low), a compressed air energy storage plant can compress air and store the compressed air in a cavern underground. At times when demand is high, the stored air can be released and the energy can be recuperated.

Because low cost electricity is stored at low demand times, and electricity is created, through releasing the stored energy, at high demand times at high prices, storing energy is not only motivated by environmental protection benefits, but is also strongly motivated by economic benefits the technology provides. In addition, the technology provides energy market support and socio-economic benefits. The essential components of a compressed air energy storage plant are illustrated as well in Figure. The compressed air is often stored in appropriate underground mines or caverns created inside salt rocks. The ground surrounding the cavern needs to be as air-tight as possible, which prevents the loss of energy through leakage. Storage in mined caverns (caverns excavated specifically for compressed air energy storage) is used for large scale CAES applications and it takes about 1.5 to 2 years to create such a cavern by dissolving salt. However, in addition to large scale facilities, **compressed air energy storage** can also be adapted for use in distributed, small scale operations through the use of high-pressure tanks or pipes (APS, 2007)[3].

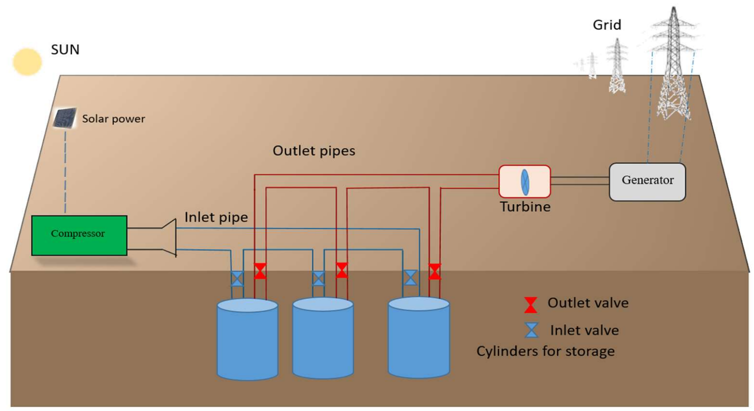

Fig 2: Block Diagram of CAES system

In addition to large scale facilities, compressed air energy storage can also be adapted for use in distributed, small scale operations through the use of high-pressure tanks or pipes (APS, 2007). Figure illustrates a small-scale application of compressed air energy storage. The process is essentially the same as for large scale compressed air energy storage technology, it is just that the reservoir is smaller and above ground. The smaller reservoir limits the amount of electricity that can be stored with small scale technology.

When the plant discharges, it uses the compressed air to operate the combustion turbine generator. Natural gas is burned during plant discharge, in the same fashion as a conventional turbine plant. However, during discharge, the combustion turbine in a CAES plant uses all of its mechanical energy to generate electricity; thus the system is more efficient [4].

The main working of this plant is the storing the compressed air, the compressor is used to create the compressed air. The compressor is supplied with the solar power and the solar power is applied to the compressor then the compressor is start running and the compressor will output is the compressed air. The compressed air will give input as the Air Cylinders or Rock Caravans. The compressed air energy is stored in the Air cylinder with the help of the pipe.

When the electrical energy is demand on the consumers side then the compressed air will used to rotate the turbine as the steam will rotate turbine same as is it is. The compressed air energy feed though the pipes to the turbine at the end of the pipe we placed a nozzle, the nozzle will be act as the air that flow as low pressure with help of the nozzle we can improve the low pressure to high pressure, when the high pressure hits the turbine blades then the turbine tends to rotate and the turbine shaft is coupled with the generator shaft, the turbine rotates then the shaft of the generator also rotate, the basic operation of the generator is it converts the mechanical energy to the electrical energy, then the generator will generates the electrical energy from the generator the electrical energy is transmitted to the Distribution station through the step-up transformer, the distribution station to the consumers. With this we can reduce the usage of fossil fuel to generate electrical energy as thermal power plant. When the solar energy is absent, during the time we are using the grid to run the compressor to store the compressed Air into the Air cylinder or Rock Caravans.

