



MODULAR CRYOGENIC ENERGY STORAGE SYSTEM: SIMULATION AND TECHNO-ECONOMIC ANALYSIS

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ABSTRACT

Sustaining economic growth while reducing reliance on fossil fuels for environmental protection is a global challenge. Efforts are made to decrease energy utilization by enhancing energy efficiency and discovering clean renewable energy sources. Cryogenic energy storage (CES) is a grid-scale energy system where electricity is stored in the form of liquefied gas. It is regarded as a solution because it allows for increased electricity generation while also providing economic benefits by avoiding costly operational consequences. The CES was modeled and simulated in Aspen HYSYS V8.8 using three system configurations: standalone adiabatic, waste heat integration, and combustion integration. Unlike in the conventional CES, Dowtherm-Q was used as the thermal fluid due to its thermal stability, non-corrosiveness, and high temperature resistance. The results indicated that the higher the adiabatic efficiency of the turbine, the greater the power generated; also, increasing the turbine inlet temperature enhanced the performance of the system configuration by lowering the pressure and increasing the power of the turbine. The economic analysis revealed that the waste heat-based system has both the lowest operating cost, capital cost, utility cost, and higher energy savings. Waste heat integration produces the most power (653.70 kW) and saves the most energy (69.58%), with lower capital costs, operating costs, and utility costs due to the increased adiabatic efficiency of the turbine. It implies that CES with waste heat integration is economically more promising compared to adiabatic standalone and the integration of combustion.

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1.0 Introduction

Sustaining economic growth while at the same time decreasing the usage of fossil fuels for environmental safety is a global challenge. Several efforts are being made, mainly in two aspects: to reduce energy consumption by improving energy efficiency and to explore clean and sustainable renewable energy sources (Wang et al., 2017). Renewable energy sources are being discovered and quickly developed. However, the high-level of penetration of renewable energy in the grid causes serious problems with power grid stability and reliability due to the intermittency and volatility of renewable energy. Suitable solutions are urgently needed and energy storage is known as one of the most promising technologies for addressing the difficulties (Xu et al., 2015). The increasing penetration of renewable energy has led electrical energy storage systems to play a key role in balancing and increasing the efficiency of the grid. Liquid air energy storage (LAES) is a promising technology, mainly proposed for large-scale applications, that uses

cryogen (liquid air) as an energy vector. The use of liquid air as a storage medium allows a high energy density to be reached and overcomes the problem related to geological restrictions (Borri *et al.*, 2020).

An essential characteristic of electricity is that electrical energy cannot be stored directly. Therefore, the supply of electricity must be continuously balanced with the demand for it. The constant balancing of supply and demand has important operational and cost implications. For instance, adequate generating capacity needs to exist to supply the highest level of demand, even though the last increment of capacity will only be needed infrequently and for short periods. Also, the inability to store electricity requires that reserve generating capacity, either in the form of spinning or non-spinning reserves, be maintained to account for changes in the amount of load or the unplanned loss of an operating generator (Nderitu, 2013). Although it is not possible to store energy in the form of electricity, it is possible to convert electrical energy into an alternative form that can be stored. The stored energy can then be converted back to electricity whenever it is desired. There are a wide variety of possible forms in which energy can be stored. Common examples include chemical energy (batteries), kinetic energy (flywheels or compressed air), gravitational potential energy (pumped hydroelectric), and energy in the form of electrical (capacitors) and magnetic fields. From the standpoint of the electrical system, these energy storage methods act as loads while energy is being stored (while charging a battery) and as sources of electricity when the energy is returned to the system (while discharging a battery) (Preckel, 2013).

Grid-scale energy storage (ES) systems are widely regarded as a solution to the problems caused by the rapid transition to higher shares of electricity generation from highly intermittent renewable energy sources (Steinmann, 2016). Apart from ensuring the security of supply, ES is supposed to introduce economic benefits by providing balancing services and avoiding costly operational inferences. Cryogenics-based energy storage (CES) is the only grid-scale ES technology without geographical constraints and a potential positive environmental impact. Cryogenics-based energy storage (CES) is a thermoelectric bulk energy storage technology that stores electricity in the form of a liquefied gas at cryogenic temperatures (Hamdy *et al.*, 2019).

Cryogenic energy storage systems have the potential to provide a cost-effective and efficient method for storing large amounts of energy. However, developing an energy storage system capable of meeting global energy demand is a global challenge. In Nigeria, like in any other developing or developed country, a real-time increase in energy demand poses a risk to energy supply. CES provides an alternative solution to energy demand, but it is not widely used due to a lack of thorough understanding of its economic viability. The outcome of this analysis will provide valuable information for the development and implementation of cryogenic energy storage systems. Hence the objective of the present study is to model and simulate a cryogenic energy storage system using ASPEN HYSYS involving multiple design configurations, implement parameter sensitivity analysis for the specified configurations, implement an economic strategy

for the selected system configuration, compare their performances and determine the best configuration.

2.0 Materials and Methods

2.1 Materials

Some of the materials used in this study include:

- Aspen HYSYS V8.8
- Air
- Perfluoropropane C₃F₈
- Methanol (CH₃OH)
- DTRM-Q

2.2 Methods

A summary of the procedure conducted from modelling and simulation, parameter sensitivity analysis, and economic analysis, is shown in Figure 1.

