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By :

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Modeling and techno-economic optimization of a Green Compressed Air Energy Storage (GCAES) system for offshore wind energy

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Summary

The large-scale generation of electrical wind energy is planned in many countries. But the intermittent nature of its supply, and variations in load profile indicate a strong requirement for energy storage to deliver it when needed. Whilst pumped hydro storage, batteries and fuel cells have some advantages, compressed air energy storage (“CAES”) has the storage capacity of pumped hydro, with lower cost and less geographic restrictions [1]. Hence, this project studies the modeling of a Green CAES system which characterized by the non-existence of the fuel-burner system. This allows us to enhance this choice as an ecological renewable energy solution. A steady state model is then developed to perform energy and exergy analyses in parallel with an exergoeconomic model. According to the refund time and the profit, this system can be considered as a promising solution in the field of renewable energy.

Résumé

La production à grande échelle de l’énergie électrique éolienne a déjà eu lieu dans de nombreux pays. La nature intermittente de l’alimentation de cette énergie et la variation de son profil de charge impliquent une forte demande de stockage afin de la délivrer en cas de besoin. Le pompage-turbinage, les batteries, et les piles à combustible ont certains avantages. Par ailleurs, le stockage d’énergie en air comprimé fourni une accumulation par pompage avec un coût plus bas et des restrictions géographiques moins compliquées. Dans ce contexte, ce projet étude le modèle du système vert CAES qui est caractérisé par l’absence de la consommation de carburant, ce qui permet de favoriser ce système comme une solution écologique pour le stockage de l’énergie renouvelable. Un modèle en régime permanent est développé pour performer l’analyse de l’énergie et l’éxergie, en parallèle avec un modèle exergoeconomique. Selon le temps de récupération et le profit, ce système peut être considérer comme une solution prometteuse dans le domaine de l’énergie renouvelable.

خلاصة

إن إستخدام الهواء كمصدر لتوليد الطاقة الكهربائية أصبح مستخدماً في كثير من الدول. ولكن بسبب طبيعة هذه الطاقة المتغيرة والمتقطعة في القوة والجهد يظهر حاجة ملحة لتخزينها من أجل توفيرها عند الحاجة. إن أنظمة كتخزين الطاقة بالمياه أو البطاريات أو خلايا الوقود لها الكثير من المزايا، إلا أن نظام تخزين الطاقة عن طريق الهواء المضغوط له القدرة المماثلة لنظام تخزين المياه بأفضلية السعر المنخفض وبقيود جغرافية أقل. إن هذا المشروع يدرس نظام بيئي لتخزين الطاقة بالهواء المضغوط مع عدم إستخدام الوقود. وهذا ما يعزز إعتباره كإحدى الحلول البيئية الواعدة للطاقة المتجددة. في هذا المشروع تمت دراسة الطاقة ونوعية الطاقة في حالة الاستقرار بالتوازي مع دراسة إقتصادية. إعتماداً على فترة الإسترداد وكمية الربح المقدر، فإن هذا النظام يعد من الحلول الواعدة والمبشرة في مجال الطاقة المتجددة البيئية.

Keywords: Compressed air energy storage, Renewable energy, Green systems, Offshore, Wind turbine.

Acknowledgments and dedications

First and foremost, all thanks to Allah, the creator of all things, for giving us the strength and ability to complete these five years and write this report.

My education at the Lebanese University - Faculty of Engineering - Branch I is almost done, and I want to express my gratitude for all the teachers and professors in the faculty for all the knowledge we have been transmitted over these years to better understand what mechanical engineering is about.

I would like to acknowledge, with sincere gratitude, the roles played by those persons who assisted in making this project a worthwhile experience.

My profound thanks and appreciations to Dr. Fadi Taychouri and Dr. Youssef Mazloum, for their patience, guidance, excellent and efficient moderation, valuable advices, beneficial criticism, suggestions and encouragement.

In addition, I would never forget the Mechanical Department Doctors, for their role played in building my Engineering knowledge.

Finally, all my respect to my parents. Ahmad "Hajj ABBAS", who shared me every exam with his name and his full support. Ibtissam "Sassuki", who can't believe that I completed these five years, thank you for your daily support which leads to success in my life.

This book is dedicated for all of them.

ABBAS Mhamad

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MAHFOUZ Youssef

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List of symbols:

A	Area, (m^2)
Amb	Ambient
CAES	Compressed air energy storage
Cp	Specific heat capacity, (J/kg.K)
CRF	Capital recovery factor
D	Destruction
DT	Temperature difference, (K)
E	Energy, (J)
ED	Energy density, (KWh/m^3)
Elec	Electric
Ex	Exergy, (W)
GCAES	Green compressed air energy storage
H	Mass enthalpy, (kJ/kg)
H	Heating heat exchanger
Hyd	Hydraulic
HP	High pressure
i	Interest rate, (%)
in	Input
ise	Isentropic
iso	Isothermal
LP	Low pressure
M	Mass, (Kg)
MP	Medium pressure
N	Number of system operating hours in a year, (years)
n	System life , (years)
o/out	Output
P	Power, (W)
p	Pressure, (Pa)
PHS	Pumped hydro storage

s	Entropy, (KJ/Kg.K)
T	Temperature, (ºC/K)
V	Volume, (m^3)
Z	Purchase cost of the components, (€)
$\dot{Z}$	Cost rate of the components, (€/s)
ρ	Density, (Kg/m3)
Δ	Difference between input and output
ϕ	Maintenance factor

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Introduction:

With the increasing depletion of traditional fossil energy sources, the use of renewable energy has attracted more and more attention. The development of renewable energy has become a primary task in many countries. However, due to the inherent randomness and volatility of wind energy, solar energy, bio-energy, etc., the development of new energy sources is a huge challenge confronted by countries all over the world. How to solve the volatility of renewable energy sources is the key issue of the development and utilization of renewable energy in the future.

Renewable energy such as wind and solar energy are clean and available as long as the wind blows or sun shines. The two main disadvantages of these energy sources are their intermittency and their availabilities which don't often correspond to power demand. For example, wind energy tends to be more abundant at night when power demand is low. The variations in wind speed and solar intensity make integrating wind and solar energy into the electric power grid a challenge. An energy storage system can provide steady and predictable power by storing excess energy and releasing it back when the demand is higher than the production.

Then, the main challenge is to find the best energy storage technology with the highest efficiency and the lowest cost.

In our project, we select the Compressed Air Energy Storage "CAES" system as it's the only technology that has the storage capacity of the pumped hydro storage system with lower cost and less geographic restrictions [1]. Thus, we study in this report its efficiency, cost-effectiveness, refund time and profit with many options of the system at a steady state conditions.

The aim of this project is to study the CAES energy storage technology, this report is divided into five chapters, conclusion and perspectives:

- Chapter one: Renewable energy technologies
  Talking about renewable energy main sources and we indicate the one we used in our project with its properties.
- Chapter two: Energy storage technologies
  Listing the energy storage technologies and we explain CAES system.
- Chapter three: Offshore CAES system
  Explaining the CAES system and its main components and listing the thermodynamic relations.
- Chapter four: Energy analysis
  Listing system conditions, Presenting the system results thermoeconomically, some efficiency and economic analysis.
- Chapter five: Exergy analysis
  Explaining exergy, presenting exergy relations, exergy results analysis.

Chapter 1: Renewable Energy technologies

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services.

1. Overview:

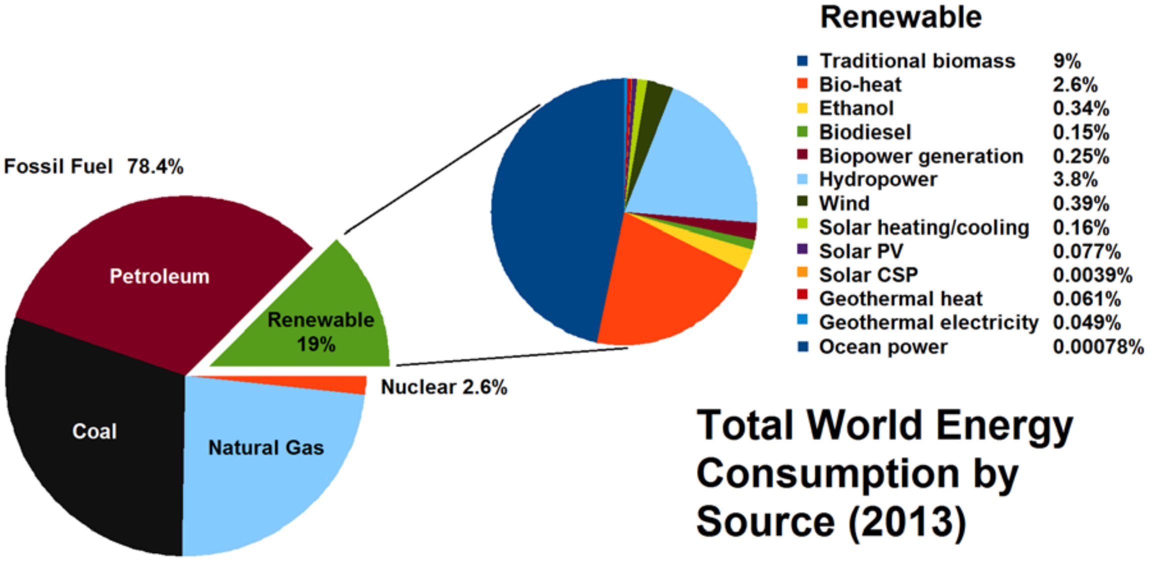


Figure 1.1: Total world energy consumption by source (2013)

In 2013, the nation was relying on just 19% of energy consumption from the renewable sources (Fig. 1.1). About 33% of the renewable energy used is by the electrical power sector for producing electricity.

In 2014, the world energy consumption for electricity generation was coal at 40.8%, natural gas at 21.6%, nuclear at 10.6%, hydro at 16.4%, other sources (solar, wind, geothermal, biomass, etc.) at 6.3% and oil at 4.3%. Coal and natural gas were the most used fuels for generating electricity (Fig. 1.2).

Recently there has been a large increase in international agreements and national Energy Action Plans, such as the EU 2009 Renewable Energy Directive, to increase the contribution of the renewable energy sources in the energy generation mix due to the growing concerns about pollution from energy sources such as oil, coal, and natural gas. One such initiative was the United Nations Development Program's World Energy Assessment in 2000 that highlighted many challenges humanity would have to overcome in order to shift from fossil fuels to renewable energy sources.

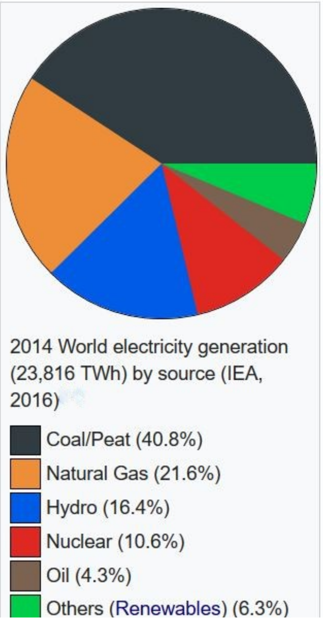


Figure 1.2: World electricity generation by source (2014)

2. Main sources:

a. Wind power:


Figure 1.3: Offshore wind turbine

Airflows can be used to run wind turbines. Modern utility-scale wind turbines range from around 600 kW to 5 MW of rated power, although turbines with rated output of 1.5–3 MW have become the most common for commercial use. The largest generator capacity of a single installed onshore wind turbine reached 10 MW in 2012. The power available from the wind is a function of the cube of the wind speed, so as wind speed increases, power output increases up to the maximum output for the particular turbine. Areas where winds are stronger and more constant, such as offshore and high altitude sites, are preferred locations for wind farms. Typically, full load hours of wind turbines vary between 16 and 57 percent annually, but might be higher in particularly favorable offshore sites [2].

b. Hydropower:


Figure 1.4: Hydropower

Hydropower is produced in 150 countries; the Asia-Pacific region alone generates 32 % of global hydropower in 2010. Among the countries having the largest percentage of electricity generation from renewables, the top 50 use primarily hydroelectric energy. China is the largest hydroelectricity producer, with 721 terawatt-hours of production in 2010, representing around 17 percent of domestic electricity use. There are now three hydroelectricity stations larger than 10 GW: The Three Gorges Dam in China, Itaipu Dam across the Brazil/Paraguay border, and Guri Dam in Venezuela [3].

c. Solar energy:

A photovoltaic system converts light into electrical direct current (DC) by taking advantage of the photoelectric effect. Solar photovoltaics have turned into a multi-billion, fast-growing industry, continues to improve its cost-effectiveness, and has the most potential of any renewable technologies together with concentrated solar power.

Italy has the largest proportion of solar electricity in the world, in 2015 solar supplied 7.8% of electricity demand in Italy. In 2016, after another year of rapid growth, solar generated 1.3% of global power [3].

Figure 1.5: Solar Energy

d. Geothermal energy:

High Temperature Geothermal energy is from thermal energy generated and stored under the ground. Earth's geothermal energy originates from the original formation of the planet and from radioactive decay of minerals.

The heat that is used for geothermal energy is from the underground. At the core, temperatures may reach over 9,000 °F (5,000 °C) [4].

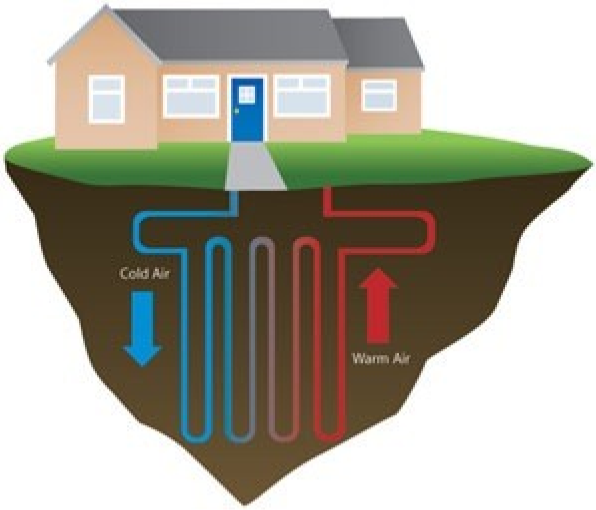


Figure 1.6: Geothermal Energy

e. Biomass energy:

Biomass is biological material derived from living, or recently living organisms. It most often refers to plants or plant-derived materials which are specifically called lignocellulosic biomass. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel. Conversion of biomass to biofuel can be achieved by different methods which are broadly classified into: thermal, chemical, and biochemical methods [4].

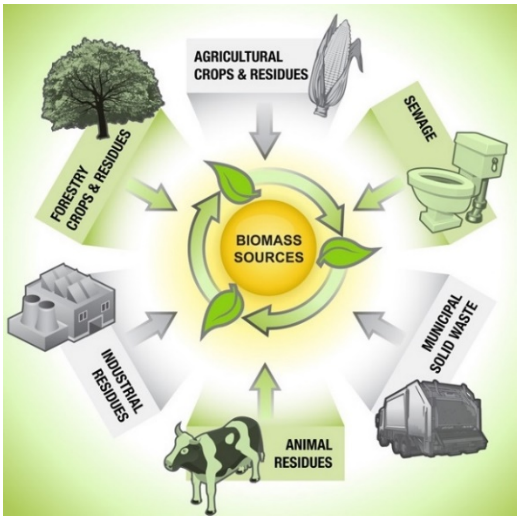


Figure 1.7: Biomass sources

3. Chapter conclusion:

Between these sources, our proposed system is presented a solution for the unused energy from an offshore wind turbine at off-pick hours.

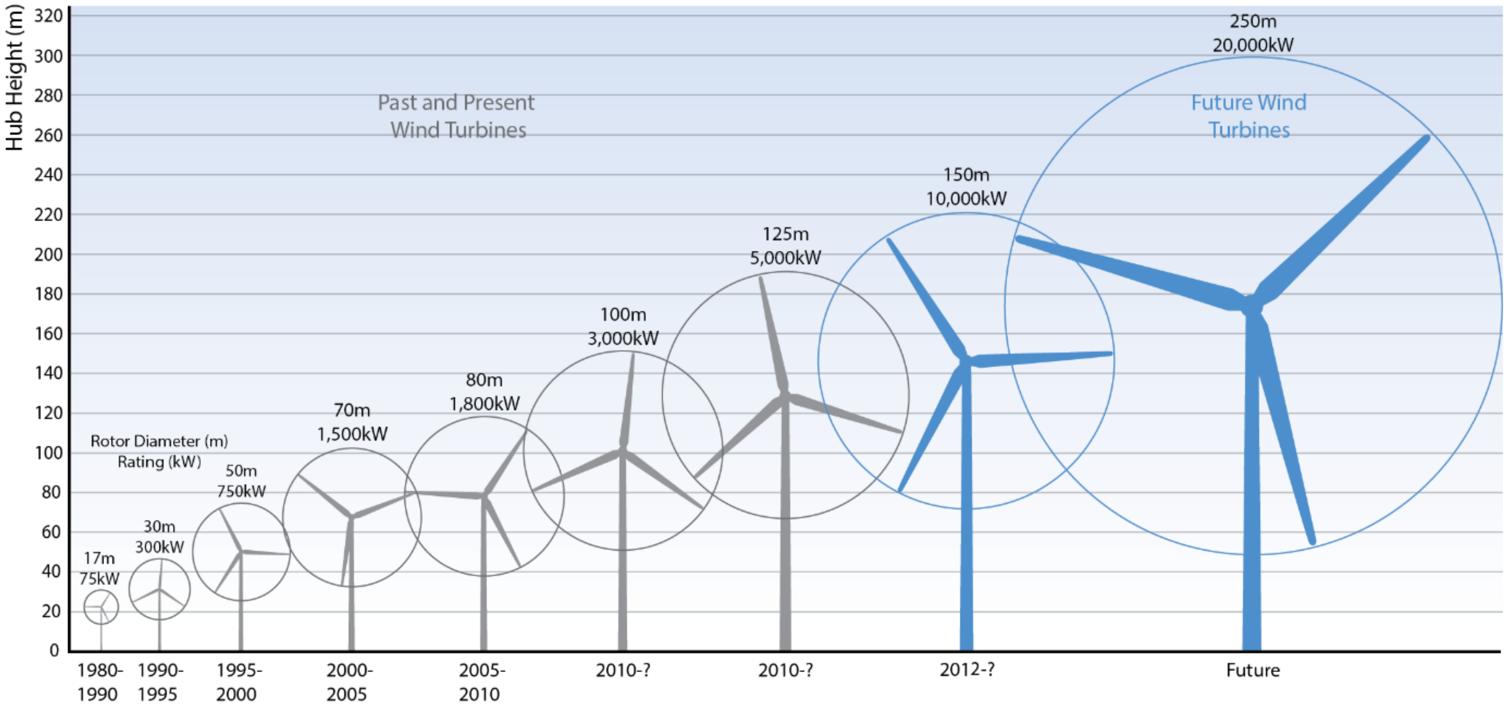


Figure 1.8: Growth in Size of Typical Commercial Wind Turbines

We can obviously notice that the progression is enormous, and the companies are competing each other to build the biggest and most power wind turbine. Today the biggest offshore wind turbine is the SeaTitan 10MW wind turbine which has a high technology to capture more power from wind speed without getting the hub higher.

The wind turbines have a remarkable evolution in the size and the power during less than 30 years. Nowadays, GE company is building what they called the biggest wind turbine with 12 MW power of capacity.

Power	*Grid frequency*	*Hub height*	*Material*	*Rotor diameter*	*Generator speed*
10 MW	50 Hz / 60 Hz	125 m	Cast iron	190 m	10 RPM

Table 1.1: SeaTitan wind turbine technical data [8]

Chapter 2: Energy storage technologies

The storage of the electrical energy is an operation that involves placing some amount of energy in a given place to use it when production is interrupted or insufficient. The techniques used for storing energy are very numerous. Depending on the nature of the storage materials, direct storage and indirect storage can be distinguished as shown in Figure 2.1.