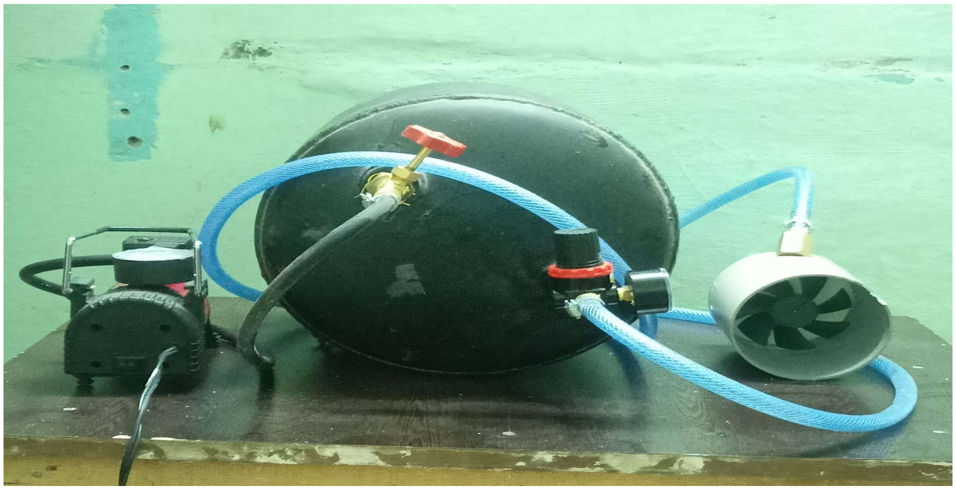

Fig3: Full setup of Prototype of CAES

IV. BACKGROUND OPERATION

The CAES Process:-The basic principle of compressed air energy storage is very simple: compress air during periods of off--peak electricity and expand it during periods of peak electricity. The CAES process can be divided into three main stages: compression, air storage and expansion. Depending on the point of view and system configuration, thermal storage can also be considered a stage in the process but bear in mind that it is not critical to the process, but an addition for improving overall performance. The setup of the system used for this report is shown in figure 1, where thermal storage is included and compression/expansion performed in two stages.

For each of these stages there are different critical aspects for obtaining optimal performance of the system. An aspect that greatly defines configuration of the entire CAES system is whether it is adiabatic or diabetic. During the CAES process heat loss occurs during all stages, and minimizing it has for a long time been one of the main focuses of CAES research (Hartmann et al., 2012). During the CAES cycle heat is produced when compressing air and used when expanding it, so for an ideal process with perfect heat storage there would be no need to add heat as the same amount is needed for expansion as gained from compression. However, storing heat is difficult and expensive, which could be why the only existing plants are diabetic [5].

Compression:- The compressor is motor-driven (Huang et al., 2018) and, depending on the dimensioning of the system, have different sizes and power output and has the main objective to compress the air going into the air storage cavity. For small-scale CAES it is possible to use compressors which also function as generators during the discharge process (Ibrahim et al., 2008), but this results in lower efficiencies and is not common procedure.

During the compression stage the main losses are mechanical conversion loss and heat loss that occurs due to the pressure increase. Referring to the ideal gas law, there is a direct connection between pressure increase and temperature increase, which is why (depending on pressure ratio) the temperature after the compressor can be several hundred degrees Celsius. These kinds of temperatures are highly destructive for most storage cavity material, which is why the air needs to be cooled by passing through a heat exchanger before entering the air storage (Donadei and Schneider, 2016). If the CAES system uses thermal energy storage (TES), compressing the air in one stage (aptly named single-stage compression) requires a TES that can withstand high pressures and high temperature, making it quite a costly affair. Instead it can be more efficient using multi-stage compression, where the air is compressed and cooled several times before reaching the air storage. Cooling the air between compression or expansion stages is called interim cooling or heating and lessens the requirements for the TES material as the heat which is transferred from the air has a lower temperature. For

Most research papers concern adiabatic and semi adiabatic CAES which always include some form of heat storage, but it is of course possible to completely ignore the thermal aspects and release the heat into the ambient air. This would require no heat TES, but the losses would be large, and efficiency be so low as not to be cost efficient. It would also require some other heat source, such as burning natural gas.

The compressor efficiency depends on the pressure ratio between inlet and outlet and with values between 70-90% (Garvey and Pimm, 2016). In published work the compressor efficiency is generally approximated as a fixed value, but in reality, the pressure ratio varies as more and more air is injected into the system which indicate that the efficiency also varies (Salvini et al., 2017)[6]. The fact that the pressure ratio varies during the compression (and by the same logic for the expander) creates some technical difficulties as both compressor and expander obtain optimal efficiency when the pressure ratio is constant, and a pressure regulator is needed, creating energy losses (Pimm and Garvey, 2016).