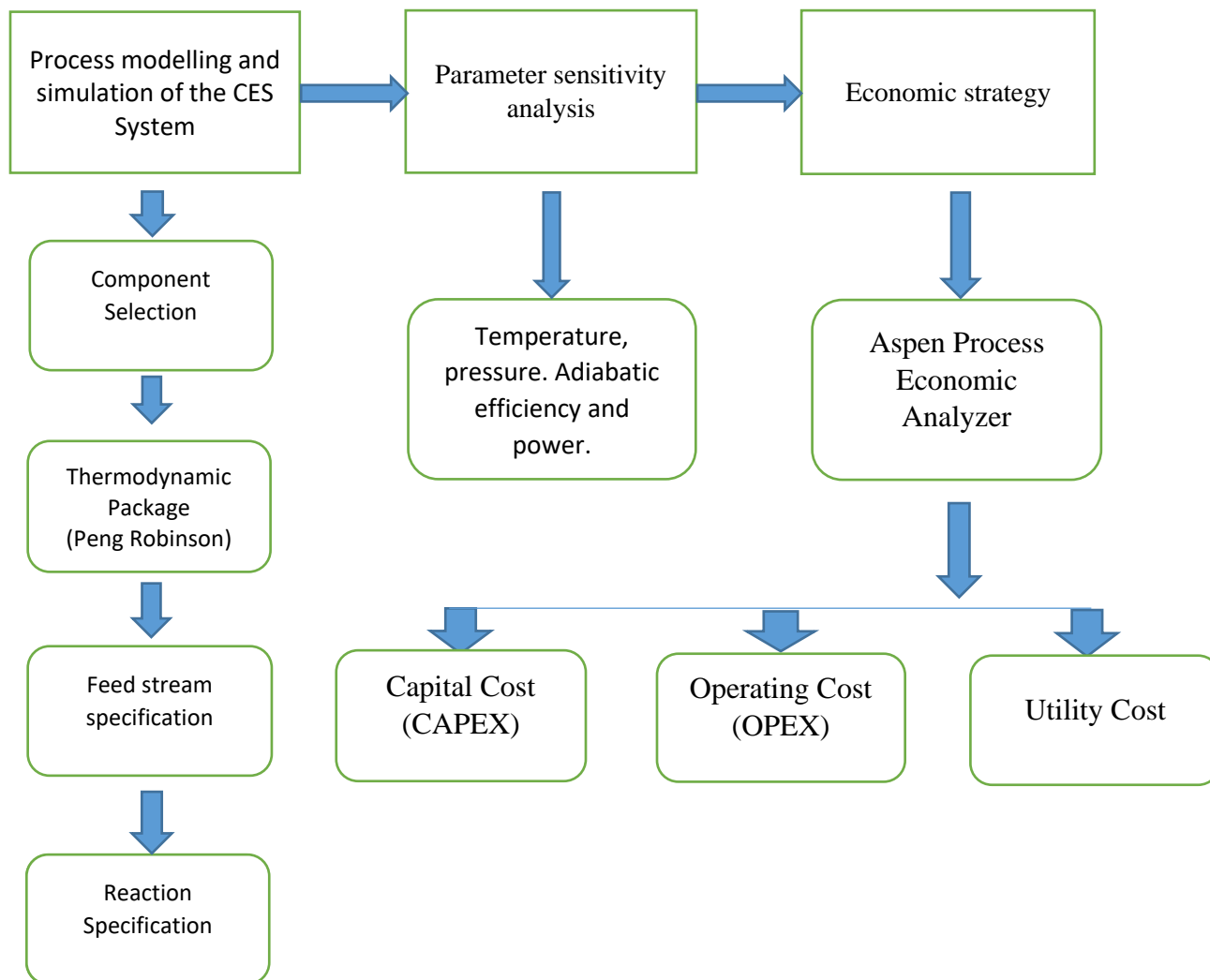


Figure 1: Description of the Process Flow Diagram for the Research

The actual functioning of the turbomachinery was presumed to operate with adiabatic efficiencies, and the values were selected based on the information found in the literature, as indicated in Table I.

Table I: Assumed adiabatic efficiencies for turbomachinery.

Adiabatic efficiencies	Value
Compressors	0.85
Cold expander	0.84
Cryogenic pump	0.75
Turbines	0.90

Source: (Li, 2011; Li et al., 2014; Sciacovelli et al., 2017).

Table 2 shows the stream values used for the simulation of the three system configurations of the CES system.

Table 2: Stream values for the states indicated in the flow sheets in Figures 2, 3 and 4 (Hamdy, 2019).

Streams	Variables		Adiabatic	Waste heat	Combustion
1	\dot{m}	Kg/s	198.3	198.3	198.3
	T	°C	15.0	15.0	15.0
	P	Bar	1.0	1.0	1.0
7	\dot{m}	Kg/s	198.3	198.3	198.3
	T	°C	18.0	18.0	18.0
	P	Bar	180.0	180.0	180.0
8	\dot{m}	Kg/s	123.8	65.5	65.5
	T	°C	18.0	18.0	18.0
	P	Bar	180.0	180.0	180.0
12	\dot{m}	Kg/s	59.4	105.7	105.7
	T	°C	-193.2	-193.2	-193.2
	P	Bar	1.1	1.1	1.1
19	\dot{m}	Kg/s	1187.0	211.4	105.7
	T	°C	194.0	450.0	194.0
	P	Bar	150.0	151.0	1.1
23	\dot{m}	Kg/s	118.7	211.4	211.4
	T	°C	194	450.0	734.0
	P	Bar	12.2	12.2	80.0
NGI	\dot{m}	Kg/s	-	-	211.4
	T	°C	-	-	718.2
	P	Bar	-	-	8.8

2.3 Process Flow Description of the Cryogenic Energy Storage System Configurations

As presented in Figures 2-4, the inlet air to the compression process is modeled with the ambient temperature at 15 °C, the ambient pressure at 1.0 bar, molar fraction of 0.79 for nitrogen and 0.21 for oxygen according to the International Standard Atmosphere (Hamdy, 2019). In all systems, the inlet air to the compressor has a mass flow rate of 198.3 kg/s, which is compressed to a pressure of 180 bar in a three-stage compression process to regulate the air temperature so that the output air has a lower temperature with inter-cooling of 18–20 °C. Thermal fluid (DOWTHERM-Q with 303 kg/s, 6 bar and 360 °C) is used as a heat storage medium to recover and store the heat of compression (Hamdy et al., 2019). The high-pressure air is further cooled and expanded until the dew point is reached. The slightly sub cooled liquid air is stored in a simple cryogenic insulated storage vessel at near ambient pressure (1.1 bar) and a temperature of -194 °C. For cold storage, the refrigerant R218 was found to recover the high-grade cold because it is neither toxic nor flammable (Li, 2011; Yokomizo, 2005). For improving the low-grade cold temperature, methanol is more appropriate as its boiling point is higher than the ambient temperature.

The recovered cold is supplied to the first cold box to increase the portion of liquefied air in the liquefaction process of the subsequent charging process. The high-pressure air is superheated and expanded in four gas turbine stages, and power is generated as shown in Figure 2. Figure 3 shows the CES system with waste heat integration similar to that of Figure 2, except for the additional heat rate Q_{in} that is supplied to the heat storage (HS). Figure 4 did not have HS, and the four-stage reheaters are replaced with a combustion chamber in which fuel is burned to supply extra heat, which increased the temperature of the high-pressure gas before the expansion process.

