**Nuclear Power, Photovoltaics, and Compressed Air Energy Storage:**

**A Low-Cost, On-Demand Power Hub for Saudi Arabia**

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Abstract – Saudi Arabia’ energy mix is shifting from oil and gas toward low-carbon solar photovoltaics (PV) and nuclear energy. PV intermittency and seasonality must be considered along its low cost which reached globally low value of in SA. Nuclear power plants, NPP, are reliable and cost stable: . NPP requires freshwater for evaporative cooling stressing water resources. NPP is best operated at constant maximum power to avoid complex operation associated with xenon poisoning and keep LCOE low due to large capital cost.

This paper explores alternative roles for NPPs in Saudi Arabia: baseload electricity generation, dedicated desalination operation, and functioning as energy hub integrating energy storage systems and PV power. Baseload operation is not competitive compared to combined cycle gas turbine (CCGT) or future PV/battery systems. NPP constructed today will keep the same LCOE at the same time where PV LCOE is much less costly and dropping rapidly. NPP can operates thermal and membrane desalination with good economics of and energy cost component of

Our study focuses on integrating constant NPPs with intermittent PV systems using compressed air energy storage (CAES). Liquid piston used in of CAES enables highly efficient quasi-isothermal compression/expansion. PV powers charging/compression and NPP heat powers discharging/expansion. The system includes ice thermal storage, 300°C phase-changing-material hot storage with a, and 200bar high-pressure tanks storing cold air. The system enables power on demand, POD independent from PV and NPP time profiles. PV-NPP-CAES POD costs 42% less than NPP-cost. Electricity generated is 2.5X higher than its NPP contribution. The system generates freshwater byproduct.

Integrating SA locally advantageous PV to reliable NPPs by utilizing industrially mature CAES and thermal storage, represents a promising energy plan for Saudi Arabia. The proposed energy hub would provide low-cost and reliable power on demand for the country.

**Keywords:** Nuclear Energy, Photovoltaics, CAES, PCM, Desalination

# I. Introduction

Nuclear fission energy is a highly stable and reliable source of energy that does not depend on large fuel transport, unlike fossil fuel power plants. Unlike solar farms, which can be greatly affected by clouds or sandstorms, nuclear power plants operate continuously, except for refueling events that occur once every 1-2 years. Moreover, nuclear energy has a much higher power output per unit of land area compared to solar and wind energies, with approximately: versus (adjusted by this author for KSA based on Smil [1]).

In terms of carbon emissions, nuclear energy is low, comparable to renewable energies, emitting only around , as per IPCC [2]. It's worth noting that some researchers estimate slightly higher emissions at [3]. Nevertheless, the immunity of nuclear energy from weather and seasonal variations should be considered an advantage when compared to solar or wind energy sources.

The fission process in nuclear reactor creates neutrons’ poisons of iodine and xenon. These isotopes’ concentrations peak after 9 hours after power reduction and effectively reduce reactivity variably for around one day which makes it more challenging to change the power level of the plant. As a result, it is generally preferred to operate a nuclear power plant as a constant baseload power source, avoiding complex power manipulations. By keeping the reactor running at full power, with only minor downtime for refueling or maintenance, the capacity factor of the plant (the fraction of time the plant operates at its maximum capacity) is increased. The capacity factor is an essential factor in determining the levelized cost of energy (LCOE) for nuclear power plants. While this factor applies to all power plants, it has a larger impact on the economics of nuclear power. For a newly built nuclear power plant, the LCOE is estimated at $85/MWh when the capacity factor is at 60%. However, as the capacity factor increases to 90%, the LCOE drops to $60/MWh [4]. This can be attributed to the relatively high capital costs of establishing a nuclear power plant, but lower operational and fuel costs. In other words, operating the plant at higher capacity factors results in a lower LCOE. Considering the presence of neutron poisons and the significant capital costs involved, it is prudent to operate nuclear power plants at high and fixed power levels.