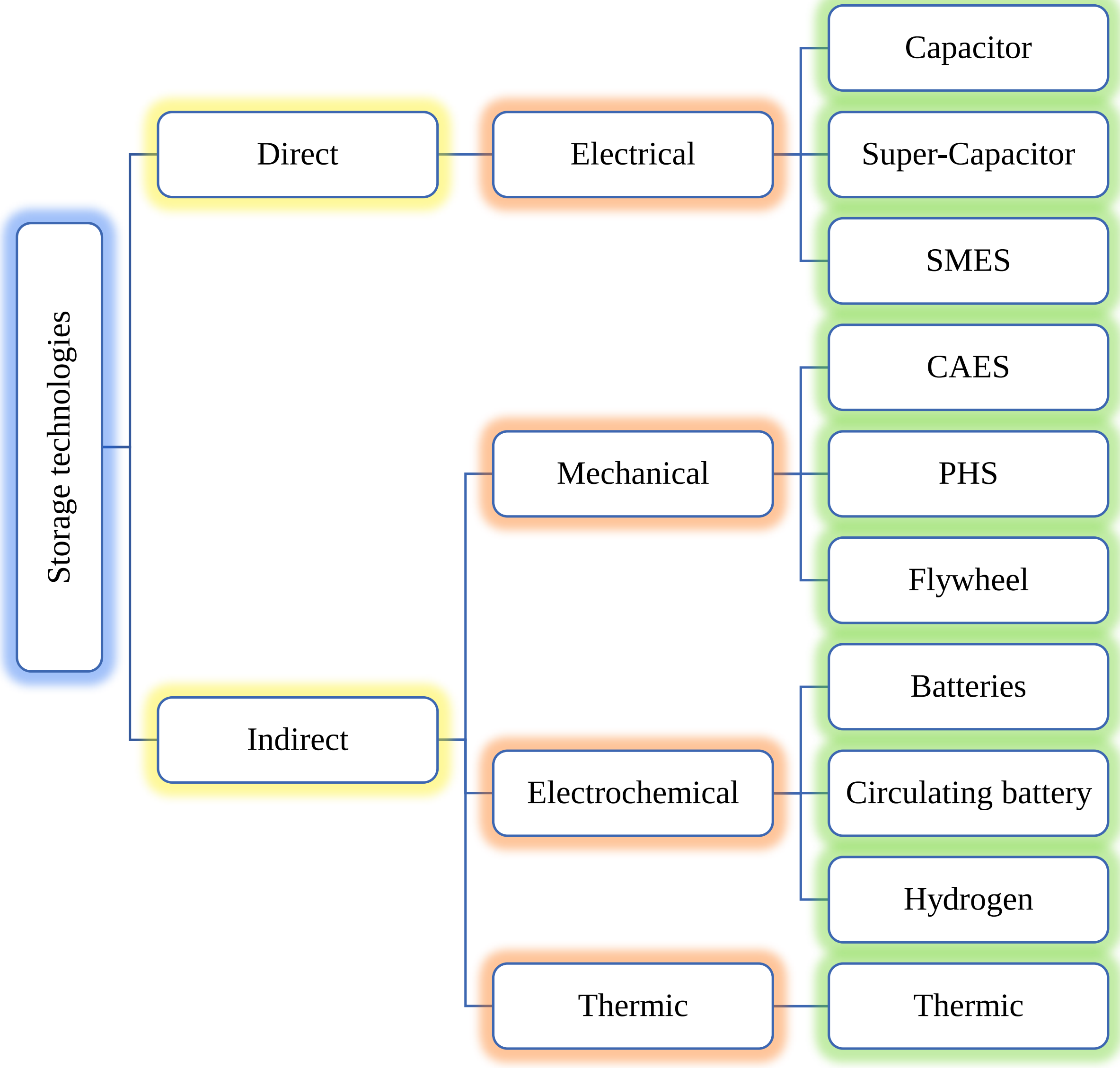


Figure 2.1: Storage devices classification, SMES (superconducting magnetic energy storage), CAES (Compressed air energy storage), PHS (pumped hydro storage)

1. Electrical storage technologies:

a. Superconducting Magnetic Energy Storage (SMES):

The SMES system is a relatively recent technology. The first system based on this technology was built in 1970. Its operation is based on storing energy in a magnetic field, which is created by a DC current through a large superconducting coil at a cryogenic temperature. The energy stored is calculated as the product of the self-inductance of the coil and the square of the current flowing through it. Thus, the characterization of the coil has a central role in the system design. Depending on the system operating temperatures, superconducting coils can be classified as: High Temperature Coils (HTS), which work at temperatures around 70K, and Low Temperature Coils (LTS), a more mature technology, with working temperatures around 5K. A balance between cost and system requirements determines the technology used. The maximum current that can flow through the superconductor depends on the temperature. The lower the operating temperatures, the higher the operating currents that can be achieved [5].

b. Super capacitor Energy Storage System (SCESS):

Super capacitors are also known as ultra-capacitors or double layer capacitors. Like batteries, super capacitors are based on electrochemical cells which contain two conductor electrodes, an electrolyte and a porous membrane whereby ion transit between the two electrodes is permitted. However, no redox reactions occur in the cells, because the operating voltage is lower, in order to electrostatically store charge on the interface between the surfaces of the electrolyte and the two conductor electrodes. In fact, this structure creates two capacitors (due to both interfaces, electrolyte – negative electrode and electrolyte – positive electrode), and for this reason, they are called double-layer capacitors. The energy stored in the capacitors is directly proportional to their capacity and the square of the voltage between the terminals of the electrochemical cell, while the capacity is proportional to the electrode-surface area and inversely proportional to the distance between the electrodes. Therefore, the main difference between capacitors and super capacitors is the use of porous electrodes with high surface-areas by the latter ones, providing higher energy density to the system [6].

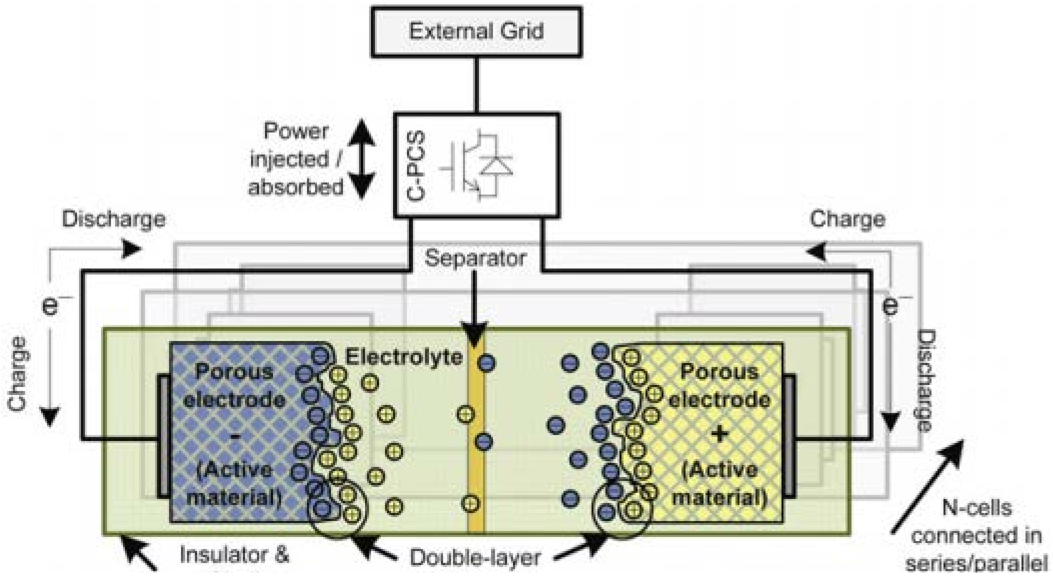


Figure 2.2: Super-capacitor energy storage system

2. Electrochemical storage technologies:

a. Battery Energy Storage System (BESS):

Batteries are one of the most used energy storage technologies available on the market. The energy is stored in the form of electrochemical energy, in a set of multiple cells, connected in series or in parallel or both, in order to obtain the desired voltage and capacity. Each cell consists of two conductor electrodes and an electrolyte, placed together in a special, sealed container and connected to an external source or load. The electrolyte enables the exchange of ions between the two electrodes; while the electrons flow through the external circuit. BESS is a solution based on low-voltage power battery modules, connected in series / parallel in order to achieve the desired electrical characteristics. BESS consist of batteries, the Control and Power Conditioning System (C-PCS) and the rest of the plant, which is in charge of providing good protection for the entire system [5].

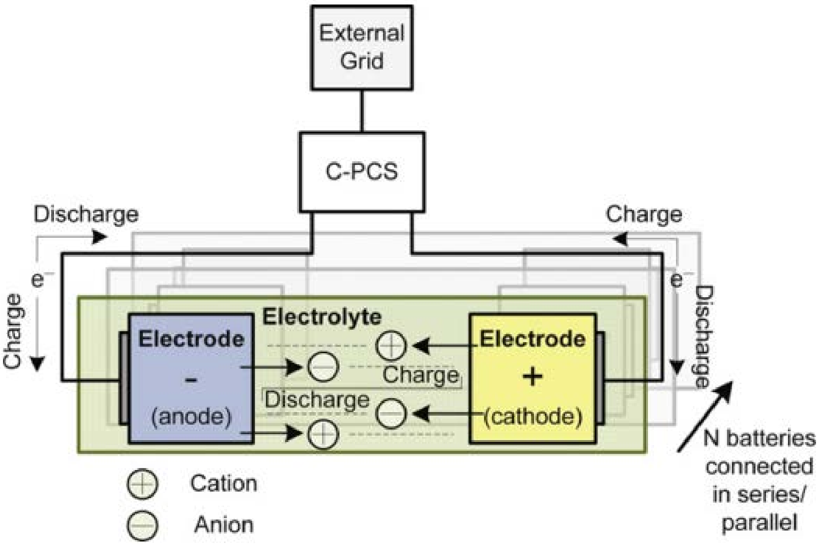


Figure 2.3: Battery energy storage system

b. Flow Battery Energy Storage System (FBESS):

Flow batteries are a relatively young technology. Their operating principle is based on reversible electrochemical reactions that occur in a set of cells connected in series, parallel or both, in order to achieve the desired voltage level. Unlike conventional batteries, two different aqueous electrolytic solutions are contained in separate tanks. During the normal operation of the battery, these aqueous solutions are pumped through the electrochemical cell where the reactions occur. Three types of commercially available flow batteries are considered in this article: Vanadium Redox Battery (VRB), Zinc Bromine Battery (ZBB) and Polycopid Bromide Battery (PSB). Since their operation is based on reduction and

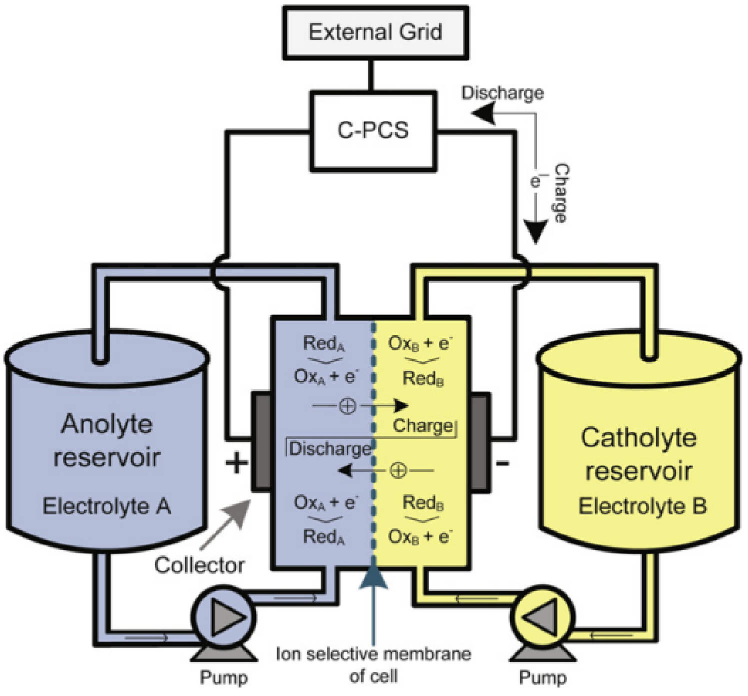


Figure 2.4: Flow battery energy storage system (FBESS)

oxidation reactions of the electrolyte solutions, these types of batteries are also called redox flow batteries. Their operating principle is presented in Figure 2.4. As shown, during the charge process, the electrolyte A is oxidized at the anode, while the electrolyte B is reduced at the cathode. The discharge cycle consists of the reverse process [7].

c. Hydrogen-based Energy Storage System (HESS):

Hydrogen can be obtained in various ways: by means of water electrolysis, from renewable energies such as solar or wind installations, gasifying biomass, coal or fuel. When hydrogen is produced from wind power plants, it can be stored in order to be used directly in fuel cells, or transported to users through pipelines to produce electricity [6].

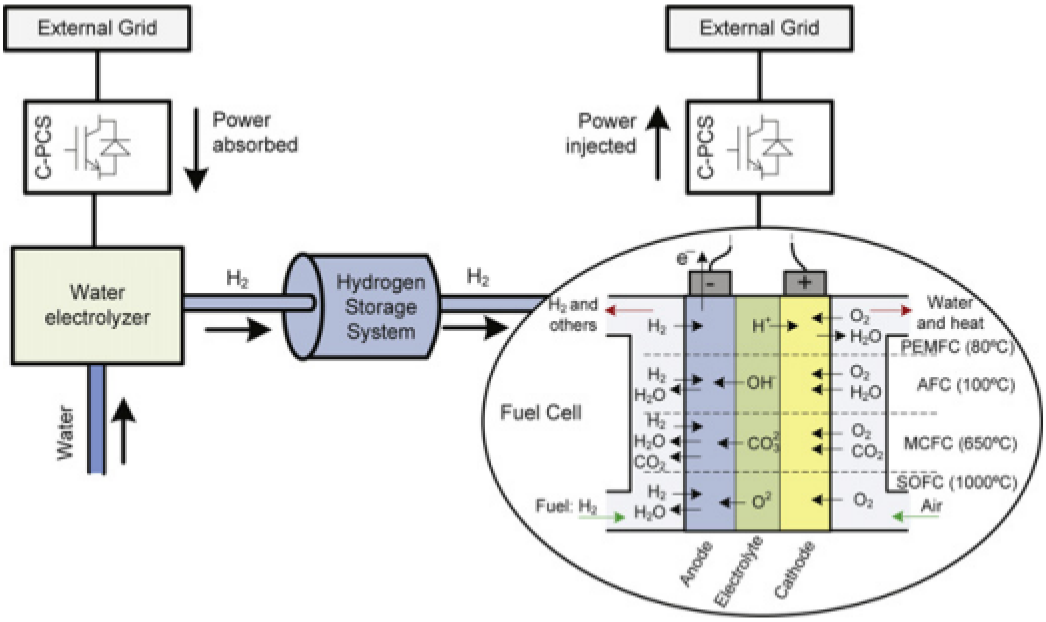


Figure 2.5: Hydrogen energy storage system

3. Mechanical storage technologies:

a. Pumped hydro storage (PHS):

PHS is a large-scale energy storage system. Its operating principle is based on managing the gravitational potential energy of water, by pumping it from a lower reservoir to an upper reservoir during periods of low power demand. When the power demand is high, water flows from the upper reservoir to the lower reservoir, activating the turbines to generate electricity. The energy stored is proportional to the water volume in the upper reservoir and the height of the waterfall [7].

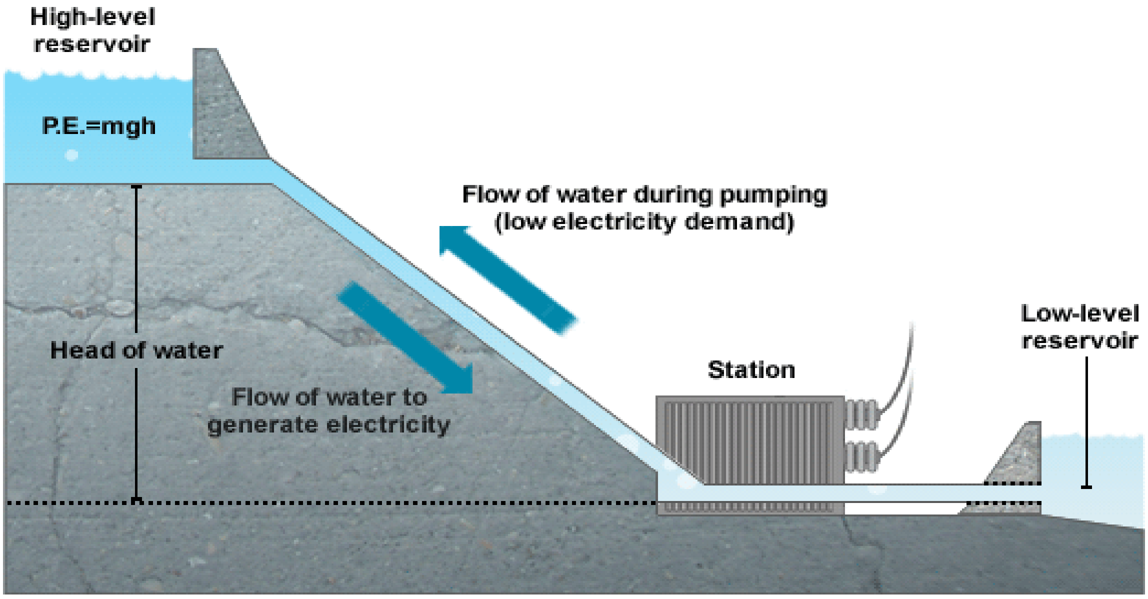


Figure 2.6: Pumped hydro storage system

b. Flywheel Energy Storage System (FESS):

A FESS is an electro-mechanical system that stores energy in form of kinetic energy. A mass rotates on two magnetic bearings in order to decrease friction at high speed, coupled with an electric machine. The entire structure is placed in a vacuum to reduce wind shear. The scheme of the system is presented in Figure 2.7.

Energy is transferred to the flywheel when the machine operates as a motor (the flywheel accelerates), charging the energy storage device. The FESS is discharged when the electric machine regenerates electricity through the drive (slowing the flywheel). The energy stored by the flywheel is dependent on the square of the rotating speed and its inertia [5].

