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# Compressed Air Energy Storage -- An Exergy-based Analysis of Turbomachinery Systems

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# Compressed Air Energy Storage -- An Exergy-based Analysis of Turbomachinery Systems

by

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ABSTRACT

Compressed Air Energy Storage (CAES) is a semi-mature technology which has been used since the 1970s for power smoothing and “spinning reserve” for the electricity grid. With the recent increase in development of intermittent energy sources such as wind, tidal and solar power, energy storage will become more important to grid stability and energy efficiency. The potential for use of CAES as an enabling technology for renewable energy in the province of Ontario is examined. An exergy-based analysis of an existing CAES facility in Alabama is presented in order to explain the potential for further development of second-generation CAES for renewable energy applications.

# DEDICATION

To my family, especially my grandparents Irene and Bill, for their love and support throughout my undergraduate and graduate studies. To my friends, for the midday and weekend "brainstorming sessions" where they shared their sage advice.

Cheers!

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## TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

## 1.0 Introduction

Compressed Air Energy Storage (CAES) has been in use since the 1970's as a short-term spinning power reserve and for power smoothing applications. The first facility was built in Huntorf, Germany and was followed in 1991 by a facility in McIntosh, Alabama.

The facility in Germany has a total generation capacity of 290MW for 2 hours, while the facility in Alabama has a generation capacity of 110MW for 26 hours [1]. Chapter two covers both facilities in more detail. Figure 1.1 presents the generic layout of a CAES facility for reference.

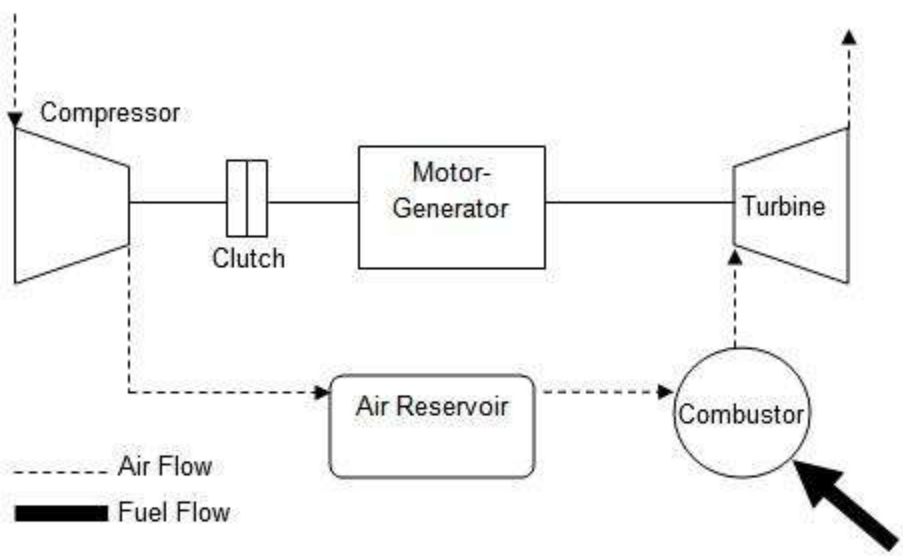


**Figure 1.1 – CAES Facility Layout**

It can be seen that a CAES facility is conceptually very similar to a simple-cycle gas turbine power plant. In fact, both types serve a similar function on the power grid; they both function as "spinning reserve" which is available to respond to sudden increases in power demand. The major difference between the two types of facilities is that while a gas turbine is a steady-flow device, the CAES facility includes a compressed air reservoir in which mass accumulates during the storage mode of operation, and from which mass is withdrawn during generation. Greenblatt et. al. [2] noted that these technologies are in direct competition for use as “spinning reserve”.