Storage:-The next step in the CAES cycle is the storage. The storage must able to store large quantities of air at high pressure, something that is not easily found and leads to one of CAES great weaknesses: it is highly location specific (Garvey and Pimm, 2016). Storage systems can be either isobaric or isochoric, isochoric being more common while isobaric gives better performance but is harder to achieve. There are three main ways of dividing storage types: underground, underwater and aboveground with each type having its own set of advantages and disadvantages.

Underground

Storing the air below ground is the most common storage type and both of the existing plants use this method. The advantages of underground storage are that it is cost efficient in relation to the high storage capacity, is protected from external impacts and has a low ecological footprint (Donadei and Schneider, 2016). There are two main disadvantages, the first being that underground storages have fixed volumes and compression and expansion process are thereby not isobaric as pressure inside the cave varies during charge and discharge, impairing overall efficiency. The other main disadvantage is that suitable underground storage can be hard to find and requires extensive geological investigation before constructing a plant.

There are five kinds of underground cavities that can be used for air storage: depleted oil and gas fields, aquifers, salt caverns, rock caverns and abandoned mines. The air in the only two existing plants, McIntosh and Huntorf plants, is stored in large salt caverns which have the benefit of the salts low reactivity with air and low pre-investigation work. Even if salt caverns are the only storage cavity used today, research focuses more on underground formations as the salt caverns are location specific and have already been investigated. While aquifers have been proved appropriate for storing natural gas they have high reactivity and require extensive pre-investigation due to its more intricate nature. The depleted oil and gas field have already been proven fit to store gas and fluids but residuals from the previous oil or gas can cause problems for CAES and no fields have been used so far. Rock caverns are similar to salt caverns but need to be sealed to minimize self-discharge and could be an option where salt cavern construction is not possible but the rock is hard enough to be adequate for storage. Finally abandoned mines could also be an option but just as for rock caverns eventual cracks need to be sealed and making the mine fit for CAES can be costly.

Artificial

As discussed both underground and underwater CAES have the problem of being location specific as they depend on naturally occurring geologies. A way to avoid this would be to construct artificial storages, which has been investigated by (Liu et al., 2014) among others. There are three different kinds of storage devices: gas storage pipelines, gas cylinders and storage tanks. Liu et al. (2014) conclude that gas storage pipelines normally have a lower cost, while air storage tanks are the only option without pressure constraints.

Expansion

After the air has been compressed and stored it is time to extract the energy by passing it through the expander. Just as heat needed to be removed during the compression, heat needs to be added during the expansion. In order to not cause harm to the expander as a result of frozen particles in the air, the air needs to be kept above freezing temperatures. For an ideal process, the energy created during the compression could be used for expansion and no heat would need to be removed or added to the system. However, due to heat storage difficulties, the two existing CAES plants need to burn fuel to provide heat during the expansion. The fuel most commonly used is natural gas (Drury et al., 2011) which contributes to global warming, but as heat storage technology has developed, future plants will likely include some form of energy management where heat from the compression is used which will decrease environmental impact.

Thermal Storage

In terms of overall efficiency, it is beneficial to store the produced heat from the compression stage to use it later on, either for expansion or other application. To increase overall efficiency of the system it is important that the losses from the thermal storage are as low as possible. For the heat to travel to the storage, heat exchangers are needed, but which specific type will depend of the kind of storage and storage medium used. For CAES a favourable configuration of a TES system is having one hot storage and one cold, albeit interconnected. The cold fluid will flow pass the compressor, cooling it and heating the fluid, which is then stored and later on will flow pass the expander, heating the air and turning the fluid cold yet again (Huang et al., 2018) [8].

Limitations of CAES

1. The CAES technology can be easily optimized for specific site conditions and economics.
2. CAES is a proven technology and can be delivered on a competitive basis by a number of suppliers.
3. CAES plants are capable of black start (further discussed below). Both the Huntorf and McIntosh plants have black start capability that is occasionally required.
4. CAES plants have fast start up time. If a CAES plant is operated as a hot spinning reserve, it can reach the maximum capacity within a few seconds. The emergency start up times from cold conditions at the Huntorf and McIntosh plants are about 5 minutes. Their normal start up times are about 10 to 12 minutes.