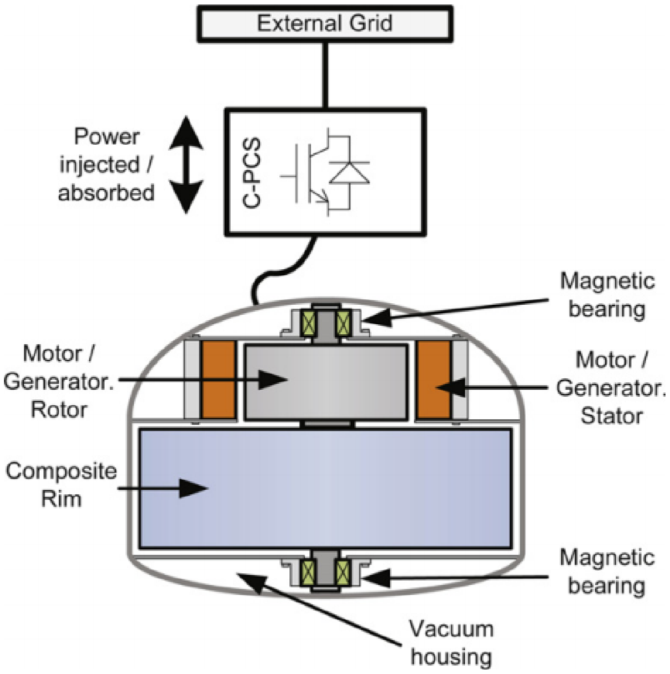


Figure 2.7: Flywheel energy storage system

c. Compressed Air Energy Storage System (CAES):

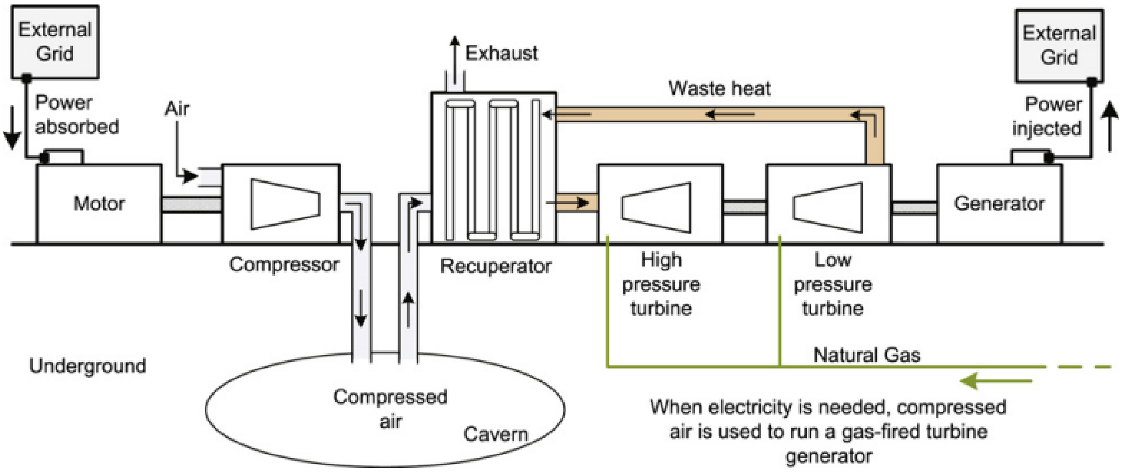


Figure 2.8: Compressed air energy storage system

CAES systems are based on conventional gas turbine technology. In this type of system, the energy is stored in the form of compressed air in an underground storage cavern. When energy is required to be injected into the grid, the compressed air is drawn from the storage cavern, heated and then expanded in a set of high and low-pressure turbines which convert most of the stored energy of the compressed air into rotational kinetic energy. The air is additionally mixed with natural gas and combusted. While the turbines are connected to electrical generators in order to obtain electrical energy, the turbine exhaust is used to heat the compressed air. The topology of the whole system is shown in figure above [5].

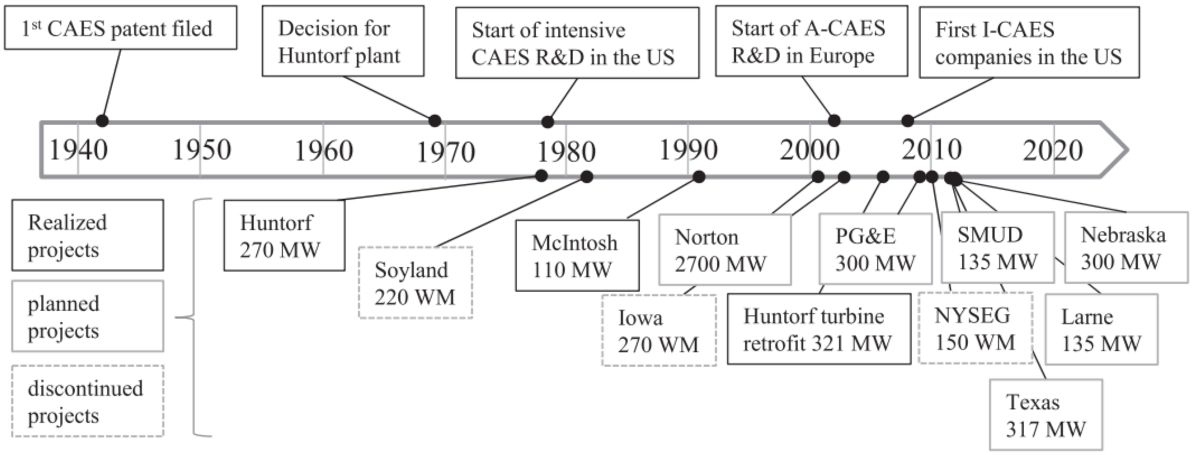


Figure 2.9: Timeline of CAES

Currently, the use of CAES systems is not widespread. Only two plants have been constructed in the world so far; one in Germany (290 MW) and the other in the USA (110 MW). Nevertheless, this technology is currently attracting much interest. One of the biggest projects that is being carried out is the Iowa Stored Energy Park, with 2700 MW of turbine power. This is being developed in conjunction with a large wind farm. The aim of CAES is to store the excess of wind energy generation. Advances in this technology have led to the development of Advanced-Adiabatic CAES (AA-CAES). As its name suggests, the air is adiabatically compressed and then pumped into an underground cavern. The key parts of this system are the heat exchangers, which are quite expensive. The effectiveness and the economics of these heat exchangers, and the compressor and expander trains are the main concerns for the success of AA-CAES. The life time of CAES installations is approximately 40 years, with an energy efficiency of 71%. Since the self-discharge of the system is very low, CAES systems are considered long-term time scale storage installations which can compete with PHS [7].

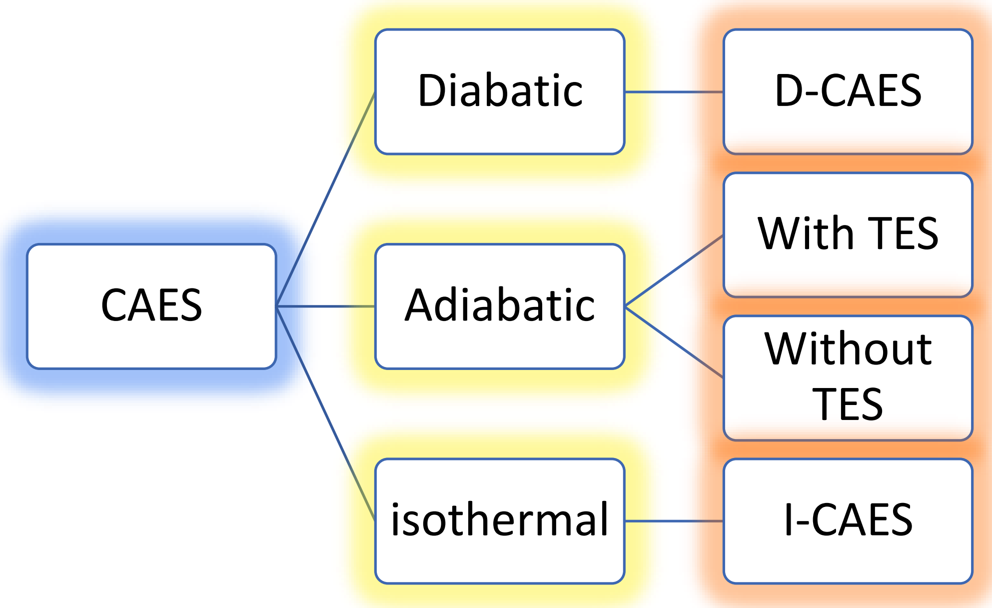


Figure 2.10: Compressed air energy storage concepts classified by their idealized change of state: (D (diabatic), TES (thermal energy storage), I (isothermal)).

The storage efficiency of the diabatic CAES plants just described is reduced by cooling of the air before it enters the cavern, and by reheating the air prior to burning it with the fuel. In the adiabatic cycle the heat energy is extracted and stored separately before the compressed air enters the cavern. When energy is required by the grid, the compressed air and heat energy are recombined, and expanded through an air turbine.

4. **Comparison:**

Technology	*Capital cost ($/KWh)*	*Energy density*	*Energy rating (MWh)*	*Life (years)*	*Energy efficiency (%)*	*Self-discharge (%)*	*Storage duration*
PHS	10-20	1 KWh/m^3 (360m)	500-8000	30-50	65-80	No	30min-4m
HESS	2-15	3-6 KWh/Kg	120	15	35-40	No	30min-4m
BESS	125-2400	33 KWh/m^3	0.2-6.75	10-20	60-90	Very low	1min-10h
FESS	400-800	1-5 KWh/Kg	0.0052	20	85-89	100	To 30min
SMES	-	1-5 KWh/Kg	0.001	20	80-95	10-15	To 30min
SCES	20000	5-10 KWh/Kg	0.01	8-17	65-90	5-20	To 1min
CAES	3-5	12 KWh/m^3 (100 bars)	580-2860	30-40	70-73	No	30min-4m

Table 2.1: Storage technologies comparison (2011)

As we could see in the above table the two highest energy ratings are the PHS and the CAES systems. With this high energy we have a good efficiency according to others.

However, the CAES system, which has the lowest capital cost of about 3-5 $/KWh with no self-discharge and a storage duration reaching 4 months with 40 years' life, is one of the important energy storage systems. [1]

5. Chapter conclusion:

Between these storage technologies, this project studies the CAES system.

The primal CAES system always burn gas to gain energy in the gas turbines. So our study had an environmental target, so we eliminate the combustion chambers from the system and change the gas turbine to air turbines. And what helped us to realize this is that we stored the heat energy in a hot water tank.

Chapter 3: Green Offshore Compressed Air Energy Storage System (static modeling)

The project proposal was a green compressed air energy storage system with electricity supply from offshore wind turbine and an underwater air storage tank, these two components are the main differences from other CAES systems.

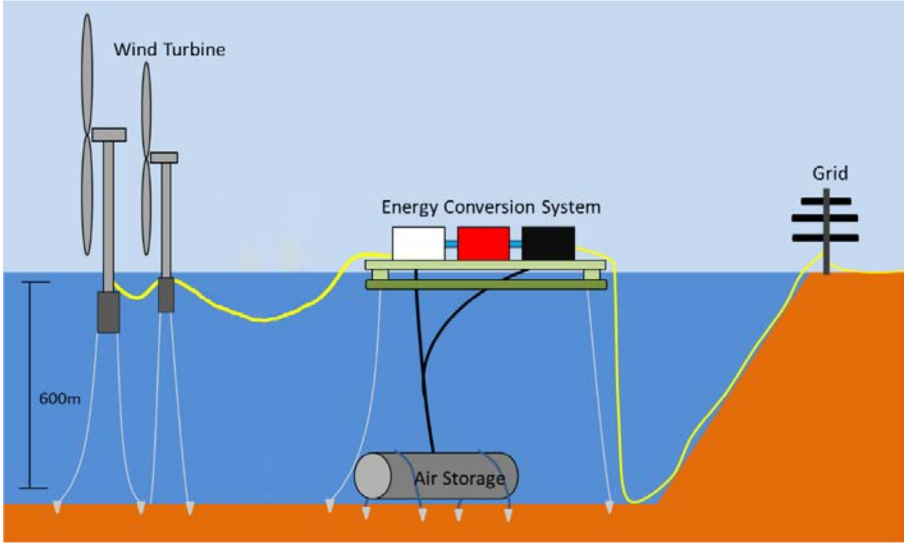


Figure 3.1: Offshore Compressed Air Energy Storage System

1. Green Compressed Air Energy Storage system:

The proposed GCAES system is shown in Figure 3.3/3.4. This system consists of a compression train with inter cooling, an expansion train with intermediate heating, centrifugal pumps, air bladder tank and hot water tanks.

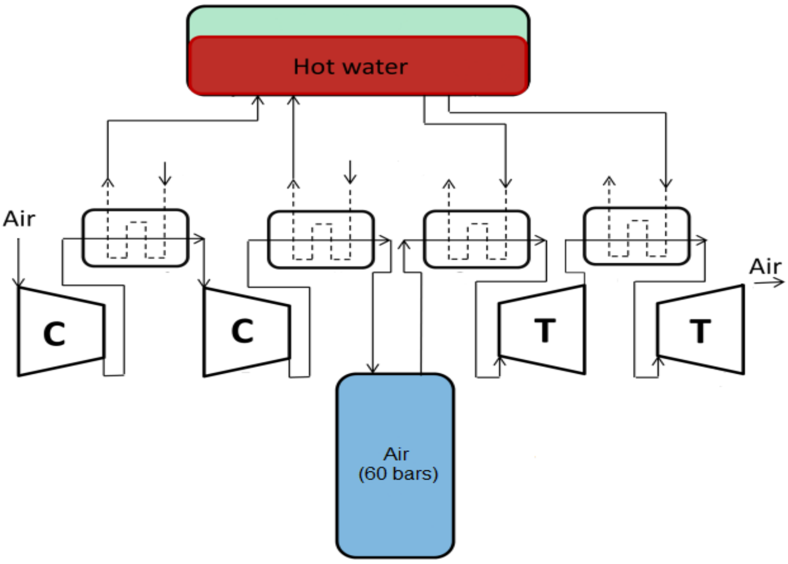


Figure 3.2: Proposed GCAES system (2 stages)

During off-peak load hours, the excess electrical energy available from the wind turbines is used to compress air from the ambient pressure to the storage pressure which is about 60 bars. The compression process is achieved by many compressors. A heat exchanger is installed after each compressor to cool down the exiting hot air by water/Therminol. The hot water/Therminol is then stored in thermally insulated tanks under pressure. During peak load hours, the compressed air is expanded in many turbines to release the stored energy. The compressed air is heated before each stage of expansion through heat exchangers using the stored hot water/Therminol.

The compressed air is stored under fixed pressure in the air bladder tank. The stored pressure is maintained constant by the counter-hydrostatic pressure under the sea through a varying volume system during the storage and the destocking phases. The consumed energy during the storage phase is then the energy consumed by the compressors, the produced energy during the production phase is the difference between the energy produced by the air turbines and the energy consumed by the pump.

Hot water is stored under pressure to prevent water evaporation. The pressure varies as function of the tank filling ratio.

The four systems we studied are:

- 2 stages (water).
- 3 stages (water).
- 2 stages (thermal fluid).
- 3 stages (thermal fluid).

Firstly, we started with the two stages (two compressors and two turbines) and three stages with water as a cooling and heating fluid and then we tried the Therminol-VP1 as a thermal fluid.

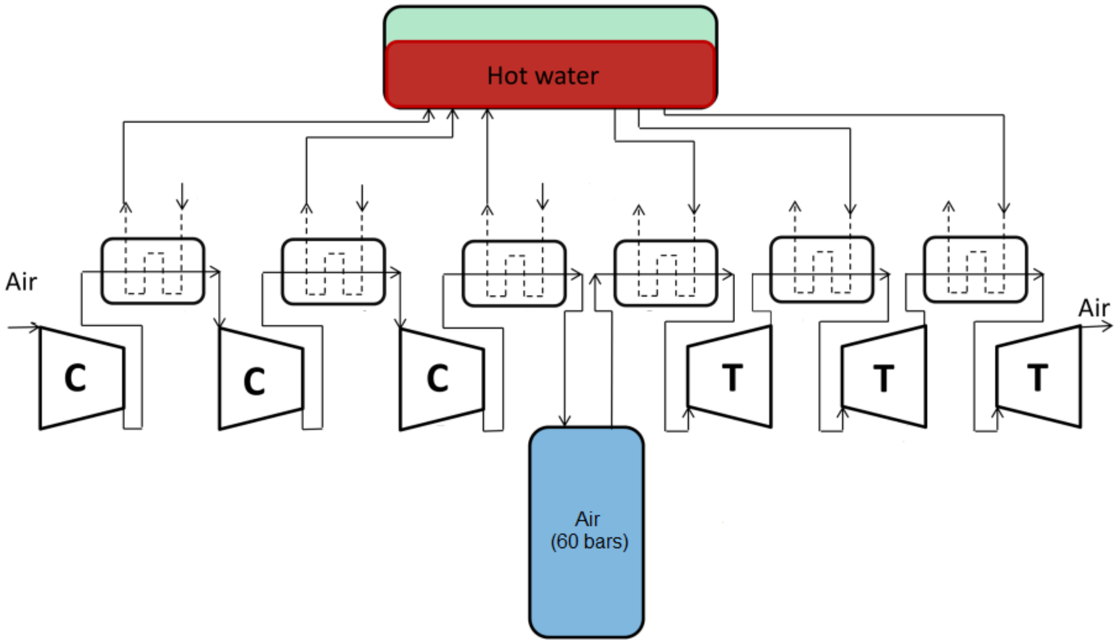


Figure 3.3: Proposed GCAES system (3 stages)

In this project, we will study the difference between 2 stages and 3 stages systems for the water as heating/cooling fluid and for Therminol VP-1 as well. Below there is further information about the main components of the system.

a. Compressor:

Industrial compressors are already used in the two existing CAES plants. However, such industrial compressors use generally intercoolers. Therefore, a new high pressure / high temperature design is required, based on industrial compressors and allied to high temperature technologies (particularly materials) e.g. of the steam turbine.

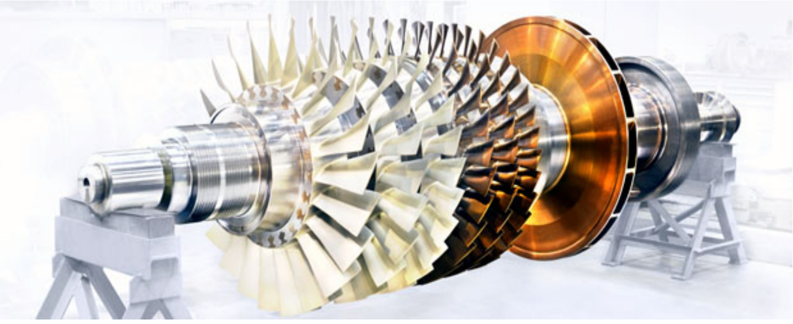


Figure 3.4: axial compressor

Within the AA-CAES Project, a range of compressor train concepts has been studied, based on the economic scenarios and end-user requirements described earlier. These have particularly affected the size, capacity and ramp rate of the compressor during the charging cycle. Short starting times, required for balancing energy have, of course, led to the need to consider carefully the thermal ramp rates within components. Results from the initial studies are now being taken forward in more details to optimize such matters as low pressure intercooling, and compressor layout. The most promising design so far includes an axial flow low pressure compressor, whose output is intercooled, and then delivered to a radial flow high pressure compressor. Whilst developing new design principles, materials choice, stability, disk-rotor fixing methods, and overall thermal behavior over a range of operational profiles are currently being considered [1].

Figure 3.5: Centrifugal compressor

b. Thermal energy store (TES):

The thermal energy storage (TES) system is essential to the optimized operation and the overall efficiency of the Adiabatic CAES plant. A thermal storage capacity of 120-1200 MWh(thermal) with high heat extraction rates, and high consistency of the outlet temperature over a generation cycle of 4-12 hours has been considered. A full range of thermal storage devices has been considered (Table 3.2), including phase-change, high heat capacity solid and liquid media and hybrid systems. Phase change methods have been discounted since no single system can cover the range of 50 to 650°C.

	Solid TES					*Liquid TES*		
Concept	Rock bed	Cowper-derivative	Concrete-walls	Cast-iron slabs	Hybrid-PCM	Two tanks	1-Tank Thermocline	Air-Liquid
	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	Indirect
Storage material	Natural stone	Ceramics	Concrete	Cast iron	Ceramics, Salt	Nitrate salt, Mineral Oil	Nitrate salt, Mineral Oil	Nitrate salt, Mineral Oil

Table 3.2: The main TES concepts considered

The particular relevance to Adiabatic CAES cycle is the need for a pressurized or non-pressurized container for the thermal storage system. In liquid systems, a heat exchanger can be used. The liquid TES systems are already used in steam plant (for pre-heating) and solar thermal power stations. Either a “Thermocline” – that is, a single tank with a temperature gradient, or a two tank system with varying liquid levels can be used.