While very few grid-scale energy storage facilities currently exist in the world, the intermittency of renewable energy sources will soon necessitate the development of energy storage as an integral part of the world’s electricity generation infrastructure. A number of energy storage methods have been proposed for this task [3]; however CAES has been proposed and studied specifically for wind power applications [4,5]. Chapter 2 shows how renewable energy and CAES can work together to facilitate further sustainable development of renewable energy sources by looking at the specific case of the province of Ontario.

From the analysis to follow, it can be seen that Ontario has what could be termed the “perfect storm” of geology, geography, and renewable energy development [6] to necessitate and facilitate the development of energy storage such as CAES. This analysis is presented as a first step towards a feasibility study for the construction of a CAES facility in Ontario.

The design and construction of new CAES facilities should not, however, be limited to the technology utilized for the two existing facilities. Further development of CAES into second-generation or Advanced Adiabatic CAES (AACAES) should be the ultimate goal. AACAES holds the promise to reduce fuel consumption and increase overall storage efficiency by utilizing heat generated through the storage process to pre-heat air during the expansion process. To this end, an exergy-based analysis of the CAES facility in McIntosh, Alabama is presented in Chapter 3.

By characterizing the exergy efficiency of existing CAES facilities and determining the major contributors to decreased efficiency, an understanding of the energy dynamics of the system can be developed [7]. From this analysis, an optimization method for AACAES facilities can be developed and utilized in the design and development of future energy storage projects.

Because the exergy analysis can identify losses more acutely than a traditional first-law analysis of a system its utility should be emphasized [8]. Utilization of exergy methods during the system design process has the potential to create more efficient systems which is of the utmost importance when discussing fossil-fuel usage and renewable energy resources.

The aim of this work is to identify opportunities for the development of CAES in electricity markets such as Ontario's, and utilize exergy-based methods to analyse existing CAES facilities. The exergy methods outlined in this thesis are expected to be of use in the future analysis and design of CAES and AACAES facilities used in conjunction with both renewable and non-renewable energy sources.

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CHAPTER II

COMPRESSED AIR ENERGY STORAGE AS AN ENABLING TECHNOLOGY FOR RENEWABLE ENERGY IN ONTARIO, CANADA

## 2.0 An Overview of Compressed Air Energy Storage

### 2.1 Context and Objectives

In 2008, the United States generated 4.119 billion kWh of electricity, 3.1% of which was produced by renewable sources such as wind and solar [1]. Europe has been an early adopter of renewable energy resources such as wind, solar, and tidal, and now North America is becoming more focused on sustainable plans for energy management. Clearly, conservation of energy resources and reduction of carbon emissions are both key in planning future generation assets and engaging other electricity infrastructure issues. Compressed air energy storage (CAES) is a technology that can be used to fulfill two niches in the electricity market. The first is an arbitrage mode where energy is stored in order to leverage low off-peak energy prices against higher peak prices. The second proposed mode of operation is in conjunction with renewable energy sources like wind farms. It is this mode that we will discuss more thoroughly. CAES facilities combined with renewable energy sources can solve some issues associated with maximizing these environmentally-friendly forms of electricity generation. For example, wind turbines often produce power at off-peak times, which sometimes requires that their operation be "curtailed" because although the electricity is available, there is not enough demand on the grid. This mode of operation is not desirable for wind farm owners who then lose potential revenue. A CAES facility co-located with a wind farm could alleviate this by allowing the excess power to be stored and released to the grid when required. In this way CAES can serve to increase wind power penetration into the North American electricity market by making it "dispatchable".

The aim of this study is to identify which factors will affect the siting and planning of CAES facilities as well as to enumerate the risk factors associated with these facilities. This is considered a stepping stone to a feasibility study where the selected factors will be studied in-depth and additional influences will be identified and characterized. The authors recognize that some of the geologic and geographic information contained herein represents an Ontario-centric slant to the work and hope readers will appreciate the content as a "case study" in the assessment of the viability of CAES which may be applied in other analogous North American locations and scenarios.

