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Evaluation of liquid air as an energy storage alternative

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Evaluation of Liquid air as an energy storage alternative

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Abstract

As renewable, intermittent energy sources are expected to increasingly replace fossil based energy, energy storage technologies are crucially important in achieving the goal of fossil free energy, a cornerstone of sustainable development. Liquid air energy storage (LAES) is a novel technology that liquefies air when excess electricity is available. The liquid air is stored and, when electricity is needed, expanded in a turbine to generate electricity. The purpose of the project is to present the round trip efficiency of LAES, discuss how it can be improved and how it depends on relevant parameters and to evaluate LAES compared to other energy storage technologies. A literary review of existing energy storage methods and LAES research is presented. The efficiency is calculated using a model of a combined Linde (liquefaction) and Rankine (discharge) cycle built in Excel. We found that the efficiency of LAES is 21,6% without heat and cold recycle and above 50% with more than 60% recycle. Access to waste heat and cold can further increase the efficiency. A heat pump affects the efficiency very little, but is useful to protect the turbines from low working temperatures that can damage them. The biggest advantage of LAES is its high energy density, comparable to batteries and chemical energy storage. It is much higher than pumped hydro and compressed air energy storage (CAES). No toxic materials are used and it has reasonably cheap and long lasting components. It uses air, which is free as an energy carrier. The biggest disadvantage of LAES is its low round trip efficiency, probably under 50%, which is much lower than that of batteries and pumped hydro. It is similar to CAES and other chemical storage. LAES is only practical on a relatively large scale. Also, concentration of oxygen and cold working temperatures pose some safety risks.

Sammanfattning

Eftersom förnyelsebara, intermittenta energikällor i allt större utsträckning förväntas ersätta fossil energi är energilagring av avgörande betydelse för att nå målet om fossilfri energi, en hörnsten i hållbar utveckling. Energilagring i flytande luft (LAES) är en ny teknologi som tillverkar flytande luft när det finns ett elöverskott. Den flytande luften lagras sedan och när elektricitet behövs expanderas den i en turbin för att generera elektricitet. Syftet med detta projekt är att presentera den totala verkningsgraden för LAES, diskutera hur den kan förbättras och hur den beror på relevanta parametrar och utvärdera LAES jämfört med andra energilagringstekniker. En litteraturstudie om existerande energilagringsmetoder och LAES presenteras. Verkningsgraden beräknas med en modell konstruerad i Excel över en kombinerad Linde (överföring till vätskeform) och Rankine (expansion). Vi fann att verkningsgraden hos LAES är 21,6% utan återvinning av värme och kyla och över 50% med mer än 60% återvinning. En värmepump har endast marginell inverkan på verkningsgraden men är nödvändig för att skydda turbinerna från låga temperaturer som kan skada dem. Den största fördelen med LAES är dess höga energidensitet, jämförbar med batterier och kemisk energilagring och mycket högre än pumpvattenkraft och tryckluftslagring. LAES använder inga giftiga material och relativt billiga och robusta komponenter. Det använder gratis luft som energibärare. Den största nackdelen med LAES är dess låga verkningsgrad, troligen under 50% vilket är mycket lägre än för batterier och pumpvattenkraft och jämförbart med tryckluftslagring och kemisk energilagring. LAES är endast rimligt i relativt stor skala. Dessutom medför koncentration av syre och låga temperaturer vissa säkerhetsrisker.

Preface

We would like to express our warmest thanks to our supervisor, Justin NW Chiu at KTH for invaluable feedback and suggestions. We have done a bachelor's degree at KTH and had Justin as a supervisor. With the help of his feedback, we have been able to design this bachelor's degree project to its level.

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Nomenclature

Constants

$\rho_{liq,air}$	Density of liquid air kg/m^3 = 871,3 kg/m^3
$v_{liq,air}$	Specific volume of liquid air = 0,0011477 m^3/kg
ΔH_{vap}	Heat of vaporization for air = 218 kJ/kg
Cp_{air}	Specific heat at constant pressure for air = 1,006 kJ/kg*K
κ	Kappa for air = 1,4
R_m	Universal gas constant 8,3143 J/mol*K

Liquefaction

E	The difference in energy per kilogram between the air at the storage state and the state when it has been vaporized and heated to ambient temperature = 442 kJ/kg.
$T,_{amb}$	The ambient temperature = 298 K.
$P,_{amb}$	The ambient pressure = 1 bar.
Cp_{air}	Specific heat air under constant pressure
$m,_r$	Mass flow recycled air (kg/s)
$m,_n$	Mass flow new air (kg/s)
$m,_{tot}$	Total mass flow (kg/s)
$m,_l$	Mass flow liquefied air (kg/s)
η_K	Isentropic compressor efficiency
$T,_{is}$	Temperature if compressor/turbine is perfectly isentropic (K)
$T,_r$	Temperature if compressor/turbine has an isentropic efficiency (K)
$W_{c,is}$	Compressor work by isentropic compressor with $\eta_K = 1$ (kW)
$W_{c,1}$	Compressor work in compressor 1 (See figure 1) (kW)
$\Delta T,_{eff}$	Efficiency of heat exchangers modelled as difference between the temperature reached and the temperature that would be reached in an infinite counterflow heat exchanger (K)
$Q_{l,1}$	Heat transfer in $HE_{l,1}$ (kW)
$W_{c,2}$	Compressor work in compressor 2 (kW)
$Q_{l,2}$	Heat transfer in $HE_{l,2}$ (kW)
ε_f	Efficiency heat exchanger 3.
W_f	Work heat exchanger 3 (kW)
$Q_{l,3}$	Heat transfer in $HE_{l,3}$ (kW)
C_c	$m_{,r}$*Cp_{air} for cold flow in counterflow heat exchanger
C_h	$m,_{tot}$*Cp_{air} for hot flow in counterflow heat exchanger
C_{min}	The lowest of C_c and C_h
Q_{max}	The amount of heat transferred in a counterflow heat exchanger with efficiency 1 (kW)
ε_h	Efficiency counterflow heat exchanger
η_E	Isentropic efficiency expansion valve
Y	Yield, mass fraction of liquefied air to total air
$W_{l,tot}$	Total work in the liquefaction cycle (kW)
η_l	Liquefaction efficiency

Discharge

$T,_{storage}$	The storage temperature for liquid air = 75K.
$m,_{d}$	Mass flow in discharge (kg/s)
η_p	Pump efficiency
W_p	Pump work (kW)
$Q_{d,1}$	Heat transfer in $HE_{d,1}$ (kW)
$Q_{d,2}$	Heat transfer in $HE_{d,2}$ (kW)
η_T	Isentropic turbine efficiency
$W_{t,is}$	Turbine work by isentropic compressor with $\eta_T = 1$
$W_{t,1}$	Turbine work Turbine 1 (kW)
$Q_{d,3}$	Heat transfer in $HE_{d,3}$ (kW)
$Q_{d,4}$	Heat transfer in $HE_{d,4}$ (kW)
$W_{t,2}$	Turbine work Turbine 2 (kW)
$Q_{d,5}$	Heat transfer in $HE_{d,5}$ (kW)
$Q_{d,6}$	Heat transfer in $HE_{d,6}$ (kW)
$W_{t,3}$	Turbine work Turbine 3 (kW)
$W_{t,tot}$	Total turbine work from all the turbines in discharge
η_d	Discharge efficiency
η_r	Round Trip efficiency

Cold and heat recycle and heat pump.

$H,_{rec}$	Percentage of heat stored and recycled
$C,_{rec}$	Percentage of cold stored and recycled
$HP,_{power}$	Power of the heat pump (kW)
$\eta_{C,HP}$	Carnot efficiency of the heat pump
$HP,_{T,cold}$	Temperature at the cold end of the heat pump (K)
$HP,_{T,hot}$	Temperature at the hot end of the heat pump (K)
COP1	Coefficient of heating for heat pump
COP2	Coefficient of cooling for heat pump
$dT,_{cold}$	Difference between ambient temperature and free cold (K)
$dT,_{hot}$	Difference between ambient temperature and free waste heat (K)

Abbreviations

Meanings	**Abbreviations**
Liquid air energy storage	(LAES)
Compressed air energy storage	(CAES)
Electrochemical energy storage	(ECES)
Mechanical energy storage	(MES)
Chemical energy storage	(CES)
Thermal energy storage	(TES)
Liquid air energy storage	(LAES)
Compressed air energy storage	(CAES)
Lithium Ion batteries	(LIB)
Sodium sulphur batteries	(SSB)
Lead acid batteries	(LAB)
Redox flow batteries	(RFB)
Sensible heat storage	(SHS)
Latent heat storage	(LHS)
Phase change material	(PCM)
Phase change temperature	(PCT)
Thermo-chemical energy storage	(TCES)

1. Introduction

Sustainable development can be defined as using natural resources to meet today's needs without compromising the ability for future generations to meet their needs (Glavič & Lukman, 2007). Sustainable development is often divided into three different dimensions; social, economic and environmental (Kuhlman & Farrington, 2010). Energy is at the heart of sustainable development and there is today wide recognition that the energy system has to move from fossil based energy to renewable sources. The cost of renewables like wind and sun has decreased a lot recently, making it economically sustainable in many situations. It is also expected to keep decreasing as technology advances and scale grows (Chu, et al., 2017).

A problem with renewable sources like solar, wind and wave energy is that they are intermittent. For example solar power produces power when the sun is shining, not necessarily when the electricity is needed. The electricity that goes into the net must be used directly, and can not be stored for later use. When excess electricity is produced it therefore goes to waste (Chen, et al., 2009). Also, when not enough energy is produced from renewable sources, the gap must be met with other sources. Today it is usually fossil-based energy (Ibrahim, et al., 2008). It can therefore be argued that the biggest challenge standing in the way of providing clean and affordable energy for everyone is *energy storage*.

Improved technologies for energy storage could help achieve several of the United Nations 17 global development goals (UN, 2016). Apart from goal 7, “Affordable and clean energy” it is also connected to goal 13, “Climate action”, as improved energy storage technologies will help a transition from fossil based energy to renewable sources (Ibrahim, et al., 2008). Since energy is fundamental for economic growth, the project is also connected to goal 8, “Decent work and economic growth”.

There are many ways to store energy, but they all have disadvantages from economical as well s sustainability perspectives. One example is pumped hydro which is cheap and with high efficiency but low in energy density. This means that huge areas need to be used, there is a limit to suitable locations and the building of dams which often means relocation of people which is problematic from a social sustainable development perspective. Another example is batteries which have a very low startup time and work from a small scale but are fairly expensive on a large scale, require a lot of resources and produces (toxic) waste (Gustavsson, 2016).

Liquid air energy storage (LAES) is a technology that has many interesting advantages making it worthwhile to study further. The basic idea is to use excess energy to produce liquid air, store it at low temperature (75K) and discharge the energy when needed. LAES is high in energy density so it does not require huge areas like pumped hydro, it does not require scarce or toxic resources like batteries and the components needed (compressors, turbines, and heat exchangers) are technically mature and relatively cheap and long lasting. The main disadvantage is the low efficiency as energy is lost in the thermodynamical processes of charge, storage and discharge (Morgan, et al., 2015). If the technology of LAES can be better understood and the efficiency improved, LAES could play an important role in the future energy system providing medium to large scale energy storage.

1.1 Purpose

The purpose of the project is to evaluate liquid air energy storage (LAES) as an energy storage alternative with a special focus on its round trip efficiency and analyzing possibilities for efficiency improvements.

1.2 Goals

- Present the overall efficiency of LAES and how it depends on the parameters discharge pressure, access to waste heat and cold, heat and cold recycle and implementation of a heat pump.
- Give pros and cons to LAES as an energy storage system compared to other energy storage technologies.

2. Method

A background literature study on the role and importance of energy storage, energy storage technologies and LAES was conducted. A model to calculate the round trip efficiency of a LAES powerplant was built in Excel.

2.1 Literary review

For the introduction and literary review, literature was searched in google scholar and web of science using search strings as “liquid air energy storage”, “sustainable development” and “energy storage”. Further literature was obtained following references and works citing these sources. Where possible, peer reviewed sources were used and in some cases textbooks on thermodynamics. One notable exception to this is a report by the Centre for Low Carbon Futures (Centre for Low Carbon Futures, 2013) It is important to note that they are advocates of liquid air and their information was therefore treated more critically.

The information about energy storage methods was summarized to give a brief overview of the technologies used with a special focus on variables such as energy density, round trip efficiency, scalability and sustainable development aspects where meaningful comparisons to LAES could be made. For LAES, the process was described with enough detail to give the reader a basic understanding of both the theoretical and practical process. The technological and thermodynamic aspects of LAES were presented with more detail and the economical and environmental aspects more briefly.

2.2 Modelling of round trip efficiency

A model was built in Excel of a combined liquefaction and discharge cycle to model round trip efficiency of a LAES power plant depending on the relevant parameters; isentropic efficiency of components, liquefaction pressures, discharge pressures, access to waste cold and heat and the possibility to recycle heat and cold between the two cycles. The scale of the power plant is about 50 MW which corresponds to a mass flow of 100kg/s liquid air. Note that the scale does not affect the round trip efficiency in the model.