The cost of nuclear power plants (NPP) is generally stable compared to fossil fuel sources. However, it is important to note that the projected cost for NPPs in the years 2030-2040 remains high at 50€/MWh [5]. According to a recent Lazard report, the levelized cost of electricity (LCOE) for new NPPs ranges from $33-88/MWh depending on the country and local regulations [6]. These estimates align with the LCOE figures stated by OECD-NEA for new reactors in different countries: Russia ($42.0), India ($47.6), South Korea ($53.3), China ($66.0), France ($71.1), United States ($71.2), and Japan ($86.7) per MWh [7]. It is worth noting that Russia, India, South Korea, and China are actively constructing new reactors both domestically and for export purposes. Currently, major exporters of nuclear power plants are Russia and China, with South Korea playing a slightly lesser role as well [8]. Therefore, their LCOE figures can serve as model estimates; however, it's important to consider that local regulations and financial factors could potentially impact the actual costs involved.

Nuclear Power Plants (NPPs) are thermal energy sources that possess unique operational characteristics. The most common type, the pressurized water reactor (PWR), operates at relatively low temperatures of around 300-330°C, resulting in an overall thermal to electrical conversion efficiency on the lower side, approximately 35%. NPP are best operated continuously at their maximum power level. In contrast, utility-scale solar photovoltaics (PV) generate energy intermittently for about 6-8 hours a day with seasonal and geographic variations. The cost of PV has been decreasing and reached a historic low of $1.04/kWh at the Al Shuaiba PV IP solar power plant in Saudi Arabia [9]. While PV is more cost-effective, it is not dispatchable and available only during certain periods. This contrast between NPPs as a continuous source of power and PV with its intermittency and variability highlights the need for an energy storage system that combines the strengths of both sources. Such integration would provide variable and reliable power on demand for the grid.

There are various energy storage technologies available, but when it comes to grid-scale applications, the options become more limited. The main grid-scale energy storage systems include pumped hydro, compressed air energy storage (CAES), and electrochemical batteries [10]. While batteries are highly effective for small-scale use, they face challenges in terms of scalability to meet the demands of grid-level storage due to factors such as cost, lifetime, and scarcity of key elements. Pumped hydro is another option for grid-scale energy storage; however, its application is limited by geographical restrictions that require two natural levels for storage and pumping. CAES is a mechanical method that involves compressing air using available electrical energy and then expanding the compressed air to regenerate power when needed [11]. To maximize efficiency, compression and expansion should ideally be done with cooling and heating in isothermal processes. This paper explores the potential use of nuclear thermal energy during the expansion phase of a CAES process.

In the past, conventional, or diabetic compressed air energy storage (D-CAES) systems utilized underground caverns to store the compressed air at pressures ranging from 46 to 75 bars. However, these systems did not capture and save the thermal energy generated during compression. Instead, heat from natural gas combustion was combined with the compressed air to drive a gas turbine during the expansion phase. To enhance CAES efficiency, thermal energy storage (TES) can be implemented. This involves storing and utilizing the thermal energy generated during compression for later use in compression again. Advancements in pressure vessel technology have allowed for much higher-pressure levels in CAES systems. The growing demand for hydrogen storage has driven developments in metallic, carbon fiber composites, and glass fiber composites vessels that can withstand high-pressure levels not achievable conventionally. Glass fiber composites vessels are capable of sustaining pressures up to 300 bars or even higher depending on their design [12].

This paper explores the energy storage potential of nuclear power and compares it to being used as baseload power or for desalination purposes. It proposes integrating nuclear power plants (NPPs) with renewable solar energy in a compressed air energy storage (CAES) system. The paper estimates the associated energy costs for this integrated approach.

# II. Methods and Discussions

This paper examines the various applications of nuclear reactors, including their use as a base power load, for desalination purposes, and as a versatile energy hub when integrated with scalable energy storage systems. The next subsection provides a detailed discussion of these alternatives. Furthermore, the paper conducts an analysis of the technical and economic aspects associated with integrating nuclear power plants (NPPs) and photovoltaics (PV) into a compressed air energy storage (CAES) energy hub to enable on-demand power supply.

## II.A Exploring Nuclear Energy Storage as a Primary Solution Among Alternative Applications

Nuclear energy is known for its stability in production and cost, making it a reliable option compared to other primary energy sources like fossil fuels and renewables. However, it's important to consider the decreasing cost of solar photovoltaic energy in long-term planning, especially when factoring in the high capital cost of nuclear power plants (NPP). For instance, recent solar projects in Saudi Arabia have achieved a levelized cost of electricity (LCOE) as low as a, whereas the estimated LCOE for a new Russian reactor is reported to be . It's worth noting that while solar energy may be cheaper, it does come with challenges such as daily and seasonal variations that require significant energy storage solutions for residential and industrial use.