Feasibility of compressed Air Energy Storage and Operational Necessities

As mentioned, the CAES technology concept is more than forty years old. The first and longest operating CAES facility in the world is near Huntorf, Germany, The 290- MWe Huntorf plant has operated since 1978, functioning primarily for cyclic duty, ramping duty, and as a hot spinning reserve for the industrial customers in northwest Germany. Recently this plant has been successfully levelling the variable power from numerous wind turbine generators in Germany. In the U.S. a 110 MWe plant has been constructed near McIntosh, Alabama and has been in operation since 1991. A third CAES facility is being planned in Norton, Ohio, USA. This facility will be the largest ever with a 2700 MWe capacity which will compress air to 1500 pounds per square inch (psi) in an existing limestone mine some 2200 feet underground [9].

Several other CAES plants have been designed and/or investigated but were not built for a variety of reasons (EPRI, 2002). Several examples are:

1. During the Soviet era, a 1050 MWe CAES plant using salt cavern geology formations for the air storage was proposed for construction in the Donbas area of Russia. Underground geological development of the air storage was initiated. However, when the Soviet Union collapsed, the construction was terminated.
2. In Israel plans were developed for several CAES facilities, including a 3 x 100 MWe CAES facility using fractured hard rock aquifers.
3. Luxembourg designed a 100 MWe CAES plant sharing an upper reservoir for a water compensation system with a pumped hydro plant located in a hard rock cavern at the Viendan site.
4. Soy land Electric Cooperative, contracted for the construction of a 220 MWe hard rock based plant. Plant engineering and the cavern sample drilling/rock analysis was completed and all major equipment had been purchased when the project was terminated due to non-technical considerations.

While most projects were not completed, the examples above show that CAES technology is clearly beyond the developmental phase. In addition, the technology is capable of establishing large scale energy storage, ranging up to 1000 MWe. Table 1 illustrates the development phase of several energy storage technologies. The APS panel on public affairs (2007) recommends further research and development efforts in CAES technology in the fields of establishing additional demonstration projects and computer modelling (APS,