2.2.1 Constants

The following constants, shown in table 1 were used in the model:

Table 1: Constants

Constant	Symbol	Value	Unit	Source
Mass flow liquid air	$m_{,l}=m_{,d}$	100	kg/s	
Density of liquid air	$\rho_{liq,air}$	871,3	kg/m^3	(Giuseppe, et al., 2015)
Specific volume of liquid air	$v_{liq,air}$	0,001148	m^3/kg	
kappa for air	κ	1,4		(Havtun, 2014)
Heat of vaporization for air	ΔH_{vap}	218	kJ/kg	(Felder, et al., 2005)
Constant pressure specific heat air	Cp_{air}	1,006	kJ/kgK	(Neutrium, 2012)

2.2.2 Set parameters

The efficiency of the components shown in table 2 is estimated following values from existing literature. It is worth noting that generally, efficiency of the components grows with scale. As the modelled powerplant is fairly large scale, relatively high component efficiencies were assumed.

Table 2: Set parameters.

Parameter	Symbol	Value	Source
Isentropic compressor efficiency	η_K	0,85	(Sciacovelli, et al., 2017)
Efficiency heat exchanger $HE_{l,3}$	ε_f	0,9	(Ameel, et al., 2013)
Efficiency counterflow heat exchanger	ε_h	0,9	(Ameel, et al., 2013)
Isentropic efficiency expansion valve	η_E	0,7	(Sciacovelli, et al., 2017)
Pump efficiency	η_p	0,9	(Chino & Araki, 2000)
Isentropic turbine efficiency	η_T	0,85	(Sciacovelli, et al., 2017)
Carnot efficiency heat pump	$\eta_{C,HP}$	0,7	(Zottl, et al., 2012)
Heat exchangers efficiency	$\Delta T_{,eff}$	5	(Sciacovelli, et al., 2017)

The amount of heat and cold that can be stored and recycled, $H_{,rec}$ and $C_{,rec}$ is hard to estimate for a real powerplant and is therefore varied from 0 to 1 in the results. For some calculations, the value 0,6, which is our best estimate on what is practically achievable, is used (See section 4.2 Heat and cold recycle).

E is the difference in energy per kilogram between the air at the storage state and the state when it has been vaporized and heated to ambient temperature. It is calculated by

E =	$m*(\Delta H_{vap}+Cp*(T_{,amb}-T_{,storage}))$ = 442,3 kJ/kg	**eq 1**

2.2.3 The combined liquefaction and discharge cycle

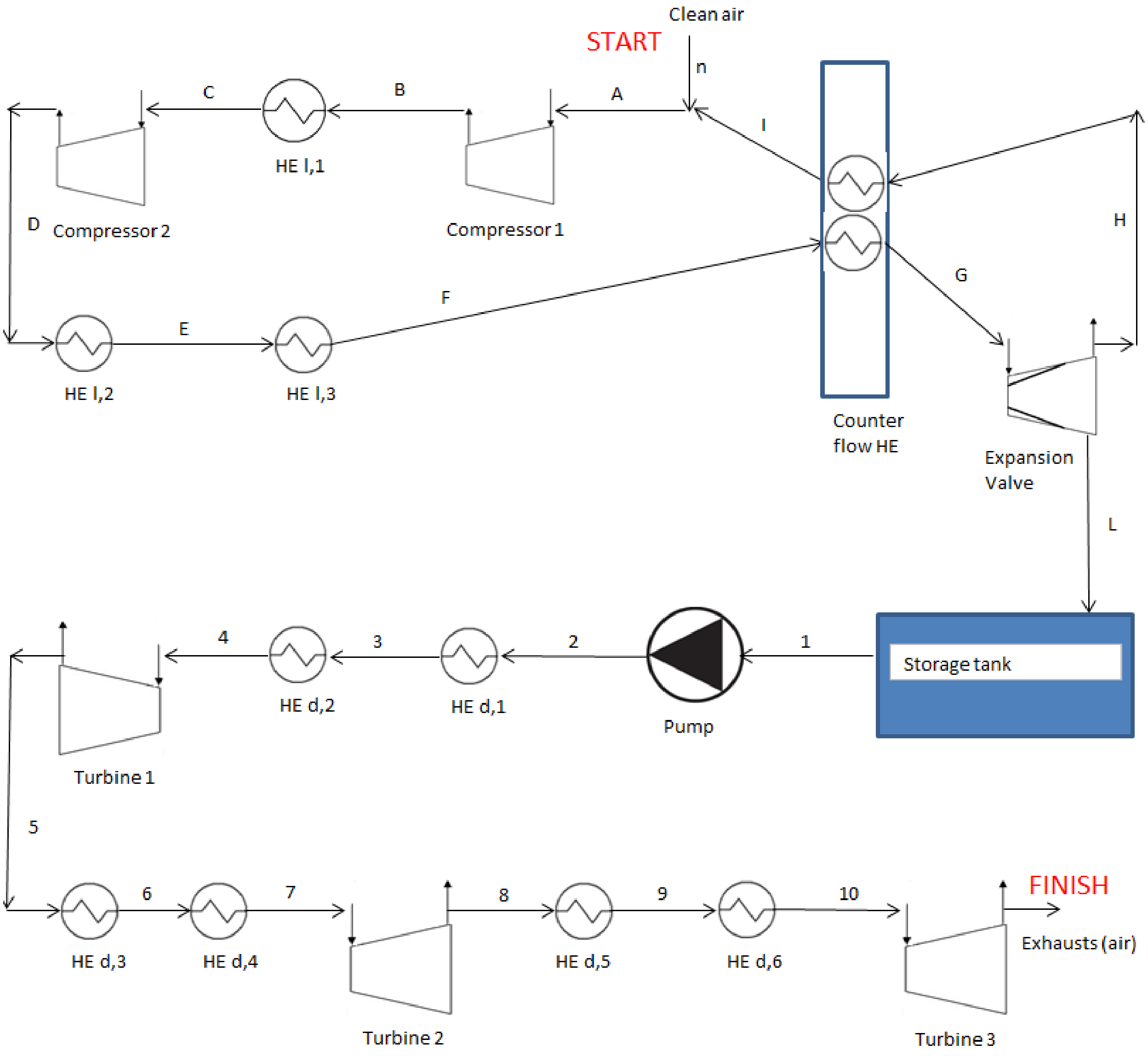


Figure 1: Schematics of the combined liquefaction and discharge cycle.

All equations, unless stated otherwise, are from (Havtun, 2014). Note that all work and heat transferred are defined so that they are positive.

In A, recycled cold air with mass flow $m_{,r}$ and temperature T(I) is mixed with new air with mass flow $m_{,n}$ at T(n). See figure 1 which shows an overview of the combined liquefaction and discharge cycle. T(n) can be at ambient temperature or colder if a heat sink is available.

T(A) =	$\frac{m_{,r} * T(I) + m_{,n} * T(n)}{m_{,tot}}$	**eq 2**
P(A) =	$\frac{m_{,r} * P(I) + m_{,n} * P(n)}{m_{,tot}}$	**eq 3**

This air is then compressed by compressor 1. Parameters: The pressure after compression, P(B) and isentropic compressor efficiency, η_K. $T(B)_{,is}$ and $W_{c,is}$ are used as a helping variables to calculate the compressor work, $W_{c,1}$, and the temperature after compression, T(B).

$T(B)_{,is}$ =	$T(A) * \frac{P(B)^{\frac{(\kappa-1)}{\kappa}}}{P(A)}$	**eq 4**
$W_{c,is}$ =	$m_{,tot} * Cp_{air} * (T(B)_{,is} - T(A))$	**eq 5**
T(B) =	$T(A) + \frac{T(B)_{,is} - T(A)}{\eta_K}$	**eq 6**
$W_{c,1}$ =	$\frac{W_{c,is}}{\eta_K}$	**eq 7**

The stream is then cooled isobarically to ambient temperature by the first heat exchanger in the liquefaction cycle, $HE_{l,1}$. Parameters: Heat exchangers efficiency, $\Delta T_{,eff}$. $\Delta T_{,eff}$ describes the efficiency of all the heat exchangers used (except $HE_{l,3}$) as the difference between the temperature reached and the temperature that would be reached in an infinite counterflow heat exchanger. Here, with $T_{,amb}$ = 298 K and $\Delta T_{,eff}$ = 5 K the $HE_{l,1}$ cools the stream to T(C) = 298 - 5 = 293K. Heat is lost to the ambient and this heat can be recycled and stored in heat storage. Equations:

$Q_{l,1}$ =	$m_{,tot} * Cp_{air} * (T(B) - T(C))$	**eq 8**

Between (C) and (D) is another compressor, compressor 2 with compressor work $W_{c,2}$ that works exactly as compressor 1. Between (D) and (E) is another isobaric cooling to ambient temperature in $HE_{l,2}$ where heat can be recycled.

$W_{c,2} =$	$\frac{W_{c,is,2}}{\eta_K}$	**eq 9**

$Q_{l,2} =$	$m,_{tot}*Cp_{air}*(T(D)-T(E))$	**eq 10**

After (E) the stream is cooled isobarically to T(F) by a heat exchanger, $HE_{l,3}$. Parameters: T(F) and heat exchanger efficiency, ε_f. Stored cold can be used to reduce the work done by this heat exchanger. The heat flow, $Q_{l,3}$, and heat exchanger work, W_f are calculated:

$Q_{l,3} =$	$m,_{tot}*Cp_{air}*(T(E)-T(F))$	**eq 11**
$W_f =$	$\frac{Q_{l,3}}{\varepsilon_f}$	**eq 12**

The cooling is separated into these two stages (D) to (E) and (E) to (F) to simplify modelling that cooling to ambient temperature is free.

After (F), The air is cooled further by recycled air from after the expansion valve at T(H) in an isobaric counterflow heat exchanger. T(H) is set to 82K, between the boiling points of N and O (Sciacovelli., et al, 2017). Parameters: Counter flow heat exchanger efficiency, ε_h.
The outlet temperatures of the two streams after the heat exchanger, T(G) and T(I) are calculated using:

$C_c =$	$m,_r*Cp_{air}$	**eq 13**
$C_h =$	$m,_n*Cp_{air}$	**eq 14**

C_{min} = the lowest of C_c and C_h.

$Q_{max} =$	$C_{min}*(T(F)-T(H))$	**eq 15**
$Q =$	$Q_{max}*\varepsilon_h = C_c*(T(I)-T(H)) = C_h*(T(G)-T(F))$	**eq 16**

These equations (2.11 to 2.14) come from (Cengel & Afshin, 2011). In actuality, C_c is always smaller then C_h but C_{min} is included in the formulas for heat exchanger for extra clarity.

After (G) the air is expanded in an expansion valve, creating a mixture of liquid air with mass flow, $m_{,l}$, that is lead into a storage tank and gaseous air with mass flow $m_{,r}$. The liquid air flow, $m_{,l}$ is the same as the mass flow in the discharge cycle described below and does not impact the round trip efficiency. This mass flow is set to 100 kg/s. Parameters: The mass fraction of air that becomes liquefied every cycle, yield or y, the pressure after expansion, p(H) and isentropic efficiency of the expansion valve, η_E. The yield depends on the temperature and pressure before expansion (lower T and higher P means higher yield). The yield is set to 0,65 corresponding to a P(G) = 110 bar, T(G) = 96K and η_E= 0,7 according to (Giuseppe., et al, 2015). P(H) is set to just above one bar to keep the flow going without needing to use another compressor. $T(H)_{,is}$ is used as a help variable, $T(H)_{,real}$ is the temperature that would be reached at (H) if it was not below the boiling point of liquid air. T(H) is the actual temperature after the expansion, set to 82 K, a mixture of the boiling points of N and O following (Sciacovelli., et al, 2017)

$m_{,l}$ =	$m_{,tot} * y$	**eq 17**
$m_{,r}$ =	$m_{,tot} - m_{,l}$	**eq 18**
$T(H)_{,is}$ =	$T(G) * \frac{P(H)^{\frac{(\kappa-1)}{\kappa}}}{P(G)}$	**eq 19**
$T(H)_{,real}$ =	$T(G)-\eta_E*(T(G) - T(H)_{,is})$	**eq 20**

The air now flows through the isobaric counterflow heat exchanger described above and reaches temperature T(I).

The cycle efficiency is the total energy in liquid air, $m_{,l} * E$, divided by the sum of the work in the two compressors and the heat exchanger 3 in liquefaction.

$\eta_{,l}$ =	$\frac{m_{,l} * E}{W_{c,1}W_{c,2}W_{c,3}}$	**eq 21**
$\eta_{,l}$ =	$\frac{m_{,l} * E}{W_{l,tot}}$	**eq 22**

The liquid air is stored at 75K and ambient pressure in a storage tank. In the powerplant, the liquefaction cycle is active filling the storage tank when cheap excess energy is available. If this is assumed to be the case maximum 3 hours before the discharge cycle is activated, the storage tank must be at least:
$3h * 3600s/h * m_{,l} / \rho_{liq,air} = 1240\ m^3$.