Stand-alone Adiabatic Cryogenic Energy Storage (ACES) system is designed to store and release energy using cryogenic fluids like liquid air. Two important modes of operation for ACES systems are Waste Heat Integration and Integration of Combustion. Their applications, as well as their differences as shown in Figure 3 and 4.

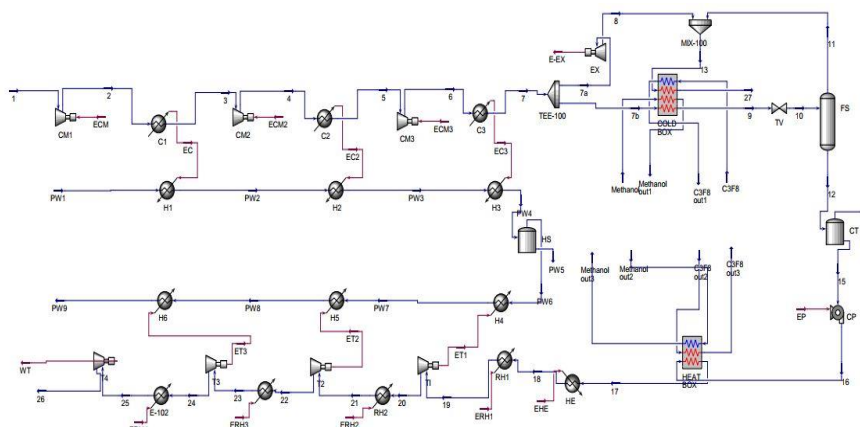


Figure 2: Flow sheet of the stand-alone adiabatic CES system (Case A)

Waste heat integration in ACES systems involves capturing and utilizing waste heat generated during the charging and discharging cycles of the system. This helps improve overall energy efficiency by making use of wasted energy. During charging, waste heat can be captured and stored, typically in a Thermal Energy Storage (HS) system. During discharging, the stored heat is used to enhance the system's output. Waste heat integration focuses on capturing and reusing heat within the ACES system to improve its efficiency without involving external combustion processes as shown in Figure 3.

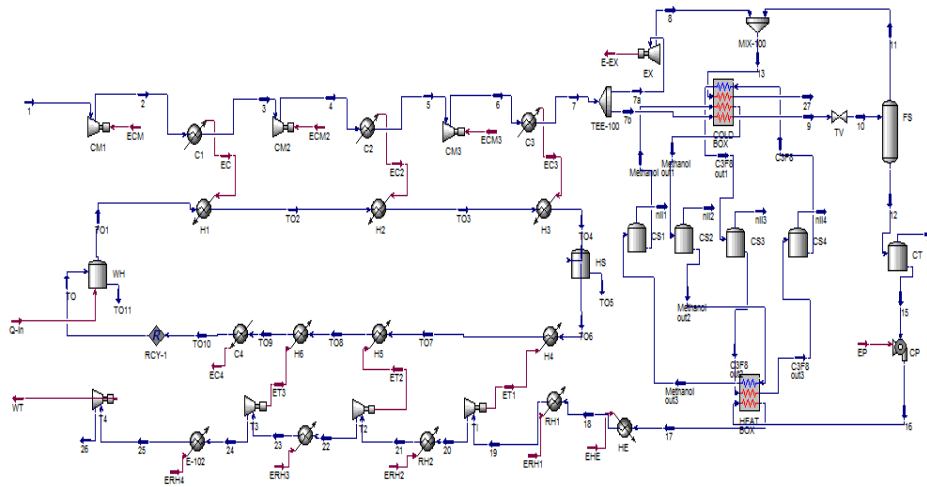


Figure 3: Flow sheet of the waste heat integration (Case B)

Figure 4 shows the integration of combustion in ACES systems involves using an external heat source, often a combustion process, to boost the system's energy output. This is particularly useful when additional power is required beyond what can be achieved with the stored cryogenic fluid alone. During the discharging phase, an external heat source, natural gas combustion is used to vaporize the cryogenic fluid, rapidly expanding it and driving a turbine for power generation. Integration of combustion relies on external combustion processes to augment the energy output of the ACES system. It's a way to provide an extra power boost when needed.

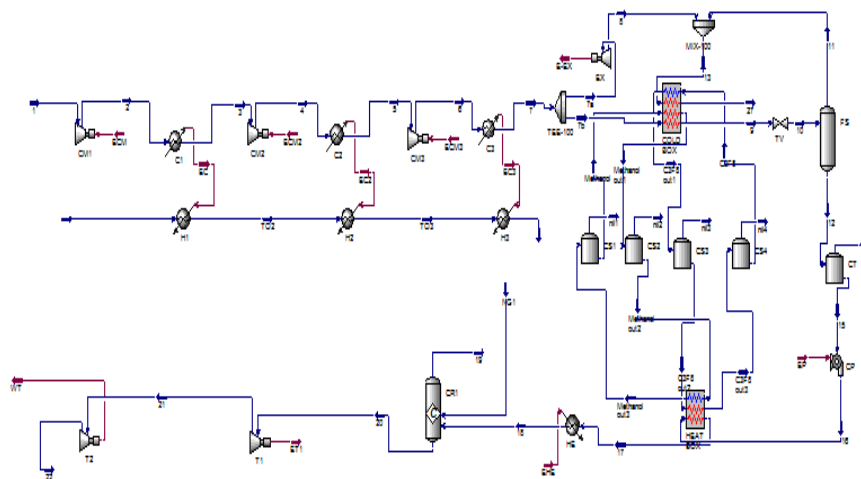


Figure 4: Integration of Combustion (Case C)

2.4 Economic Analysis

The economic analysis was carried out by a cost estimating software called Aspen Process Economic Analyzer, which is integrated in the HYSYS, and generates capital cost (CAPEX) estimates, operating cost (OPEX) estimates, as well as investment cash flow curves to evaluate the lifecycle economic impact of process decisions during conceptual design with the Aspen Process Economic Analyzer.

3.0 Results and Discussion

3.1 The Results and Discussion of the Sensitivity Analysis for Case A, B and C

Figure 5 shows the sensitivity analysis result of the three parameters where the adiabatic efficiency, as an independent variable, affected the two dependent variables, that is, power and delta T. It is clearly seen that increases in adiabatic efficiency result in increased power output, while higher temperature differences lead to reduced adiabatic efficiency and subsequently lower power output. These relationships highlight the importance of optimizing the adiabatic efficiency of the system to maximize power generation.