Nuclear energy can be envisioned to assume three different roles:

### II.A.1 Nuclear Power Plant serving as baseload electrical energy source:

a) The nuclear cost assumed in the range of is close to combined cycle gas turbine CCGT in the range of according to Lazard's estimates for the US market [6]. However, the implementation of a carbon tax could potentially alter this balance.

b) If the total output of nuclear energy falls below the minimum demand on a daily and seasonal basis, then it remains an economical choice compared to gas power and has a lower carbon footprint.

c) Expanding the contribution of nuclear energy beyond its role as baseload power requires careful consideration, especially considering lower-cost solar options and the potential combination of solar PV and battery storage systems.

d) The declining costs of batteries in the coming few years might make the solar PV and battery combination more economically favorable than nuclear power during nighttime hours. However, this prediction relies on assumptions that battery technology costs will continue to decrease without facing supply bottlenecks for rare elements. It's worth noting that stationary grid storage can utilize lower-cost and readily available elements where specific weight is not as critical as in mobility or personal electronics applications.

e) Solar energy faces challenges related to weather variations and seasonal fluctuations, particularly for industrial processes where demand does not align with weather patterns (e.g., non-HVAC loads). In such cases, nuclear energy offers better reliability compared to solar power.

### II.A.2 Nuclear reactor as both electrical and thermal energy can be used for desalination:

a) One key aspect of nuclear energy is its thermal nature, which results in the generation of significant waste heat. The disposal of this waste heat requires water consumption, which can be quite substantial [13]. There are several methods for the final rejection of heat in a nuclear reactor which could be water burden:

i) Conventional cooling towers that rely on evaporation. This method requires low-salinity water, which can create competition with other uses of fresh water in water-stressed regions like Saudi Arabia. Assuming the conversion efficiency from thermal to electric is 35%, the water evaporated is estimated from latent heat of evaporation to be at least ; see Equation (1). This estimate aligns well with published data indicating approximately or [14].

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|  | (1) |

ii) Cooling nuclear reactors by utilizing running water from rivers or surface water bodies is not feasible in Saudi Arabia due to the absence of permanent rivers or lakes. However, the open sea could be considered as an option. It's important to note that using seawater for cooling purposes can lead to thermal disturbances in aquatic life and potentially contribute to increased salinity levels. This increase in salinity is already a concern due to the high evaporation rates and low rainfall rates in regions such as the Gulf, Red Sea, and Mediterranean Sea. An example of seawater cooling can be seen at the Shenzhen nuclear power plant, where approximately 0. of seawater is passed through once for cooling purposes. This approach may have ecological consequences that need careful consideration [15].

iii) Dry cooling tower: In our hot region, the efficiency of this technology is expected to be lower due to the high air temperature and the absence of evaporative cooling effects typically associated with dry climates in Arabia.

b) Nuclear reactor operation can be redesigned to incorporate thermal desalination as a permanent product NPP.

c) PWR is operated between and . The greater the temperature difference, the more energy can be extracted. We propose increasing the lower temperature limit to , which would allow for waste heat to be utilized in a multi-effect distillation (MED) process. However, this modification would result in a reduction of power output and efficiency from 35% to 26%, as depicted in Figure 1. Nonetheless, this alteration would yield water at a rate of ; see Equation 2. In contrast, if this electricity were diverted to a reverse osmosis (RO) process, only would be achieved as shown in Equation 3. Some may argue against this nuclear scheme due to its higher cost of energy compared to solar power, which is approximately four times less expensive. However, it should be noted that PV power is available for only a fraction of the day (1/4-1/3) which means that RO equipment would operate at low capacity driving up the effective cost per unit product. On the other hand, MED coupled with NPP could utilize its full potential effectively.

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|  | (2) |

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|  | (3) |

d) NPP can be both redesigned as in the above scheme and the remaining electricity can be used generate water through RO process at the above productivity. Thus, water is desalinated by the electricity through RO process and is generated as a by-product from the relatively high-grade heat through MED process; see Equation 4. Presently, the overall cost of desalination is approximately [16][17]. The suggested scheme costs only per cubic meter of water which is quite economical.

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| --- | --- |
|  | (4) |

e) Coupling NPP rejected heat to desalination system has been simulated [18] [16]. Multiple configurations have been studied but modification of the steam cycle was not discussed.