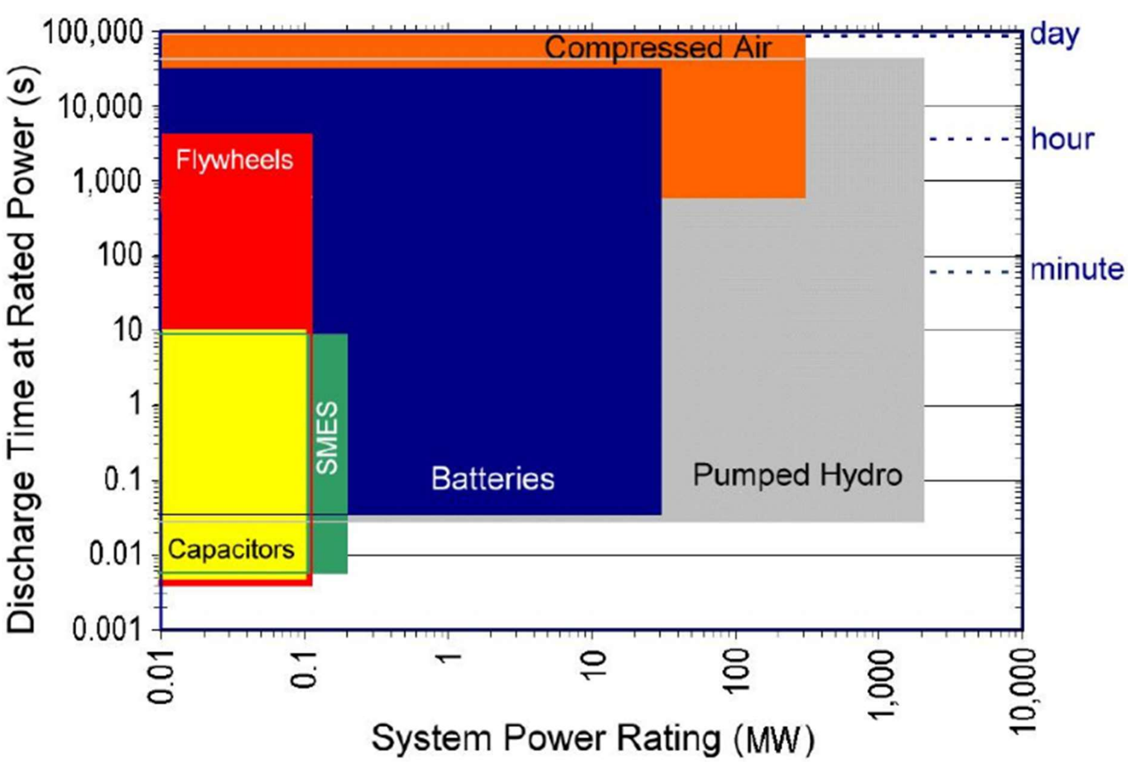

Fig 4: System power ratings and discharge times

Result:

Fig 5: Pressure reading

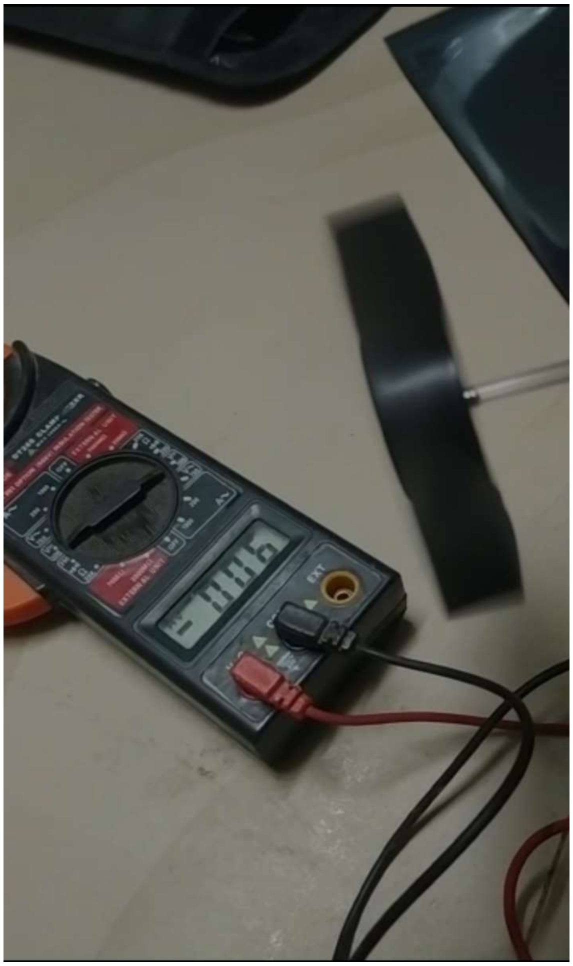

Fig6: Volt meter reading of CAES Prototype

This project of the result is given out by the DC current and the result of the CAES prototype is shown in above figure 6. And the inlet of the cylinder pressure is shown in above figure 5.

The output pressure of the cylinder is 26psi, and the turbine output is 6v.

Load Profile of the household

For the purpose of deciding the demand of the households, the following load profiles are developed and shown in figure. Note that the values of the y-axes are for one household and are later multiplied by ten to accommodate ten households. For weekdays the system is set to be discharged between 6:00-9:00 and 16:00-22:00. As the charge period is seven hours is it set to be charged between 9:00-16:00 and 23:00-6:00? For weekends the need is greater (note that the y-axis is twice as long during weekend) and therefore calculations shows that the system can only supply electricity for a few hours. Therefore, discharge hours are set to be 8:00-12:00 and 15:00-22:00 to be charged between 12:00-15:00 as well as 01:00-08:00.