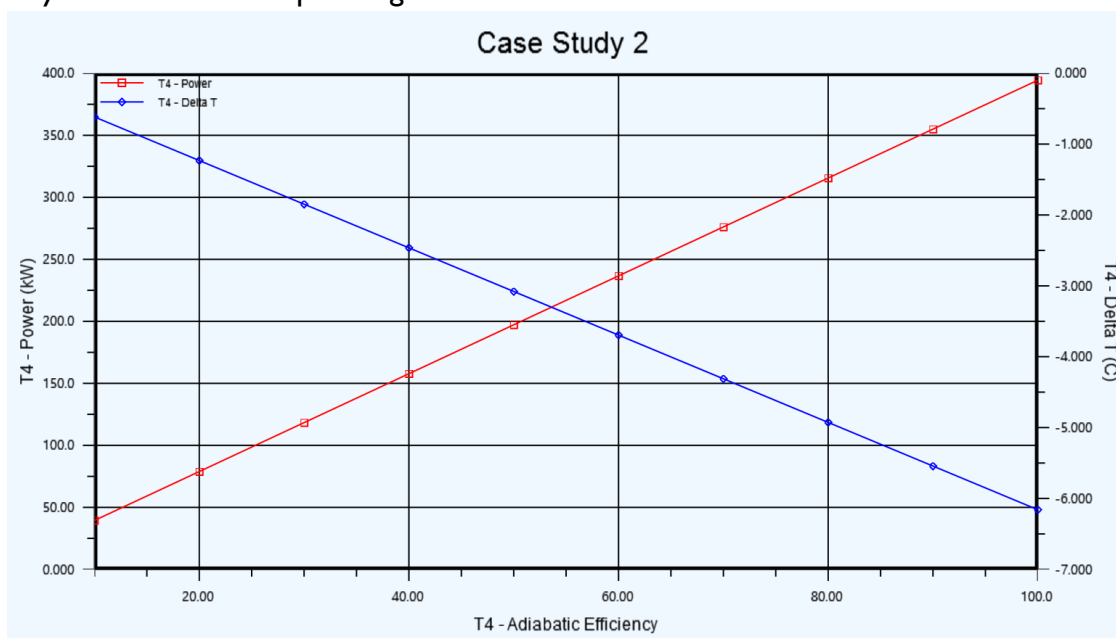
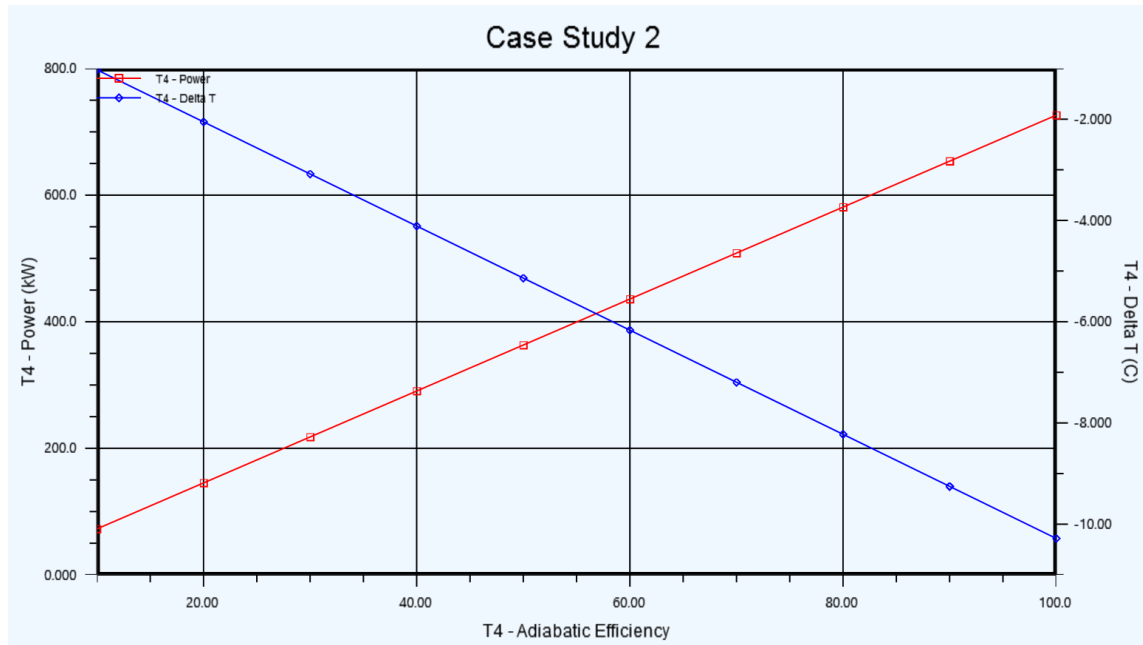


Figure 5: A graph of sensitivity analysis for the Case A

As shown in Figure 6(a), an increase in adiabatic efficiency affected the turbine by increasing its power and decreasing the temperature. This case noticeably shows that the power of the turbine increases with an increase in adiabatic efficiency and reduces with increases in delta-T. Figure 6(b) presents the relationship between the two dependent variables, which are temperature changes and power. The power of the turbine increased as the temperature decreased. Generally, the increase in adiabatic efficiency allows the turbine to convert more energy into useful work and reduces the temperature drop across the turbine, resulted in increased power output.

(a) Sensitivity analysis of the Case B with power, adiabatic efficiency, and Delta-T