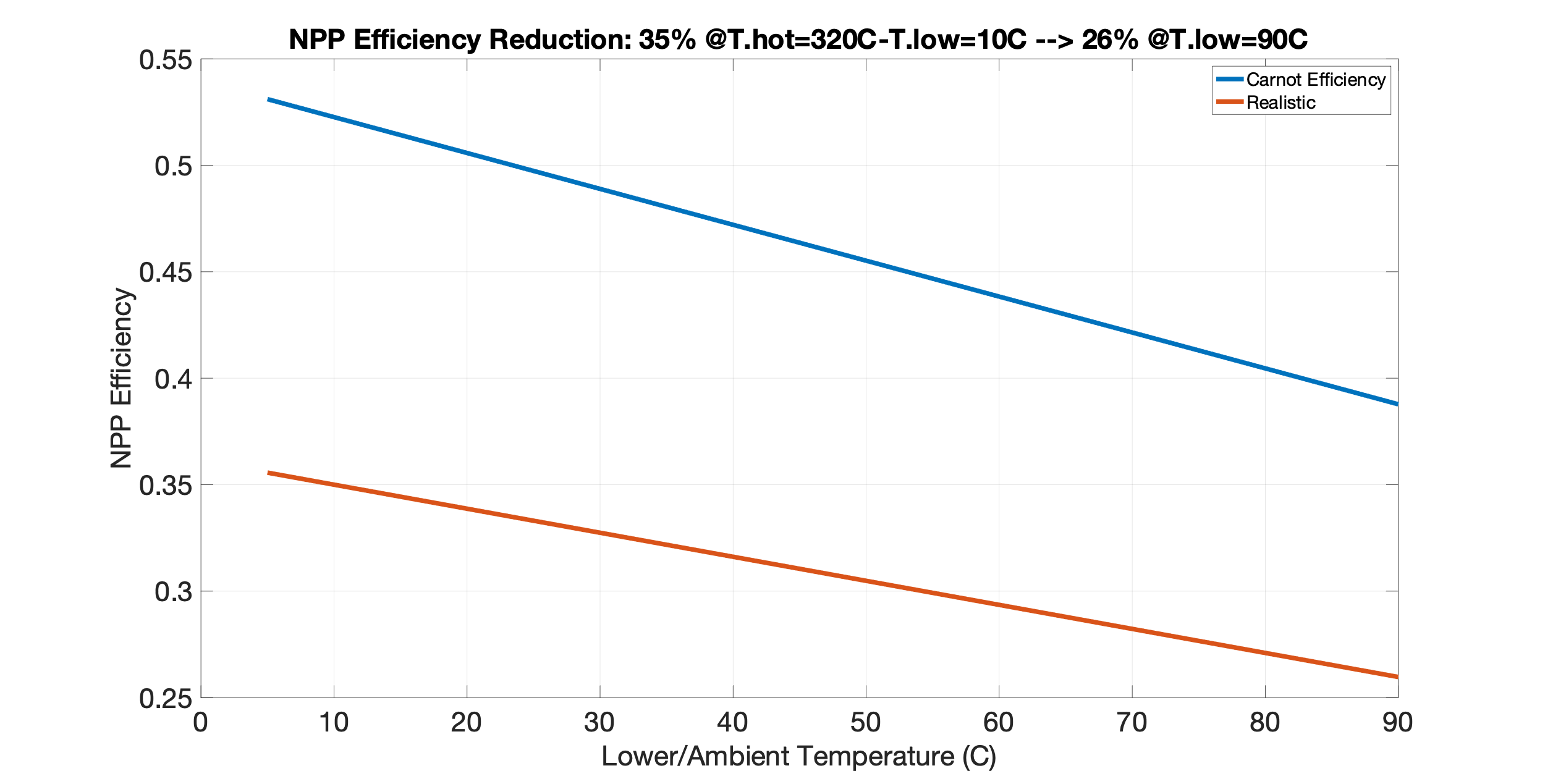


Figure 1: Designing the steam generation in NPP to feed MED process reduces the efficiency but generates more water than the lost fraction if fed to the RO process.