### 2.1.1 What is CAES?

Compressed Air Energy Storage (CAES) is a process by which atmospheric air is compressed and utilized as an energy storage medium for power generation. A traditional CAES facility as depicted in Figure 2.1 consists of five major components: a compressor train, a motor/generator, a storage cavern/reservoir, a combustion chamber and an expander train. A more detailed overview is found in Gardner and Haynes [2].

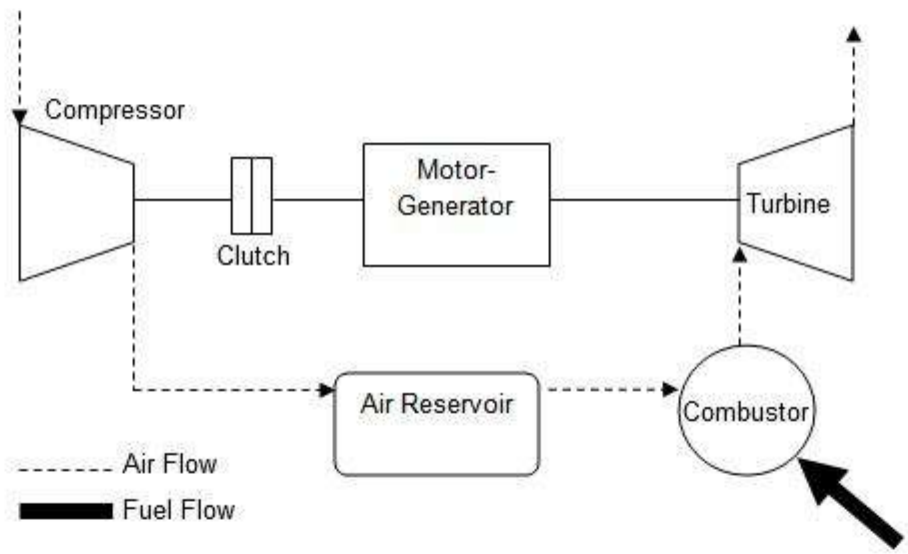


**Figure 2.1 – Traditional CAES Facility.**

A CAES facility which is not co-located with another power generation source can be connected to the grid and operated in arbitrage mode. In this instance, when energy is inexpensive, such as during off-peak overnight hours, the facility can consume energy to store compressed air underground. The energy is used to run the motor/generator as an electric motor to drive the compressor train. During peak daytime hours, when electricity prices have increased and the facility can be operated in generation mode, expanding the stored air through the combustor, mixing the air with a fuel such as natural gas (number 2 fuel oil has also been used) and burning the mixture in the combustor to add heat energy to the stream. The hot gas stream then flows through the turbine which drives the motor/generator as a generator and the facility sells electricity back to the grid at the higher peak rate. In more advanced designs, the waste heat from the combustion process is used to pre-heat the expanding air before it enters the combustor, therefore reducing the natural gas usage and increasing overall efficiency. By reducing fuel usage during the electricity generation process, CAES also helps to reduce emission levels.

The storage of compressed air underground as part of a CAES facility is principally justified on the basis of minimizing use of the land surface, avoiding the maintenance of easily corroded, limited size surface tanks, and reducing storage costs. The main options for a CAES reservoir in places such as Southwestern Ontario are depleted oil and gas reservoirs, reservoir configurations of strata without hydrocarbons, and artificial caverns, formed through the controlled solution mining of salt deposits.

Operating in this mode, the CAES facility can be used as a “peak shaver” to allow other generating facilities such as nuclear, natural gas, coal, and oil to reduce the number of output changes they make as well as providing an emergency “spinning reserve” to the grid which requires a minimal amount of time to move from idle or non-generating to full power. This would allow these types of facilities to be operated at their peak performance point more often, reducing emissions and maximizing efficiency. As depicted above, by taking advantage of the method of energy arbitrage the facility could conceivably be operated for a profit. What is perhaps more interesting is the promise of using this technology as a buffer for renewable energy sources such as wind, tidal, and solar. In Ontario, the initial considerations of wind resources, planned and existing wind capacity, and geology suggests that the Southwestern region of the province could be well-suited to the combination of these two technologies.