(a) Sensitivity analysis of the Case B with Delta-T and power

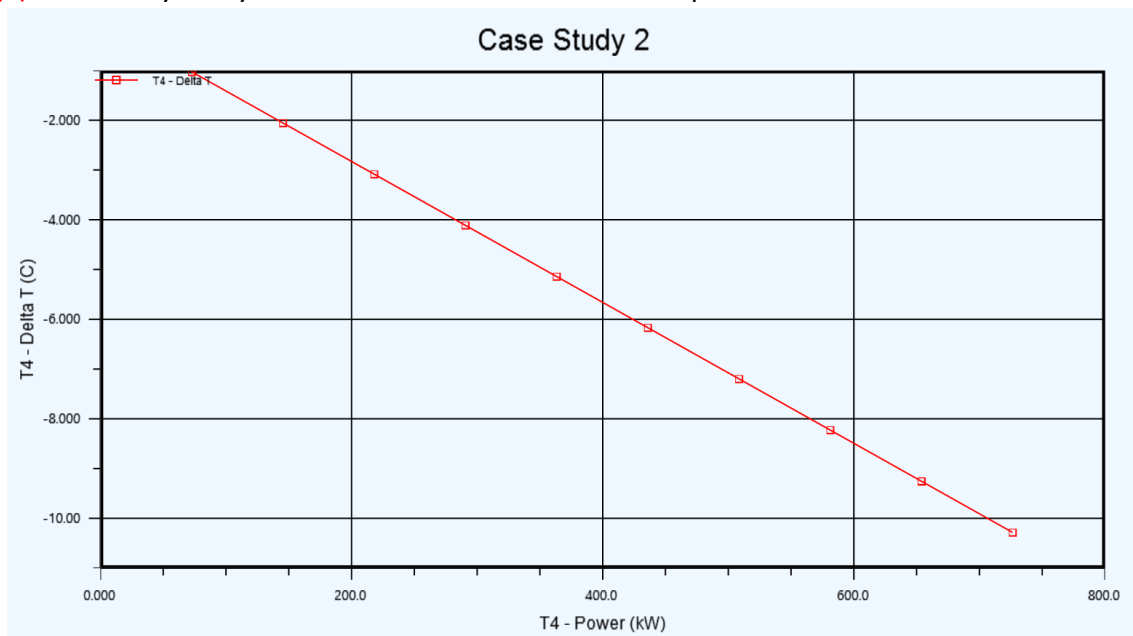
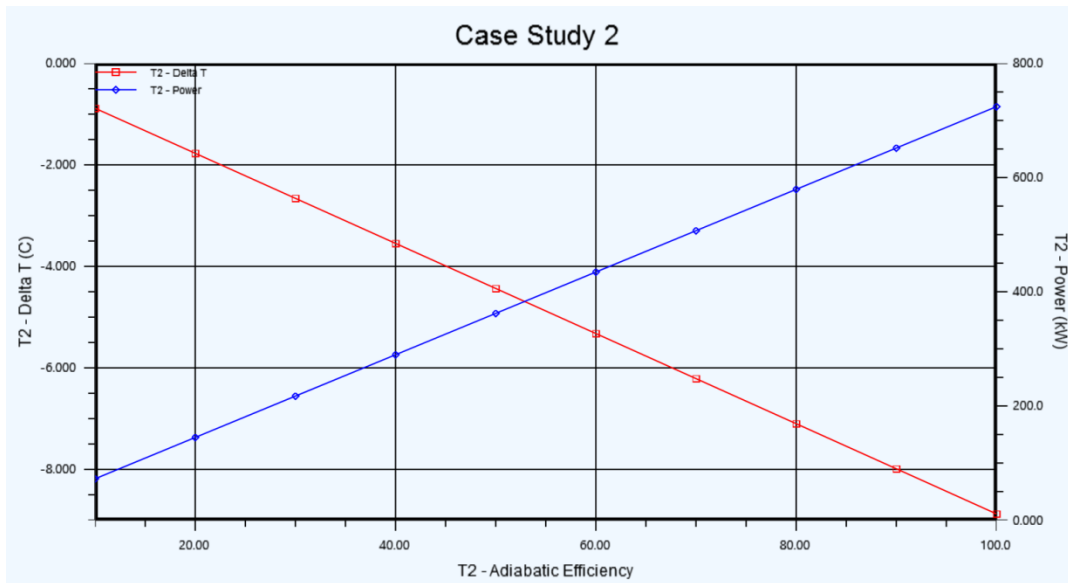


Figure 6: A graph of sensitivity analysis for the Case B

Figure 7(a) indicates the variation of the adiabatic efficiency as an independent variable with delta-T and power as independent variables. In the sensitivity analysis of Case C, the power of the turbine increases with an increase in adiabatic efficiency. Additionally, an increase in temperature decreases (delta-T) resulted in a decrease in adiabatic efficiency, again leading to a decrease in turbine power, as seen in Figure 7(b).

(a) Sensitivity analysis of the Case C with Delta-T, adiabatic efficiency and power.



(b) Sensitivity analysis of the two dependent variables

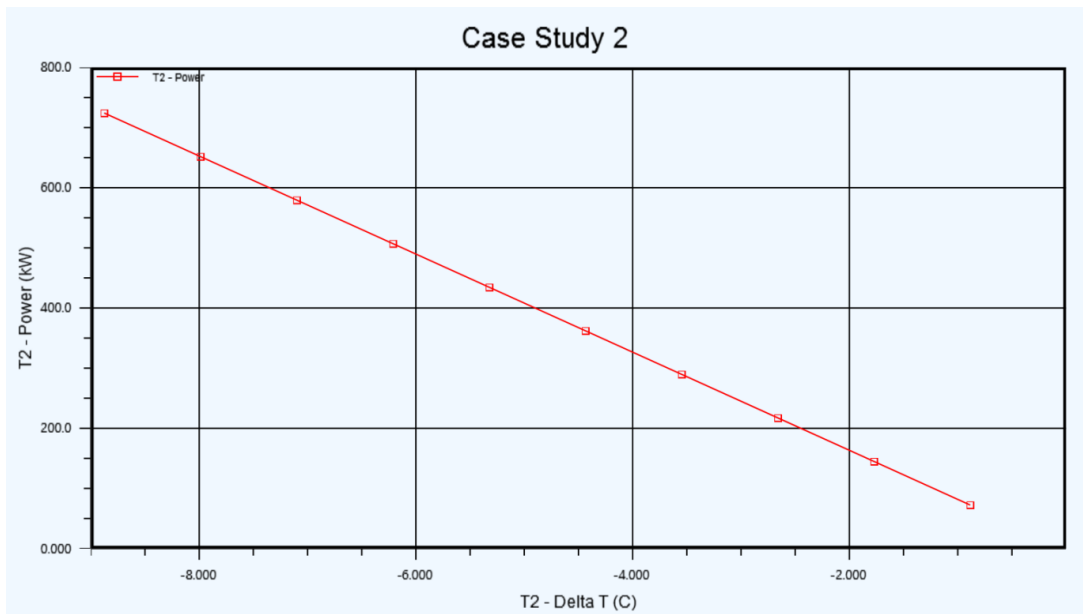


Figure 7: A graph sensitivity analysis of the Case C

The chart in Figure 8 represented the overall performances of the CES system that involved the turbine power of three design configurations at constant adiabatic efficiency. CASE A had 354.98kW of power produced. CASE B had an optimum power of 653.750kW and CASE C had a turbine power of 651.71kW.