When energy is high in demand, the discharge cycle is activated. During discharge, liquid air with mass flow $m_{,d}$ at T(1) and P(1) is taken from the storage tank and pumped to a higher pressure. Parameters: The pressure after the pump, (P2) and pump efficiency, η_p. The pump work, W_p, is calculated:

W_p =	$\frac{m_{,d} * v_{liq,air} * (P(2) - P(1))}{\eta_p}$	**eq 23**

The liquid air in (2) is then evaporated and heated isobarically to ambient temperature by the first heat exchanger in discharge, $HE_{d,1}$. This gives off cold that can be stored and recycled.

$Q_{d,1}$ =	$m_{,d}*(Cp_{air}*(T(3)-T(2))+\Delta H_{vap})$	**eq 24**

In the next step, before (4), there is an alternative heat exchanger, $HE_{d,2}$ that can heat the air isobarically to T(4) before entering the first turbine.

$Q_{d,2}$ =	$m_{,d}*Cp_{air}*(T(4)-T(3))$	**eq 25**

After (4) the air is expanded in a turbine to produce work. Parameters: Pressure after expansion, p(5) and isentropic efficiency of the turbine, η_T. The temperature that would be reached after the turbine if it was perfectly isentropic, $T(5)_{,is}$ is used as a help variable. The work that would be produced by an isentropic turbine, $W_{t,is}$ is also included as a help variable. The temperature after the turbine, $T(5)_{,real}$ and the turbine work, W_t, are calculated:

$T(5)_{,is}$ =	$T(4) * \frac{P(5)^{\frac{(\kappa-1)}{\kappa}}}{P(4)}$	**eq 26**
$W_{t,is}$ =	$m_{,d}*Cp_{air}*(T(4)-T(5)_{,is})$	**eq 27**
$T(5)_{,real}$ =	$T(4)-\eta_T*(T(4)-T(5)_{,is})$	**eq 28**
$W_{t,1}$ =	$W_{t,is}*\eta_T$	**eq 29**

After the first turbine, the flow is heated isobarically by $HE_{d,3}$ with heat transfer $Q_{d,3}$ to ambient temperature and potentially by $HE_{d,4}$ with heat transfer $Q_{d,4}$ to a higher temperature. The flow then enters turbine 2 which produces the work $W_{c,2}$, and is heated by two heat exchangers with heat transfers $Q_{d,5}$ and $Q_{d,6}$. Finally, the flow is expanded in turbine 3 producing work $W_{c,3}$ and released into the atmosphere. The pressure fraction is the same in all three turbines. The sum of the work in all three turbines is $W_{t,tot}$. The reason for using several turbines is that the flow can be reheated between the expansions, thus giving more total work. It is also a way to avoid very low temperatures that are hazardous to material and people.

The cycle efficiency is:

η_d =	$\frac{W_{t,tot}-W_p}{m_{,d}*E}$	**eq 30**

And the round trip efficiency of liquefaction and discharge is:

η_r =	$\frac{W_{t,tot}-\ W_p}{m_{,d}*E}*\frac{m_{,l}*E}{W_{l,tot}}$	**eq 31**

Because $m_{,d} = m_{,l}$:

η_r =	$\frac{W_{t,tot}-\ W_p}{W_{l,tot}}$	**eq 32**

2.2.4 Heat and cold recycle

Heat and cold recycle is modelled introducing the variables $C_{,rec}$ and $H_{,rec}$ that can vary from 0 to 1 describing the percentage of heat and cold that is stored and recycled. It is important to understand that the liquefaction and discharge cycles never run at the same time so the heat and cold must first be stored from one cycle before it is recycled in the other cycle.

Heat is recycled from after the two compressions in the liquefaction cycle, from (B) to [C) and (D) to (E). The temperature of the recycled heat is the average of the temperature at these two stages. Cold is recycled from the evaporation in the discharge cycle, from (2) to (3).

The recycled heat can be used before the first, second and third turbine in the discharge cycle. The recycled cold can be used before the first compression, in (A), before the second compression, in (C], and in the heat exchanger between (D) and (E).

Depending on the other parameters, the recycled heat will be of a certain temperature and it can of course not be used to heat to a higher temperature than that. This problem does not exist with the cold recycle as it is very high grade cold.

The solver in Excel is used to optimize where the recycled heat and cold are used to maximize round trip efficiency.

2.2.5 Heat pump

A heat pump is modelled introducing the parameters heat pump power, $HP_{,power}$, heat pump Carnot efficiency, $\eta_{C,HP}$, the temperature at the cold end of the heat pump, $HP_{,T,,cold}$ and the temperature at the hot end of the heat pump, $HP_{,T,hot}$. The COP1 and COP2 are calculated as:

COP_1 =	$\frac{\eta_{C,HP}*\ HP_{,T,hot}}{HP_{,T,hot}-\ HP_{,T,cold}}$	**eq 33**

$COP_2 =$	$COP_1 - 1$	**eq 34**

The mass flow is set to 100 kg/s and has no effect on round trip efficiency but the heat pump power is related to this mass flow. A mass flow of 100 kg/s and a heat pump of 800 kw gives the same result as a mass flow of 10 kg/s and a heat pump of 80 kW.

During liquefaction, the cold from the heat pump is used immediately and the heat is stored and later recycled with an efficiency $H_{,rec}$. Similarly, during discharge, the heat from the heat pump is used directly and the cold recycled with efficiency $C_{,rec}$.

$HP_{,power}$ is included in the formulas for the efficiencies:

$\eta_l =$	$\frac{m_{,l} * E}{W_{l,tot} + HP_{,power}}$	**eq 35**
$\eta_d =$	$\frac{W_{t,tot} - W_p - HP_{,power}}{m_{,d} * E}$	**eq 36**
$\eta_r =$	$\eta_d * \eta_l$	**eq 37**

The Excel solver is used to optimize $HP_{,T,,cold}$ and $HP_{,T,hot}$ and where the heat pump heats and cools to maximize round trip efficiency. As with the heat recycle, the heat pump can of course not heat to a higher temperature higher than $HP_{,T,hot}$ or cool to a lower temperature than $HP_{,T,cold}$.

2.2.6 Additional details

Access to a heat sink, is modelled with the parameter $dT_{,cold}$ which describes the temperature difference between the ambient and the heat sink medium. A similar $dT_{,hot}$ is used to model access to free waste heat, for example from a nearby industrial plant.

In all heatings, the flow is first heated to the ambient temperature or available waste heat temperature. It is then heated by the heat pump (which produces low grade heat) and then heated by heat recycle which has more high grade heat. Similarly, in all the coolings the flow is cooled by free waste cold, then the heat pump and finally cold recycle.

The Excel solver is used to maximize round trip efficiency, manipulating the hot and cold side of the heat pump, where heating and cooling is applied as well as the pressure between the compressors in liquefaction, P(B).

2.3 Delimitations

A potentially big subject and limited time means delimitations are necessary. These are divided into model delimitations which only concern the model and project delimitations which concern the entire project.

2.3.1 Model delimitations

- The model assumes ideal gas behavior which is not completely accurate at low temperatures and high pressures.
- Hot and cold recycle is modelled as percentages of the available heat and cold and the solution is steady state. A more detailed model could include how the temperature and amount of available heat and cold varies over time.
- Cp_{air} is assumed to be constant 1,006 kJ/kg*K when in actuality it varies slightly with the temperature (Neutrium, 2012).
- Temperature and Pressure before expansion in the liquefaction cycle and thus yield can not be varied and use values from (Giuseppe, et al., 2015).
- Cold is not recycled from after the expansions in the discharge cycle, this is theoretically possible but probably not worthwhile if heat recycle is used.
- The loss from storage is set to 0. The actual loss is 2,08*10^-5/h (Morgan, et al., 2015). This is so low it does not affect the round trip efficiency for the storage times expected in the modelled powerplant (a couple of hours).
- Weighted averages of nitrogen and oxygen in the air are used. In actuality, nitrogen and oxygen behave a little differently which could be accounted for in a more ambitious model.
- Values for efficiency of compressors, turbines, heat exchangers and other components are taken from research literature and are assumed to tolerate the working pressures and temperatures.

A further discussion of how these delimitations might affect the results can be found in section 6, Discussion.

2.3.2 Project delimitations

Financial and environmental analysis of LAES could be topics of entire theses in themselves and are therefore held brief to focus more on the efficiency of LAES. There are many possible ways to discharge the energy in liquid air but the project is about expanding it in a Rankine cycle to produce work (See sections 2.2.3 The discharge cycle and section 3.2.1 LAES Process for further details). This is due to the fact that it is the method suggested by most other researchers.

3. Literary review of energy storage and LAES (8p)

3.1 Energy storage

Energy storage has been proven useful to strengthen electricity grids. In the grid, the supply has to match the demand every single second. To ensure this, when demand is high, plants like hydro and fossil fuel power plants are turned on or increase their power output (Ibrahim, et al., 2008). When demand is low or supply high, any excess electricity produced goes to waste (Chen, et al., 2009). With a larger share of intermittent, renewable energy sources, both these problems grow. One way to address these problems is with energy storage; excess cheap energy is stored and sold when the energy is needed and the price higher. Effective energy storage would therefore lead to a greater possibility of using renewable energy sources. It could also lead to financial benefits and further reductions of CO_2 emissions by reducing the need for fossil backup power (Ibrahim, et al., 2008).

Energy storage is not only useful to balance supply in the power grid. It can also be used on a much smaller scale at off-grid locations or as backup power for example for hospitals (Ibrahim, et al., 2008). The focus in this report is on medium to large scale energy storage and its role in the electricity grid.

3.1.2 Energy storage technologies (EST)

Energy storage technologies can be divided into four different areas. These are electrochemical storage, mechanical storage, chemical storage and thermal storage. Different energy storage systems have been divided into these different groups depending on how the technology works. Depending on the different environmental conditions and what properties you are looking for they are different in different things. Therefore, it is important to talk about the pros and cons of the different technologies, comparing them in different situations. A combination of different storage technologies may be the future solution for the problems that energy storage can solve. When comparing and choosing energy storage technologies, the most important variables are: Energy density, cost, efficiency, start - up time, scalability and sustainable development (Gustavsson, 2016).

3.1.3 Electrochemical energy storage (ECES)

Electrochemical energy storage is a collective name for all energy storage using batteries. The stored energy can be converted to electrical energy. Batteries have the advantages that they can be easily transported and used anywhere in the world. They also have a very short start-up time. There are batteries that can be recharged and those that can only be used once. In the area of large-scale energy storage, rechargeable batteries are the only ones that are interesting. Batteries can easily convert the stored energy into electric energy with a low start-up time (Gustavsson, 2016).

3.1.3.1 Lithium ion batteries (LIB)

The lithium ion battery is the most common type used. It consists of a positive electrode (cathode) of lithium oxide, a negative electrode (anode) consisting of graphite. Between them there is an electrolyte of lithium salt and an organic solvent (Andrews, et al., 2013). The efficiency of the lithium battery is usually over 90% (Jernkontorets energihandbok, 2018). Lithium has a low density and high energy content which gives the battery high energy content per kg lithium (Gustavsson, 2016). It also has a high energy density of 1,08 GJ/m^3 or 300 kWh/m^3. The low density along with the high energy density makes it convenient to use in small electronic devices such as mobile phones, iPads and walkie talkies. The batteries are also used to some extent in the automobile industry for electric vehicles. Lithium batteries are used on a very large scale and the use has risen sharply in recent years (Wolf, 2014).

As electric cars are becoming increasingly popular, there will be a shortage of lithium. Therefore, not all batteries can be lithium (Narins, 2017). Also, mining of lithium causes some environmental damaging effects like destroying surrounding water and environments. In a sustainable development view, that’s not very good. New solutions need to be invented in the future (European Comission, 2012).

3.1.3.2 Sodium sulphur batteries (SSB)

Sodium sulfur batteries consist of two active materials, molten sulfur as the positive electrode and molten sodium as the negative electrode. A sodium alemina works as an electrolyte that separates the two (Energy Storage Association, 2018). Both of these materials have a low cost and weight (Andrews, et al., 2013). The battery has a long life, a high energy density of 540-864 MJ/m^3 or 150-250 kWh/m^3, and a high efficiency of typically 89% (Luo, et al., 2015) (Energy Storage Association, 2018). All of these features make the battery attractive for large-scale energy storage systems. At a project called Reunion Island Pegase Project, the power is up to 1 MW and the battery can provide energy to 2000 households (Sandia National Laboratories, 2014).

3.1.3.3 Lead acid batteries (LAB)

Lead acid batteries were invented in 1859 and it was the first rechargeable battery. It consists of lead oxide (PbO2) cathodes and lead (Pb) anodes. They are immersed in sulfuric acid (H2SO4) with cells connected in series. The inventor was a french man named Gaston Planté (Moseley, et al., 2014). It has an overall efficiency of 85% which is quite high (Solar-Facts, 2018). The energy density is quite low compared to other batteries, but it has the advantage of creating a big current. This is useful in applications like starting a car (Andrews, et al., 2013). This technique is also used in backup power supplies, emergency lighting, personnel carriers, golf cars and wheelchairs (Battery university, 2016). Lead which is toxic both for nature and for humans can cause great damage if not handled properly. However, it can be recycled several times and is the most reused product in the world. Given that the product is recycled, it is harmless for nature as well as for people (Battery Council International, 2016). The energy density is 252 MJ/m^3 or 70 kWh/m^3 (Wolf, 2014).

