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Improving Grid Reliability in Jordan: A Proposal for Integrated Demand Side Management and Energy Storage Solutions

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ABSTRACT: Increased use of Renewable energy systems (RES) in Jordan has posed a major challenge in maintaining our grid stability. Jordan a country that relies on imported natural resources to power up its grid, is using more and more RES to cut back on costs and CO_2 emissions. This paper investigates the usage of Demand Side Management (DSM) and Energy Storage Systems (ESS) to improve the grid's reliability. A survey was conducted to analyze the opinion and acceptance of the Jordanian population on implementing DSM in Jordan. (ESS) mentioned in detail in this paper are Compressed Air Energy Storage Systems (CAES) and Superconducting Magnetic Energy Storage Systems (SMES). The survey conducted showed a general scope of willingness of participation from people, with 71.7% out of the 385 individuals who participated in the survey saying that they would participate in such a program if implemented in Jordan.

Keywords: Demand Side Management (DSM), Demand Response (DR), Energy Storage Systems (ESS), CAES, PHES

1. Introduction

The electrical energy consumption in Jordan continues to surge in line with a global trend. According to NEPCO's annual reports, Jordan's recorded peak load consumption in 2021 reached 3770MW, marking a 3.71% increase compared to the previous year [1,2]. The "governmental and household" sector accounts for the highest consumption at 44.49% [2]. Jordan heavily relies on imported natural resources for its energy needs, but there has been a gradual decline in recent years due to an increased utilization of renewable energy sources. In fact, as of 2018, renewable energy sources accounted for 92% of the country's energy mix [3]. The development of renewable energy systems (RES) in Jordan is on the rise, aiming to reduce carbon emissions and environmental impact in alignment with the Paris Agreement's objective of limiting global warming to 1.5°C and achieving net zero emissions by 2050 [4]. In 2021, renewables accounted for 28.7% of the country's total energy generation [5]. This poses a main challenge on the Jordanian grid as the usage of renewable energy sources as sources of supply makes it harder to match demand [6] especially since the main RES used in Jordan (Wind and Solar) are weather dependent.

The Jordanian transmission grid code lists the permissible voltage variations on the transmission network to be:

1. for 400KV and 230KV lines.
2. for 132KV lines

with an extra permissible 5% for an under-stress system or following a fault [7]

Multiple solutions have been developed to solve this issue, with controlling the demand side through demand side management (DSM) being one of the main ones [8]. DSM controls and manages consumers' electrical consumption and modifies the consumption pattern to align with the generation.

Another solution commonly being looked into is using Energy storage systems(ESSs) to store the excess energy produced by RES during light loads or peak generation and use during peak loads or insufficient generation [9].

This paper investigates the possible challenges to be faced when implementing DSM in Jordan and what motivates the Jordanians the most to participate in such programs if they were to be implemented in Jordan. It also suggests three different ESS solutions to be used to further increase the flexibility and reliability of the Jordanian grid.

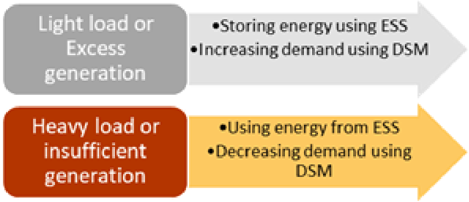


Figure 1. Proposed Solutions

2. Demand Side Management (DSM)

DSM is used to control the demand by either increasing or decreasing to match our generation. It can be defined as “a set of techniques that can be used to modify the consumption pattern of the end users of electricity over time” [10]. Many countries have resorted to using the demand side management program to reduce the value of high demand at times, and these countries have used several principles, including mandatory and optional between the distributing company and the customer. [11] DSM consists of two main branches: Energy efficiency (EE) and demand response (DR) [12]. It gives the customers or consumers the ability to participate in and be part of the electrical grid by making decisions that can influence the grid through either shifting, increasing, or decreasing their demand. DR programs are of three types these types depending on the motive for the consumer to alter their load these types:

1. Incentive programs: Programs that offer incentives to consumers for modifying their consumption during a specified period. Incentives offered could either be in the form of credit or financial rewards.
2. Market-Based Programs: Using dynamic pricing, the electrical tariff changes based on the amount of demand and generation available. Thus, encouraging consumers to either lower or increase their consumption based on pricing signals received.
3. Price-Based Programs: Different rates apply during different times of the year. Rates are increased during peak timings and lowered during off peak times of the year.

2.1. Demand Response (DR):

DR is one of the easiest and most efficient solutions that can be implemented to improve the reliability of our electrical grid. However, it still faces a lot of challenges to be implemented. These challenges can be classified as either technical or social challenges.

Technical challenges involve the design and implementation of effective DR programs. These challenges include developing robust communication systems, establishing accurate and real-time data monitoring capabilities, and ensuring the seamless integration of DR into existing grid infrastructure.

Social challenges pertain to human behaviour and acceptance of DR programs. Encouraging end-user participation and engagement requires effective communication, education, and incentives. Overcoming resistance to change and fostering a culture of energy conservation and responsiveness are essential for of successfully adopting DR.

DR programs can be further classified into different types based on their functions [13]:

1. **Peak Load Clipping**: This type of DR is deployed during peak load periods to reduce electricity consumption to bring it closer to the regular consumption pattern. By curtailing non-essential loads or implementing load-shedding strategies, peak load clipping helps alleviate strain on the grid during periods of high demand.
2. **Load Shifting**: Load shifting DR programs are implemented during peak load periods as well. The objective is to shift consumer electricity consumption to non-peak hours, thereby balancing the load curve. By incentivizing consumers to adjust their usage patterns, load shifting helps distribute demand more evenly throughout the day, optimizing grid operations and reducing the need for additional generation capacity.
3. **Valley Filling, Load Building, or Flexible Load**: This type of DR is utilized during periods of surplus generation from renewable energy sources (RES). The aim is to encourage increased electricity consumption by end-users to utilize the excess generation capacity. By aligning consumer demand with renewable energy availability, valley-filling programs enhance the utilization of clean energy sources and contribute to grid stability.