### 2.1.2 CAES and Renewable Energy

In international markets such as Denmark [3]; which have high levels of renewable energy generation, CAES has been identified as a possible solution to the intermittency of renewable energy sources. By enabling these higher levels of wind penetration, CAES can enable electricity producers to lower their fuel consumption and emissions profiles. Because of the rapidly increasing amount of wind energy generation in Ontario, it is used as a case study in this section.

#### 2.1.2.1 Intermittency of Wind in Southwestern Ontario

Power demand and wind speeds (and therefore available power from wind energy) vary not only hourly, but seasonally as well. Figure 2.2 shows a 72 hour moving average of both wind speed and Ontario power demand for the period from 1 January 2010 to 31 December 2010. Utilization of a moving average, where each data point is averaged over the previous 72 hours of data, smooths the data to more clearly show the associated seasonal trends.

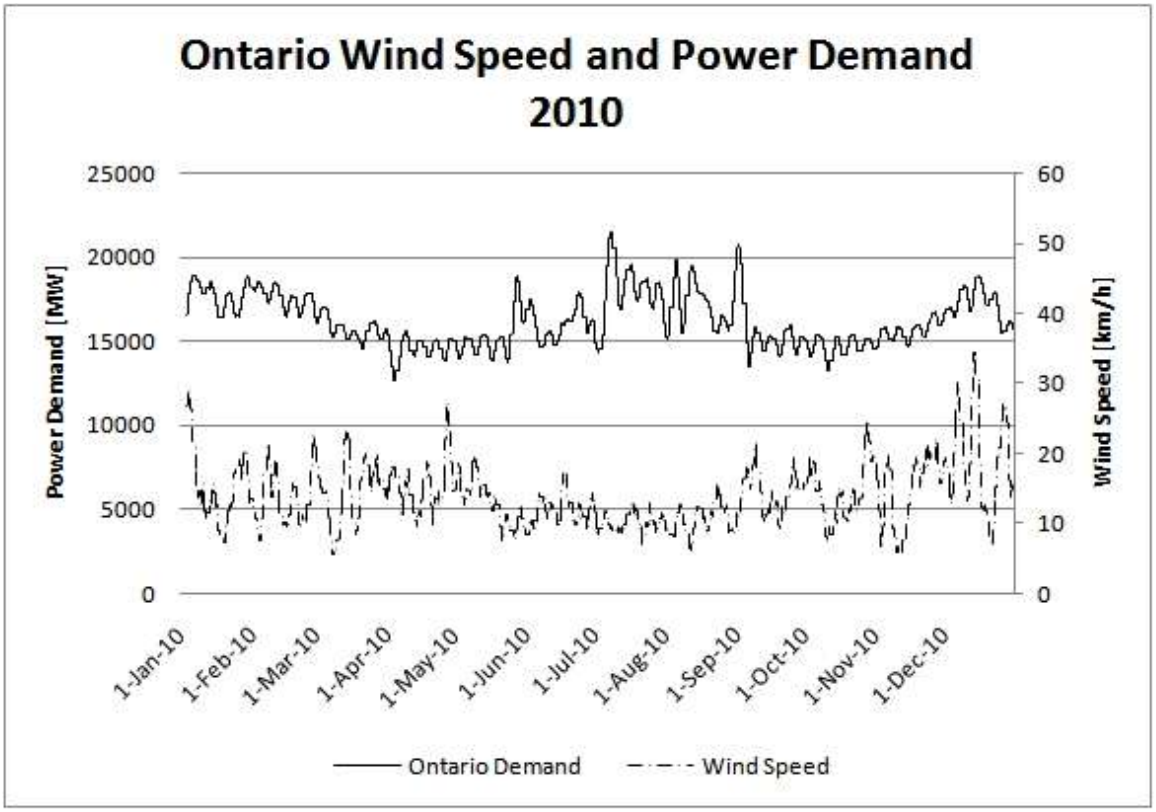


**Figure 2.2 – 2010 Yearly Wind Speed and Power Demand**

Inspection of Figure 2.2 shows increases in Ontario's power demand during the winter and summer months. The graph also shows a revealing trend for wind power penetration in Ontario. During the summer, when power demand tends to be higher, average wind