3.1.3.4 Redox flow batteries (RFB)

In redox flow batteries, two electrolytes are pumped to the opposite side of an electrochemical cell. The two masses stay dissolved so no phase change takes place. They are both contained in two separate large tanks. The ions undergo reduction- or oxidation reactions when they are in contact, or near the current collector. A membrane between the two masses allows transport of non-reaction ions to maintain the electrolyte balance and neutrality (Giddey, et al., 2014). The power density from the electrochemical cell is defined from the size and design (Wang, et al., 2013). The pros of this battery are that it has a high efficiency of 75-85%, a long lifetime and an ability to store a large amount of energy (de Leon, et al., 2006). The cons are that it needs a good amount of techniques like pumps, sensors and control units (Sandia National Laboratories, 2016). Energy density for this battery is about 90-126 MJ/m^3 or 25-35 kWh/m^3 (Luo, et al., 2015).

3.1.4 Mechanical energy storage (MES)

Common to all types of mechanical energy storage techniques is that you convert kinetic energy into electrical energy by means of physical movements. The most common technologies in this field are compressed air technology and pumped hydro storage. Liquid air energy storage is a variant of compressed air where you make it liquid instead (Kyriakopoulos & Arabatzis, 2016).

3.1.4.1 Compressed air energy storage (CAES)

Compressed air energy storage is based on pumping air to a reservoir using an electrical source. This is done when there is a low need for energy, and is later used when there is a greater demand for energy (Andrews, et al., 2013). The storage of the compressed air can occur adiabatically or diabatically (Cleveland & Morris, 2006). The compressor compresses the air to make it warm. A radiator then transports the heat from the compressor. When you expand the air again to convert the energy, the air becomes cold. You need to heat this air before expanding it in a turbine. This is done by burning with fossil or biofuels. If the process is adiabatic, the heat from the processor is stored and will be returned to the air when it expands. This leads to higher efficiency with an increase of about 20%. The process will then also be CO_2 neutral when you do not need to burn with fuel. The stored heat will in reality lose some energy due to heat losses. A CAES needs about 10 minutes to start-up which is relatively low. At present, there are only two power plants that use this type of technology. The oldest is in Huntorf, Germany with a capacity of 320 MW that was built in 1978. The newer was put into operation in 1991 and has a capacity of 110 MW. It is located in McIntosh, USA. Both of these power plants are operated diabatically, which means that fuel needs to be burned to heat the air during expansion. This results in a lower efficiency that is 42% respectively 54% for the two power plants. The energy density is very low for CAES around 7-22 MJ/m^3 or 2-6 kWh/m^3. This means that you need very big reservoirs when using it (Moseley & Garche, 2014).

3.1.4.2 Pumped hydro energy storage (PHES)

Pumped hydro energy storage systems are connected to a hydroelectric system. When the demand of energy is low, a pump uses energy to pump water uphill in a reservoir. Later when the demand is higher again, water is released and drives a generator that can produce electricity (Andrews, et al., 2013). A PHES system helps to avoid using expensive backup power plants. PHES has the largest storage capacity and the biggest efficiency compared to all other TES. The efficiency is around 70-85% (Mahlia, et al., 2014). The start-up time is really low which makes it able to respond fast to a sudden surge in demand (Andrews, et al., 2013). The system has geographical restrictions, and needs major quantities of water. The energy density is 1,00 MJ/m^3 or 0,28 kWh/m^3 at 100 metres height (Wolf, 2014).

3.1.5 Chemical energy storage (CES)

A chemical storage system stores energy in the bonds of molecules. Endothermic reactions require energy to create the various chemical bonds, while exothermic reactions release energy from the chemical bonds. This is utilized and you save the chemical, until you need to use it. Because the energy is in the bonds, and the molecules do not react without added energy, there are no losses in the storage process. This is a major advantage of this technology. One disadvantage is that in general, the energy being converted is of a low quality, in terms of heat (Gustavsson, 2016).

3.1.5.1 Hydrogen

Hydrogen (H_2) can be formed by transforming natural gas with steam, or by electrolysis with water. The first has a greater efficiency, but does not go well with sustainable development as there will be a greater amount of CO_2 in the atmosphere (Amid, et al., 2016). A water molecule (H_2O) consists of two hydrogen atoms and an oxygen atom, attached to each other. When you make hydrogen and oxygen with electrolysis, energy is added to a water molecule, which divides itself into hydrogen and oxygen. The system has then taken up energy, and stored it in these two chemical components. What happens is a redox reaction that forms oxygen at the anode, and hydrogen at the cathode (Moseley & Garche, 2014). To store the hydrogen, an increase of pressure is needed to make it dense and then stored in a container. You can also liquefy the hydrogen which takes a much smaller amount of space (Energy Storage Association, 2018). When energy is needed, hydrogen can be burned in a combustion engine to produce heat, or used in a fuel cell to produce electricity (Wolf, 2014).

Hydrogen is explosive if mixed with oxygen to form a mixture with the correct oxygen-to-hydrogen ratio. To explode, a heat source is needed that is large enough to reach the activation energy. Compared to other liquids and gases, hydrogen is quite similar in how flammable it is. Gasoline also creates vapors that are flammable. In an open environment, the hydrogen gas often evaporates quickly and disappears from the ground, causing the fire to disappear upwards. In confined spaces, the hydrogen gas remains and can cause more damage if it starts to burn (NyTeknik, 2013). The energy density of hydrogen is 576 MJ/m^3 or 160 kWh/m^3 at 700 bars of pressure and the efficiency is between 20-50% depending on the technique (Zhang, et al., 2016).

3.1.5.2 Methane

Methane can be produced from a multi-step process. First you divide the water molecule that turns into hydrogen and oxygen. Then you follow a process called the Sabatier process where hydrogen reacts with carbon dioxide and forms methane. This is also called methanation.

Methane is easy to store and can also be mixed with stored natural gas. Both the water and the carbon dioxide are reused in the process (Sterner, 2009). The energy density of methane is 23,5 MJ/m^3 or 6,5 kWh/m^3 (Neutrium, 2014). Both the electrolysis and methanation form heat. This should be taken care of and stored in some form of energy storage. This would make the whole process more efficient and provide a benefit to the public through heat supply. The efficiency for the whole process is between 28-45% (Sterner, 2009).

3.1.6 Thermal energy storage (TES)

Thermal energy storage is a collective name for all technologies where heat energy is stored in a medium. You can also do the opposite where you cool down a medium, to store a lack of heat energy. When you then need the heat energy, you let the medium pass a heat exchanger where the medium absorbs or emits the heat energy to another medium. The technologies that will be addressed are sensible heat storage, latent heat storage, thermo-chemical energy storage and cryogenic energy storage (Akeiber, et al., 2016).

3.1.6.1 Sensible heat storage (SHS)

With sensible heat storage, you heat either a liquid or solid material to store the thermal energy (Bruel, et al., 2013). The thermal energy is based on energy difference between the medium and the ambient temperature (Gustavsson, 2016). The liquid that has the largest specific heat is water, so it's frequently used. In this case you store water in a tank and allow cold water to pass into the bottom of the tank. At the bottom water is extracted and circulated and heated by solar energy outdoors. When the water has a higher temperature, it flows into the upper part of the tank again. Since water has the property of having a lower density at a high temperature, it will be warmer at the top of the tank and colder at the bottom. This makes it natural depending on temperature and if you need to pick up warm water, you can remove it from the top of the tank (Gang, 2015). Advantages of the technology are that it has a long service life, can be stored for a long time and is cost effective (Kyriakopoulos & Arabatzis, 2016) (Gustavsson, 2016). The disadvantages are that it needs to be stored in large volumes and has a heat loss to the environment during storage (Kyriakopoulos & Arabatzis, 2016) (Gang, 2015). To prevent heat losses to the environment, a lot of insulating material is used. Due to heat losses to the surroundings, this results in an efficiency between 50-90%. The energy density is 90 MJ/m^3 or 25 kWh/m^3 (Gustavsson, 2016).

3.1.6.2 Latent heat storage (LHS)

Latent heat storage technology involves storing a material that is close to its phase change. This is called a phase change material (PCM). The material changes phase at its phase change temperature (PCT). Technically, it works so that the chemical bonds in a material absorb energy and break the bindings at the phase change temperature. This is an endothermic reaction as the material takes up energy from the environment. When energy is needed, you let the temperature go below the phase change temperature and the material will emit energy in an exothermic reaction and become solid (Kalnaes & Jelle, 2015). This technique also allows you to store cold. The only thing you do differently is to let the reaction go in the opposite direction. In addition to the phase change between solid-liquid there is also gas-solid and gas-liquid. The phase change enthalpy change is greater than the difference in enthalpy between the two temperatures in SHS. This results in higher energy density in LHS than SHS. The efficiency ranges between 75-90% and the energy density is 360 MJ/m^3 or 100 kWh/m^3 (Gustavsson, 2016).

3.1.6.3 Thermo-chemical energy storage (TCES)

Thermo-chemical energy storage is based on storing energy in chemical components. It's first a chemical substance formed of two other chemical substances. By adding heat you can break the bond between them. They then form two separate substances that can be stored separately. When you need energy, you add these two together and heat is released (Gustavsson, 2016). The difference with this technique compared to SHS and LHS is that there are no energy losses to the environment (Zhang, et al., 2016). The efficiency is high and is somewhere between 75-100%. Energy density is one of the highest of all storage technologies. It is somewhere between 432-900 MJ/m^3 or 120-250 kWh/m^3. This makes this technology a great potential energy storage technology for the future. However, research is still lacking and the necessary technology still needs to be developed (Gustavsson, 2016).

3.1.6.4 Cryogenic energy storage

A cryogen is a liquid that boils below -150°C, for example nitrogen, hydrogen or air. Cryogenic energy storage is different from other thermal storage because the temperature is *decreased* in the cryogen which is used as storage medium. This is good because it is possible to extract more work from the same material 100°C below the ambient temperature than 100°C above it. The energy is stored both as sensible heat from the temperature change and latent heat from the phase change. The energy stored in the cryogen can be recovered for example by expansion in a turbine to generate electricity. The energy density of cryogens is relatively high compared to other storage method, in the hundreds of MJ/m^3. An advantage of cryogens as energy storage is that they can be used to recover low grade heat (<150°C). It is not a fully matured technology so it is hard to give an exact efficiency, but it is low compared to many other storage methods, somewhere between 20 - 60% for the matured technology (Li, et al., 2010).

3.2 Liquid air energy storage (LAES)

3.2.1 LAES Process

LAES is a cryogenic energy storage that consists of three parts, charging, storing and discharge. When excess energy is available it is used to liquefy air (Yulong, et al., 2016). One way to do this is via a Claude cycle where air is compressed to supercritical pressure, then cooled to about 100K and then expanded to cool it further (Chino & Araki, 2000). Another way is the Linde cycle with 5 steps; 1. Air is heated through compression, 2. Cooled by the ambient, 3. Cooled through heat exchanger with cold from stage 5, 4. Cooled through expansion. 5. Heated when used as coolant for step 3 and sent back to step 1 (De Waele, 2017). Figure 1 (from place A to place I) shows a variant of a Linde cycle. In actuality more complex cycles are used and in the industry about 1080 kJ are needed to liquefy 1 kg of air (Ameel, et al., 2013). These cycles have low thermodynamical efficiency partly because a lot of cold is lost to the environment. The efficiency can be greatly increased if recycled cold can be used (Morgan, et al., 2015).

The liquid air is stored until needed in well isolated tanks (Yulong, et al., 2016).
Losses from storage are low, 2,08*10^-5/h (Morgan, et., 2015) so this part of the process has not been researched so well.

When energy is needed (high demand or no sun or wind) the energy stored in liquid air is discharged (Yulong, et al., 2016). To recover the energy many methods can be used. The most straight forward is the Rankine cycle used in normal steam power plants, but with air as the working fluid instead of water. The standard Rankine cycle with water and steam has four stages; 1. Increase pressure of the working fluid. 2. The fluid is heated by an external heat source (burning fossil fuels, nuclear energy or concentrated solar for example) until it boils to create dry saturated vapour. 3. Expansion of the vapour in a turbine to create electricity, 4. Condensation of the wet vapour (Havtun, 2014). The Rankine cycle with stored liquid air is the same in principle but the practicalities are very different because of the low boiling point of air compared to water. In stage 2, the air can be heated by the ambient instead of an external heat source and in stage 4 the air is released into the atmosphere instead of reliquefied.

3.2.2 LAES Research

Liquid air was first proposed as an energy carrier in 1977 (Yulong, et al. 2016). Since then, quite a lot of research has been done about the topic. Chino & Araki (2000) note that the advantages of liquid air as energy storage medium is its high energy density and that it can be stored at atmospheric pressure, reducing storage costs. Using liquid air to improve combustion in a gas turbine is suggested as an efficient way to discharge the energy.