Implementing and diversifying these DR strategies can bring numerous benefits, including enhanced grid reliability, reduced peak demand, improved energy efficiency, and increased integration of renewable energy. Overcoming technical and social challenges associated with DR implementation is crucial for unlocking its full potential and realizing a more sustainable and resilient electrical grid.

2.2 Price-Based DR programs:

Price-based DR programs are based on the principle of different prices for electric tariffs at different times [14]. Their main types are:

1. Time of use (TOU) pricing: It is one of the types used in the application of the price-based program, which is based on the idea of segmenting the day into several periods, and each period contains a certain number of hours according to high demand, and the customer is charged for hours of consumption within periods of high demand at a price higher than consumption outside periods of high demand. Through this method, we can encourage consumers to change the consumption time in proportion to the peak time. [14]
2. Real-time pricing (RTP): This type is used in the application of the price-based program. It is based on the principle of dividing the day into 24 hours, and each hour has a different price; the price depends on the high demand. The customer must be notified of the price per hour separately. [14]. One of the concerns that customers feel about this system is the possibility of large fluctuations in the hourly tariff rates.

Some companies applying this system have resorted to making the customer pay a fixed price for his basic consumption, and any consumption above the basic consumption will apply the RTP system. One of the factors that must be taken into consideration when applying the RTP program is the date of announcing the hourly tariff price before entering the hourly time. [15] . One of the drawbacks of this system is that the monthly bill may increase due to fluctuations in prices, and this makes it unacceptable in terms of customers. [16]

3. Critical peak pricing (CPP): It is a system similar in its working mechanism to the TOU system, but with a slight difference, which is that this system is used only when there is danger on the electrical network (several limited hours per year) and very large fees are imposed when applied. [14]

3. Survey on Demand Side Management Programs

3.1 Participators' Backgrounds

3.1.1 The Nationality of the Participants

One of the most crucial aspects of demand-side management is the willingness of people to participate in these programs. We surveyed Demand Side Management programs in the Hashemite Kingdom of Jordan to assess this. A total of 385 individuals from various backgrounds, residing in Jordan, participated in this survey, as shown in Table.1.

Table.1 The nationality of the participants

Nationality	Number of participants
Jordanian	370
Palestinian	7
Syrian	4
Libyan	1
Saudi	1
Yemeni	1
Egyptian	1

Given that 30.6% of Jordan's population comprises immigrants, it is important to gather their opinions on these programs [17].

3.1.2 Age of Participants

It is important to know the age of participants to assess the likelihood of their engagement in these programs. Figure.2 shows the age of the participants.

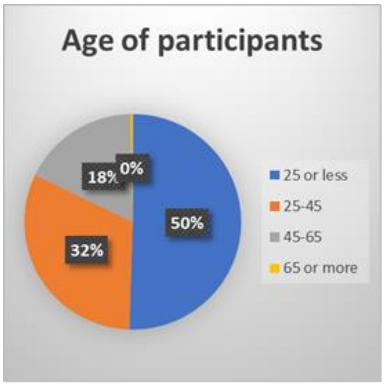


Figure 2. Age of participants.

Based on our research, we found that respondents who were 25 or younger made up the largest group in the poll, accounting for more than 50% of all respondents. Therefore, it is very likely that implementing similar initiatives in Jordan's next generation would provide positive results. Furthermore, given that 32% of participants were between the ages of 45 and 65, we can start the initial deployment right away.

3.1.3 The Educational Background of the Participants

It is important to find out the participants' educational backgrounds to determine the most effective means of communication and presentation for these programs. Figure 3 displays the educational background of the participants.

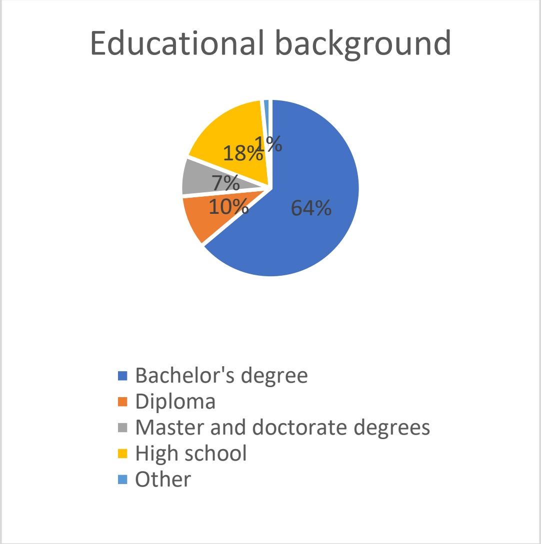


Figure 3. The Educational Background of the Participants

3.1.4 The Geographical Distribution of the Participants

Knowing the geographical distribution of the participants within Jordan is a crucial factor in determining the program's starting point, identifying areas that require greater advertising efforts, and planning the next steps. Table 2 provides insight into the participants' current locations within the country.

Table 2. The Geographical Distribution of the Participants

Region	Percentage
Amman	56.5%
Balqa	30.1%
Madaba	3.4%
Zarqa	2.3%
Irbid	2.3%
Mafraq	0.3%
Jerash	1.8%
Ajloun	0.3%
Karak	0.8%
Aqaba	1.6%
Ma’an	0.3%
Tafilah	0.3%

As shown in Table 2 its easier to start in the central region (Amman, Zarqa, Balqa, Madaba) than go to the northern region (Irbid, Mafraq, Jerash, Ajloun) and southern region (Karak, Aqaba, Ma’an, Tafilah).