### II.A.3 Nuclear Reactor Plant when combined with energy storage CAES servs as the central energy hub for the power grid:

a) Nuclear energy is thermal source operating at intermediate temperature, currently approximately 320oC with conversion efficiency about 35%. The LCOE is around $4.2-7.1 with significant capital investment required but relatively low operational costs. Due to its operational and economic characteristics, it is necessary to run nuclear power plants at a constant maximum capacity.

b) CAES, requires cooling in the charging/compression phase and heating the generation/expansion phase. Cooling is done most efficiently by electrical compressor-based cooling. Heating beyond is not done by compressors so it should be done by the nuclear heat. The heating process can be split into two stages: . The initial stage of heating can be accomplished using PV power.

c) Low-cost solar PV power utilized for the following purposes:

1. Provide energy for cooling in form of ice storage ().
2. Provide compression energy that raises the pressure of ambient air to 200 bar in quasi-isothermal process using liquid piston technology.
3. Provide intermediate heating of around in the regeneration process ().

d) High-cost nuclear energy can be utilized for these purposes:

1. Provide high heating of around for the regeneration process ()
2. Provide heating in the quasi-isothermal expansion using liquid piston technology.

e) As a result, CAES has the capability to integrate PV with NPP. This integration allows for:

1. Power on demand from both a constant source, NPP, and an intermittent PV
2. The cost of NPP is reduced due to the utilization of PV in charging the CAES.
3. The energy from NPP is "amplified" at the expense of the low-cost PV source.

Based on the above discussions, NPP can be employed as baseload power source in the grid especially if the contribution of NPP is less than then national minimum. NPP in its current form can be a water burden in our water stressed region. NPP can be redesigned for desalination purposes with favorable economics. Alternatively, NPP can be redesigned to generate less electrical output while still offering continuous desalination, which would also be economically advantageous.

The integration of high-cost nuclear power plants (NPP) with low-cost photovoltaic (PV) systems using compressed air energy storage (CAES) can offer cost-effective on-demand power to the national grid. This combination creates an NPP-PV-CAES system, which functions as an energy hub that stabilizes the grid while also providing scalability and a minimal carbon footprint.

## II.B. Integrating NPP and PV into CAES

A simulation was conducted [19] [17] to explore the use of thermal energy storage to provide power on demand and enhance the flexibility of a constant output nuclear power plant (NPP). The main objective of this study, however, is to integrate a substantial input from low-cost and intermittent photovoltaic (PV) sources, thereby reducing the cost of the NPP. Like other storage systems, compressed air energy storage (CAES) operates through charging and discharging phases in addition to its storage state. Figure 2 illustrates the different states of air as the chosen storage medium. The computations for this simulation were carried out using CoolProp package, which provides air properties under various conditions [20] [18]. These computations were performed through a Python wrapper called from Matlab.

(1) The system admits ambient air at atmospheric pressure and an assumed temperature of . This air is then washed and cooled to 0°C. The cost of cooling is calculated based on the change in internal energy of the air, based on its initial and final temperatures of and respectively. The efficiency of the cooling process is assumed to be 45% of the Carnot cycle cooling operating from -10°C to 40°C with the additional range for effective heat transfer. The reference amount of air used for calculations is taken as one cubic meter at a temperature of 0°C and a pressure reading of 200 bar as in Equation (5). The cooling coefficient of performance used is given in Equation (6) where the electrical energy cost to perform this cooling is given in Equation (7).

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| --- | --- |
|  | (5) |
|  | (6) |
|  | (7) |

(2) The air, which has been cooled, undergoes a quasi-isothermal compression process to increase its pressure from atmospheric pressure to 200bar at State 2. This compression process is highly efficient, with a reported efficiency of 93% based on liquid piston literature technology. The reference amount is still State 3 volume of 1 cubic meter. The work required for this compression can be calculated using Equation (8). This compression work must be accompanied by simultaneous cooling of identical amount. The cooling process has the same temperature bounds of & 3 and thus the cooling cost is computed with the same cooling coefficient as shown in Equation (9).

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| --- | --- |
|  | (8) |
|  | (9) |

(3) The compressed air is stored at a high pressure of 200 bar and a low temperature of until it is required for on-demand power. It is assumed that both air leakage from the pressurized tank and thermal leakage are minimized to the point where they can be considered effectively negligible.