Li, et al. (2010) explore the potential of cryogens in general as energy carriers. They point out that an advantage of using cryogens in thermodynamic cycles is that they can be used to recover low grade heat. They also claim exergy is better to use than energy to evaluate cryogenic energy storage. One of their conclusions is that a Brayton cycle to extract energy from cryogens is a good option if high grade heat is available. If only low grade heat is available, a Rankine cycle is better.

Ameel, et al. (2013) calculate a round trip efficiency of LAES from 20 - 50% which is comparable to hydrogen storage and CAES. They claim that a Rankine cycle has an efficiency of 36,8% if waste heat at 300 K is available and compression and expansion are isothermal. A combined Linde cycle to liquefy air and a Rankine cycle has an efficiency of 43,3% and this is very sensitive to the efficiency of the heat exchangers and compressors. If compression and expansion are not isothermal the efficiency drops to 22%.

Morgan, et al. (2015) evaluated a pilot power plant using LAES. The pilot plant is in Birmingham and of the scale around 500 kW and has all three stages, liquefaction, storage and discharge. It uses a combined Linde and Rankine cycle for charging and discharge. This means that during charging, heat from the compression of air is stored until needed during discharge. Also, the cold from evaporation and heating to ambient temperature during discharge is stored and used in charging. They first did theoretical modeling and concluded a maximum theoretical round trip efficiency for the powerplant of 76% with infinite charging pressure and 50 bar discharge pressure and 65% with both pressures 50 bar. The actual measured round trip efficiency for the pilot plant was 8%. This big discrepancy was because of several reasons; the plant is small in scale, it only recycles half the cold, the heat from compression is not recycled and low charging (13 bar) and discharge pressures (60 bar) were used for economical reasons. They also discussed scaling up and economic aspects of LAES. They concluded that a scaled up mature LAES technology could achieve above 50% round trip efficiency and be competitive to other storage techniques. One advantage with LAES is that the components needed are technically mature and relatively cheap.

Sciacovelli, et al. (2017) made dynamic modeling of a 100 MW LAES power plant with a 300MWh storage capacity. They used EES software, COMSOL and MATLAB to model different parts of the process. They stressed the importance of correctly modelling the relation between component and system level efficiency. They concluded that charging pressure, discharging pressure and effective cold recycle are the most important variables for a high round trip efficiency. They validated the model with data from the Birmingham Pilot plant and got a good match between predictions and data. Their estimation of efficiency is also around 50% with heat and cold recycle.

The energy density of liquid air depends on how you define it and different sources give different numbers. In this report, 442 kJ/kg or 385 MJ/m^3 (107 kWh/m^3) which is the energy needed to liquefy the air and cool it to 75K is used. Note that how you define this does not affect the round trip efficiency but affects the relative efficiencies of the liquefaction and discharge cycles.

The reported round trip efficiency of LAES range from 8% in an existing pilot pant to 65% under very optimistic assumptions. The latest and most ambitious model found (Sciacovelli, et al., 2017) a round trip efficiency of about 50%.

3.2.3 LAES and sustainable development

A detailed economical analysis of LAES is beyond the scope of this report but some basic ideas are important to present. The comparably low round trip efficiency is the biggest economical problem for LAES but as long as there is a lot of (cheap) excess energy available at off peak hours, this is not a huge problem (Giuseppe, et al., 2015). The efficiency can also be increased, thereby lowering the cost per kW, if high grade waste heat is available from for example power production or other industries (Ameel, et al., 2013).

The investment costs are around 400 - 2000 USD / kW depending on where the plant is built, wage levels, climate and environmental considerations (Giuseppe, et al., 2015). One reason the investment costs are not higher is that the components needed are mature and manufactured in large scale (Morgan, et al., 2015). The maximum scale is in the order of hundreds of megawatts which is a little lower than CAES and a lot lower than pumped hydro and much higher than batteries and hydrogen storage. The lifetime of the components is 20 - 60 years which can be compared to that of batteries, 5 - 15 years (Yulong, et al., 2016).

The relatively high energy density of LAES means less physical space is needed for storage (compared to pumped hydro for example) which is good from a sustainability perspective. LAES does not require any environmentally hazardous materials and does not produce any toxic waste (Giuseppe, et al., 2015).

Compared to hydrogen which is highly inflammable LAES is safer and therefore better from a social sustainability perspective (Yulon, et al., 2016). But, handling liquid air which contains liquid oxygen can also pose safety risks as pure oxygen pose fire and explosion risks. This can be managed fairly effectively and safely though, for example by using well insulated systems, monitor the oxygen content in the liquid air and by keeping organic material away from where oxygen enrichment occurs. Also, the very low operating temperatures can be hazardous to both people and materials (Centre For Low Carbon Futures, 2013).

4. Results

The results are, unless stated otherwise, calculated with the constants and parameters in tables 1 and 2.

4.1 Round trip efficiency without heat and cold recycle

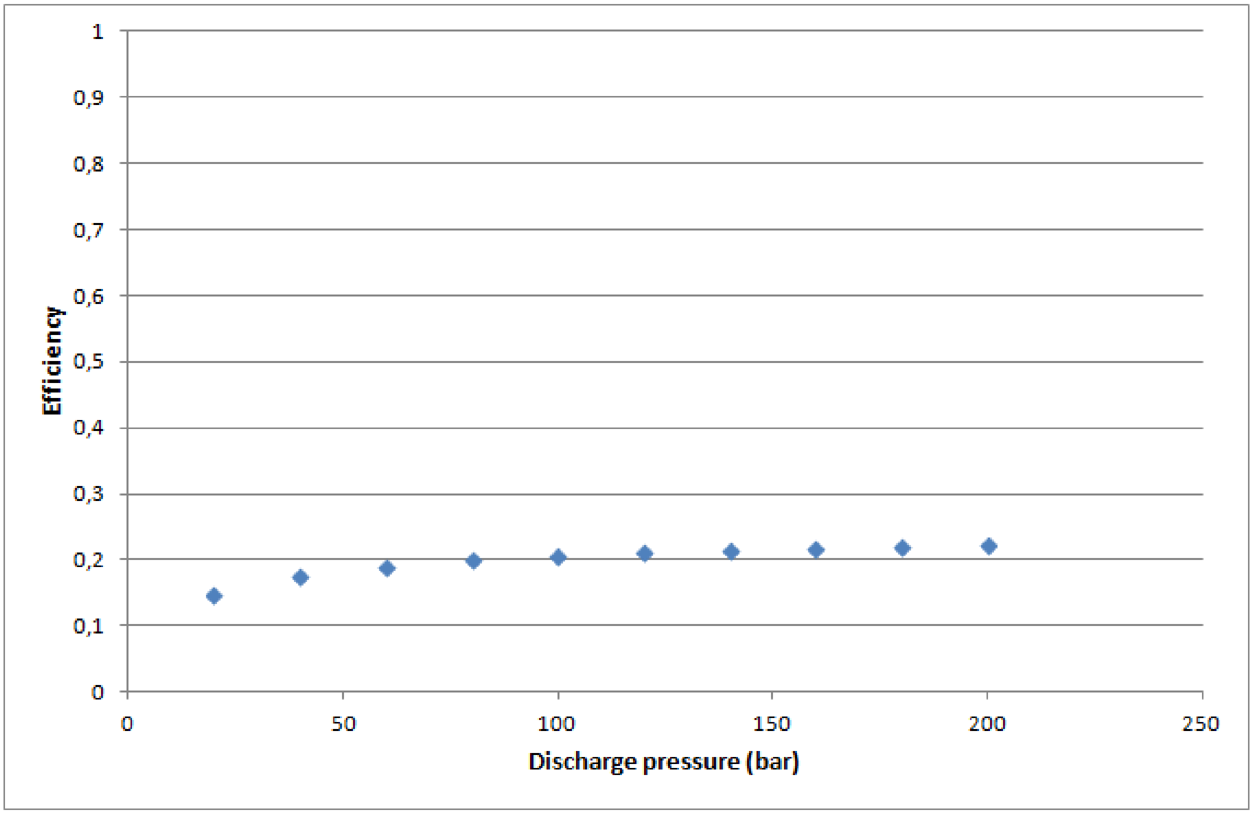


Figure 2: Round trup efficiency as a function of discharge pressure.

Figure 2 shows round trip efficiency as a function of discharge pressure, P(2) in the model (see section 2.2.3 The combined liquefaction and discharge cycle). P(B) is constant 16,6 bar which gives the highest liquefaction efficiency. The efficiency increases with discharge pressure. Pressures above 200 bars are not included as this is assumed the maximum pressure the equipment can tolerate. From now on, in the further results, the discharge pressure:
P(2) = 150 bars.

With access to waste heat the discharge efficiency increases increasing the round trip efficiency:

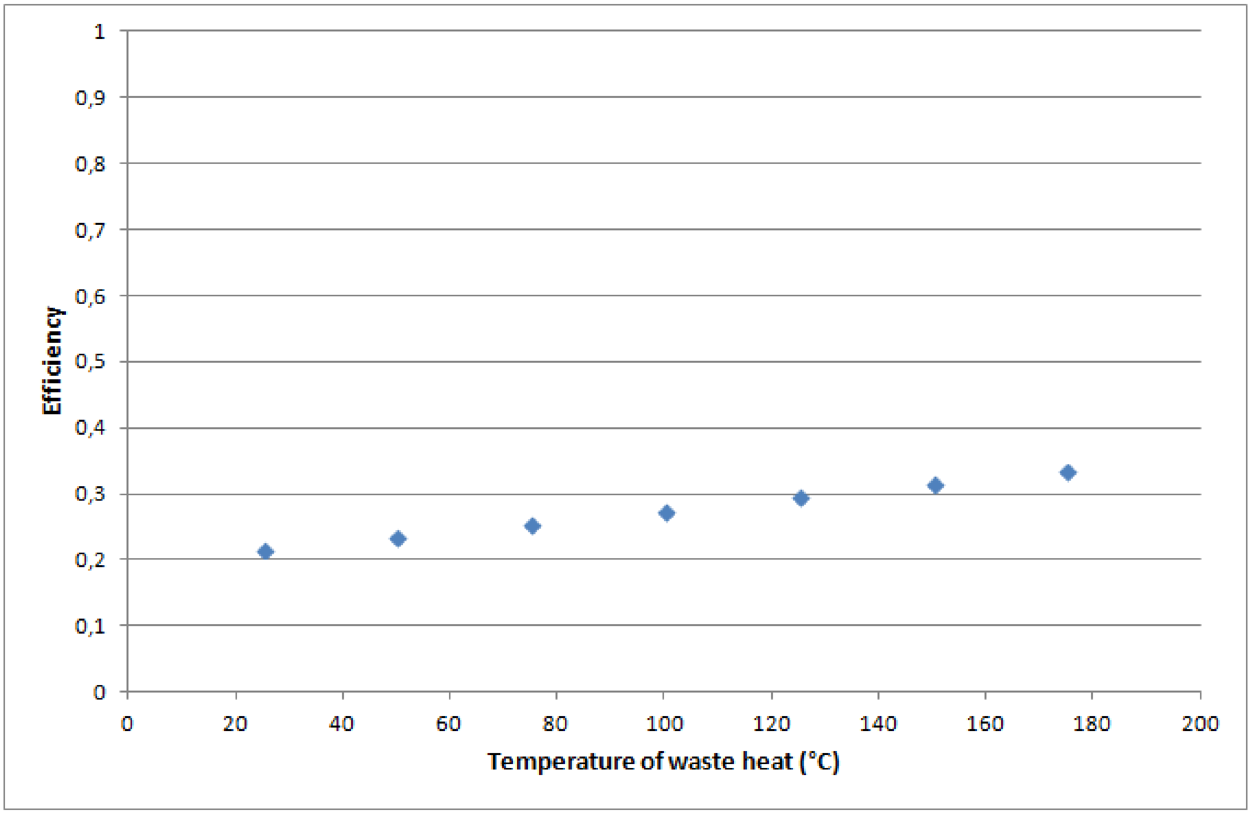


Figure 3: Round trup efficiency as a function of waste heat temperature.

Figure 3 shows how the round trip efficiency can be increased with access to waste heat. Note that when the temperature is 25 °C the temperature difference between the waste heat and the ambient is 0.