Direct contact between the pressurized air and the storage medium in a solid TES system has the advantage of a high contact area for heat transfer, and the storage materials are generally cheap, however the pressurized container costs are greater. Present work is considering the characteristics of a range of solid media (natural stone, concrete, fireproof material and metal), and it is notable that “Cowper” heat storage devices are already used widely in the glass and metallurgical industries for preheating temperatures of up to 1,500°C [6].

c. Air turbine:

Figure 3.6: Air Turbine

In general, the function of the air turbine is to produce electricity through compressed air by driving generator. To maximum the efficiency early studies have shown that the turbine should be able to adapt to a range of pressures and mass flow rates from the cavern. Inlet pressures are likely to vary by a factor of 2, and existing steam turbine control methods such as valve throttling are unattractive due to their efficiency losses. Therefore, adaptive stages, common in gas turbines, are being introduced into the air turbine designs, leading to the so-called sliding pressure air turbine. The main challenges for the designer have been to develop such stages at the very high pressures and relatively high temperatures.

Besides the introduction of adaptive stages, the sliding pressure air turbine is being developed in a modular fashion. This is for two main reasons: firstly, the AA-CAES Project has yet to finalize the optimum parameters for the overall cycle; and secondly, local constraints (size of compressor/cavern, role of the storage device etc.) demand flexibility. Further design work is in progress to ensure that the turbine meets the requirements identified from the economic research, for example ramp rate. Special consideration is being given to pre-heating of the turbine using excess heat from the compression cycle so that fast start-up can be achieved [1].

2. Thermodynamic relations:

The energy storage system is modeled by using the mass conservation law and the energy conservation law for each component, and by neglecting the inertias of the system. Thus, the steady state regime is only modeled whose equations are presented in the table below:

a. Compressor:

The compression process is considered polytropic. The model’s inputs are the air properties (pressure and enthalpy), the air mass flow rate, and the compression ratio. The output enthalpy is evaluated as a function of the isentropic efficiency, as shown below.

Flow	$M_i = M_o$
Pressure	$P_o = P_i \times Rate_{Comp}$
Enthalpy	$h_o = h_i + \frac{h_{ot} - h_i}{\eta_{isentropique}}$
Temperature	$T_o = T_i \times (\frac{P_o}{P_i})^{\frac{k}{k-1}}$
Electric power	$Power = M_i \times (h_o - h_i)$ $Electric\ Power = \frac{Power}{\eta_{electric}}$

Table 3.3: Compressor formulas [9]

b. Turbine:

The expansion process is also considered polytropic. The turbine model is similar to the compressor model. However, the parameters become:

Flow	$M_i = M_o$
Pressure	$P_o = \frac{P_i}{Rate_{Expansion}}$
Enthalpy	$h_o = h_i - (h_{ot} - h_i) \times \eta_{isentropique}$
Temperature	$T_o = T_i \times (\frac{P_i}{P_o})^{\frac{k}{k-1}}$
Electric power	$Power = M_i \times (h_o - h_i)$ $Electric\ Power = Power \times \eta_{electric}$

Table 3.4: Turbine formulas [9]

c. Air heater:

Air should be cooled down, in storage mode, in order to protect the compressor from high temperatures and warmed up in discharge mode to protect the turbine from low temperatures.

Pressure	$P_{air_o} = P_{air_i} - P_{Drop}$
Air Flow	$M_i = M_o$
Water flow	$M_{water_i} \times Cp_{water} = M_{air_i} \times Cp_{air}$
Output water temperature	$T_{water_o} = T_{air_i} + Pinch$
Output air enthalpy	$M_{air_i} \times \left(h_{air_o} - h_{air_i}\right) = M_{water_i} \times \left(h_{water_i} - h_{water_o}\right)$
Power	$Power = M_{water_i} \times \left(h_{water_i} - h_{water_o}\right)$
UA	$\Delta T_1 = T_{water_i} - T_{air_o}$ $\Delta T_2 = T_{water_o} - T_{air_i}$ $LMTD = \frac{\Delta T_2 - \Delta T_1}{\log\left(abs\left(\frac{\Delta T_2}{\Delta T_1}\right)\right)}$ $UA = \frac{Power}{LMTD}$

Table 3.5: Air heater formulas [9]

d. Air cooler:

The water mass flow rate is calculated by assuming an ideal heat exchanger. The pinch, given as a parameter, allows calculating one of the outlet temperatures. The other outlet temperature is obtained by the energy conservation law. The pressure loss is considered constant and given as a parameter in the static model.

Pressure	$P_{air_o} = P_{air_i} - P_{Drop}$
Air Flow	$M_i = M_o$
Water flow	$M_{water_i} \times Cp_{water} = M_{air_i} \times Cp_{air}$
Output air temperature	$T_{air_o} = T_{water_i} + Pinch$
Output air enthalpy	$M_{air_i} \times (h_{air_i} - h_{air_o}) = M_{water_i} \times (h_{water_o} - h_{water_i})$
Power	$Power = M_{water_i} \times (h_{water_o} - h_{water_i})$
UA	$\Delta T_1 = T_{air_i} - T_{water_o}$ $\Delta T_2 = T_{air_o} - T_{water_i}$ $LMTD = \frac{\Delta T_2 - \Delta T_1}{\log\left(abs\left(\frac{\Delta T_2}{\Delta T_1}\right)\right)}$ $UA = \frac{Power}{LMTD}$

Table 3.6: Air cooler formulas [9]

e. Air tank:

The air is stored under pressure in the underground cavern. The pressure and the temperature in the cavern are calculated by the conservation laws of mass and energy.

Pressure, temperature	$input(P, T) = output(P, T)$
Output air flow	$M_{air_o} = M_{air_i} \times (\frac{Time_{usage}}{Time_{charge}})$
Tank volume	$V_{air} = \frac{M_{air}}{\rho_{air}}$

Table 3.7: Air tank formulas [9]

f. Hot water tank:

The hot water tanks are kept under pressure to prevent the evaporation of the hot water. The hot water in the static model is considered as a single volume with one temperature and one pressure. The inlet enthalpy of the hot water is the average of the inlet enthalpies weighted by the mass flow rate. The static model of the hot water tanks takes into account the thermal inertia of the insulated tank

Water flow	$Q = M_{i_1} + M_{i_2}$
Pressure	$P = \frac{P_{i_1} + P_{i_2}}{2}$
Mass of water	$M_i = \frac{\rho_{water} \times \pi \times d_{tank}{}^2 \times L_{steel}}{4}$
Volume of water	$V_{water\ in\ tank} = \frac{M_i}{\rho_{water}}$
Tank volume	$V_{tank} = \frac{\pi \times d_{tank}{}^2 \times L_{tank} \times n_{tank}}{4}$
Mass of steel	$M_{steel} = \frac{\rho_{steel} \times \pi \times ((d_{tank} + 2 \times t_{tank})^2 - d_{tank}{}^2) \times L_{tank}}{4}$
Output enthalpy	$M_i \times (h_i - h_o) = M_{steel} \times Cp_{steel} \times \Delta T_{steel}$
Water temperature	$M_i \times C_p \times \Delta T = M \times C_p \times \Delta T$

Table 3.8: Hot water tank formulas [9]

ΔT_{steel} is the steel's temperature variation between beginning and end of each cycle.

g. System:

Efficiency	$\eta_{net} = \frac{E_{turbine}}{E_{compressor} + E_{pump}}$
Energetic density	$ED = \frac{E_{turbine}}{V_{storage}}$

Table 3.9: System formulas [9]

In the next chapter, we will use the thermodynamic relations in the tables above to calculate the efficiency of the system and make some analysis.

Chapter 4: Energy analysis:

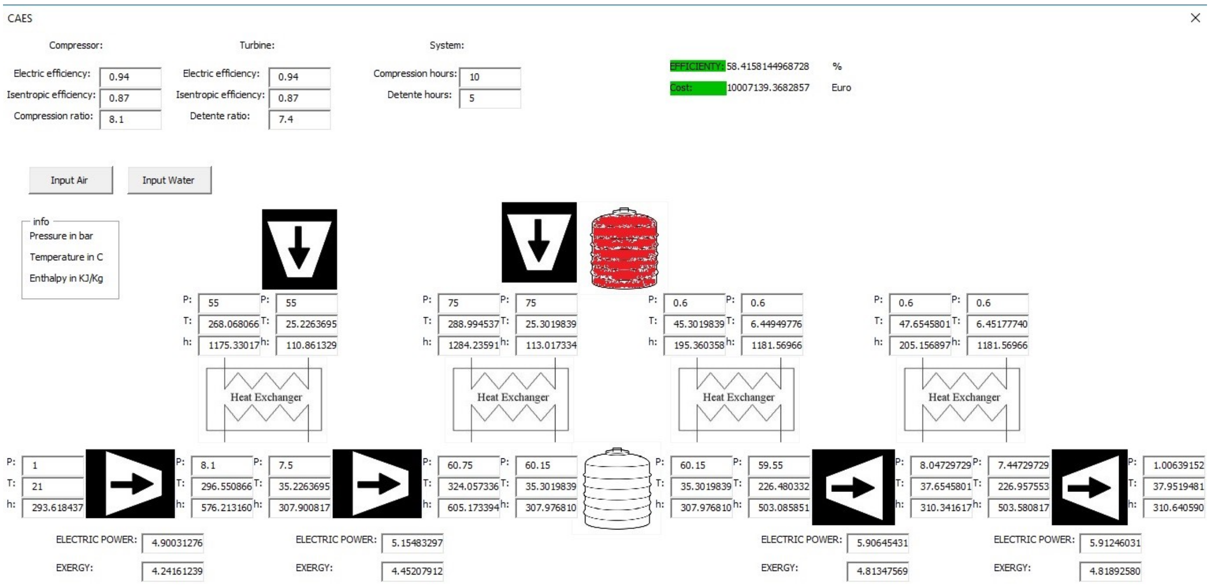
In this chapter, we carry out a thermoeconomic study that combines the energy analysis and the economic principles of a thermodynamic system. It helps the designers to optimize the design and the operation of the considered system in a cost effective way. Thus the purpose of the thermoeconomic analysis is multiple:

- Evaluate the cost of production of each component.
- Explicit the flow of costs in the system.
- Find the optimum variables in a subsystem or the overall system by fixing an objective function [10].

1. Software:

The modeling is carried out using Excel, you can include to this software several fluid libraries among which air and water have been used [11]. We programed an Excel form as the Figure 4.1 shown below.

With this form you can change every parameter of the system to see the difference in the system efficiency and other results



Compressor:
Electric efficiency: 0.94
Isentropic efficiency: 0.87
Compression ratio: 8.1

Turbine:
Electric efficiency: 0.94
Isentropic efficiency: 0.87
Detente ratio: 7.4

System:
Compression hours: 10
Detente hours: 5

EFFICIENTY: 58.4158144968728 %
Cost: 10007139.3682857 Euro

info
Pressure in bar
Temperature in C
Enthalpy in KJ/Kg

P: 55 T: 268.068066 h: 1175.33017
P: 55 T: 25.2263695 h: 110.861329

P: 75 T: 288.994537 h: 1284.23591
P: 75 T: 25.3019839 h: 113.017334

P: 0.6 T: 45.3019839 h: 195.360358
P: 0.6 T: 6.44949776 h: 1181.56966

P: 0.6 T: 47.6545801 h: 205.156897
P: 0.6 T: 6.45177740 h: 1181.56966

P: 1 T: 21 h: 293.618437
P: 8.1 T: 296.550866 h: 576.213160
P: 7.5 T: 35.2263695 h: 307.900817
P: 60.75 T: 324.057336 h: 605.173394
P: 60.15 T: 35.3019839 h: 307.976810
P: 60.15 T: 35.3019839 h: 307.976810
P: 59.55 T: 226.480332 h: 503.085851
P: 8.04729729 T: 37.6545801 h: 310.341617
P: 7.44729729 T: 226.957553 h: 503.580817
P: 1.00639152 T: 37.9519481 h: 310.640590

ELECTRIC POWER: 4.90031276
EXERGY: 4.24161239

ELECTRIC POWER: 5.15483297
EXERGY: 4.45207912

ELECTRIC POWER: 5.90645431
EXERGY: 4.81347569

ELECTRIC POWER: 5.91246031
EXERGY: 4.81892580

Figure 4.1: CAES Excel form

2. Operating parameters:

The operating parameters of the base case are given in the table below

Water input	Pressure	1 bar
	Temperature	25 °C
Air input	Pressure	1 bar
	Temperature	21 °C
Work time	Compression	10 hours
	Expansion	5 hours
Compressor / Turbine	Isentropic efficiency	0.87
	Electric efficiency	0.94
Heat exchanger	Pinch	10 °C
	Pressure drop	0.6 bar
Water pump	Isentropic efficiency	0.92
	Electric efficiency	0.94
Air tank	Pressure	60 bar

Table 4.1: System given data

3. Assumptions:

In the Logical Framework, assumptions are listed below:

- All the transient phases in the storage cycle are neglected and only the steady states are modeled.
- The isentropic and hydraulic efficiencies of the compressors, turbines and pumps are fixed.
- All the components operate without heat loss.
- No pressure drop in the tube installations.
- Tubes have negligible cost comparing to the system.
- Air tank has a cost equal to 25% of the system’s cost.

4. Efficiency enhancement:

At the beginning of our study, our target was to get the best efficiency from the system. So we were searching any way to get this target.

So we started with the efficiency formula in the table 3.9 and we noticed that we can enhance the efficiency of the system if we decrease the water pump energy. So we decided to use a thermal fluid as a cooling/heating fluid and for this matter we choose the Therminol fluid.

After that we analyze the effect of every parameter of the system on the energy efficiency of the system.

5. Therminol VP-1:

Figure 4.2: Therminol company logo

Therminol is a synthetic heat transfer fluid produced by Eastman Chemical Company.

Therminol fluids are used in a variety of applications, including:

- Hydrocarbon processing (oil and gas, refining, asphalt, gas-to-liquid, etc.)
- Alternative energy and technologies (concentrated solar power, biofuel, organic Rankine cycle, desalination, etc.)
- Plastics processing
- Chemical processing (pharmaceutical, environmental test chambers, etc.)
- Food and beverage processing
- Heat transfer system maintenance

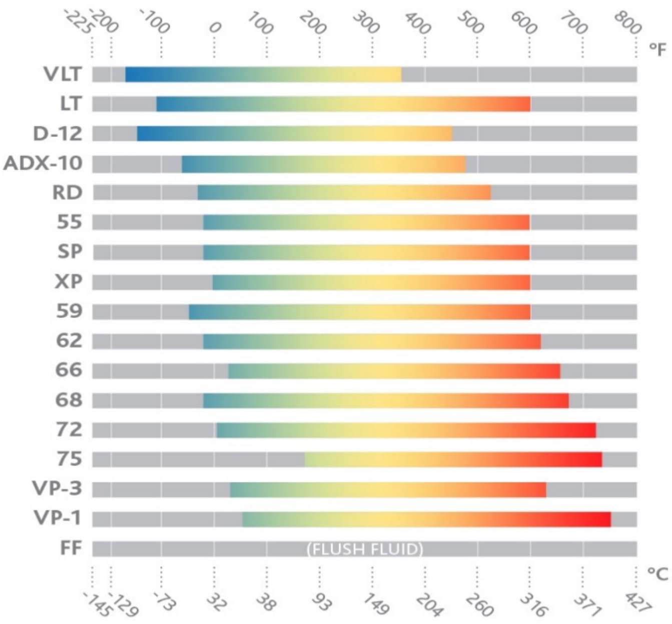


Figure 4.3: Therminol Products

Prior to 1997, Therminol fluids were sold in Europe under the trade names SantoTherm and GiloTherm. Since 1997, all forms of Therminol fluid have been sold with the Therminol name and extension to define its uses.

For the choice of the product, we choose the Therminol VP-1 because it supports higher temperature than the others and it has good global reviews.

And then after many emails with the company and their sales representative in middle east we reach an offer with 4$/Kg, and they looked interested in our project, so they asked about the project, location, size and many other things. So they sent us more thermodynamic properties showed in the appendix (A).

6. Analysis and conclusion:

In the strategy of our study, a comparison is made between the 2-stages and the 3-stages systems to find the best performant solution and the economic factor, and the best thermal fluid to be used in the thermal storage system. In this report, we chose 2 types of fluid to be studied, water and Therminol VP-1. Then our project is divided into 4 parts to locate the advantages of each installation.

The simulation shows that the efficiency of the systems is between 54 and 59.5 and that the best efficiency is for the system of 3 stages where water is used as the thermal fluid.

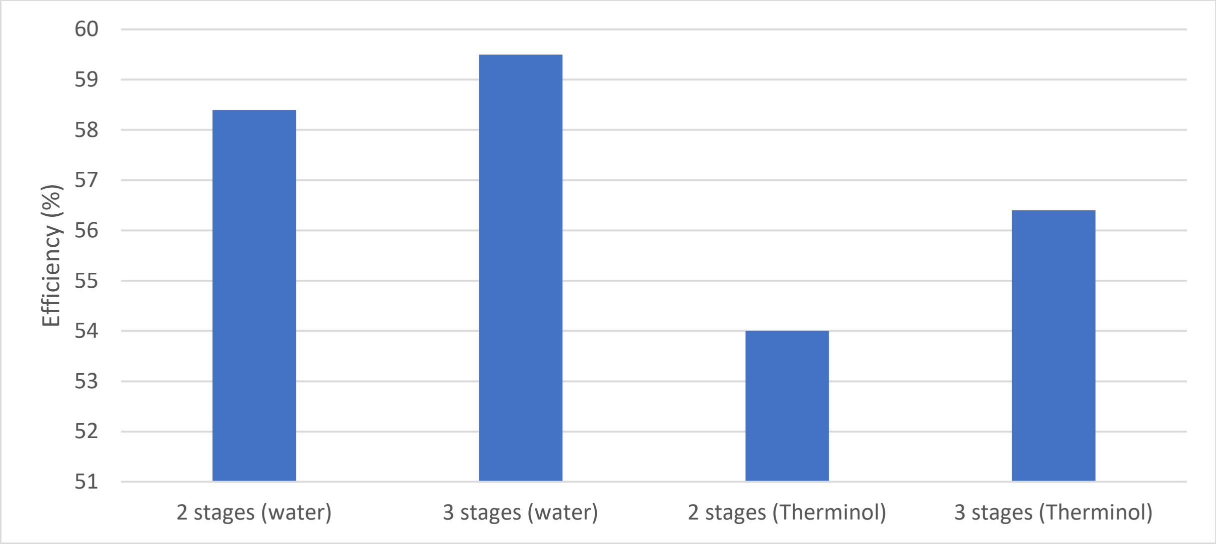


Figure 4.4: Systems efficiency results

Then, increasing the energy density has a positive effect on the total purchase cost. It leads to reduce the volume of the air storage tanks, which have the major investment cost, and then to decrease the total purchase cost. Where we have 2 size 8500 m^3 (2 stages) and 9200 m^3 (3 stages) which are depended on the air mass flow rate which is related to the wind turbine power in consequence of the constant pressure ratio of the compressors.

The main difference between the water and Therminol systems is that we eliminate the usage of high pressure pumps, that's why we could notice in the table that the Therminol systems' pumps are only flow pumps without compression rate and they've negligible price. However, since the specific heat capacity of the water is higher and almost double than that of the Therminol so in the case when we used Therminol as a thermal fluid the fluid mass flow in the heat exchangers has a noticeable high values.

Through this pumps flow, the thermal tank is much bigger for Therminol than for water with no pressure restriction. So we have to choose what do we need a big size or pressure restriction.

The construction conditions lead us to choose the preferable system. For example, if we want to limit the price we will choose immediately the 3 stages (water), which has another advantage concerning high efficiency but this advantages are accompanied by some disadvantages like the large air tank and hot water tank volume. In addition, it requires a large work space, so if we are limited by the work space area we have to choose the 2 stages.