3.1.5 The Financial Background of the Participants

Given that the programs are incentive-based, market-based, and price-based, with a primary focus on the financial aspect, gathering information about the participants' financial backgrounds is essential. This data will enable us to determine the most suitable program for successful deployment in Jordan.

3.1.5.1 The Participants' Home Ownership Status

Another critical factor to consider is the homeownership status of the participants. Our findings indicate that 81.6% of the participants own their homes, while 18.4% rent. Notably, individuals who own their homes are more inclined to remain engaged in the program for an extended duration than those who rent their homes.

3.1.5.2 Monthly Income

Income is a main factor influencing people's decision to participate in the program. Financial incentives might encourage people with lower incomes to participate. The data shows that 55.4% of participants with an income of 500 JD or above monthly income may prefer different types of programs than the 44.6% of participants with a lower monthly income.

3.2 What do participants think about demand-side management?

Participants were asked if they had any prior knowledge of DSM programs. 84.4% of the 385 participants stated that they had no prior knowledge about such programs. Meanwhile, 15.6% stated that they had some sort of previous knowledge about the programs.

3.2.1. Indirect Load Control

Indirect load control includes programs where an agreement is made in advance with consumers to monitor and regulate their consumption during agreed-upon times. Such programs were explained to participants and 71.7% of participants responded positively, stating their willingness to participate. On the other hand, 28.3% responded negatively. Among those who approved, Figure 4 shows the reasons for their agreement. The primary reason for approval was the potential for a reduced electricity tariff, suggesting that a program offering this benefit could be successful in Jordan and contribute to energy conservation and environmental sustainability. Approximately 23% of participants were motivated by this reason alone. Additionally, a significant number of participants expressed interest in programs that combined two or more of the reasons suggested in the survey.

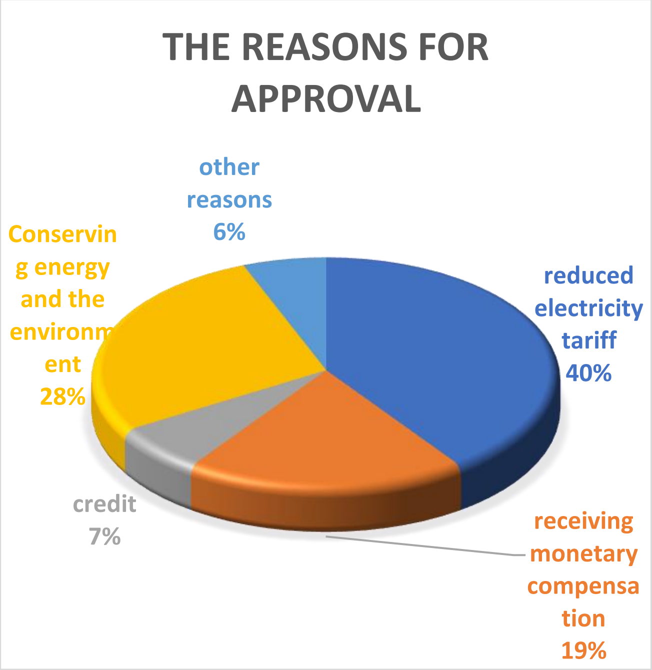


Figure 4. The reasons for approval of indirect load control.

According to Figure 5, the main reasons for participants' unwillingness to engage in the programs are a lack of knowledge about the program and a lack of trust in the responsible companies. These factors pose significant barriers to participation. By addressing these concerns and focusing on increasing awareness and building trust, we can potentially convince more individuals to participate in the programs. We asked participants if they would continue to support the idea if penalties were imposed for non-compliance with the agreed-upon time. The results showed that 62.9% of participants stated they would not continue to support the idea under these circumstances.

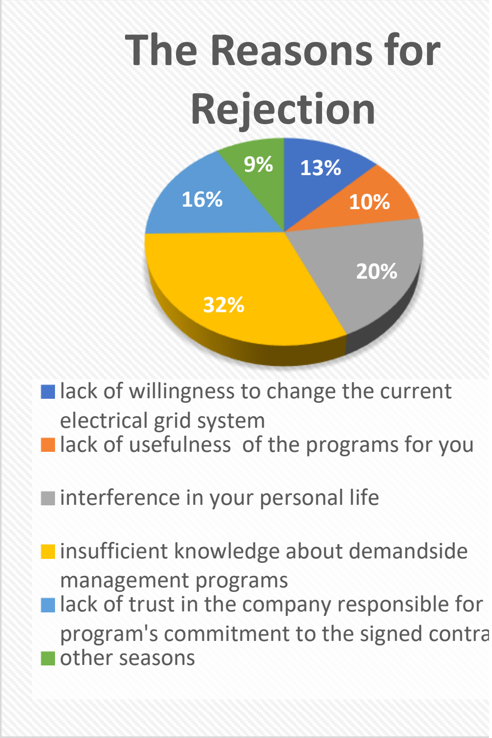


Figure 5. Reasons for rejection of indirect load control.

3.2.2. Direct Load Control

In our survey, we also asked about participants' willingness to participate in a program where the responsible company would have direct control, such as setting temperature limits for air conditioning or disconnecting certain appliances without prior notification. In exchange, participants' electricity consumption would be regulated, and they would receive either a greater reduction in the electricity tariff or greater monetary compensation compared to the previous phase. The results revealed that 51.9% of participants responded negatively to this proposition, as indicated in Figure 4, citing various reasons. However, 48.1% of participants responded positively to the idea, as shown in Figure 5. Upon comparing the responses, it is evident that the deployment of indirect load control is more accepted by participants than direct load control.