With access to waste cold the liquefaction efficiency increases, improving the round trip efficiency:

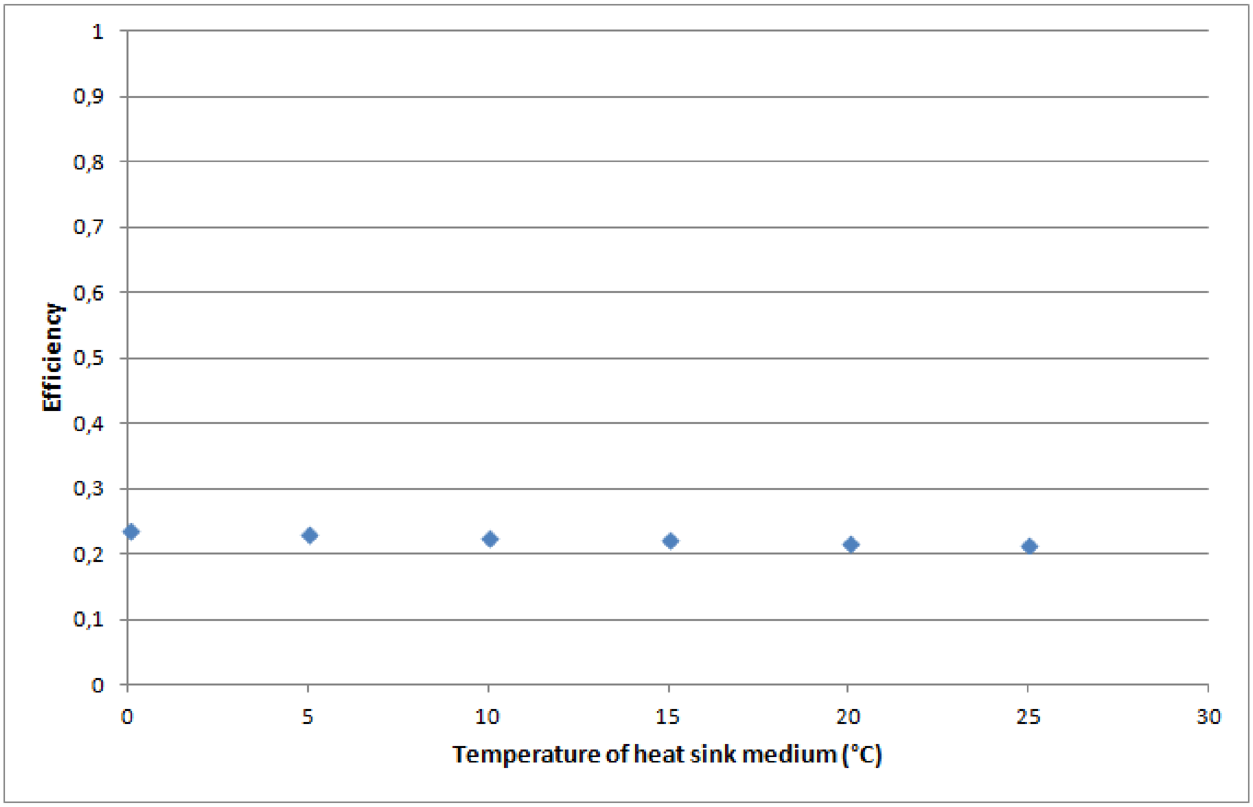


Figure 4: Round trup efficiency as a function of heat sink temperature.

Figure 4 shows how the efficiency can be increased with access to waste cold. With access to waste cold the optimal P(B) changes slightly from 16,6 bar at 25 °C to 15,7 bar if waste cold at 0°C is available. The efficiency increase is modest but probably relatively easy to achieve. Without cold heat sink medium, the efficiency is 21,6% and with heat sink medium at 5 °C the efficiency is 23,1%.

4.2 Round trip efficiency with heat and cold recycle

If heat and cold is stored and recycled between the two cycles, both liquefaction and discharge efficiency increases:

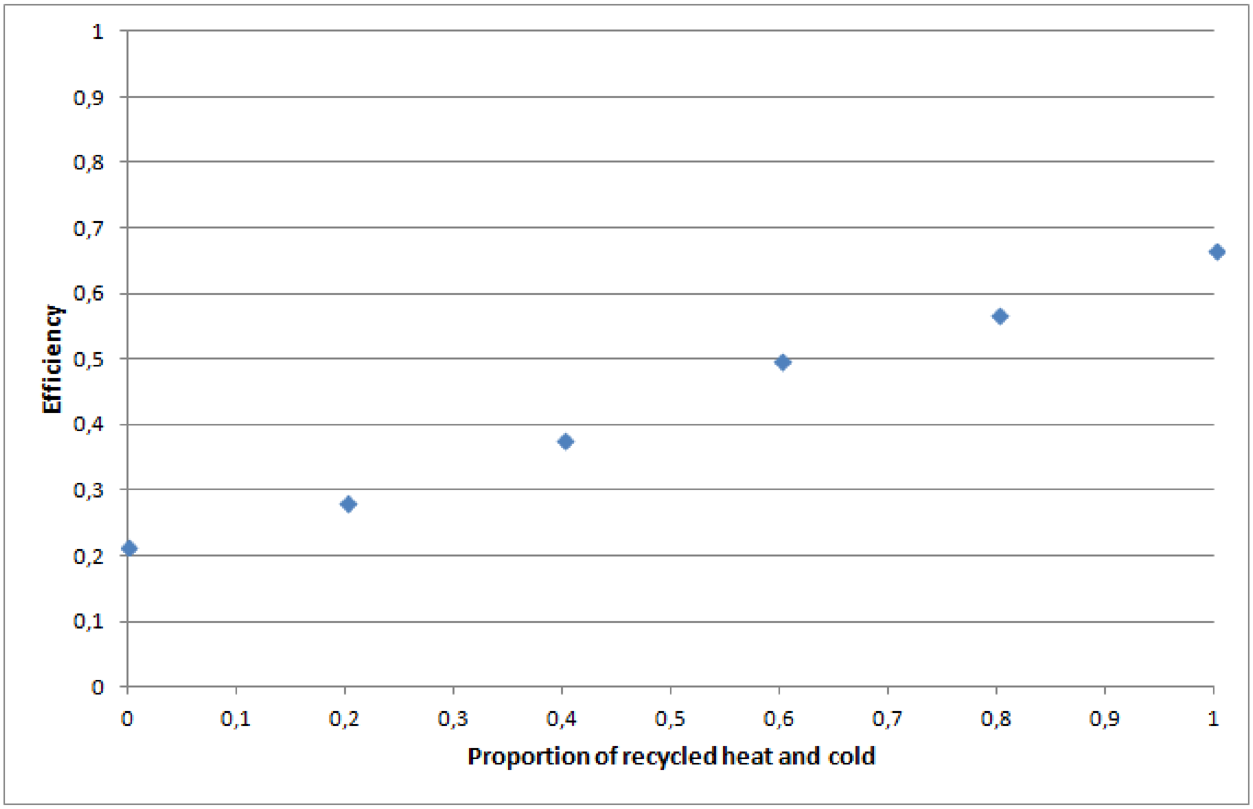


Figure 5: Round trup efficiency as a function of hot and cold recycle.

Figure 5 shows round trip efficiency as a function of $H_{,rec}$ and $C_{,rec}$, the percentage of heat and cold that is stored and recycled between the two cycles. A percentage of recycle at 100% is not practically possible. Also, we do not trust the model under these extreme conditions. The optimized solution means cooling to 88K in (A) which is not reasonable in reality. This also means that P(B) = 86 bar and almost all the compression is done by the first compressor. If 80% of heat and cold can be recycled we trust the model. This is because almost all the recycled cold is used in $HE_{I,3}$, only marginally lowering T(A) and increasing P(B).

From now on, when heat and cold recycle is active, the assumption:
$H_{,rec} = C_{,rec} = 0{,}6$ is used (See section 2.2.2 Set parameters).

4.3 Implementation of a heat pump

A heat pump is added to the model. The main reason is that the temperatures in the turbines become too low which could damage them. This could be solved by heating the air by means of the heat pump before it enters the turbines so that the temperature does not get so low as it is expanding. With some powers for the heat pump, the efficiency increases slightly. However, these graphs should be interpreted as meaning that we want to check how much the efficiency is affected by the need to add a heat pump, not as if we use the heat pump to try to maximize the efficiency of the cycle.

4.3.1 Heat pump with no heat and cold recycle

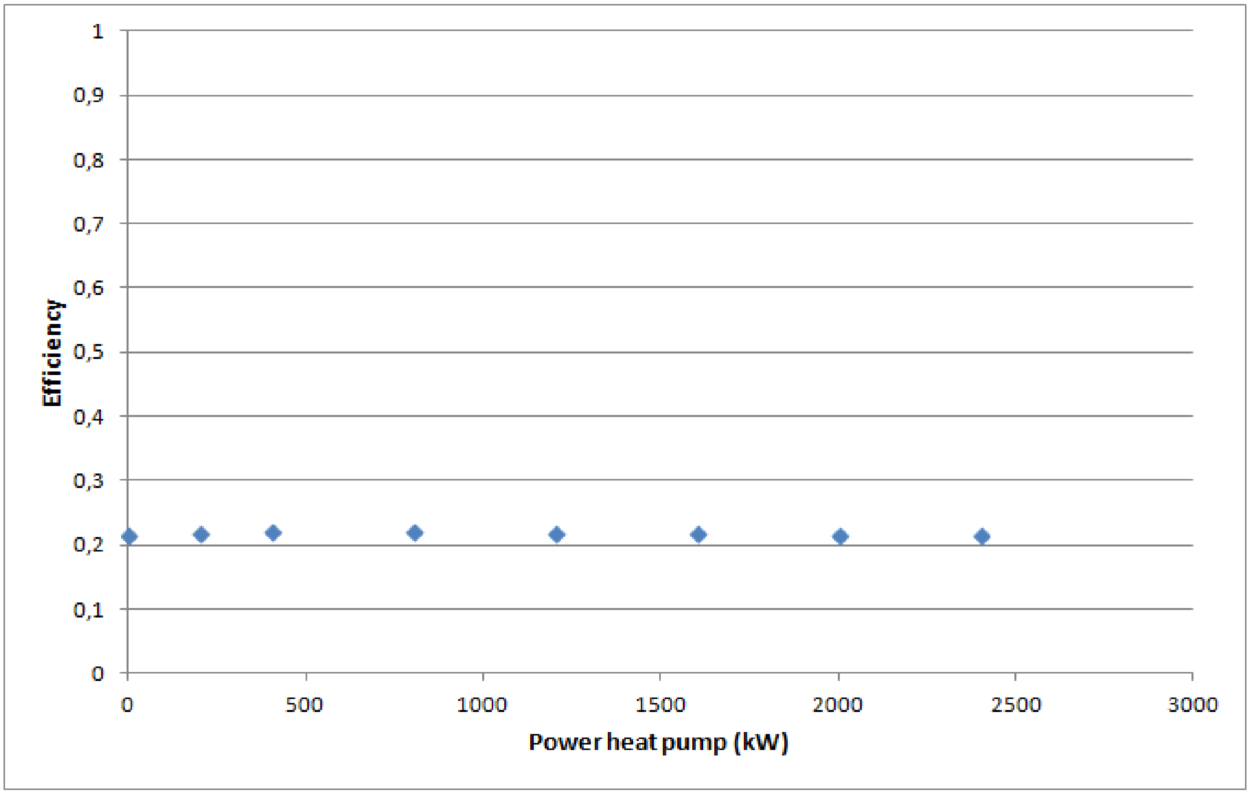


Figure 6: Round trup efficiency as a function of power heat pump.

Figure 6 shows how the round trip efficiency varies with the power of the heat pump where HP,$_{T,hot}$ and HP,$_{T,cold}$ are optimized to maximize round trip efficiency. A higher HP,$_{T,hot}$ and lower HP,$_{T,,cold}$ means higher grade heat/cold but decreases the COP1 and COP2. The efficiency is minimally affected by the heat pump's power. A heat pump produces cold and heat that increase efficiency but also needs energy which decreases it.

4.3.2 Heat pump with heat and cold recycle

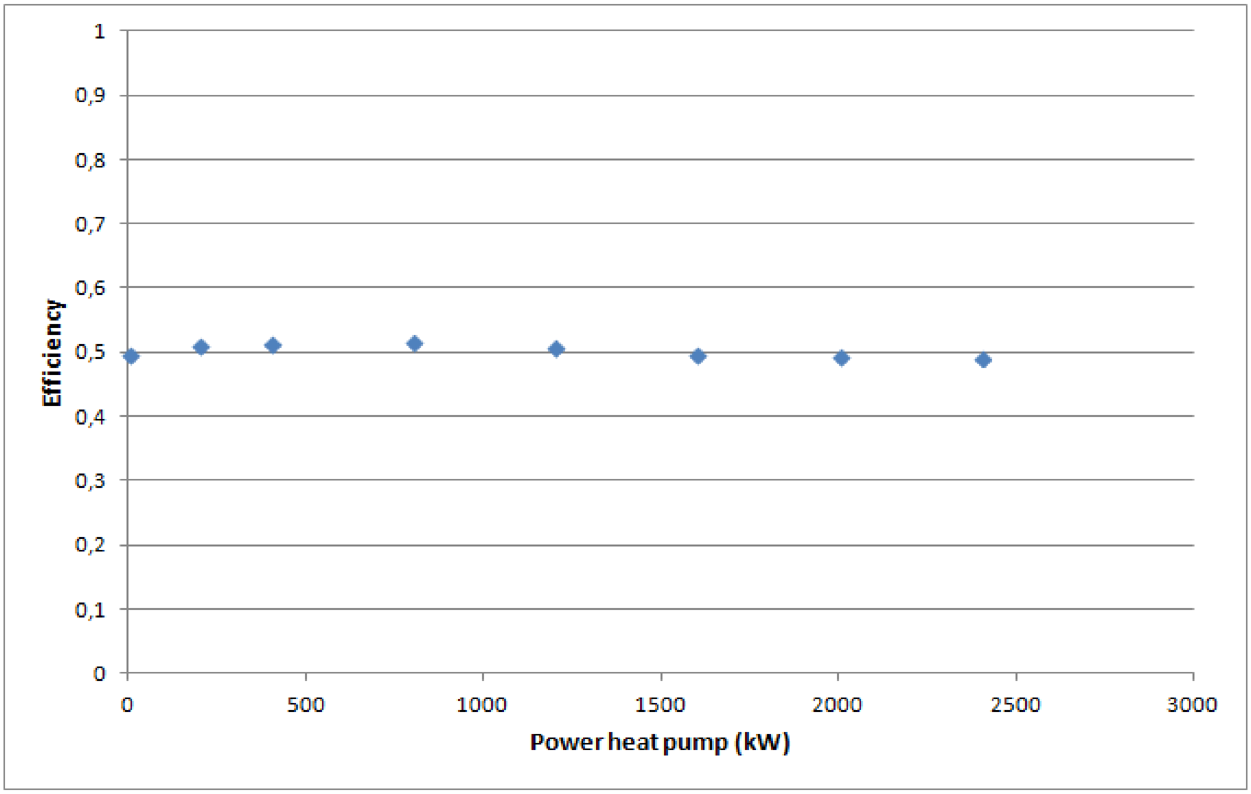


Figure 7: Round trip efficiency as a function of power heat pump with heat and cold recycle.