Parameter	***2 stages (water)***		***3 stages (water)***			***2 stages (therminol)***		***3 stages (therminol)***		
Compression rate (bar)	8.1		4.2			8.1		4.2		
Expansion rate (bar)	7.4		3.7			7.4		3.7		
Compressor mass flow rate (Kg/s)	16.3		17.5			16.3		17.5		
Turbine mass flow rate (Kg/s)	32.6		35			32.6		35		
Compressor electric power (MW)	4.9	5.1	3.2	3.4	3.4	4.9	5.1	3.2	3.4	3.4
Turbine electric power (MW)	5.9	5.9	4	4	4	5.4	5.4	3.8	3.8	3.8
Pump compression rate(bar)	55	75	10	20	15	1	1	1	1	1
Pump power (KW)	25.7	35.4	4.5	9.5	7	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
Pump flow (Kg/s)	4.1		4.3			10.9		11.6		
Hot water tank temperature (ºC)	269		185			220		163		
Hot water tank pressure (bar)	65		15			1		1		
Hot water tank volume (m^3)	400		540			920		1340		
Air tank temperature (ºC)	35		35			35		35		
Air tank pressure (bar)	60		60			60		60		
Air tank volume (m^3)	8500		9200			8500		9200		
Energy density (KWh/m^3)	13.9		13			12.8		12.3		
Efficiency (%)	58.4		59.5			54		56.4		

Table 4.2: Systems calculation results

7. Energy analysis:

Any variation in any parameter changes too much parameters in the system so we will mention the variation of the main parameters that affect the efficiency (Table 3.9). In our project, we fix the wind turbine power to 10 MW so the mass air flow will change to match this power.

a. Efficiency:

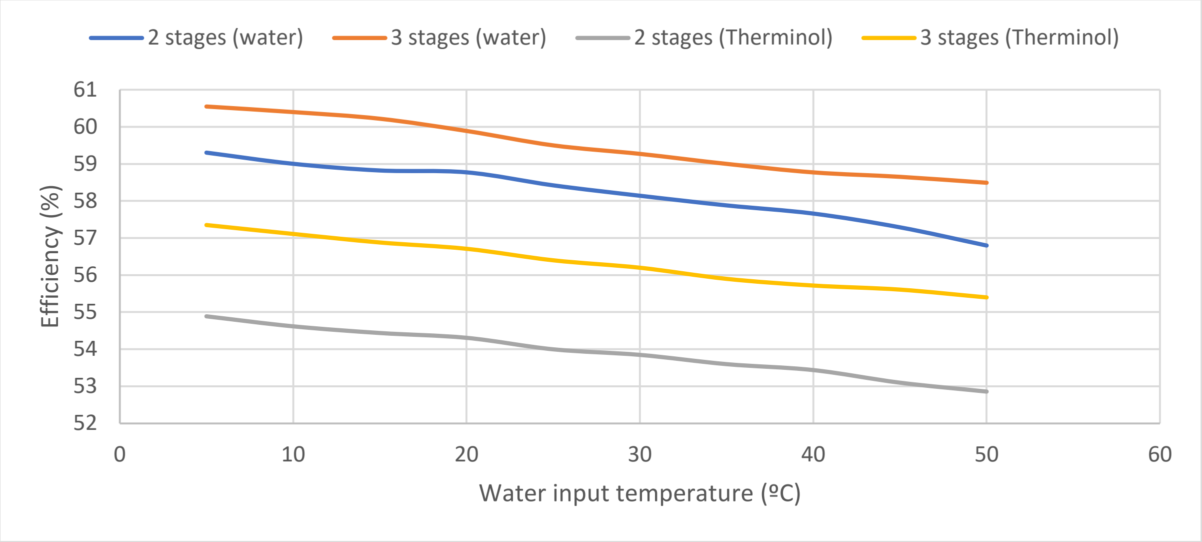


Figure 4.5: Efficiency variation compared to the water input temperature

The augmentation of the water input temperature causes a variation in two main parameters, the air mass flow rate and the second pump pressure, so the former decrease while the latter increase. With the decreasing of the air mass flow rate, the powers of compressor and turbine decrease with the same ratio. However, the overall efficiency decreases since the output pressure of the second pump is higher.

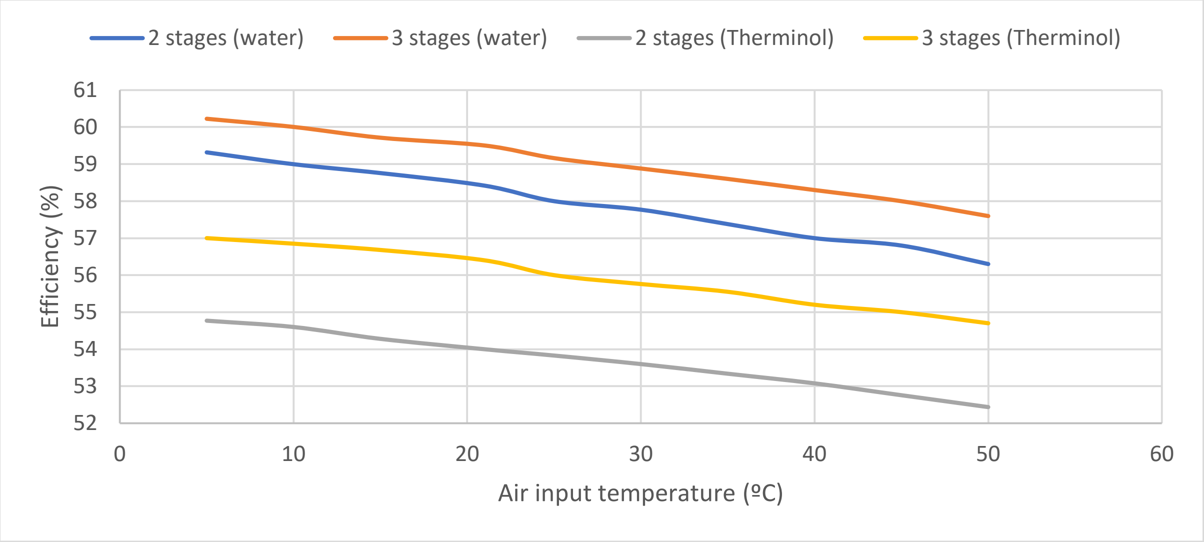


Figure 4.6: Efficiency variation compared to the air input temperature

The augmentation of the air input temperature causes a decrease in the air mass flow rate and an increase in the first pump pressure ratio, so that the overall efficiency decreases.

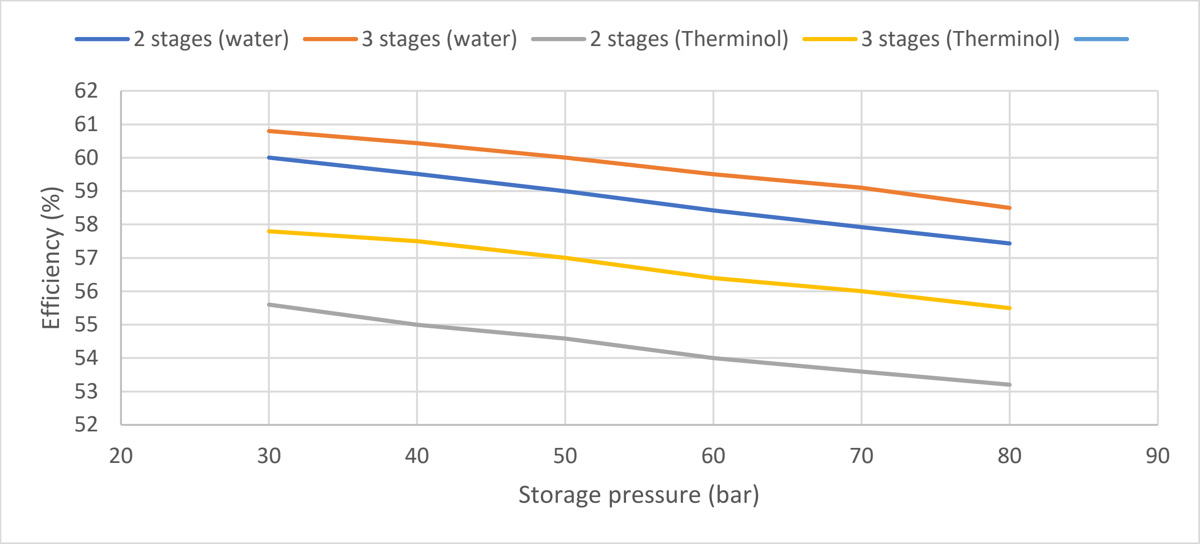


Figure 4.7: Efficiency variation compared to storage pressure

The augmentation of the storage pressure with fixed wind turbine power causes a decrease in the air mass flow rate and an increase in the both pump pressure ratio, so that the overall efficiency decreases.

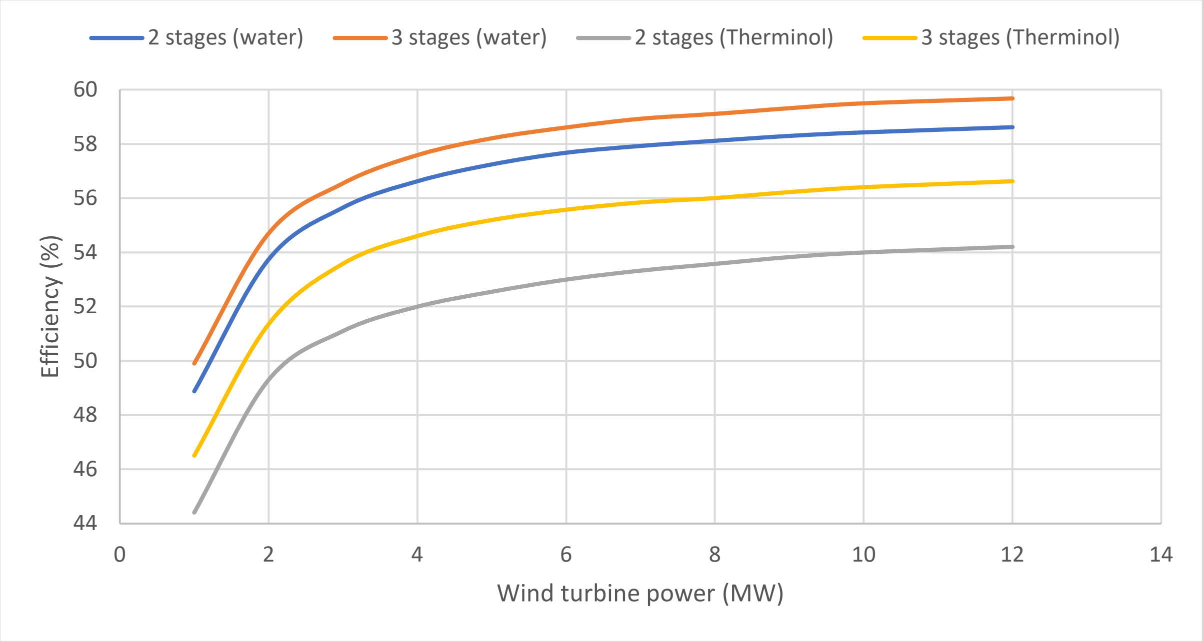


Figure 4.8: Efficiency variation compared to wind turbine power

In this case, efficiency variation compared to the wind turbine power, the mass air flow and the pump pressure both increase. To explain this, we have the chart below (Fig 4.9) that show the augmentation of the turbine, compressor and pump power in function of the augmentation of the wind turbine power.

Because we have a 10 hours' storage and 5 hours' generation so the efficiency has a coefficient of 0.5, and as the chart below shows us that the slope coefficient of the turbine is 1.1972 and that for the compressor and pump is 2.0083 so the ratio is 0.596. This ratio explains the increase of the overall efficiency. And to have a constant efficiency we must have a ratio of 0.5.

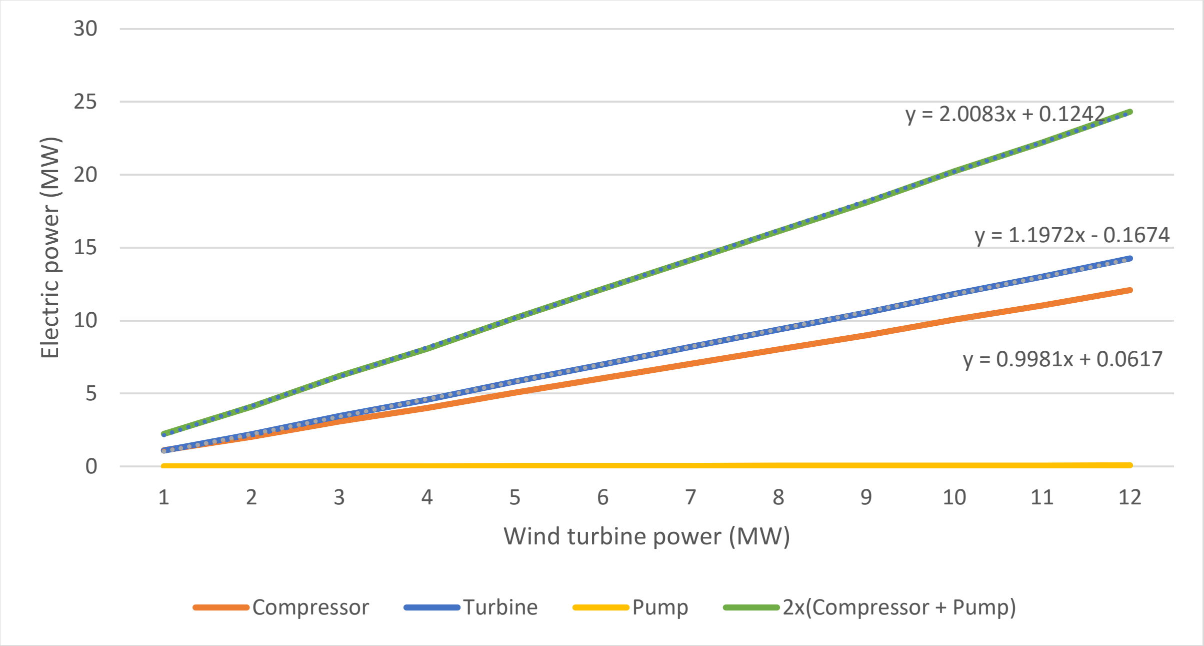


Figure 4.9: Components electric power variation compared to wind turbine power

b. Cost:

The coefficients in the capital investment equations Z are calculated based on real data supplied by the manufacturers to evaluate the real purchase cost of the components. Regarding the purchase costs of the air storage tanks and the hot water tanks (steel pipes), they are calculated as a function of the storage volume and the storage pressure (function of the materials resistance). The purchase costs of the tanks' accessories are also included [9].

Compressor	$Z = \frac{C_1 \times M_{air}}{0.9 - \eta_{ise}} \left(\frac{P_{out}}{P_{in}}\right) \ln\left(\frac{P_{out}}{P_{in}}\right)$	C_1=218
Turbine	$Z = \frac{C_2 \times M_{air}}{0.92 - \eta_{ise}} \ln\left(\frac{P_{in}}{P_{out}}\right)\left(1 + \exp(0.036T_{in} - 54.4)\right)$	C_2=896
Pump	$Z = C_3 \times {P_{elect}}^{0.71}$	C_3=50
Heat exchanger	$Z = C_4 \times Area^{0.78}$	C_c^{BP}=1242; C_c^{MP}=1216; C_c^{HP}=584 C_H^{BP}=1495; C_H^{MP}=980; C_H^{HP}=413
Hot water tank	$Z = C_5 \times Volume$	C_5=1750
Air tank	$Z = 0.25 \times Z_{total}$	System total cost
Therminol VP-1	$Z = \frac{4 \times Mass}{1.18}$	Mass of thermal fluid

Table 4.3: Components capital investments formulas [9]

$$\dot{Z} = \frac{Z.CRF.\emptyset}{3600.N} \qquad (4.1)$$

Where $\dot{Z}$ represents the amortization cost rate due to the capital investment and the operating and maintenance costs of the considered component [9].

So the parameters are: [9]

- Φ: maintenance factor = 1.06.
- N: system operating hours in a year.
- (Capital Recovery Factor) CRF: $\frac{i(1+i)^n}{(1+i)^n-1}$.
- The interest rate "i" in the above equation is supposed equal to 10%.
- n=system life.

	2 stages (water)	*3 stages (water)*	*2 stages (Therminol)*	*3 stages (Therminol)*
Compressor	4M	2.3M	4M	2.3M
Turbine	2.34M	2.46M	2.34M	2.46M
Pump	152K	80K	≈ 0	≈ 0
Heat exchanger	407 K	712K	470K	1M
Hot water tank	595K	458K	20K	30K
Air tank	2.5M	3M	2.5M	3M
Therminol	N/A	N/A	2.7M	4.3M
Total	10M	9M	12M	13M

Table 4.4: Components capital investments results (€)

As we can see in this table the total capital investment cost of the 2 stages and 3 stages for the same cooling fluid doesn’t change too much, but the systems with Therminol has the highest cost because of the price of the Therminol as we mentioned before, so if we eliminate this item wen will have almost the same price of 9M€. We can notice that the 3 stages system has lower cost than the 2 stages, the factor which has this effect is the compressors, that because we have a high pressure rate. So we can say that the 2 stages systems are working at full power.

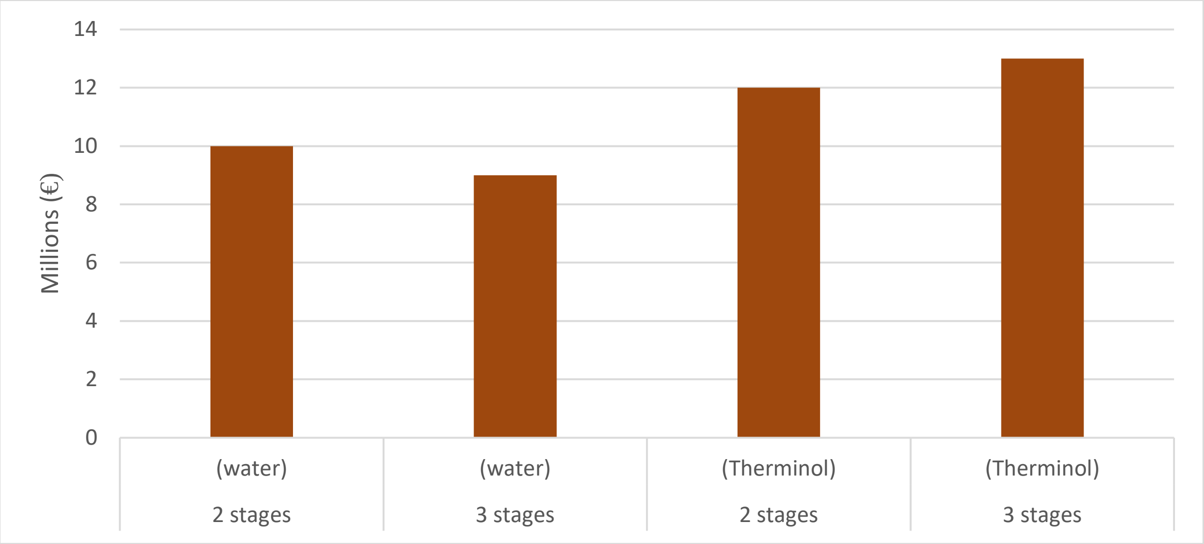


Figure 4.10: System’s total cost

According to Figure 4.11, we can notice that the cost of the pumps, heat exchangers and hot water tank is negligible for all systems compared to the total cost, same thing for the hot water tank for Therminol systems. Turbines' cost is almost constant between these four systems and that's a good thing to build on, same thing for the air tank. The compressors' cost vary noticeably between the 2 stages and the 3 stages systems because of the higher compression rate. The Therminol cost will be discussed later.