Figure 2: CAES stages of changes to the air broken down by temperature and pressure (not to scale). PV power is used in the stages () while nuclear is used in ()

(4) During the regeneration phase, the cooled compressed air undergoes heating at a constant volume in two stages from State 3 to an intermediate State i utilizing PV heat and subsequently nuclear heat to reach State 4. The PV work can be determined using Equation (12), while the nuclear heat can be calculated using Equation (13). As a result of this heating process, the pressure of the compressed air is raised, in accordance with fundamental thermodynamic properties of air digitally tabulated in CoolProp package. The new pressure values are 289 and 526 bars respectively.

|  |  |
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|  | () |
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|  | () |

(5) The heated compressed air expands through the liquid piston generating mechanical work with similar efficiency to decrease its pressure from around 526 bar to atmospheric pressure. As the air expands heat is supplied by the liquid piston; see Equation 14-15. This heat could have been used to generate power at the NPP efficiency as shown in Equation (16).

|  |  |
| --- | --- |
|  | (14) |
|  | (15) |
|  | (16) |

(6) Efficiencies can be calculated by dividing the output work by the total input work in electrical terms, as shown in Equation (17). The energy cost component of the input energy can be determined by multiplying PV and NPP with their respective unit costs. The cost of NPP is estimated based on the LCOE estimated in other countries. As for PV LCOE in KSA, it is known due to several projects with publicized power purchase agreements.

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| --- | --- |
|  | (17) |
|  | (18) |

## II.B. Energy Cost Estimate of the Integrated NPP-PV-CAES

Accurate cost estimates for the integrated system can only be determined after a detailed design of the system. Figure 3 illustrates a basic design of the main components and their relationships. However, in this investigation, only the costs of the energy inputs have been estimated based on the above basic thermodynamic analysis. The NPP LCOE is not uniform. To narrow down our focus, we will consider only countries that export nuclear power technology to the rest of the world: Russia, China, South Korea, France, and the United States. In these countries, the LCOE range is limited to 4.2- 7.1 *.*

As for photovoltaic (PV) energy, the lowest PPA is is a historic low and the extent of subsidies are not announced and thus the cost of PV is taken to be scenarios in the range of . According to Lazard report the average cost is . Figure 4 show the combined cost as function of the assumed NPP cost in the horizontal axis and as function of the PV cost shown as different lines. The dashed line shows the NPP cost. The CAES energy cost is generally less costly than NPP which means that PV contribution lowered the combined cost despite the conversion losses. If there is no PV input, then naturally the CAES cost will be higher due to the losses as shown in the red line. Table 1 provides the summary of cost ranges and efficiencies.

Based on the analysis of integrating NPP to PV through CAES, we obtain:

1. Power on demand from a constant source NPP and intermittent PV source.
2. If NPP is counted as its electrical equivalent, then it contributes 34.7% to the inputs (or 60.3% based on thermal).
3. Cost of unit energy from CAES is reduced from NPP by 15-42%
4. Energy of NPP is “amplified” by 2.51X factor utilizing the low-cost PV.
5. By-product fresh water is generated at rate of .

The given preliminary results are promising since they integrate the locally advantageous low-cost PV to the highly stable NPP in a new system that provide power on demand. Modeling a particular system should shed light on the capital cost of the integrated system.



Figure Schematic of components and relations including thermal energy storage systems and pressurized storage

Table 1: Efficiency (primary and roundtrip) of the various systems and estimated cost of the energy input per output energy unit

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| # | NPP | PV | CAES-PV | CAES-NPP | CAES-PV- NPP |
| Efficiency | 35% | 21% | 86% | 86% | 87% |
|  | 4.2-7.1 | 1.04-3.5 | 1.21-4.07 | 4.30-5.45 | 2.42-3.58 |