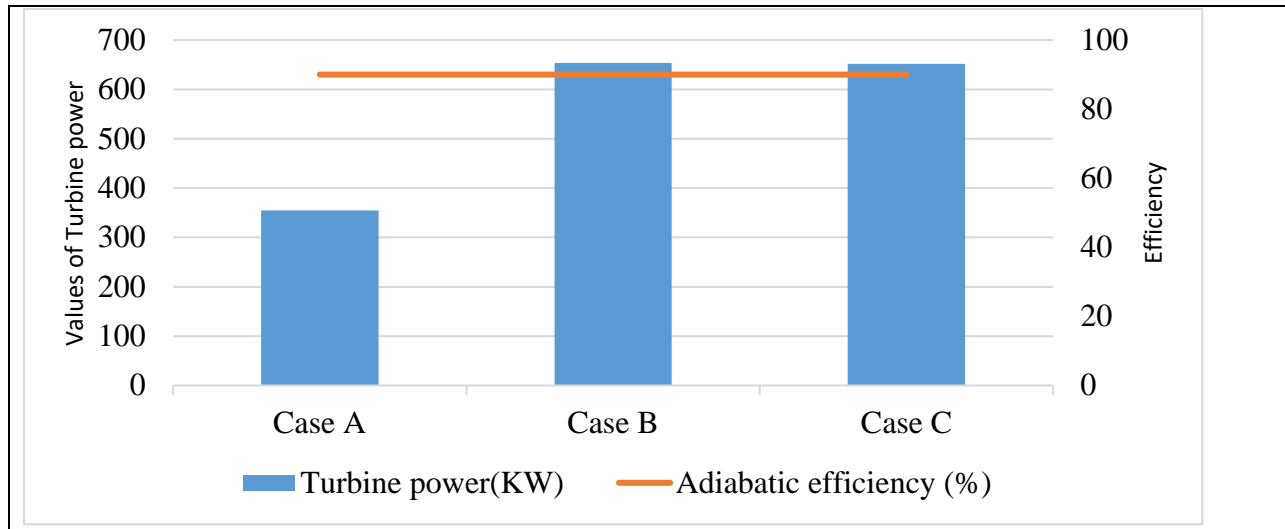


Figure 8: A chart showing power generated for the three cases of system configurations.

The responses obtained from the sensitivity analysis in Figure 9 showed that as the turbine inlet pressure decreased, the inlet temperature increased. This elevated temperature, along with the subsequent higher enthalpy drop across the turbine, leads to an increase in the power generated by the turbine.

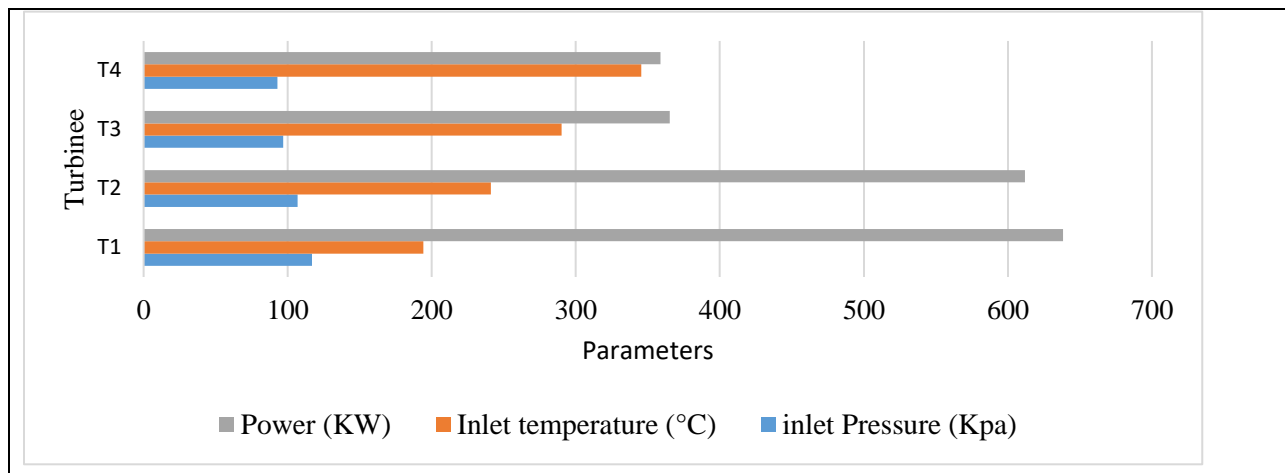


Figure 9: Chart showing the relationship between pressure, temperature and power for the Case A

The influence of turbine inlet temperature is illustrated in Figure 10. The result shows that there is a significant increase in electricity efficiencies with a large decrease in the pressure and an increase in the turbine inlet temperature (TIT). However, the net power output only increases with a decrease in turbine inlet pressure. Increasing the turbine inlet temperature is a very effective way to enhance the performance of the system configuration in terms of power generation. In this system, a decrease in the turbine inlet pressure increased both the turbine inlet temperature and the power generated by the turbine, because as the temperature increases,

the molecules will get energetically further apart from each other, and the attraction between the molecules will decrease and eventually the pressure will decrease, leading to high power output.

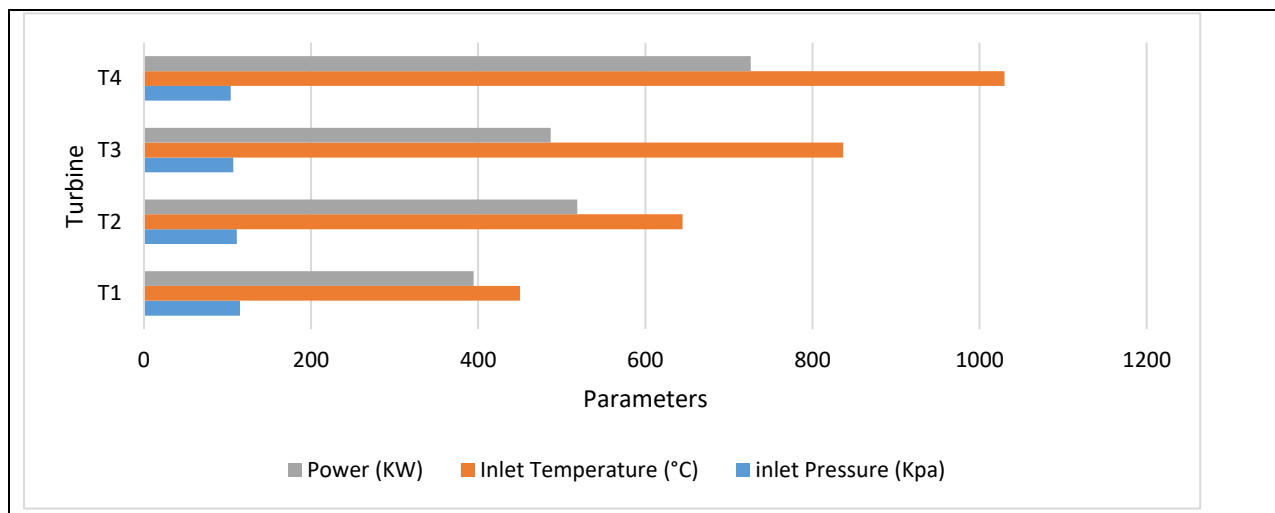


Figure 10: Chart showing a relationship between pressure, temperature and power for Case B