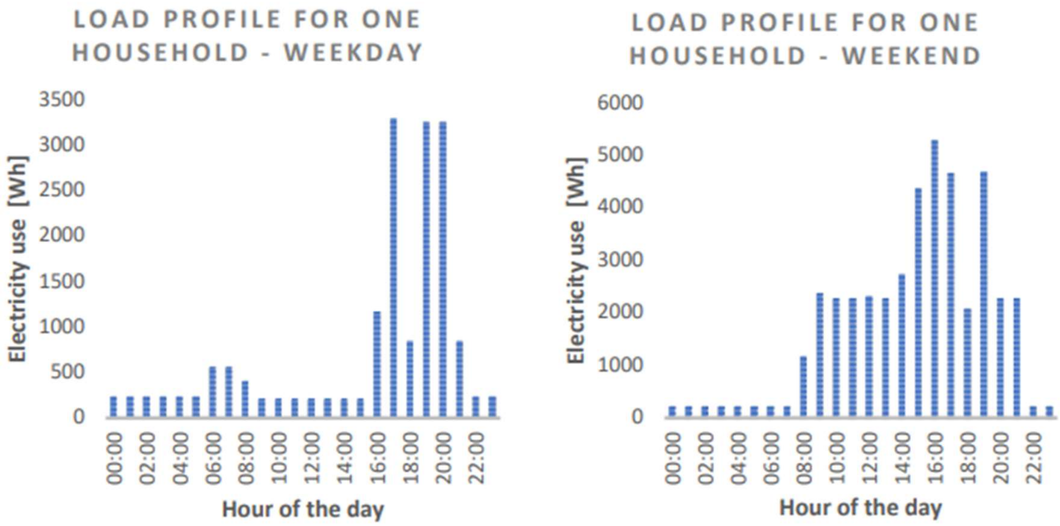

Fig 7: *Load profiles for one household during Monday-Friday and Saturday-Sunday*

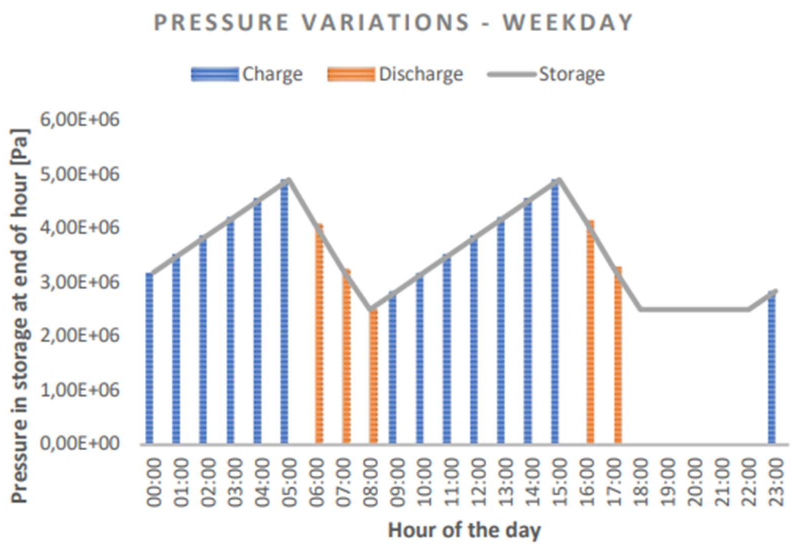

Fig 8: *The blue and orange staples show variations in pressure during charge phase, discharge phase and the grey lines follows the pressure in the storage. During periods where only the grey line is present the storage has been emptied to minimum pressure and the system is at rest. This figure is true for Monday to Friday*

pressure ratios the storage functions between a maximum pressure of 49 bar (high pressure compressor outlet) and a minimum pressure of 25 bar (high pressure turbine inlet). As it is assumed that the ambient temperature cancels out any temperature variation from pressure changes within the storage the ideal gas law is used to decide how much mass these two pressures represent.

mass that can be extracted from the storage. This is clarified in figure where it can be observed that for certain hours that maximum amount of mass that the storage can provide during an entire charge period is not enough for one single hour.