Figure 6. The reason for rejection of direct load control

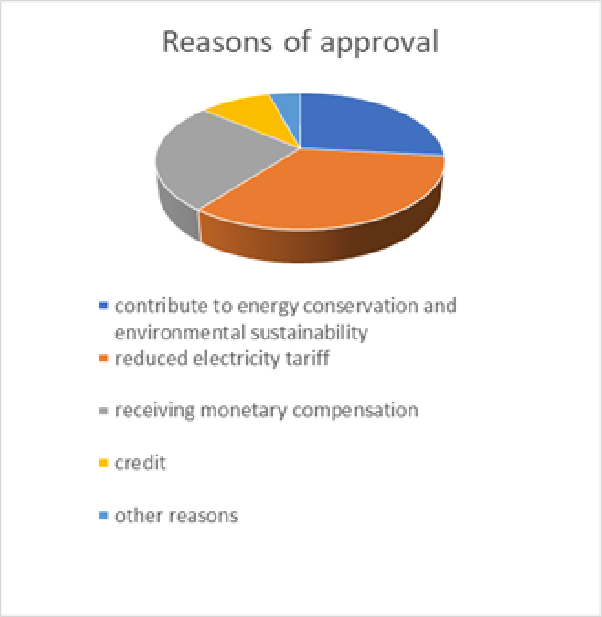


Figure 7. The Reasons for Approval of Direct Load Control

3.3 Recommendations

The data collected suggests that the implementation of DSM programs in Jordan might face some challenges, such as those stated in Figures 3 and 4. However, Figures 4 and 5 stated some scopes, such as financial incentives and reduced electricity bills, that could be focused on to increase the chances of successfully implementing such programs.

Efforts should also be made to solve the social challenges associated with such programs, such as the lack of knowledge and trust from people, as shown in figures 3 and 4, respectively.

Alternatively, exploring energy storage systems could present an alternative solution. Storage energy systems offer the potential to store and utilize energy more efficiently, providing a means to address demand and supply fluctuations effectively. By considering these factors and exploring suitable approaches, overcoming barriers and effectively deploying demand-side management programs or exploring alternative solutions like energy storage systems is possible.

4. Energy Storage System

4.1 Compressed Air Energy Storage (CAES)

4.1.1. Introduction to Compressed Air Energy Storage (CAES)

The idea of energy storage is becoming increasingly significant day by day for several reasons. One of these reasons is the combination of renewable energy systems (such as wind and solar energy) into the power generation systems used today to address intermittent power supply issues. Another reason is to meet periods of high demand by utilizing pre-stored energy.[18]

In Jordan, we are witnessing a significant rise in the use of renewable energy, especially solar energy, which leads to the requirement for electrical energy storage methods.

One type of energy storage is Compressed Air Energy Storage (CAES), which operates on the principle of compressing ambient air using compressors and saving it in the reservoir. The compressed air is then released through expanders to operate turbines that generate electrical energy during periods of high demand.[18]

4.1.1.1 Definition and Explanation of CAES

The principle of compressor air, in terms of operation and composition, shares similarities with gas turbine power plants. Both rely on using air as the primary working fluid for power generation and storing air under pressure. In terms of composition, gas turbine power plants consist of three main sections: compression, combustion, and the presence of turbines. Air is compressed and mixed with fuel, and then electricity is generated by rotating the turbines. As for compressed air, there are a few slight differences. There is a storage tank where compressed air is stored, and an expansion process occurs after the storage phase. One key difference that allows for higher efficiency in compressed air systems is the time gap between the compression and expansion processes, as they do not occur simultaneously.[19]

To summarize the compressed air process simply, we compress the ambient air during low demand using compressors, mix it with fuel for combustion, and then store it in tanks. When demand increases, we release the compressed air through expanders, which then drive air to the turbines that generate electricity through the generators [20]

4.1.1.2 Historical Development of CAES

The ideas for compressed air energy storage began to spread in terms of energy storage starting in 1940. However, there was no follow-up in developing and implementing the idea of compressed air energy storage, both economically and scientifically, until the end of the 1960s. This may be attributed to the lack of urgent need and necessity for energy storage compared to production at that time. In 1969, Germany, specifically the northern region, decided to develop and produce a factory for compressed air energy storage for electricity generation. The geology of that specific region facilitated the easy implementation and development of this type of energy storage, as there were suitable salt caverns underground for storing compressed air for use in the electricity production process. [18]

One of the challenges many current compressed air energy storage plants face is the occurrence of significant energy losses at low cost in the 1960s. This led to the need for development and research to reduce this significant energy waste. [20]

4.1.1.3 Advantages and Disadvantages of CAES

The CAES system, like other energy storage systems, has both advantages and disadvantages. In any energy storage system, the advantages must outweigh the disadvantages for its success. One of the major benefits of the CAES system is relatively low capital costs compared to other storage systems, low self-discharge, long lifespan, high durability, and the capacity to store enormous amounts of energy. [20]

As for the disadvantages, there are several drawbacks to this system, One of the disadvantage of this system is the long response time compared to other types of storage. [20] and one of the major ones is the requirement for suitable geographic storage sites for storing the compressed air. This factor poses one of the main obstacles in the CAES system. [21]

- This drawback can potentially be a critical point in the lack of success of this system in Jordan.