The behavior of the parameters described in Figure 11 are attributed to the integration of combustion system and turbine. Therefore, decreases in the inlet pressure, it causes a decrease in turbine inlet temperature but leads to an increase in turbine power. This behavior is a result of the interplay between pressure, temperature, and power in the gas turbine system.

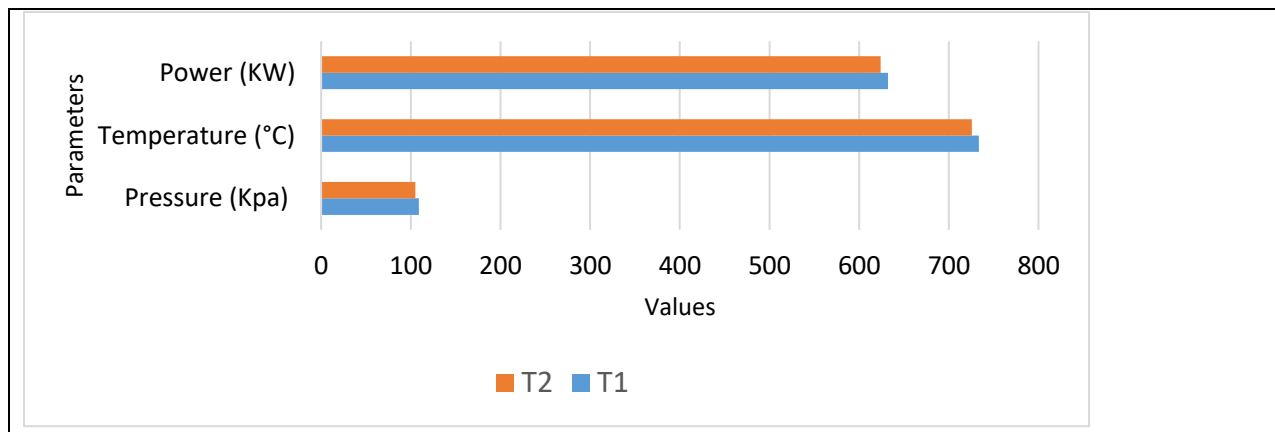


Figure 11: Chart showing a relationship between pressure, temperature and power for case C

3.2 The Results and Discussion of the Economic Analysis for Case A, B and C

The economic analysis was conducted using Aspen Economic Analyzer in Aspen HYSYS, for the CES systems configurations in terms of capital cost, operating cost and utility cost at the same desired rate of return. The plot in Figure 12 showed that Case B is more economical with the

lowest total capital cost, total operating cost and the total utility cost compared to Case A and Case C at the same minimum level of acceptable compensation for the investment's level of risk.

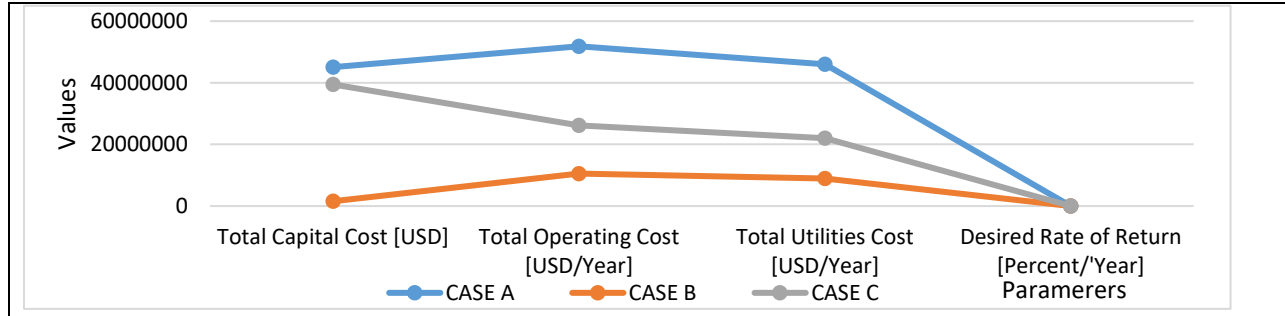
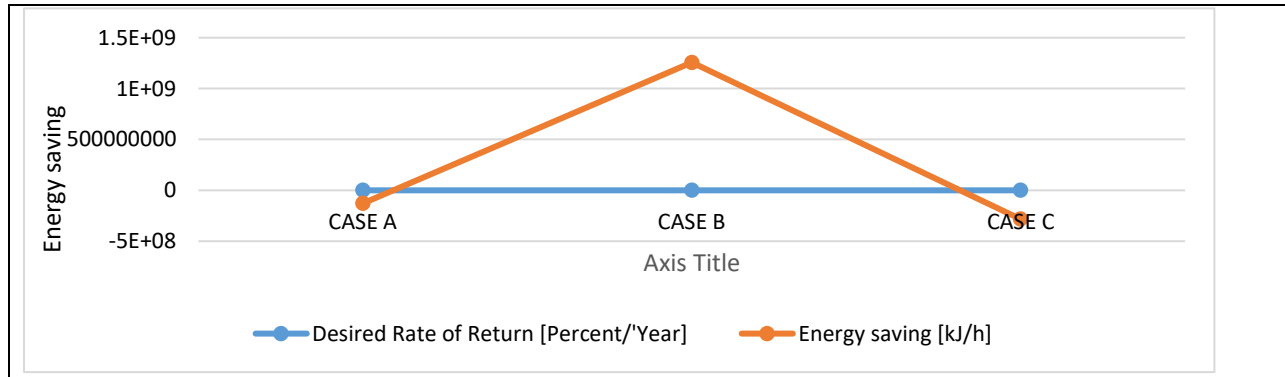


Figure 12: Graph for the total capital cost, Total Operating Cost, Total Utilities Cost and Desired Rate of Return for the three Cases

Figure 13(a) shows Case B, where the integrated systems with waste heat recovery are more economical with a higher positive energy savings of $1.257E9$ KJ/h. Compared to the negative energy savings of a standalone adiabatic system with $-129,200,000.00$ KJ/h and the integration of a combustion system with $-283,200,000.00$ KJ/h. As shown in Figure 13(b), the Case B systems reached energy savings efficiencies of 69.58%. The energy destruction in the charging process of the two cases A and B dominated with a share of 74.35 and 134.66 % of the energy destroyed in the overall system, respectively. The energy losses are caused almost entirely by the thermal energy emitted from the heat storage to the environment after the discharge process. The effects of cold storage and heat storage were found to be significant to the overall performance of the overall system.