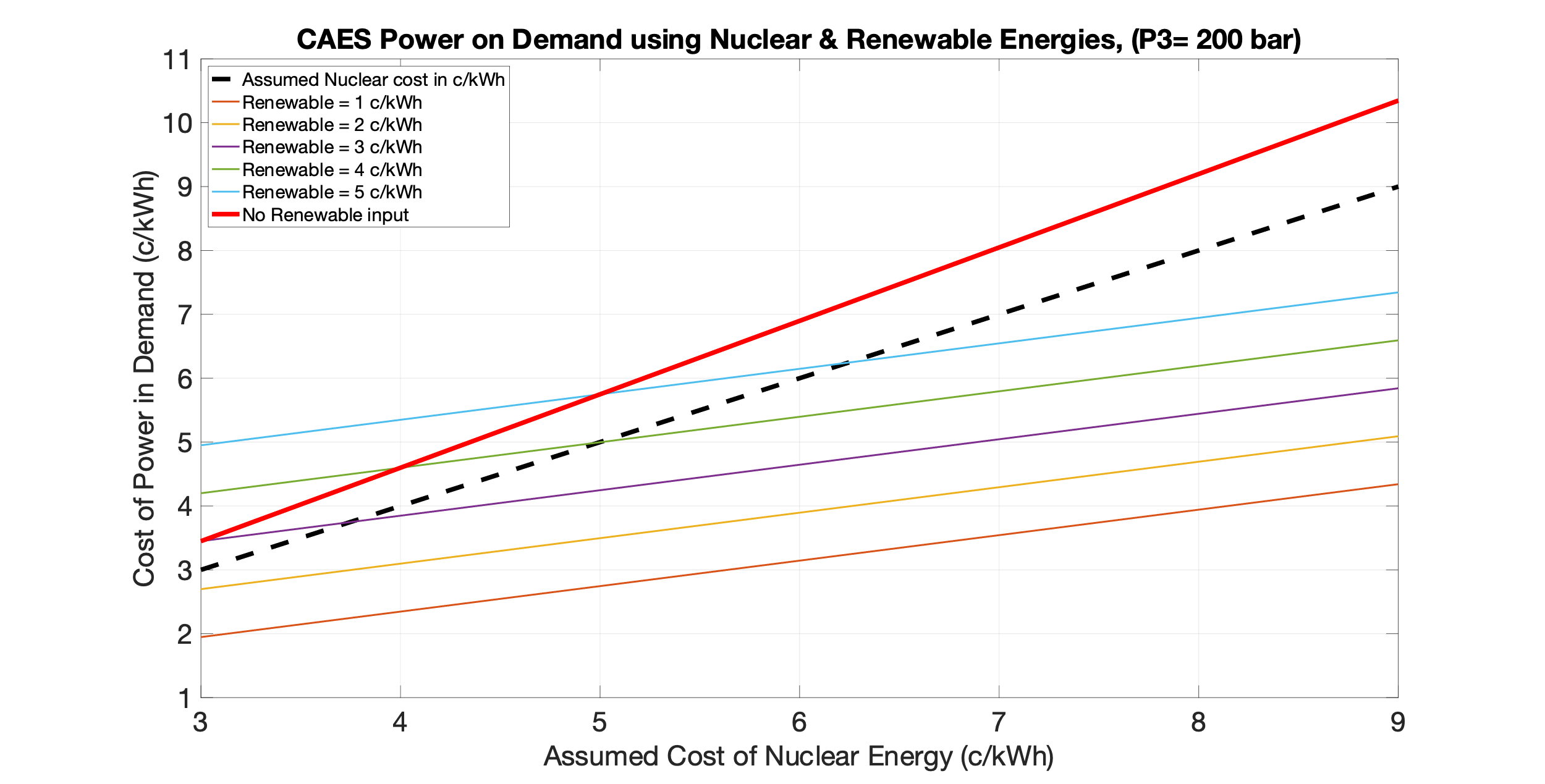


Figure : The cost of energy inputs to the CAES per unit of output energy

IV. Conclusions

This study explores the potential roles of nuclear energy in Saudi Arabia's energy landscape. It discusses the advantages of nuclear power, such as cost stability and lower carbon emissions compared to fossil fuels. The paper evaluates various applications for NPPs, including baseload electricity generation, desalination operations, and integration with PV power and energy storage. While baseload operation is currently economically viable, falling costs of PV technology pose a risk in the long term. The use of nuclear reactors for desalination is reasonable but requires modifications to support both thermal and membrane desalination. The study proposes a Compressed Air Energy Storage (CAES) system that combines PV and NPP inputs to reduce overall energy costs while ensuring an on-demand power supply. Integrating PV into the NPP-PV-CAES system can reduce generated power costs by up to 42% compared to a fixed output NPP alone. This integrated system produces on-demand power that is 2.5 times greater than a conventional NPP and generates byproduct water 3times used for evaporative cooling. Overall, this research suggests that integrating renewable PV sources with reliable NPPs through CAES technology is a promising approach for future energy planning in Saudi Arabia, but further studies are needed for specific implementation details and cost optimization.

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