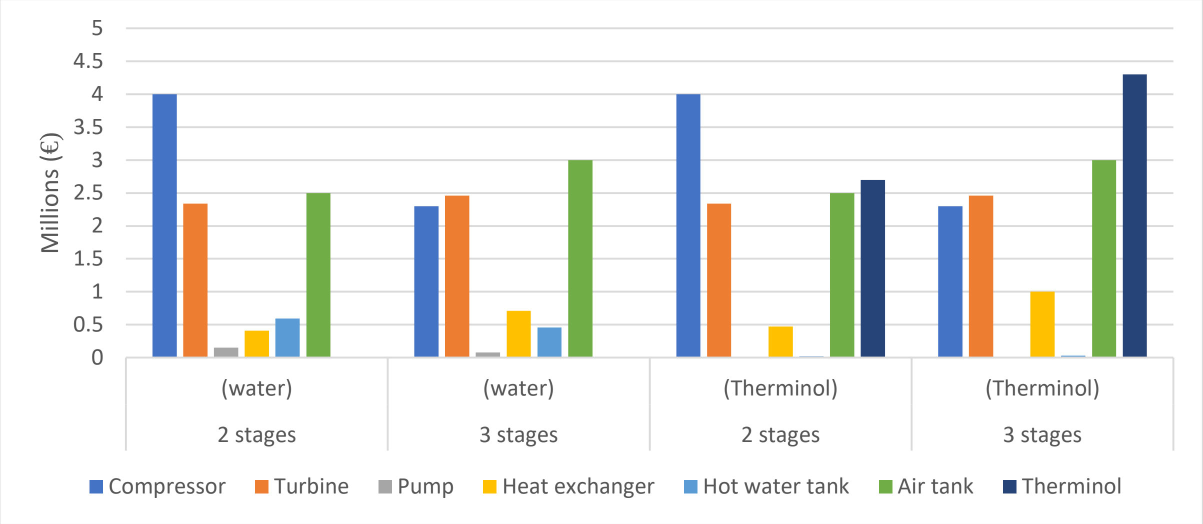


Figure 4.11: Components' capital cost

The equation below represents the profit of the system yearly, which is depending on the sum of the turbines' power and the expansion hours.

$$Profit = Electric\ Power_{Turbine} \times Hours_{Detente} \times Price_{KWh} \times 365 \tag{4.2}$$

Using the equations (4.1) and (4.2) we can draw the Cost-Time-Profit chart of the studied systems, this chart indicates the refund time of the system and the profit after 40 years of work which is the system assumed life time.

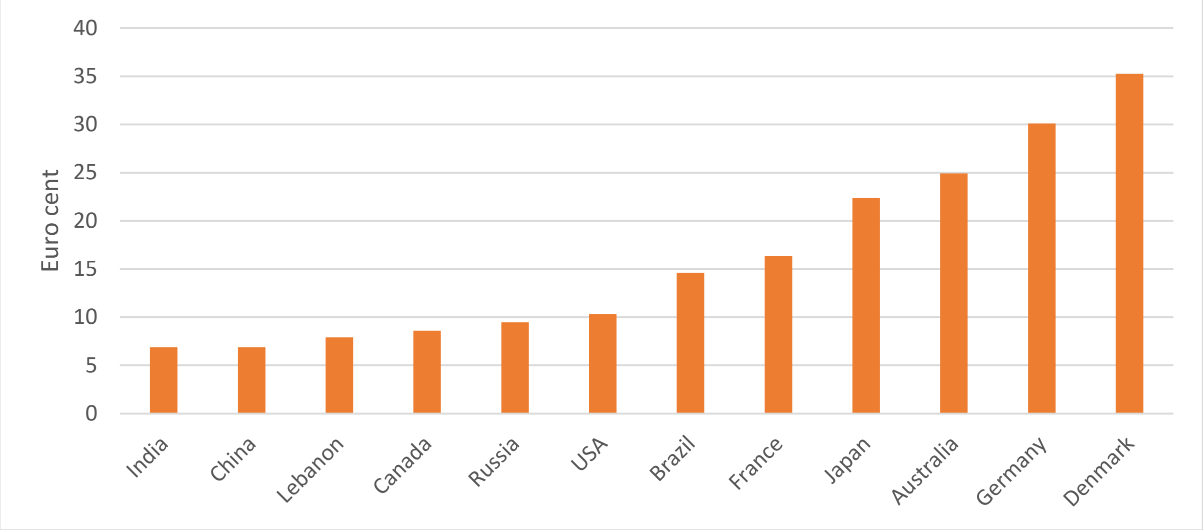


Figure 4.12: KWh price (source: International Energy Agency)

All these results are taken in Lebanon with a price of 140LL/1KWh (around 0.079€) according to the Lebanese electricity tariffs showed in the appendix (B). So it could be more profit or less if we took another country as shown in the figure above.

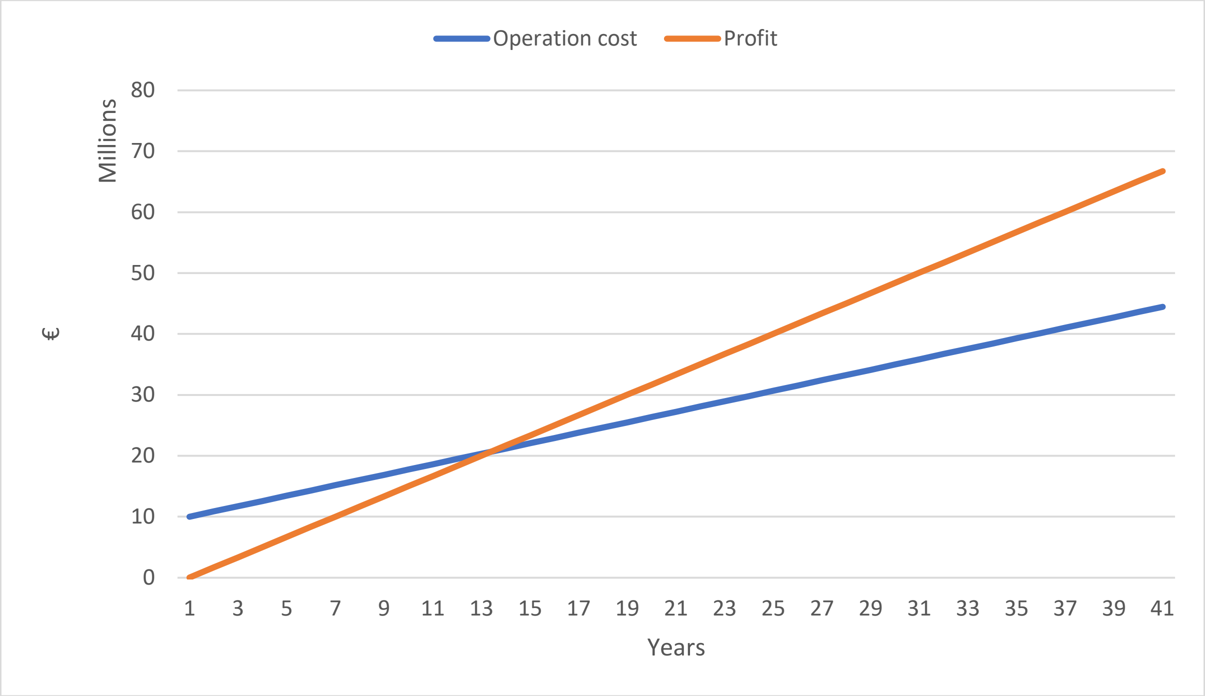


Figure 4.13: Profitability chart of 2 stages (water) system

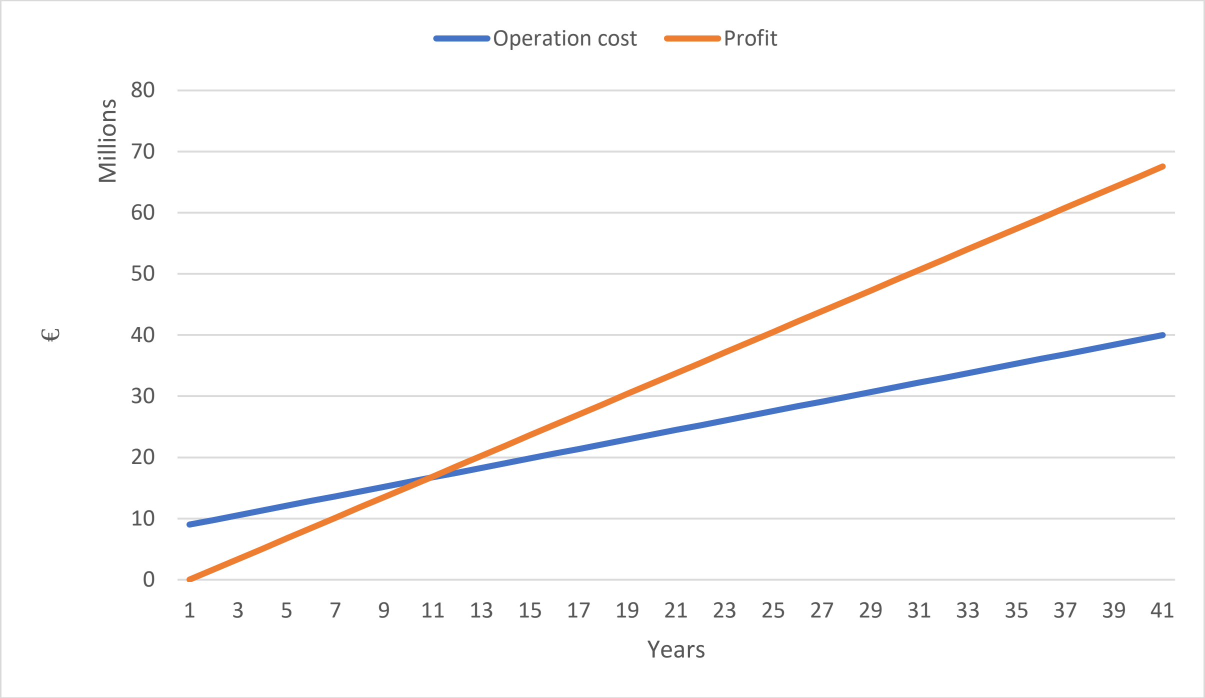


Figure 4.14: Profitability chart of 3 stages (water) system

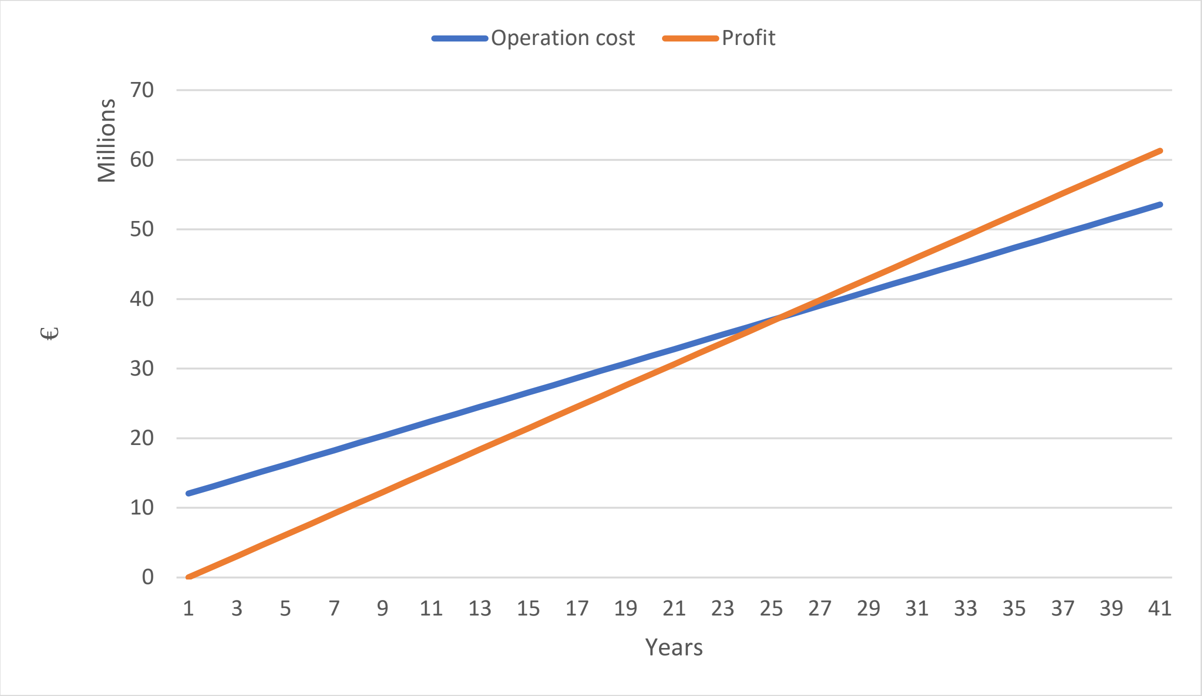


Figure 4.15: Profitability chart of 2 stages (Therminol) system

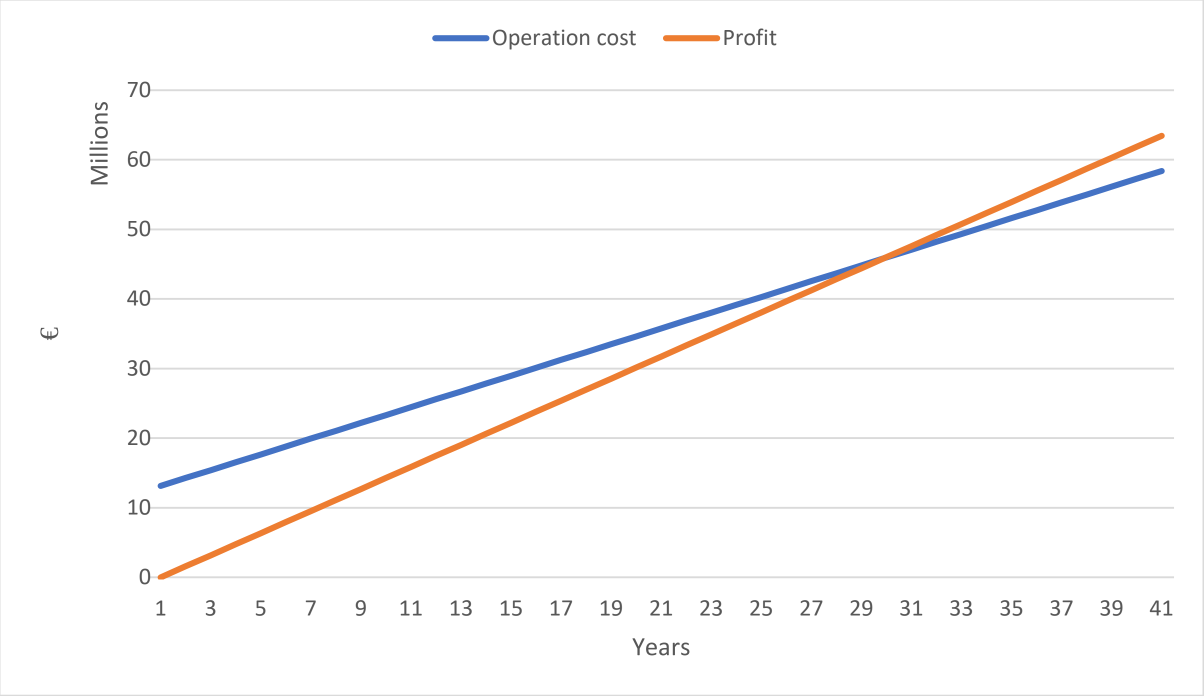


Figure 4.16: Profitability chart of 3 stages (Therminol) system

According to the figures below, the minimum lifetime for water system has to be more than 13 years whilst for thermal fluid system it's more than 28 years. We have a huge difference in the profit even if the capital investments aren't that much different, it's quite a 20M€ difference which can invest two other water systems.

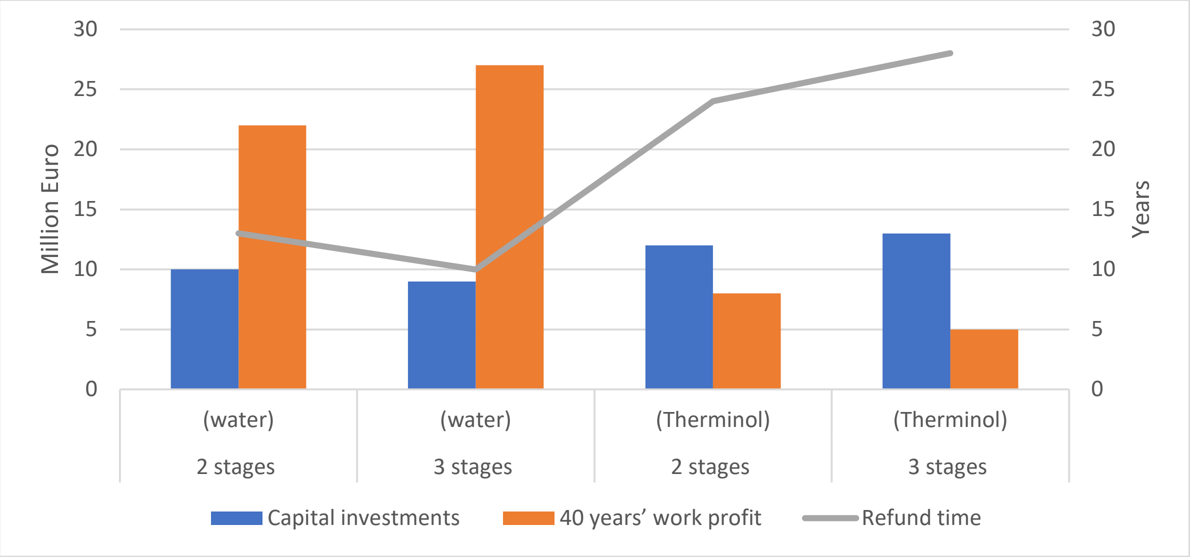


Figure 4.17: Economic results comparison

The Therminol systems can be successful systems if we decrease the cost of the thermal fluid so it could be a competitor. To see the results if we eliminate that cost we have the figure below.

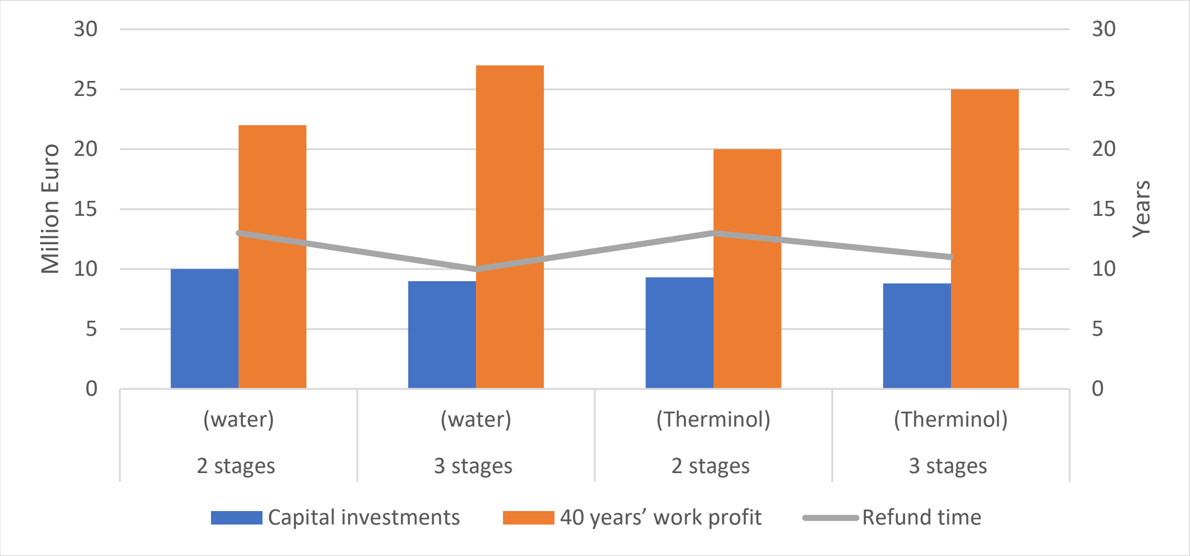


Figure 4.18: Economic results comparison (Therminol excluded)

Here we can see that the heating fluid solution is a bright solution if we can exclude its price, so it's cost the less with a remarkable profit. We can find that the 3 stages (Therminol) is a better solution economically than the 2 stages (water) even if it has less efficiency. So as a result, the thermal fluid is a good solution. But it can't reach the water system because of its low specific heat capacity value.