Figure 7 shows round trip efficiency as a function of heat pump power. In this graph, hot and cold recycle = 0,6 is added. The efficiency changes marginally with the size of the heat pump also when there is hot and cold recycle. But the optimal parameters change more.

Figures 6 and 7 can be interpreted as implementing a heat pump does not affect efficiency too much. Because very low temperatures could be damaging to the turbines, a small heat pump that increases the temperatures before and between the turbines could still be useful to the process.

4.4 Results details

Below, in table 3 and figure 8 the reader can follow the temperature and pressure of the flow during the entire combined cycle with $H_{,rec} = C_{,rec} = 0,6$. The work and heat flow in the components are also shown:

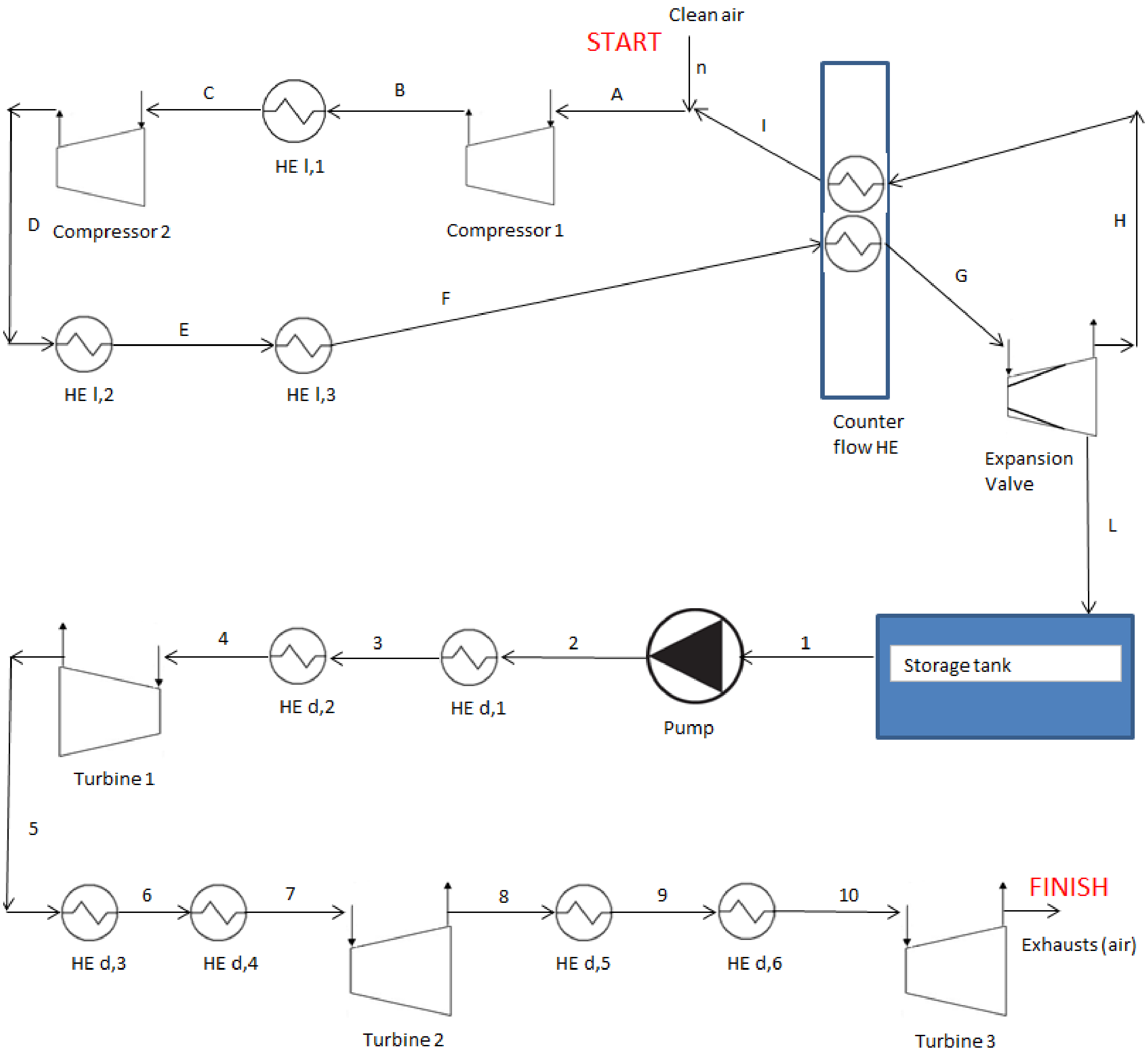
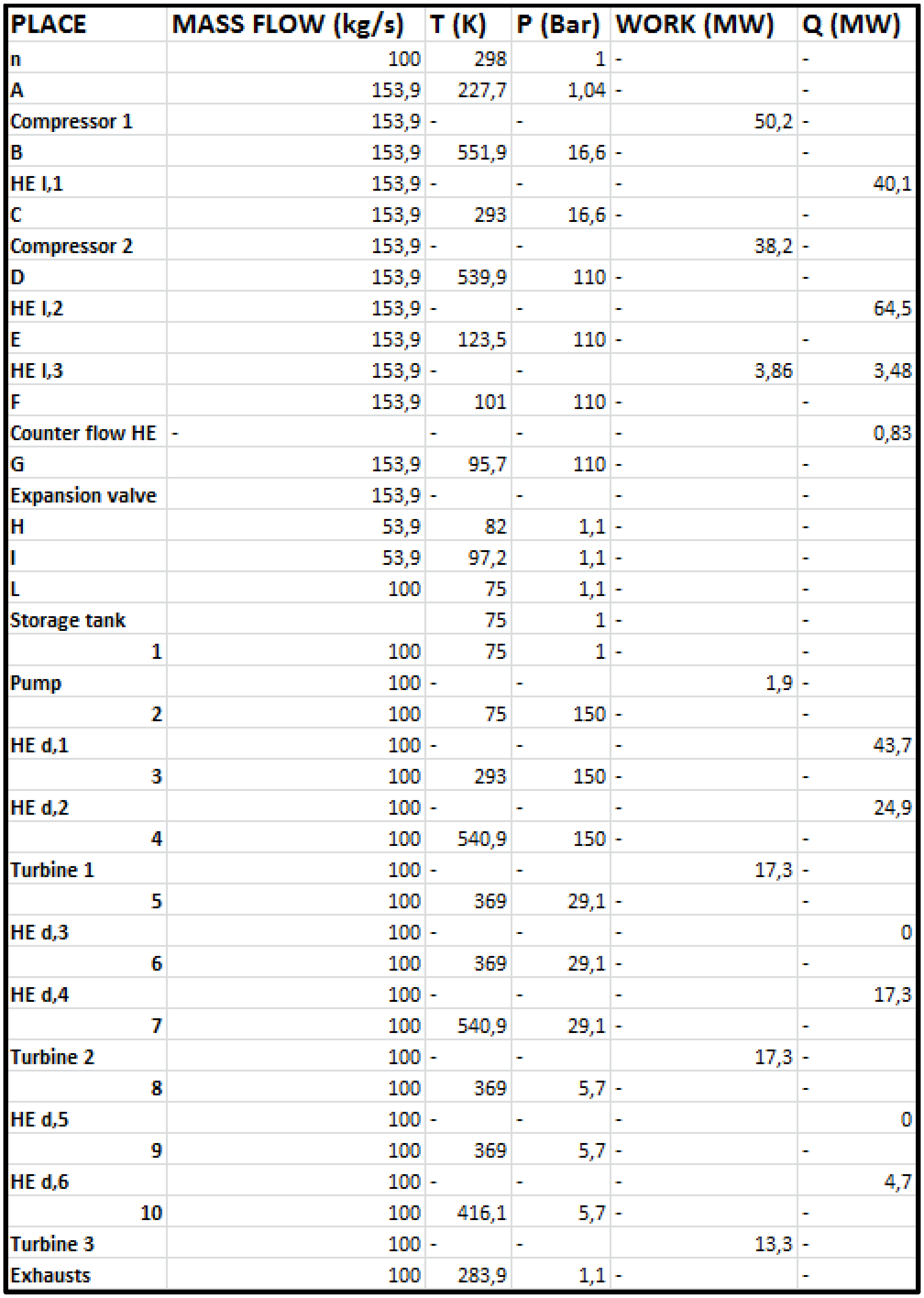


Figure 8: Schematics of the combined liquefaction and discharge cycle.

Table 3: Results details.



PLACE	MASS FLOW (kg/s)	T (K)	P (Bar)	WORK (MW)	Q (MW)
n	100	298	1	-	-
A	153,9	227,7	1,04	-	-
Compressor 1	153,9	-	-	50,2	-
B	153,9	551,9	16,6	-	-
HE l,1	153,9	-	-	-	40,1
C	153,9	293	16,6	-	-
Compressor 2	153,9	-	-	38,2	-
D	153,9	539,9	110	-	-
HE l,2	153,9	-	-	-	64,5
E	153,9	123,5	110	-	-
HE l,3	153,9	-	-	3,86	3,48
F	153,9	101	110	-	-
Counter flow HE	-	-	-	-	0,83
G	153,9	95,7	110	-	-
Expansion valve	153,9	-	-	-	-
H	53,9	82	1,1	-	-
I	53,9	97,2	1,1	-	-
L	100	75	1,1	-	-
Storage tank		75	1	-	-
1	100	75	1	-	-
Pump	100	-	-	1,9	-
2	100	75	150	-	-
HE d,1	100	-	-	-	43,7
3	100	293	150	-	-
HE d,2	100	-	-	-	24,9
4	100	540,9	150	-	-
Turbine 1	100	-	-	17,3	-
5	100	369	29,1	-	-
HE d,3	100	-	-	-	0
6	100	369	29,1	-	-
HE d,4	100	-	-	-	17,3
7	100	540,9	29,1	-	-
Turbine 2	100	-	-	17,3	-
8	100	369	5,7	-	-
HE d,5	100	-	-	-	0
9	100	369	5,7	-	-
HE d,6	100	-	-	-	4,7
10	100	416,1	5,7	-	-
Turbine 3	100	-	-	13,3	-
Exhausts	100	283,9	1,1	-	-

Worth noting in Table 3 is that in the solution from the Excel solver that optimizes round trip efficiency compressor 1 has a higher compression ratio and does more work (50,2MW) than compressor 2 (38,2 MW). This is because the air in A is cooled by recycled air and it requires relatively less work to compress cooler air, thus it is more efficient to do more of the compressing here. Worth noting is also that the heat exchanger $HE_{l,3}$ in the liquefaction cycle requires work (3,86MJ) to lower the temperature from 123,5K to 101K. The heat transfer in $HE_{l,3}$ is slightly lower (3,48MJ) because the efficiency of that heat exchanger, ε_f = 0,9. Also note that with this level of heat recycle, $HE_{d,3}$ and $HE_{d,5}$ which heat the flow to ambient temperature after the expansions are not active as there is so much heat applied before turbine 1 and turbine 2 that the temperature after expansion is higher than $T_{,amb}$.

4.5 Sensitivity analysis

There are many assumptions used in the model, therefore a sensitivity analysis is included with a lower bound, the standard scenario and a higher bound. The heat pump is not active in the sensitivity analysis and $H_{,rec}$ = $C_{,rec}$ = 0,6.

Table 4: Sensitivity analysis.