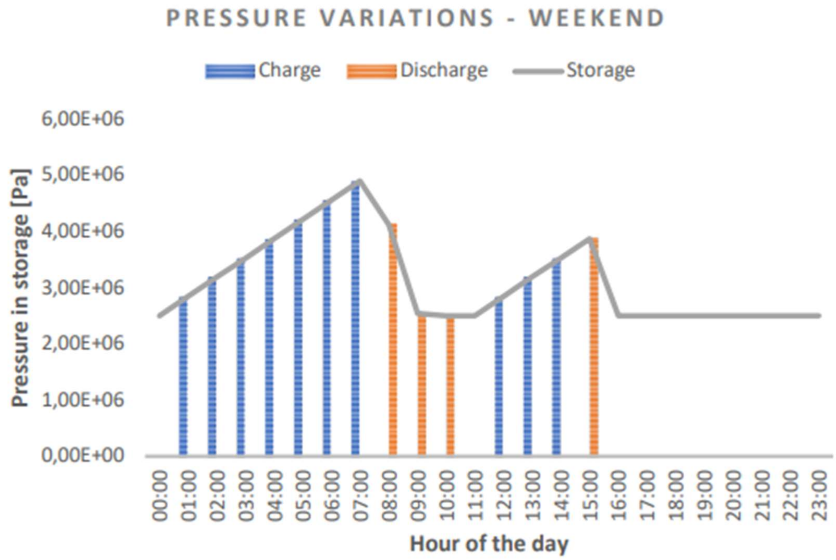

Fig 9: *The blue and orange staples show variations in pressure during charge phase, discharge phase and the grey lines follows the pressure in the storage. During periods where only the grey line is present the storage has been emptied to minimum pressure and the system is at rest. This figure is true for*

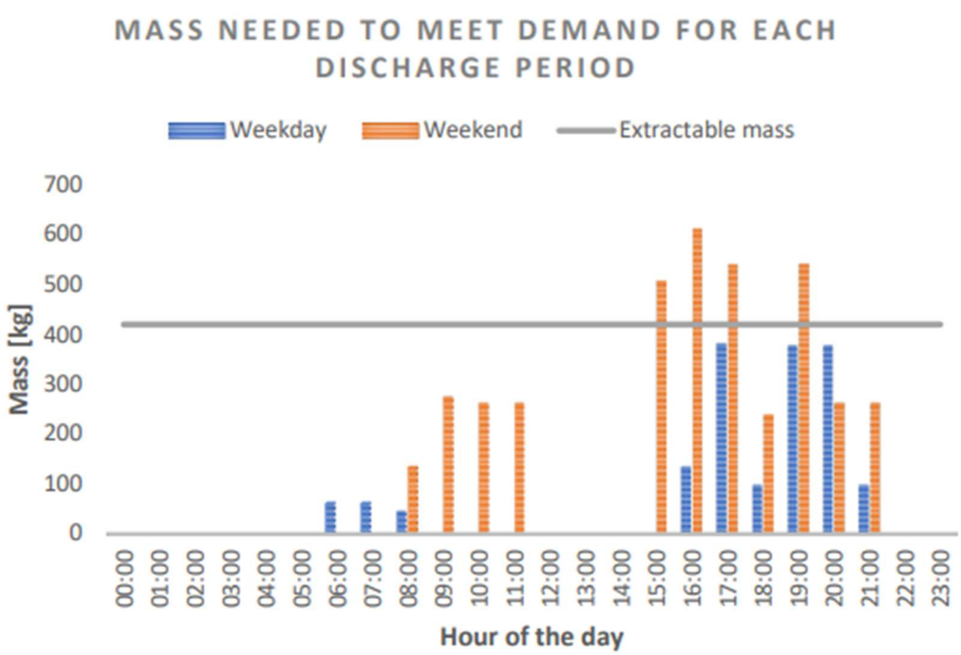

Fig 10:the blue and orange staples show the mass that needs to be expand to satisfy the demand .Saturday and Sunday except for the small detail that for the last hour of Sunday the pressure increases like in figure.

CONCLUSIONS

There are several different ways of designing a CAES system and there are elements in the entire cycle from compression to expansion that are of interest from an engineering perspective. This report proposes one system set-up alternative but for future studies an important objective is to develop an optimization model that could vary certain properties within the system to determine optimal values to improve efficiency and economic gains. The results from this report suggests that using small scale CAES is not economically viable if the electricity used for charging is bought at today's electricity price and without any other economic benefits. It could however be made feasible during other circumstances which might inspire further studies on the subject especially since CAES have potential to be a more sustainable alternative to fossil fuels in the energy system. The results show that the positive effects of CAES concern the grid as a whole proposing that the stakeholders with most interest in CAES should be the energy companies and grid developers, not the end consumer. For developing CAES infrastructure it is therefore recommended that this is carried out by the main benefitting stakeholders, rather than the consumers or other smaller actors.

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