Chapter 5: Exergy analysis

1. What is exergy?

Exergy is a thermodynamic concept, used for many years within engineering analyses of chemical and mechanical processes and systems. Officially, exergy is defined as:

The maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment.

In other words, it is the *capacity of energy to do physical work*. To explain the concept, we'll use four basic principles:

a. Exergy is a measure of energy quality:

Energy has many different forms, all of a different inherent *quality*. 'Quality' can refer to a number of attributes – ease of transport, energy density, environmental impact, etc. – but we refer here to its most fundamental form, which encapsulates the ability to perform physical work, i.e. to overcome a resistance to make an object *move*. This is important when considering thermal energy (heat), which is intrinsically of a lower quality than other forms of energy (such as electricity or mechanical motion). This is because for a given amount of heat, a portion – depending upon its temperature – will constitute the low-grade waste heat which cannot then be recovered and made to do physical work (for example, in a heat engine).

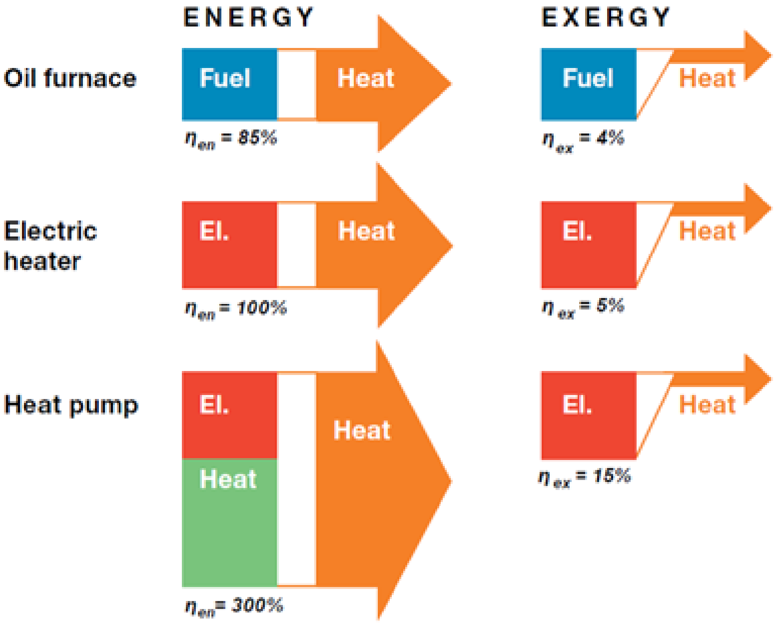


Figure 5.1: Energy vs exergy efficiency

Whereas one can theoretically recover all of the heat energy from a device such as an electric heater, very little of this low-quality energy can be subsequently made to do work (e.g. in moving an object). Thus the device is said to have a low exergy output. [12]

b. Exergy is destroyable:

The first law of thermodynamics dictates that in any transformation process, energy is always conserved. In any real process, this translates into a certain amount of input energy being converted to low-temperature waste heat. The sum of the waste heat and useful energy output will always equal the input energy.

Exergy, on the other hand, takes its basis in the second law of thermodynamics, which in one form states that every transformation process involves the loss of some measure of quality of the system. This measure is represented by exergy; taking the same units as energy (e.g. Joules), exergy corresponds to the portion of an energy flow which can be made to do useful work in a subsequent conversion process. Thus, it is partially destroyed in every process. Destruction, in this sense, refers to an irreversible process of entropy creation, though it's sufficient to say that this corresponds to the low-temperature waste heat generated [13].

c. Exergy is relatively defined:

Exergy is a property of all material and energy flows, and depends upon characteristics such as temperature, chemical composition and electric potential relative to an external environment. In other words, it is the contrast between a thermodynamic system and its environment that defines the amount of exergy available; the greater the difference between the two (in temperature, or in gravitational/electrical/chemical potential), the greater the exergy of the system.

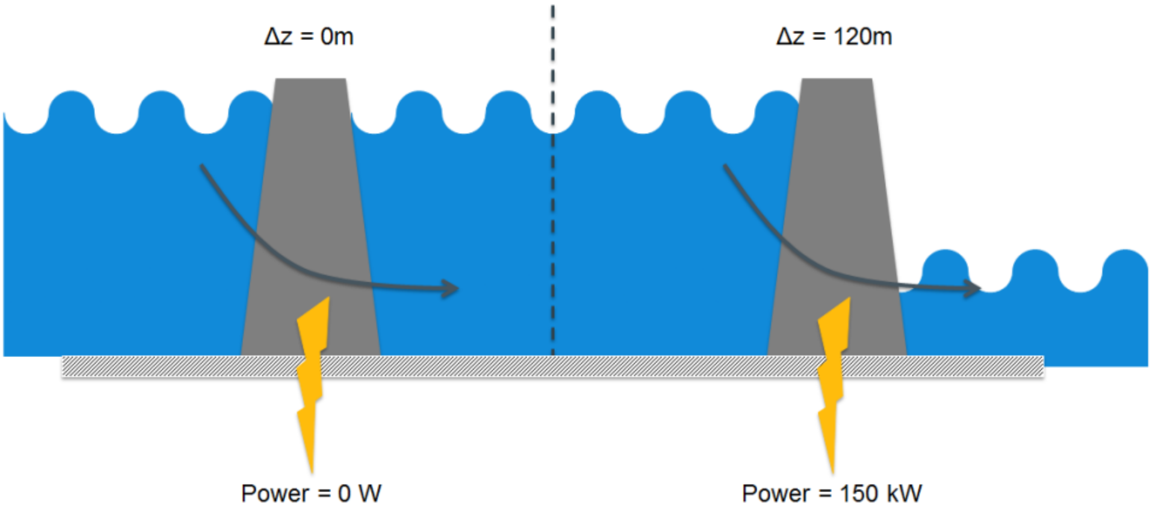


Figure 5.2: Hydroelectric dam exergy demonstration

Demonstration of the relative nature of exergy – in a hydroelectric dam, exergy cannot be extracted from one body of water until it is at a higher point relative to another (thus having more gravitational potential energy). In the case that both are at an equal height, both bodies possess energy, but as a whole there is no exergy within the system [12].

2. Energy and exergy relations:

The exergy analysis based on the second law of thermodynamics takes into account the quantity and the quality of energy in any real process. Unlike the energy analysis based on the first law of thermodynamics, the exergy is not conserved during any real process due to irreversibility's. Consequently, the exergy analysis of a system including several forms of energy such as the proposed storage system (mechanical, thermal, electrical and potential) is necessary. In the proposed storage system, the chemical exergy is negligible because of the absence of the chemical reactions, then the total exergy is the physical exergy.

$$\Delta Ex = M \times (h - h_a - T_a(s - s_a)) \tag{5.1}$$

The exergy destruction of a component is the difference between the exergy resource and the exergy recovered (Equation 5.1). The thermodynamic equations and the exergy destruction within the different components of the storage system are presented in Table 5.1. [9]

Compressor	$\Delta Ex = P - M \times (h_{out} - h_{in} - T_{in}(s_{out} - s_{in}))$
Turbine	$\Delta Ex = P - M \times (h_{out} - h_{in} - T_{in}(s_{out} - s_{in}))$
Pump	$\Delta Ex = P - M \times (h_{out} - h_{in} - T_{in}(s_{out} - s_{in}))$
Heat exchanger	$\Delta Ex = -(\Delta Ex_{hot} + \Delta Ex_{cold})$

Table 5.1: Exergy destruction relations

3. Analysis and results:

	2 stages				*3 stages*					
	Energy		Exergy		Energy			Exergy		
Compressor	4.9		4.24		3.24			2.77		
Turbine	5.91		4.81		4			3.42		
Pump	0.026	0.035	0.022	0.031	0.0045	0.0095	0.007	0.0035	0.0079	0.0057
Cooling exchanger	4.37	4.84	2.87	3.2	2.8	3.2	3.2	1.51	1.57	1.5
Heating exchanger	6.36	6.3	3.23	3.35	4.75	4.3	4.27	1.75	1.5	1.85

Table 5.2: Exergy results (MW)

The efficiency given by Table 3.9 presents the energy efficiency. In fact, the electrical energy consumed or produced by the rotating machinery are pure exergy. So we did another study to indicate the exergy efficiency of the systems.

	2 stages (water)	*3 stages (water)*	*2 stages (Therminol)*	*3 stages (Therminol)*
Energy efficiency (%)	58.4	59.5	54	56.4
Exergy efficiency (%)	55	59.6	50.4	56.1

Table 5.3: Energy and Exergy efficiency comparison

With these results we can assure that the 3 stages systems are better than the 2 stages systems, and as seen above the exergy efficiency of 3 stages systems is approximately equal to the energy efficiency that's due to the low difference of the enthalpy in the turbines and the compressors.

4. ZMERLY & CO visit:

In our technical search journey, we visited Zmerly company to get more information, so we met engineer Wael ZMERLY, ZMERLY & CO's CEO, and explain our project.

ZMERLY
SMART HEATING

Figure 5.3: ZMERLY & CO logo

ZMERLY & CO, according to their official website, quality systems engineered to deliver reliability & performance representing outstanding value. Based in Tripoli Lebanon, ZMERLY & CO is the leader in the highest heating technologies in Lebanon. With over 20 years' experience selling heating systems of the highest quality, design and engineering, ZMERLY & CO products are installed in a wide list of references in Lebanon.

He gave us some ideas and advices:

- Looking for somewhere we could make this project real (sea with depth of 600m, politic reason, fixation of the air-water tank).
- Heating water directly from electric power of the wind turbine.

For the first point, we can see with the Figure 5.4 that we have region water with depth reaches 2130 m, for our project we need 600 m so we must keep around 10 Km away from the beach. [14]

And for the second point, we discussed this idea too much and studied it to find if it's beneficial to the system or not.

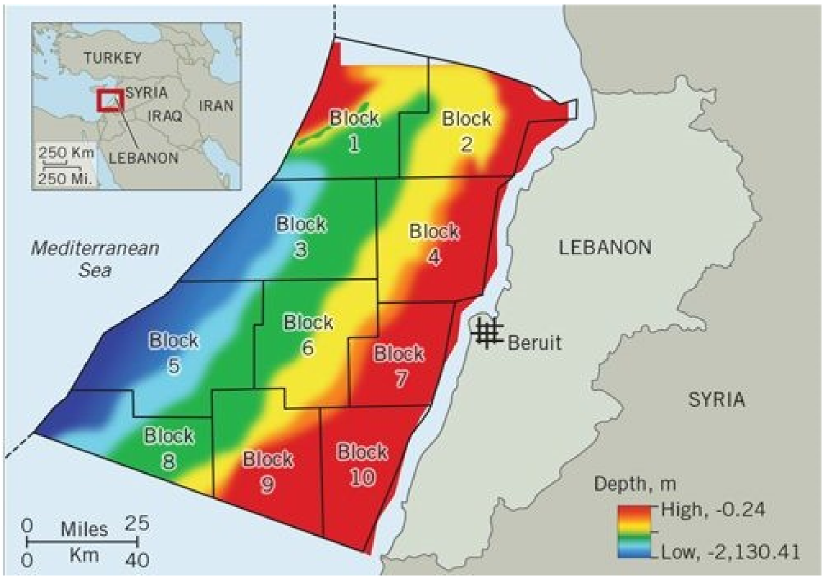


Figure 5.4: Lebanese seabed depth

So as energy efficiency we've got a huge enhancement, so reached 70%, but when we studied the exergy efficiency we've found the problem of this idea when we lost around 5% of the exergy efficiency.

To explain why the electrical heater has this low exergy efficiency we have below a calculation example:

If we assume that we have 1 liter of water at 20ºC, and we need to get it to 30ºC.

$$E = M \times C_p \times (T_2 - T_1) \tag{5.1}$$

E=41.8 KJ

To calculate the exergy:

$$Ex = E\left(1 - \frac{T_{amb}}{T}\right) \tag{5.2}$$

We've got Ex=0.033E (3.3%)

In systems like CAES system, which has more than type of energy electrical, mechanical and thermal, the energy efficiency has no physical meaning, so we have to calculate the exergy efficiency which give us the quality of the energy.

Conclusion:

The growing integration of the renewable energy sources into the electrical grid requires energy storage systems to overcome the intermittency of these sources. Thus, a green compressed air energy storage system is studied in this report with four options which are 2 stages (water), 3 stages (water), 2 stages (Therminol) and 3 stages (Therminol).

Exergy and exergoeconomic analyses are then carried out to improve the cost-effectiveness of the storage system.

The thermoeconomic analysis shows that the efficiency is between 54% and 59.5% and the energy density is between 12.3 KWh/m^3 and 13.9 KWh/m^3. Regarding the capital cost, it is between 9 M€ to 13 M€. Consequently, the usage of Therminol as a thermal fluid induce a lower system efficiency with higher capital investment and longer refund time. This is due to the higher cost of Therminol and its thermodynamic properties which increase the exergy destruction in the heat exchangers. By the end, the system of 3 stages (water) shows the best results starting with the energy efficiency to the components capital cost ending with the profit.

The exergy analysis illustrates high exergy destruction in the heat exchanger, and an exergy efficiency between 50.4% to 59.6%. This analysis promotes the advantages of the 3 stages systems on the 2 stages systems, it indicates that the exergy destruction for the 2 stages system is quite bigger compared to the 3 stages systems which is almost negligible.

Finally, this project helped us to improve our knowledge about energy storage technologies and their usage and specifications, renewable energy sources, green systems, and CAES systems specially. It helped to know the meaning of exergy much better, it was substantial to know the difference between these two terms “Energy” and “Exergy”.

Prospect:

- Optimization of the bladder tank installation under the sea with a minimum cost.
- Reduction of the bladder tank cost by optimization the system parameters.
- Technico-economical optimization of the GCAES system by taking into account the exergy and the economic constraints at the same time.
- Study the cogeneration of the storage system with other systems like a gas turbine by using the exhaust heat.

Construction system study for bladder tank in the deep water:

In fact, the bladder tank used for the CAES system is located underwater with a depth of 600 meters which causes some problem due to the large volume of the tank when it is empty under the effect of Archimedes shoot and Water currents that exists at this depth.

Bladder tank price reduction study:

When looking to reduce the price of our project we found that the tank bladder admits a high price (25%).

In the future, this may require a less expensive solution either by changing the structure of the bladder or by exchanging the bladder by another tank.

Techno economic optimization of CAES system taking into account energy and economic constraints at the same time:

In order to increase the efficiency of the system which increases the competitiveness of our project, we must carry out the optimization study between the parameters that can be varied such as the air storage pressure, number of stages of compression, temperature of the thermal storage system, pressure ratio in the turbines.

In fact, the isentropic efficiency that we fixed on 0.87 is variable between 0.84 and 0.94, and the electric efficiency we fixed on 0.94 is variable between 0.82 and 0.95

All these parameters with more information about the price variation of each component must be treated according to a function of optimization on Matlab to obtain the best results which realize a compromise between a high efficiency with a reduced price.

Study of the system with external contribution of the thermal energy from another station:

In this part we must study an external contributions of the energy, we must look for an installation which must be cooled and that we can build both projects in a close entourage

Then the heat is transmitted to overheat the compressed air before entering the turbine which serves to increase the efficiency of the system without variation in price and without any combustion and these harmful effects to the environment.

References:

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Appendix (A)

Therminol VP-1

THERMINOL® VP-1

Heat Transfer Fluids By SOLUTIA™

Applied Chemistry, Creative Solutions

VP-1

Vapour Phase
Liquid Phase
Heat Transfer Fluid

12°C to 400°C

+400°C
+350°C
+300°C
+250°C
+200°C
+150°C
+100°C
+50°C
+0°C
-50°C
-100°C

TM

Therminol VP-1 liquid/vapour phase heat transfer fluid, is a stable, high temperature medium that delivers process heat at temperatures up to 400°C with reliability and precise control.

Therminol VP-1 is a eutectic mixture of 73.5% diphenyl oxide / 26.5% diphenyl, and as such can be used in existing liquid, or vapour phase systems, for top-up or replacement of heat transfer fluids of the same composition. Vapour phase operation is possible at temperature above 257°C.

Heat Tracing System

Since Therminol VP-1 heat transfer fluid solidifies at 12°C, precautions must be taken to ensure lines do not freeze, particularly in outdoor installations. Heat tracing must be installed wherever lines run a danger of cooling below this point. All pipelines and equipment which may contain stagnant liquid should be traced, including all streams, vapour, drain and charge lines.

Thermal Stability at 400°C

Thermal stability of a heat transfer is one of the most important considerations in the selection of a fluid for operation under specific heat transfer conditions. Therminol VP-1 has a reputation for outstanding stability in operation.

Therminol VP-1 is based on raw materials of high purity produced by a first intent manufacturing process. This results in a reduced level of high boiler formation, superior thermal stability and benefits to the user in terms of extended fluid life and dependable trouble-free system operation.

Therminol VP-1 is thermally stable and suitable for operation over long periods at bulk temperatures up to 370-400°C.

Flammability

Although the DP/DPO eutectic can burn at elevated temperature, its chemical nature is such that its use as heat transfer medium in a properly designed and operated system does not normally constitute a serious fire or explosion hazard. Vapour freed into the air rapidly cools to below the fire point. High pressure mists, however, can form an explosive mixture with air.

Typical Physical, Chemical and Thermal Properties of Therminol VP-1

Composition		Diphenyl oxide/diphenyl
Appearance		Clear, sediment free liquid
Max. bulk temperature		400°C
Max. film temperature		430°C
Kinematic viscosity @ 40°C	DIN 51562 - 1	2.48 mm^2/s (cSt)
Density @ 15°C	DIN 51757	1068 kg/m^3
Flash point	DIN EN 22719	110°C
	DIN 51376	124°C
Fire point	ISO 2592	127°C
Autoignition temperature	DIN 51794	621°C
Pour point	ISO 3016	12°C
Boiling point @ 1013 mbar		257°C
Coefficient of thermal expansion		0.00097/°C
Moisture content	DIN 51777 - 1	< 300 ppm
Total acidity	DIN 51558 - 1	< 0.2 mg KOH/g
Chlorine content	DIN 51577 - 3	< 10 ppm
Copper corrosion	EN ISO 2160	<< 1a
Average molecular weight		166

Note: Values quoted are typical values obtained in the laboratory from production samples. Other samples might exhibit slightly different data. Specifications are subject to change. Write to Solutia for current sales specifications.