One of the disadvantages that has been overcome is the environmental impact. The old and traditional CAES systems relied on the principle of fuel combustion. However, modern and advanced systems have developed storage mechanisms and eliminated the fuel combustion process by using a TES tank. [21]

4.1.1.4 Types of CAES systems

There are three main types of CAES systems: diabatic, adiabatic, and isothermal. [20]

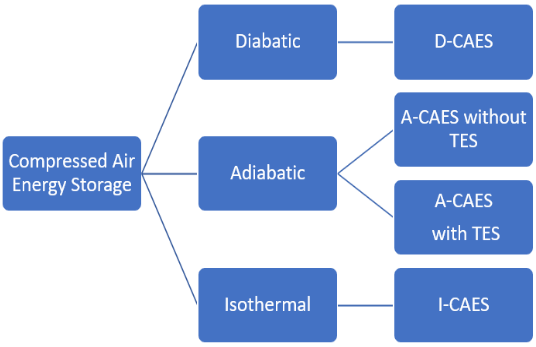


Figure 8. Types of CAES systems [18]

The first type, diabatic, is considered one of the initial real-world applications and the traditional system for CAES. When using this type, there is significant energy loss during the compression and expansion processes. To reduce these losses, outer energy sources, such as a gas burner, are used to heat the air released from the storage tank. Additionally, an intercooler is used after the compression process to reduce the temperature of the compressed air. To overcome these issues, extensive research and experimentation have led to developing an adiabatic system. This system includes an additional tank called TES, which stands for Thermal Energy Storage, to address the problem of using external energy sources and improve the system's efficiency. As for the third type, it is considered more efficient than other systems because it does not use fuel during the compression process. Instead, it utilizes the principle of pressure using liquids. However, this system has not been implemented in practical applications yet. [20]

4.1.1.4.1 Diabatic (D-CAES)

As we discussed earlier, this system is the first system to be applied on the ground and less efficient due to the use of external sources to heat the compressed air after it leaves the tank.

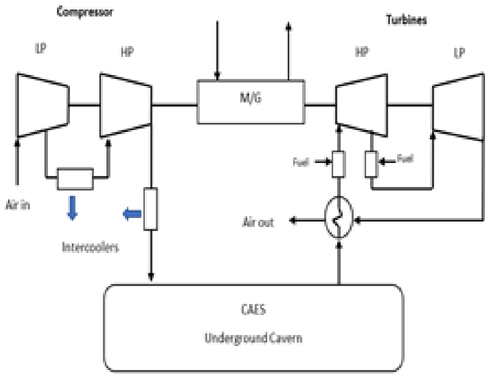


Figure 9. D-CAES Plant [20]

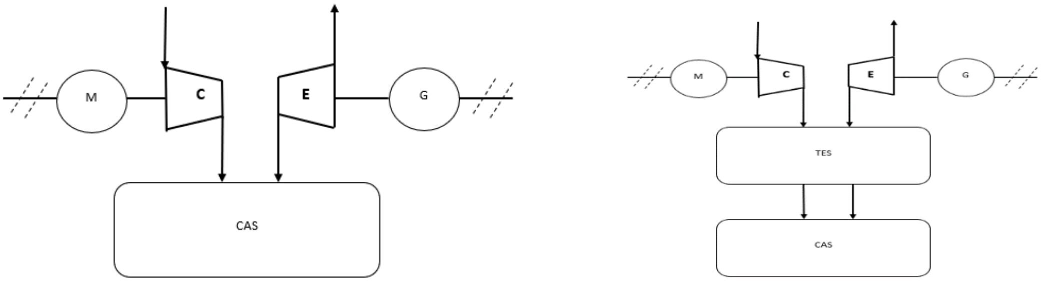
4.1.1.4.2 Adiabatic (A-CAES)

This type represents a development of the Diabatic system. In this system, the process of heating the air using fossil fuel has been eliminated. Instead, the air is heated after it exits the compressed air storage through the recovery and storage of the heat created during the compression stage, which is stored in the TES tank. This eliminates the final use of fossil fuel in the expansion process. One of the advantages of this system is also its quick start-up compared to the Diabatic system [20]

A pilot plant has been built by the Institute of Physics affiliated with the Chinese Academy of Sciences with a capacity of 1.5 megawatts, and they are working on developing it to reach a capacity of 10 megawatts [20]

The A-CAES system has two types: TES (Thermal Energy Storage) and without TES. The type that comes with TES is the traditional A-CAES system, while the other type without TES is similar to D-CAES. However, it doesn't have any external source for heating and cooling the air, limiting its usage due to its lower efficiency. [22]

See Figure 11 to see the basic concept for A-CAES between with TES and without TES



(a) A-CAES without TES

(b) A-CAES with TES

Figure 10. Basic Concept for A-CAES Between with TES And Without TES
C Compressor), E(Expansion), CAS (Compressed Air Storage), M(Motor), G (Generator)[30]

4.1.2. Components of a CAES System

The CAES system consists of a set of essential components, including compressors, expanders, storage tanks, combustion devices, engines, generators, and turbines, along with some secondary components such as fuel tanks and TES. Through these components, the compressors, expanders, and storage tanks play a crucial role in the system's overall efficiency. [19]

4.1.2.1 Compressors

The compressor is indeed a crucial component in a CAES system, as it is the first component in the system and is responsible for consuming electrical energy. The size, capabilities, and specifications of the compressor depend on the size and design of the CAES system. Therefore, you can find different sizes of compressors.[23]

The primary objective of the compressor is to compress the air. However, it incurs several losses, such as heat losses due to increased pressure and mechanical losses due to movement and friction. The temperature after the compression process can reach several times the temperature before compression. To maintain the system, a cooling process is required after compression and before the compressed air comes in the storage reservoir.[23]

To reduce heat losses during the compression stage, some plants have implemented multiple compression stages. This approach helps lower the temperature and increase the efficiency of compression.[23]

4.1.2.2 Storage tanks

The storage tanks are important elements in the CAES system. Compressed air can be stored in two ways. One method is based on the principle of constant volume (isochoric) storage, where the pressure is equalized. This method is the most common for compressed air storage because it does not require an additional tank. The storage can be done inside salt caverns, mines, or above-ground steel tanks. In contrast, the other method is storage at a constant pressure (isobaric). To maintain a constant pressure, an additional tank is required, with the liquid level in it higher than the main storage tank. [18]

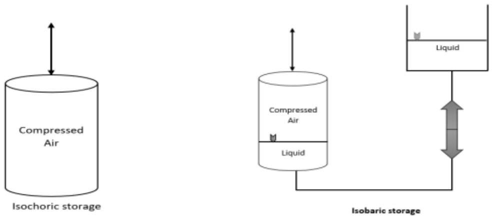


Figure 11. isochoric storage and isobaric storage [30]