(a) Energy saving at the same desired rate of return



(b) Percentage of actual of the three cases

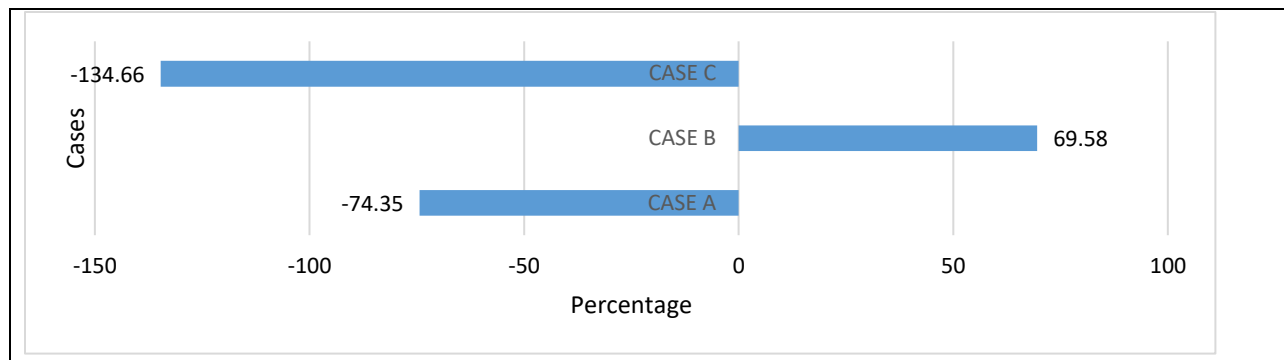


Figure 13: Energy saving and percentage of actual of the systems configurations. (a) Energy saving at the same desired rate of return. (b) Percentage of actual of the three cases

4.0 Conclusion

A successful modelling and simulation of the cryogenic energy storage system using three design configurations was carried out. The sensitivity analysis indicates that adiabatic efficiency, temperature, pressure, and power influence the operations of each configuration. It indicated that adiabatic efficiency had significantly increased by 90-100 %. It also showed that the lower the pressure, the higher the temperature, and the more power generated. The economic analysis revealed that the waste heat integration system has the lowest operating cost, capital cost, utility cost and higher energy savings compared to the other two system configurations. Waste heat integration was found to be only beneficial to turbine power generation and resulted in energy savings of 69.58%. The integrated systems reach significantly lower capital costs, operating costs and utility costs due to the increased adiabatic efficiency. The CES system with waste heat integration achieved the highest power of 653.70 kW. The adiabatic standalone CES systems and the system with combustion integration reached low power at the discharge phase of 354.98kW and 651.71 kW, respectively. It is recommended that parameter optimization be carried out on the primary system case B, to achieve the best design which include maximizing the round-trip efficiency and minimizing the costs.

References

- Borri, E., Tafone, A., Zsembinski, G., Comodi, G., Romagnoli, A. and Cabeza, LF. 2020. Recent trends on liquid air energy storage: A bibliometric analysis. *Applied Sciences Switzerland*, 10(8): 1–19, <https://doi.org/10.3390/AP10082773>.
- Hamdy, S. 2019. Cryogenic energy storage systems: An exergy-based evaluation and optimization. M.Sc Dissertation. University of Leeds.
- Hamdy, S., Morosuk, T. and Tsatsaronis, G. 2019. Exergetic and economic assessment of integrated cryogenic energy storage systems. *Cryogenics*, 99: 39–50, <https://doi.org/10.1016/j.cryogenics.2019.02.009>.
- Hamdy, S., Moser, F., Morosuk, T. and Tsatsaronis, G. 2019. Exergy-Based and Economic

Evaluation of Liquefaction Processes for Cryogenics Energy Storage. *Energies*, 12(493): 1–18, <https://doi.org/10.3390/en12030493>.

Li, Y. 2011. Cryogen Based Energy Storage : Process Modelling and Optimisation. PhD Thesis. University of Leeds.

Li, Y., Cao, H., Wang, S., Jin, Y., Li, D., Wang, X. and Ding, Y. 2014. Load shifting of nuclear power plants using cryogenic energy storage technology. *Applied Energy*, 113: 1710–1716, <https://doi.org/10.1016/j.apenergy.2013.08.077>.

Nderitu, D. and Preckel, PV. 2013. Lucart to try out PM, 16(44): 1-3.

Sciacovelli, A., Vecchi, A. and Ding, Y. 2017. Liquid air energy storage (LAES) with packed bed cold thermal storage – From component to system level performance through dynamic modelling. *Applied Energy*, 190: 84–98, <https://doi.org/10.1016/j.apenergy.2016.12.118>.

Steinmann, W. 2016. Thermo-mechanical concepts for bulk energy storage. *Renewable and Sustainable Energy Reviews*, 75: 205-219, <https://doi.org/10.1016/j.rser.2016.10.065>.

Wang, J., Lu, K., Ma, L., Wang, J., Li, J., Wang, D., Miao, S. and Dooner M. 2017. Technology Development. *Energies*, 10(7): 991. <https://doi.org/10.3390/en10070991>.

Xu, F., Jin, S., Zhong, H., Wu, D., Yang, X., Chen, X., Wei, H., Fu, R. and Jiang, D. 2015. Electrochemically active, crystalline, mesoporous covalent organic frameworks on carbon nanotubes for synergistic lithium-ion battery energy storage. *Scientific Reports*, 5: 1–6, <https://doi.org/10.1038/srep08225>.

Yokomizo, O. 2005. United States Patent, 2(12): 610-612.