THERMINOL® VP-1

Properties of Therminol® VP-1 vs Temperatures - Liquid Phase

Temperature °C	Density kg/m^3	Thermal Conductivity W/m.K	Heat Capacity kJ/kg.K	Viscosity		Vapour pressure (absolute) kPa*	Enthalpy kJ/kg	Latent Heat vap. kJ/kg
				Dynamic mPa.s	Kinematic mm^2/s**			
12	1071	0.137	1.523	5.48	5.12	-	0.0	419.0
20	1064	0.136	1.546	4.29	4.03	-	12.3	414.7
30	1056	0.135	1.575	3.28	3.10	-	27.9	409.3
40	1048	0.134	1.604	2.60	2.48	-	43.8	403.9
50	1040	0.133	1.633	2.12	2.03	-	60.0	398.6
60	1032	0.132	1.662	1.761	1.707	-	76.4	393.3
70	1024	0.131	1.690	1.492	1.458	-	93.2	388.1
80	1015	0.130	1.719	1.284	1.265	-	110.3	382.9
90	1007	0.129	1.747	1.119	1.111	-	127.6	377.8
100	999	0.128	1.775	0.985	0.986	0.5	145.2	372.7
110	991	0.126	1.803	0.875	0.884	0.8	163.1	367.6
120	982	0.125	1.831	0.784	0.798	1	181.3	362.6
130	974	0.124	1.858	0.707	0.726	2	199.7	357.5
140	965	0.123	1.886	0.642	0.665	3	218.4	352.6
150	957	0.121	1.913	0.585	0.612	5	237.4	347.6
160	948	0.120	1.940	0.537	0.566	7	256.7	342.7
170	940	0.118	1.968	0.494	0.526	9	276.2	337.7
180	931	0.117	1.995	0.457	0.491	13	296.0	332.8
190	922	0.115	2.021	0.424	0.460	18	316.1	327.9
200	913	0.114	2.048	0.395	0.432	24	336.5	323.0
210	904	0.112	2.075	0.368	0.407	32	357.1	318.0
220	895	0.111	2.101	0.345	0.385	42	378.0	313.0
230	886	0.109	2.128	0.324	0.366	54	399.1	308.0
240	877	0.107	2.154	0.305	0.348	68	420.5	303.0
250	867	0.106	2.181	0.288	0.332	86	442.2	297.9
260	857	0.104	2.207	0.272	0.317	108	464.1	292.7
270	848	0.102	2.234	0.258	0.304	133	486.3	287.5
280	838	0.100	2.260	0.244	0.292	163	508.8	282.2
290	828	0.098	2.287	0.232	0.281	198	531.6	276.8
300	817	0.096	2.314	0.221	0.271	239	554.6	271.2
310	806	0.095	2.341	0.211	0.262	286	577.8	265.6
320	796	0.093	2.369	0.202	0.254	340	601.4	259.7
330	784	0.091	2.397	0.193	0.246	401	625.2	253.8
340	773	0.089	2.425	0.185	0.239	470	649.3	247.6
350	761	0.086	2.454	0.177	0.233	548	673.7	241.3
360	749	0.084	2.485	0.170	0.227	635	698.4	234.7
370	736	0.082	2.517	0.164	0.222	732	723.4	227.8
380	723	0.080	2.551	0.158	0.218	840	748.8	220.7
390	709	0.078	2.588	0.152	0.214	959	774.4	213.2
400	694	0.076	2.628	0.146	0.211	1090	800.5	205.3
410	679	0.073	2.674	0.141	0.208	1230	827.0	197.0
420	662	0.071	2.729	0.137	0.206	1390	854.0	188.0
425	654	0.070	2.760	0.134	0.205	1470	867.7	183.3

*1 bar = 100 kPa **1 mm^2/s = 1 cSt

Note: Values quoted are typical values obtained in the laboratory from production samples. Other samples might exhibit slightly different data. Specifications are subject to change. Write to Solutia for current sales specifications.

Physical Property Formulae of Liquid

Density (kg/m^3) = $- 0.90797 * T(°C) + 0.00078116 * T^2(°C) - 2.367 * 10^{-6} * T^3(°C) + 1083.25$

Heat Capacity (kJ/kg.K) = $0.002414 * T(°C) + 5.9591 * 10^{-6} * T^2(°C) - 2.9879 * 10^{-8} * T^3(°C) + 4.4172 * 10^{-11} * T^4(°C) + 1.498$

Thermal Conductivity (W/m.K) = $- 8.19477 * 10^{-5} * T(°C) - 1.92257 * 10^{-7} * T^2(°C) + 2.5034 * 10^{-11} * T^3(°C) - 7.2974 * 10^{-15} * T^4(°C) + 0.137743$

Kinematic Viscosity (mm^2/s) = $e^{\left(\frac{575.118}{T(°C)+185} - 2.79221\right)}$

Vapour Pressure (kPa) = $- 0.190859 * T(°C) + 4.35824 * 10^{-3} * T^2(°C) - 3.6106 * 10^{-5} * T^3(°C) + 1.08408 * 10^{-7} * T^4(°C) + 2.12329$

Enthalpy (kJ/kg) = $1.51129 * T(°C) + 1.2941 * 10^{-3} * T^2(°C) + 1.23697 * 10^{-7} * T^3(°C) - 18.72677$

Latent Heat Vaporisation (kJ/kg) = $- 0.528933 * T(°C) - 7.50103 * 10^{-5} * T^2(°C) + 1.5622 * 10^{-6} * T^3(°C) - 3.771 * 10^{-9} * T^4(°C) + 425.18$

Properties of Therminol® VP-1 vs Temperatures - Vapour Phase

Temperature °C	Density kg/m³	Thermal Conductivity W/m.K	Heat Capacity kJ/kg.K	Enthalpy kJ/kg	Viscosity Dynamic mPa.s
12	-	0.0081	0.975	419.0	0.0057
20	-	0.0085	1.003	427.0	0.0059
30	-	0.0090	1.037	437.2	0.0061
40	-	0.0095	1.070	447.7	0.0063
50	-	0.0100	1.104	458.6	0.0065
60	-	0.0105	1.137	469.7	0.0067
70	-	0.0110	1.170	481.3	0.0069
80	-	0.0116	1.203	493.2	0.0071
90	-	0.0121	1.235	505.4	0.0073
100	-	0.0126	1.267	517.9	0.0075
110	0.042	0.0132	1.299	530.7	0.0077
120	0.065	0.0137	1.331	543.9	0.0079
130	0.099	0.0143	1.362	557.2	0.0081
140	0.148	0.0149	1.393	571.0	0.0083
150	0.214	0.0154	1.424	585.0	0.0085
160	0.303	0.0160	1.454	599.4	0.0087
170	0.422	0.0166	1.484	613.9	0.0089
180	0.575	0.0171	1.514	628.8	0.0091
190	0.772	0.0177	1.543	644.0	0.0094
200	1.02	0.0183	1.572	659.5	0.0096
210	1.33	0.0189	1.601	675.1	0.0098
220	1.71	0.0195	1.629	691.0	0.0100
230	2.17	0.0201	1.657	707.1	0.0102
240	2.72	0.0207	1.685	723.5	0.0104
250	3.38	0.0213	1.712	740.1	0.0106
260	4.17	0.0220	1.739	756.8	0.0108
270	5.09	0.0226	1.766	773.8	0.0110
280	6.17	0.0232	1.792	791.0	0.0112
290	7.42	0.0238	1.819	808.4	0.0114
300	8.86	0.0245	1.845	825.8	0.0116
310	10.5	0.0251	1.871	843.4	0.0118
320	12.4	0.0258	1.897	861.1	0.0120
330	14.6	0.0264	1.923	879.0	0.0122
340	17.0	0.0271	1.948	896.9	0.0124
350	19.8	0.0277	1.974	915.0	0.0126
360	22.9	0.0284	2.001	933.1	0.0128
370	26.5	0.0291	2.027	951.2	0.0130
380	30.5	0.0298	2.054	969.5	0.0132
390	35.0	0.0304	2.082	987.6	0.0134
400	40.1	0.0311	2.111	1005.8	0.0136
410	45.8	0.0318	2.142	1024.0	0.0138
420	52.4	0.0325	2.175	1042.0	0.0140

Note: Values quoted are typical values obtained in the laboratory from production samples. Other samples might exhibit slightly different data. Specifications are subject to change. Write to Solutia for current sales specifications.

Physical Property Formulae of Vapour

Density (kg/m³) = $- 0.0303917 * T(°C) + 4.34615 * 10^{-4} * T^2(°C) - 2.41006 * 10^{-6} * T^3(°C) + 5.33458 * 10^{-9} * T^4(°C) + 0.553905$

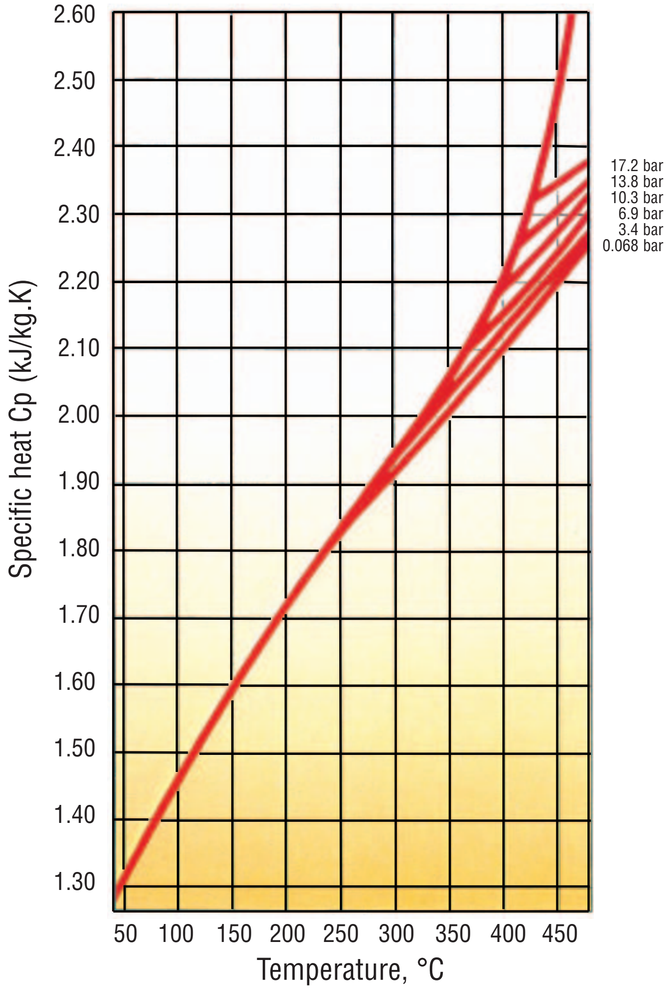
Heat Capacity (kJ/kg.K) = $0.003703 * T(°C) - 3.0274 * 10^{-6} * T^2(°C) + 2.9324 * 10^{-9} * T^3(°C) + 0.92709$

Enthalpy (kJ/kg) = $0.982357 * T(°C) + 1.219 * 10^{-3} * T^2(°C) + 1.6859 * 10^{-6} * T^3(°C) - 3.771 * 10^{-9} * T^4(°C) + 406.4532$

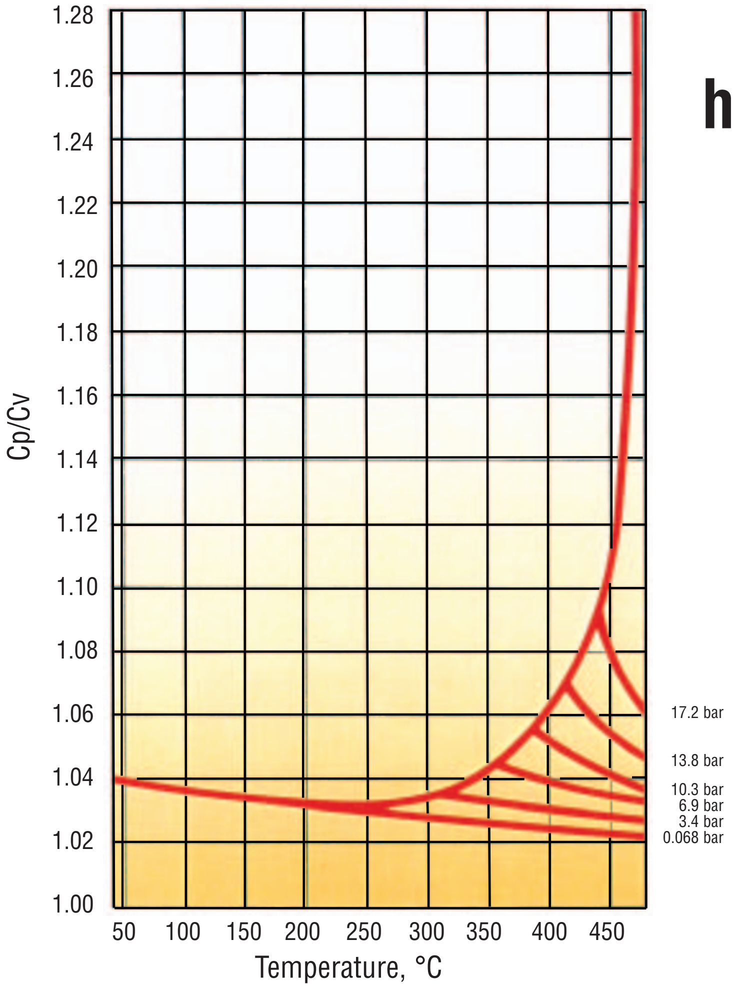
Dynamic Viscosity (mPa.s) = $2.0124 * 10^{-5} * T(°C) + 3.4557 * 10^{-9} * T^2(°C) - 7.1288 * 10^{-12} * T^3(°C) + 0.005449$

Thermal Conductivity (W/m.K) = $4.84257 * 10^{-5} * T(°C) + 2.9067 * 10^{-8} * T^2(°C) - 6.5306 * 10^{-12} * T^3(°C) + 0.0075110$

Calculated specific heat[(1)] for vaporized Therminol VP-1

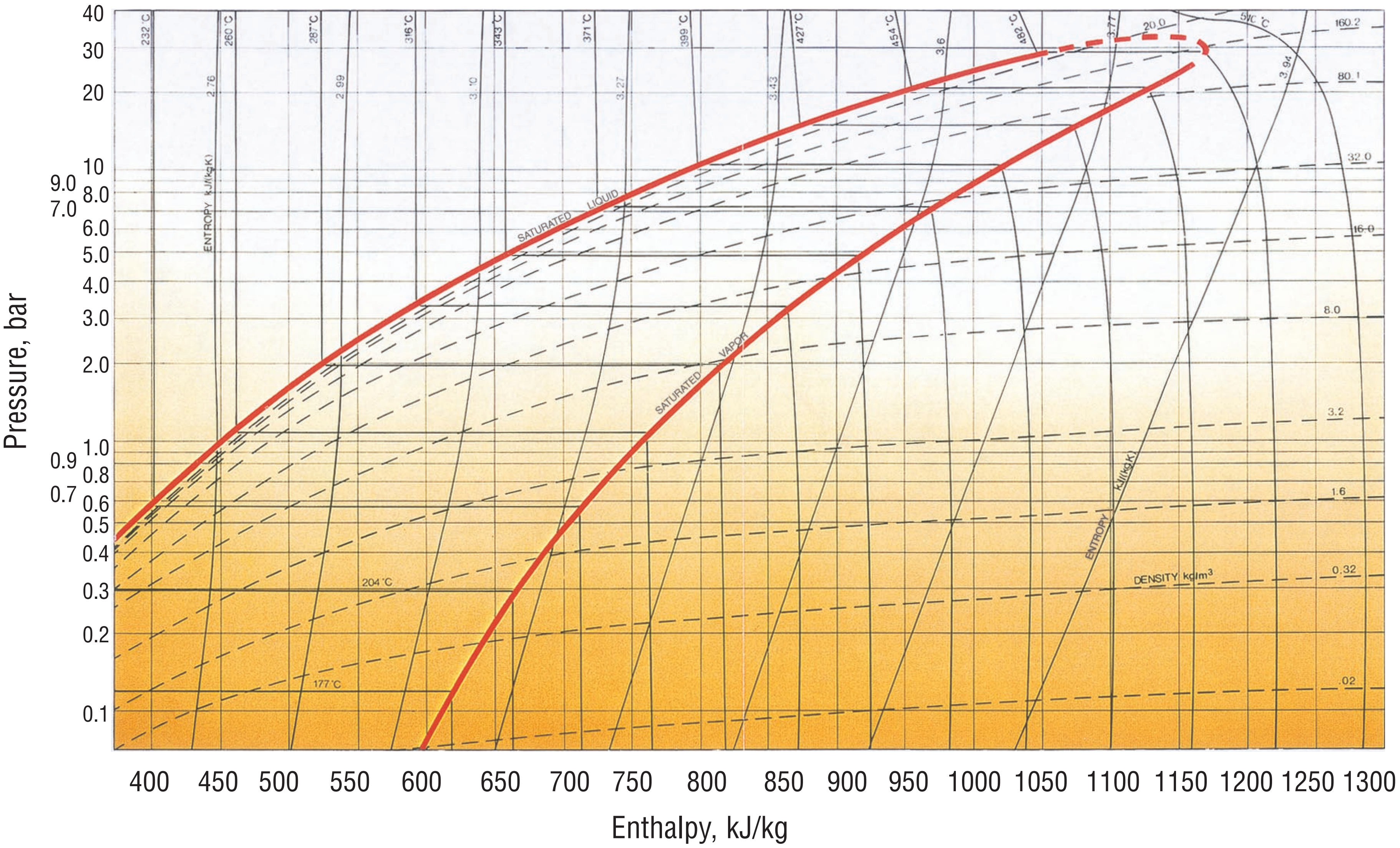


Calculated specific heat ratio[(1)] for vaporized Therminol VP-1



(1) These data are based upon calculations. They are representative and typical of the fluid but are not guaranteed for all samples. Write to Solutia for sales specifications for Therminol VP-1

Therminol VP-1 mollier chart : pressure vapour enthalpy[1]



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[1] These data are typical of the fluid; they are based upon samples tested in the laboratory but are not guaranteed for all samples. Write to Solutia for sales specifications for Therminol VP-1 heat transfer fluid.

The Therminol® Range

Therminol VP-1 is one of the of the Solutia synthetic heat transfer fluids covering an operating range from -85°C to +400°C, suitable for most process heating or waste heat recovery applications, and capable of operation at or near atmospheric pressure within their recommended operating temperature range.

As a user's process temperature demands change there is always a Therminol fluid capable of meeting the new requirements. In addition, Therminol fluids are often interchangeable allowing conversion by a simple top-up procedure where this is preferred.

Quality Management

All our manufacturing units have obtained ISO 9002 quality control certification. This registration means that plant procedures, quality control systems, material sampling, product storage, handling, packaging, shipping, product literature and characteristic data, record keeping and other company procedures are in line with the quality requirements of the ISO 9002 standards and its other national equivalents.
This is your quality assurance.

Health, Safety and Environmental Information

Please contact the Solutia Europe/Africa HQ for the Material Safety Data Sheet, or if any other information concerning health, safety and environmental issues is required during filling or operation of your heat transfer system with this product.

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Therminol is a trademark of Solutia. *Therminol* has now been adopted as a world-wide brand for the Solutia Heat Transfer Fluid range.
Fluids known previously under the Santotherm and Gilotherm brands are identical in composition and performance to the corresponding *Therminol* brand fluids.

Appendix (B)

Lebanese electricity tariffs

dynamic
ENERGY & WATER SOLUTIONS

Lebanon Electricity Tariffs

Electricité du Liban

Low Tension

	Lighting, home and commercial use	*Street lighting, public establishments, free medical care centers, hospitals, mosques, churches, cinemas, charity groups, hotels*	*Industry, craftsmen, agriculture, water treatment and pumping stations*
Slab in kWh	**Tariff in LBP/kWh**	**Tariff in LBP/kWh**	**Tariff in LBP/kWh**
1 - 100	35	140	115
101 - 200	55	140	115
201 - 300	55	140	115
301 - 400	80	140	115
401 - 500	120	140	115
over 500	200	140	115

Medium Tension

High Tension

Industry, craftsmen, agriculture		*Other subscribers*		*All subscribers*
Tariff in LBP/kWh *(Active Energy)*	**Tariff in LBP/kVARh** *(Reverse Energy)*	**Tariff in LBP/kWh** *(Active Energy)*	**Tariff in LBP/kVARh** *(Reverse Energy)*	**Tariff in LBP/kWh** *(Active Energy)*
130	50	140	50	115

Industrial

Summer Season (April 1 - September 30)		*Winter Season (October 1 - March 31)*	
	Tariff in LBP/kWh		**Tariff in LBP/kWh**
Night Rate (from 00:00 to 07:00)	80	Night Rate (from 00:00 to 07:00)	80
Day Rate (from 07:00 to 18:30)	112	Day Rate (from 07:00 to 16:30)	112
Peak Rate (from 18:30 to 21:30)	320	Peak Rate (from 16:30 to 20:30)	320
Day Rate (from 21:30 to 23:00)	112	Day Rate (from 20:30 to 23:00)	112
Night Rate (from 23:00 to 24:00)	80	Night Rate (from 23:00 to 24:00)	80