Indeed, storing compressed air within salt caverns is considered the best method due to the strength and tolerance of salt caverns to handle high pressure and temperature. However, it is important to ensure that the compressed air temperature is lower than the maximum allowed temperature to maintain the stability of the cavern. In some countries where the geography lacks salt caverns, alternative options such as mines are used, as was the case in Japan.[18]

One of the reasons that make salt caverns a good option for air storage is their large size, which allows for storing large quantities of air. However, there are some drawbacks, such as the presence of rodent holes within these caverns and the treatment of saline water.[19]

One of the methods used in the process of drilling and forming salt caverns is solution mining. This method involves using specific fluids to dissolve the salt and extract all the caverns, creating a suitable cavity for compressed air storage.[21]

One of the reasons that made the use of hard rock caverns less ideal is the high capital cost compared to salt caverns. As for porous rocks, although the cost is low, they cannot withstand high temperatures like salt caverns can.[21]

- Storing air in tanks is considered one of the costliest components of a CAES system. Therefore, establishing such a system in Jordan can be expensive due to the lack of suitable storage locations.

4.1.2.3 Expanders

The expander is indeed a fundamental component in a CAES system, and its type and size depend on the specifications of the CAES system. It is responsible for decompressing the air after it has been stored in the compressed air reservoir. When needed, the air is extracted through the expander.[23]

As we discussed earlier regarding the compressor, where it is necessary to reduce the temperature during compression, the expander works in the opposite principle. It is important to increase the temperature of the air during the expansion process to prevent damage to the expander from cold air particles and to facilitate the movement of air and maximize its energy utilization.[23]

To achieve this, heat can be supplied either from an external heat source, such as fuel, or by utilizing the heat generated through the compression process. However, the most common method is to use fuel, particularly natural gas, due to the difficulty of storing the heat generated through the compression process.[23]

4.1.2.4 Thermal Energy Storage (TES)

The inclusion of a Thermal Energy Storage (TES) tank in a CAES system is indeed beneficial as it has several environmental advantages and improves the system's efficiency. The TES tank operates on the principle of storing the heat generated after the compression process and utilizing it later during the expansion process. [23]

From an environmental perspective, the TES tank eliminates the need for fuel during the expansion process. It takes advantage of the stored heat instead. In terms of efficiency, it reduces the temperature after the compression process, resulting in cost savings by avoiding fuel use during the expansion process.[23]

To implement this tank and make the most of it, two heat exchangers are required. One heat exchanger is positioned after the compression process and contains a cold fluid to decrease the temperature of the air after compression. The other heat exchanger is located during the expansion process and works to heat the cold air, utilizing the heat from the air after the compression process.[23]

4.1.2.5 Turbines

are indeed essential and important components in the CAES system. The stability of turbine rotation at a fixed speed and proper blade count are crucial factors that must be considered. When the compressed air is released from the storage tank, the turbine rotation speed is high, and it is necessary to maintain this speed to ensure the stability of the turbine. Failure to maintain turbine stability can lead to turbine disturbance and potential damage [19]

4.1.3. *Efficiency of CAES*

The efficiency of the system in electric energy storage systems has been determined in terms of its ability to convert the input electric energy into various other shapes of energy, such as thermal energy, chemical energy, or other types of energy, and to convert it back into electric energy with the least possible amount of energy losses. [21]

One of the advantages of Compressed Air Energy Storage (CAES) over other energy storage systems is its low self-discharge. This significantly contributes to improving the system's efficiency.[21]

In the D-CAES system, the efficiency is around 54%. This can be attributed to several factors, with one of the most important being the presence of thermal energy that is inputted into the process of air discharge from the storage tank. This means that there are two energy inputs in this system. The efficiency can be calculated using the following equation.[18]

$$\eta = \frac{E_{out}}{E_{in,ele} + E_{in,th}} \quad (2)$$

The efficiency of the A-CAES (Adiabatic Compressed Air Energy Storage) system is approximately 70%. This is attributed to the presence of a single energy input, which is the electric energy. Furthermore, the system eliminates the need for thermal energy by utilizing a Thermal Energy Storage (TES) tank. The efficiency can be calculated using the following equation. [18]

$$\eta = \frac{E_{out}}{E_{in,ele}} \quad (3)$$

Indeed, it is possible to further increase the efficiency by adding a heat exchanger in conjunction with the TES tank. However, this also leads to increased project costs and greater complexity. The decision to incorporate a heat exchanger should be carefully considered, taking into account the cost-benefit analysis and the specific requirements of the project.[24]

4.1.4. *Applications of CAES*

CAES (Compressed Air Energy Storage) system has numerous applications that can be utilized, such as implementing a UPS (Uninterruptible Power Supply) system. This system can provide backup or alternative electrical power when there is an outage for critical users like hospitals, military bases, airports, banks, and other important sectors as well.[19]

One of the applications that can benefit from a CAES (Compressed Air Energy Storage) system is demand-side management. Users can store energy during periods of low demand when the cost is lower and utilize the stored energy during periods of high demand. This allows for more efficient and cost-effective energy usage, optimizing the balance between energy generation and consumption.[19]

4.1.5. *CAES for Renewable Energy Systems*

Renewable energy has become increasingly popular over time due to its environmental friendliness and the fact that it can be produced for free. However, one of the major disadvantages of renewable energy is its inherent instability in production. Therefore, it is advisable not to rely on it entirely. Energy storage is considered one of the best solutions to mitigate the intermittency of renewable energy sources. For several reasons, CAES (Compressed Air Energy Storage) is among the most effective systems that can integrate with renewable energy. These include its low capital costs, long lifespan, minimal self-discharge, and its clean nature that does not harm the environment. Additionally, CAES is known for its strong reliability. [20]