Lower bound		**Standard**		**Higher bound**	
η_K	0,8	η_K	0,85	η_K	0,9
ε_f	0,8	ε_f	0,9	ε_f	0,95
ε_h	0,8	ε_h	0,9	ε_h	0,95
η_E	0,65	η_E	0,7	η_E	0,75
η_p	0,8	η_p	0,9	η_p	0,95
η_T	0,8	η_T	0,85	η_T	0,9
$\Delta T_{,eff}$	8	$\Delta T_{,eff}$	5	$\Delta T_{,eff}$	2
Cp_{air}	1,15	Cp_{air}	1,006	Cp_{air}	1
η_r	**0,454**	**η_r**	**0,498**	**η_r**	**0,534**

The difference between the pessimistic and optimistic scenario is 0,534/0,454 = 1,18 so about 18%. This means that the results have an error margin about 10%.

The biggest uncertainty in a real powerplant is how much heat and cold can be recycled. This has such a large impact on the results it is not included in the uncertainty analysis. The reader is instead invited to study figure 5 to understand how round trip efficiency varies with heat and cold recycle.

4.6 Comparison to other methods of energy storage

Considering LAES as an energy storage alternative, it must be compared with other available methods. The main parameters to consider are efficiency, energy density and sustainable development considerations regarding the environment, people and cost.

4.6.1 Advantages of LAES

One advantage with LAES is its relatively high energy density (385 MJ/m^3 or 107 kWh/m^3). This is similar to batteries, around 20 times higher than CAES and 400 times higher than pumped hydro at 100 meters height. In practicality, this means that a LAES integrated powerplant can be placed without geographical constraints. Pumped hydro seems to be the overall best large scale energy storage method but its biggest limitation is that suitable locations for large scale dams are scarce.

Another advantage with LAES is that it does not require any scarce or toxic materials and does not produce toxic waste. This is an advantage when compared to most batteries. LAES is reasonably safe compared to chemical storage methods like hydrogen and methane which are flammable and explosive.

Finally, LAES can have economical advantages because the medium is free and the components used are technologically mature, long lasting and mass produced and therefore relatively low cost over time. This is especially true compared to batteries which are costly to produce and have a limited lifespan.

4.6.2 Disadvantages of LAES

The biggest disadvantage with LAES is its low round trip efficiency. The pilot plant that exists has a round trip efficiency of 8% and theoretical modelling in this report and by other researchers shows a round trip efficiency of around 50% if effective heat and cold recycle is used, and just above 20% when the heat and cold storage is depleted (See section 3.2.2 for further details). Assuming further advancement of this relatively new research field, that the theoretical models work in practice and that the operating of the power plant can be calibrated so that heat and cold recycle is available most of the time, it seems a round trip efficiency of 50% is within reach. With a suitable location, with access to waste cold and especially waste heat, this might be further improved. Efficiency is still much lower than batteries and pumped hydro and similar to CAES and chemical storage. It is important to note however, that if there is excess energy in the grid, and the pumped hydro and battery storage facilities are full, it is of course better to store this energy in liquid air than to let it go to waste.

Another disadvantage with LAES, especially compared to batteries, is that it is not practical for small scale energy storage. If it will play a role in the future energy system, it will be for grid balancing and maybe as backup power for neighborhoods or large buildings like hospitals.

There are also safety aspects regarding LAES. Firstly, because nitrogen and oxygen have different boiling points, there is a risk of concentration of oxygen and explosion risks. Secondly, the very low operating temperatures can be hazardous to both people and materials.

Finally, the cost of LAES could also be considered a disadvantage, depending on which energy storage technology you compare it to. Even though it uses mature components, it still needs much more costly equipment than for example pumped hydro.

Table 5 below shows a comparison of efficiency and energy density between LAES and other energy storage technologies:

Table 5: LAES comparison of efficiency and energy density.

	Efficiency	Energy density
Liquid air energy storage with heat recovery, cf. fig 5	21,6-56,9%	107 kWh/m^3 (See section 3.2.2)
Compressed air energy storage	42-54% (Moseley & Garche, 2014)	2-6 kWh/m^3 (Moseley & Garche, 2014)
Lithium ion batteries	>90% (Jernkontorets energihandbok, 2018)	300 kWh/m^3 (Wolf, 2014)
Sodium sulphur batteries	89% (Luo, et al., 2015)	150-250 kWh/m^3 (Luo, et al., 2015)
Lead acid batteries	85% (Solar-Facts, 2018)	70 kWh/m^3 (Wolf, 2014)
Redox flow batteries	75-85% (de Leon, et al., 2006)	25-35 kWh/m^3 (Luo, et al., 2015)
Pumped hydro energy storage	70-85% (Mahlia, et al., 2014)	0,28 kWh/m^3 (Wolf, 2014)
Hydrogen	20-50% (Zhang, et al., 2016)	160 kWh/m^3 (Zhang, et al., 2016)
Methane	28-45% (Sterner, 2009)	6,5 kWh/m^3 (Neutrium, 2014)
Sensible heat storage	50-90% (Gustavsson, 2016)	25 kWh/m^3 (Gustavsson, 2016)
Latent heat storage	75-90% (Gustavsson, 2016)	100 kWh/m^3 (Gustavsson, 2016)
Thermo-chemical energy storage	75-100% (Gustavsson, 2016)	120-250 kWh/m^3 (Gustavsson, 2016)

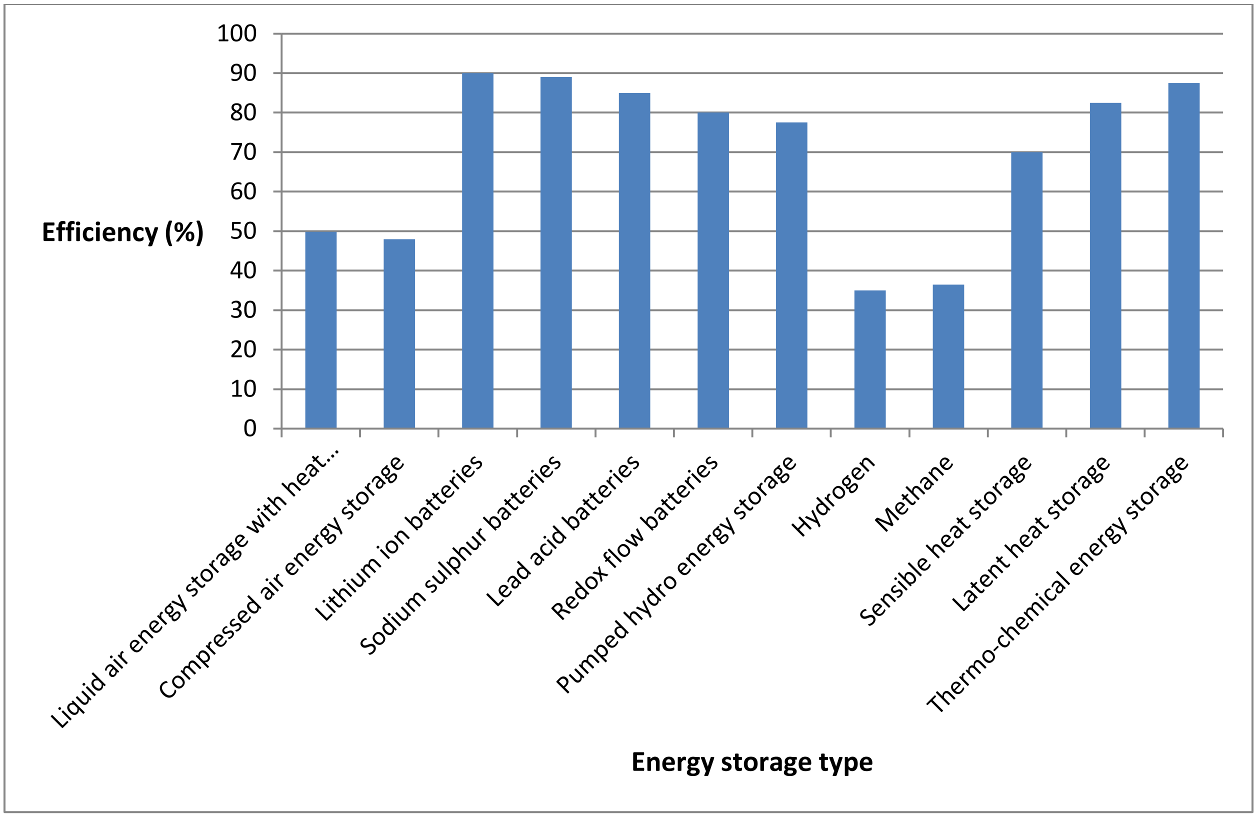


Figure 9: Efficiency for every energy storage technique

Figure 9 shows a bar chart of the efficiencies of different energy storage technologies. For liquid air, the value 49,8% which corresponds to $H_{,rec} = C_{,rec} = 0,6$ and is our best assumption as to what is practically achievable. For the other technologies, the mean value of the interval in table 5 is used.

5. Discussion

The results are based on a number of delimitations and simplifications. The two most important ones are that ideal gas behavior is assumed and the hot and cold recovery is modelled without transient consideration. The results are still fairly robust as they are similar to other researchers. For example, Ameel, et al. (2013) reported 22% round trip efficiency without cold and heat recycle and this report concluded 21,6% (a difference of 2%). With recycle, Sciacovelli, et al. (2017) reported about 50% and this report 49,8%, almost identical results. For the liquefaction cycle alone, our model shows efficiencies similar to those in the industry. The uncertainties that come from assumptions about the components efficiency and assuming a constant Cp_{air} are about 10%.

Thus, we believe we have met our main objectives. We can calculate the round trip efficiency of LAES and how it depends on relevant parameters with a fair degree of certainty. We have also found enough relevant information on other energy storage methods to make meaningful comparisons about the pros and cons of LAES as an energy storage alternative.

There are though, three important aspects that we would have liked to implement in the model if more time had been available. The first one would be to be able to vary the yield in the liquefaction process by varying the pressure and temperature before expansion in the liquefaction cycle. Higher pressure and colder temperature naturally requires more compressor power input and more power input in the heat exchanger but also increases the yield and it is very possible that the optimal solution is pretty far from the yield = 0,65 that we work with. The second one would be to model the heat and cold storage temperature over time which would make it possible to make much more stringent assumptions about how much heat and cold can be recovered between the two cycles. Now we are forced to just choose a reasonable percentage according to existing literature. The third one is to better research the properties of existing compressors, turbines, heat exchangers and other components needed in the cycles and put more detailed constraints on the temperatures and pressures used.

More research, with larger and more detailed models and pilot plants is definitely needed to evaluate if LAES has a place in the future energy system. More research is also needed on the overall economic performance of LAES. It is positive that many other researchers work on the topic. It seems improbable that LAES could ever achieve round trip efficiencies comparable to the most efficient energy storage methods, but its advantages are so strong that it is definitely worth investigating further. Considering the crucial importance of a transition from fossil based energy to renewable, intermittent sources and their need for energy storage, LAES is definitively worth investigating further.

6. Conclusions

The round trip efficiency of LAES is 21,6% without heat and cold recycle. The round trip efficiency can be increased substantially with heat and cold recycle. If 60% of the heat and cold is recycled, which seems to be a reasonable practical assumption, the efficiency goes to 49,8%. The uncertainty is about 10% so the correct values should be within 19,5 - 23,8% without cold recycle and within 45 - 55% with 60% recycle. Effective high grade heat and cold storage and recycle are crucial to achieve competitive round trip efficiency.

Access to a heat sink can marginally increase the efficiency, one or two percent so that the round trip efficiency reaches 23,6% without recycle. Placing LAES power plants close to a heat sink could be an interesting alternative. Access to waste heat can substantially increase the efficiency up to 33,4% if the temperature of the waste heat reaches 175 °C, making locations close to industrial plants suitable. This temperature could be reasonable if there is an industry nearby.

Adding a heat pump to the combined cycle does not increase the round trip efficiency in a significant manner. It might be useful to avoid dangerously low temperatures in the turbines though. With 60% recycle, the efficiency becomes a maximum of 51.6% for a heat pump power of 800 kW and then decreases with increasing heat pump power. For a power of 2400 kW, the efficiency is 49.3% which is the maximum value tested in the model.

The biggest advantage of LAES compared to other storage methods is its high energy density of 442,3 kJ/kg or 385,4 MJ/m^3 (107 kWh/m^3) which is comparable to electrochemical energy storages like sodium sulphur batteries (540-864 MJ/m^3 or 150-240 kWh/m^3) and chemical energy storages like hydrogen (576 MJ/m^3 or 160 kWh/m^3). It has a much higher energy density than pumped hydro (1,00 MJ/m^3 or 0,28 kWh/m^3) and CAES (7,2-21,6 MJ/m^3 or 2-6 kWh/m^3). It is also free from toxic materials, relatively safe and uses relatively cheap, mass produced and long lasting components and air, which is free, as energy carrier.

The biggest disadvantage of LAES is its low round trip efficiency, probably under 50%, which is much lower than that of batteries (75-90%) and pumped hydro (70-85%) and similar to CAES (42-54%) and other chemical storages (28-50%). LAES is also only practical on a relatively large scale and concentrated oxygen and cold working temperatures may pose some safety risks.

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