Batteries have been considered one of the best solutions for energy storage, but due to their short lifespan and difficulty in recycling, alternative storage systems such as CAES have been sought.[25]

4.1.6. Real example

Several factories and projects have been implemented in real life as applications of the CAES system. One of them is the Huntorf plant in northern Germany, which has a capacity of 290 megawatts and was the first CAES plant implemented in 1978. Another plant is located in McIntosh, United States, with a capacity of 110 megawatts established in 1991. These two projects are considered the largest CAES implementations. They were both based on D-CAES system and utilized salt caverns. Additionally, there have been several smaller projects in Japan and Italy as well.[18]

Indeed, both the Huntorf and McIntosh plants utilize natural gas as a heat source. The higher efficiency of the McIntosh plant is attributed to its use of three compressors, whereas the Huntorf plant utilizes only two compressors. As for the expanders, both plans have two expanders each.[20]

Table 3. Comparison between the Huntorf and McIntosh plans [31]

location	Years of operation	Power Rating (MW)	Charge Time/Discharge Time (h)	Air Pressure (bars)	Heat sources	Efficiency
Huntorf	1978	290	8/2	46-66	Natural Gas	42%

Mcintosh	1991	110	40/46	45-74	Natural Gas	54%

4.1.7. Challenges and Future Directions for CAES

4.1.7.1. Challenges

Some of the challenges facing CAES systems include the need for advancements in compressors to achieve higher pressure and the development of CAES components that can withstand higher temperatures. Another challenge is the geological aspect of finding suitable locations for compressed air storage. Additionally, there is a need to develop storage systems that are cost-effective and independent of specific locations, and that can withstand high temperatures. [18]

4.1.7.2. Future developments

Indeed, the CAES system, like other energy storage systems, requires future developments for which we must find possible solutions. One future direction is to find specific methods to reduce the costs of constructing compressed air storage tanks, whether they are underground or above-ground tanks, since more than 60% of the CAES system's construction cost goes towards building the tanks. It is also important to research and develop effective methods for resource identification underground to facilitate tank construction. Additionally, investigating the long-term impact of underground storage on the environment is crucial, as many CAES systems rely on the principle of fossil fuel combustion.[21]

5. Superconducting Magnetic Energy Storage (SMES)

5.1 Definition of SMES

Superconducting Magnetic Energy Storage (SMES) is an advanced technology that enables the storage of electrical energy in the form of a DC magnetic field within a superconducting coil. With the achievement of superconductivity, the coil experiences negligible resistance losses. However, to attain superconductivity, it is essential to operate the coil at extremely low temperatures, necessitating the use of a cooling system [26].

In Jordan, the implementation of SMES holds great potential for various applications, particularly in energy storage. By reducing the dependence on oil imports, SMES contributes significantly to the evolution of the energy sector.

The energy stored within a superconducting coil can be mathematically described by the following equation [27]:

$$E = \frac{1}{2} \cdot L \cdot I^2$$

Where:

E: is the energy measured in Joules.

I: is the current passing through L measured in Ampere.

L: is the inductance of the coil measured in Henry.

The formula shows that the energy saved in the coil is directly proportional to both the inductance and the square of the current passing through it.

When the electrical system requires the energy stored in a superconducting coil, the coil is discharged, supplying the grid with the amount of energy needed [27]

The versatile characteristics of the SMES system make it suitable for addressing numerous challenges encountered in electrical networks. In the table below, several attributes of the SMES system are outlined, highlighting its efficacy in resolving voltage stability and power quality issues [27]:

Table 4. SMES significant characteristics [27]

Property / Parameter	Value
Specific energy	0.5 - 5 Wh/kg
Specific power	500 2000 W/kg
Power Density	1000 4000 W/L
Energy density	0.2 - 2.5 Wh / L
Self-discharge rate	0% at 4 K -100% at 140 K
Charge/discharge efficiency	95%
Discharge time	ms to 8
Cycle durability	Unlimited cycles
Energy Cost	$ 1000-10000 /kWh

5.2 Components of SMES

5.2.1 Superconducting coil

SMES contains of three main components: [28]

1. The superconducting coil
2. power conditioning system
3. Cryogenic system

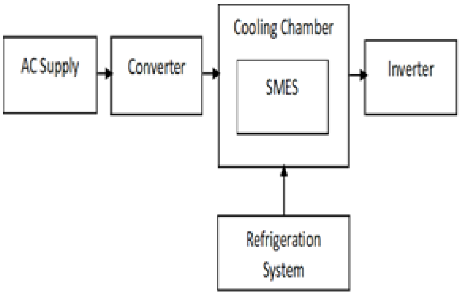


Figure 12. Schematic of SMES [28]

Superconductivity is a property of a conductor when resistance is made zero by cooling the conductor to low temperatures allowing conductors to carry larger currents more efficiently [28]

SMES are used in many applications, for applications that fall under medium or small scale, the arrangement of the superconducting coil used is the Solenoid coil configuration.

when the application falls under the large scale, the arrangement of the superconducting coil used is the toroid coil configuration. [29]

One property acquired by a superconductor due to its transformation into a superconducting state, is the ability to conduct and carry large currents. Several materials are used to make superconducting coils, such as niobium and titanium alloys. These materials can carry a current of up to 2000 A/mm2. [28]

5.2.2 Cryogenic system

The Cryogenic system is a major part of the SMES system because it is the part that works to cool the superconducting coil so. This cooling process is essential to maintain the coil at a low temperature, allowing energy to be stored efficiently because the resistance losses become almost zero. [30]

However, the energy requirement for the cryogenic system's operation is a major challenge. The cooling process requires a lot of energy to keep the low temperatures needed for superconductivity. [30]

5.2.3 Power conditioning system

PCS is the Mediator between the electrical network and the SMES system. The PCS consists of a rectifier and an inverter.[26]

The rectifier is a component that converts the alternating current (AC) supplied by the electrical network into direct current (DC). This process involves transforming the waveform and adjusting its shape to fit with the SMES system. The rectifier ensures a smooth transfer of power from the electrical grid to the SMES system, allowing for effective energy storage and retrieval. [26]

An inverter is a component that reverses the function of a rectifier. It converts the stored DC energy within the SMES system back into AC. The inverter ensures the seamless injection of power from the SMES system into the grid when needed. [38]

When the rectifier and inverter work together, this allows the SMES system to store excess energy and return it to the electrical grid when demand is high or the stability of the grid is compromised. [26]

5.3 Types of SMES depending on its power conditioning system

5.3.1 Thyristor-based SMES

It is a type of SMES system that consists of a superconducting coil, a Y-Delta transformer, and a thyristor. This type can control active power and reactive power but not alone, but its ability to control active power is greater than its ability to control reactive power. Therefore, it is used in applications that need to control active power. [31]

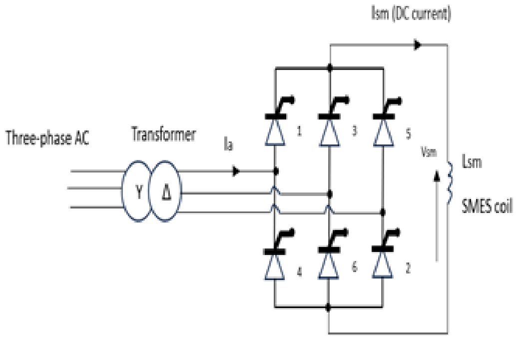


Figure13. Basic circuit of the thyristor-based SMES.[31]

5.3.2 Voltage-Source Converter-Based SMES

When comparing this type with the thyristor-based SMES, this system excels in the ability to control the active power and the reactive power independently.[31]

When we combine SMES with a Voltage-Source Converter, we get a Voltage-Source Converter-based SMES system. In this design, the SMES unit is connected to the DC side of the Voltage-Source Converter, allowing the SMES to store and release energy as needed.[31]

The combination of SMES and a Voltage-Source Converter offers several advantages. Firstly, SMES systems have high energy storage density and fast response times, allowing them to quickly absorb or release energy when required. Secondly, the Voltage-Source Converter provides bidirectional power flow control, enabling efficient energy transfer between the SMES system and the grid.[30]

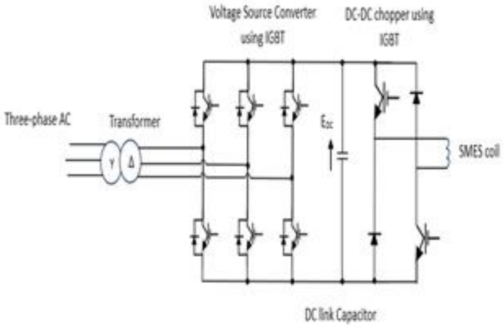


Figure 14. Basic circuit of the VSC-based SMES.[31]

5.3.3 Current-Source-Converter-Based SMES

This type is similar to voltage-source converter-based SMES regarding independence in controlling active and reactive power.[31]

In an SMES system based on a current-source converter, the CSC is responsible for controlling the charging and discharging of the superconducting coil. It acts as an interface between the power grid and the superconducting coil, regulating the flow of current to and from the coil.[30]

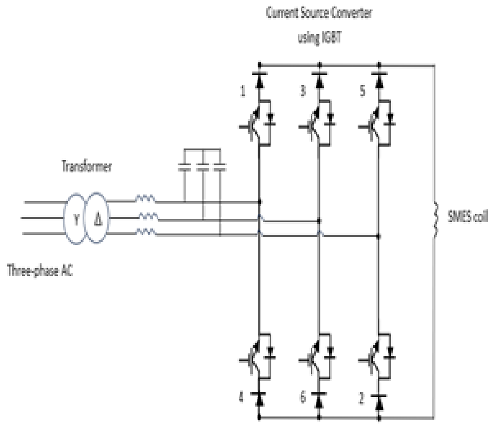


Figure 15. Basic circuit of the CSC- based SMES.[31]

5.3 Advantages and Disadvantages of SMES

The SMES system has many good features that can be used to improve the power quality and the electrical network's stability. Here are some notable applications of SMES:

Improving voltage stability, Improving FACTS performances, Protection of critical loads, Load leveling, and Reducing area control error.[32]

The SMES system has many advantages and disadvantages, which can be identified in the following table:

Table 5. SMES system advantages and disadvantages [28]

Advantages	**Disadvantages**
There are no moving parts, so maintenance is low	High initial construction cost
It handles large amounts of energy	The cooling system is very energy consuming
High efficiency is greater than ninety percent (> 90%)	
The rapid response is less than a hundred milliseconds (<100ms)	
The SMES system does not produce any harmful gases to people and the environment because it does not contain chemical reactions.	

6. Conclusion

With the increased dependence on RES in Jordan, the challenges faced with maintaining the security and stability of the grid intensified. Solutions developed include controlling consumers' demands through DSM by actively engaging consumers in managing their electricity consumption patterns. However, this could face social challenges that were examined through a survey to further understand the thoughts of Jordanian citizens on its implementation.

Technological challenges could also be faced with installing fast and reliable monitoring and communication systems.

As a result, another solution proposed that can also be used with DSM to further increase the grid's reliability was storing the excess energy generated by ESS such as CAES and SMES which have been discussed in detail.

With the execution of the proposed solutions, the Jordanian electrical grid would face reduced outages and higher voltage stability and pave an easier way to reach 100% clean energy generation. Further research can be conducted on such projects' feasibility and optimal sizing and placement.

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