speeds are lower. The daily trend shown in Figure 3 depicts a situation where CAES could be utilized to store otherwise wasted power and supply it to the grid during peak demand. Figure 2.3 presents the average hourly wind speeds and power demand in Southwestern Ontario for August of 2010. Weather data was chosen from the Sarnia, Ontario station and Ontario power demand data was collected from the IESO [4,5]. Figure 2.3 shows that while wind speeds do increase on average during the day, they tend to peak later than demand, which could create a problem for electricity system operators relying on wind power for peak generation. In this case, a CAES facility could allow power which had been generated by renewable sources overnight to be used in place of so-called "peaker" plants such as simple cycle and combined cycle gas turbines during peak demand.

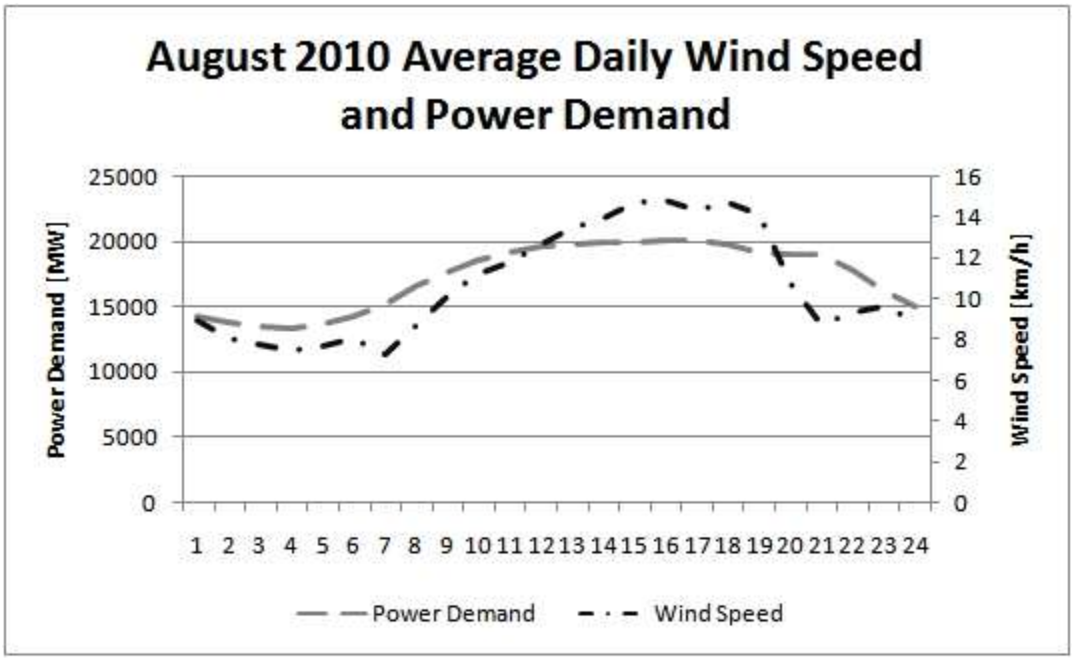


**Figure 2.3 – Average Daily Power Demand and Wind Speed August 2010.**

### 2.1.2.2 CAES as a Buffer for Renewable Energy

As can be seen in Figures 2.2 and 2.3, the potential for an energy storage facility to act as a buffer between renewable energy sources and the power grid in Ontario exists. By utilizing a CAES facility in this way, renewable sources such as wind and solar could be left "always-on" as opposed to curtailing them when their supply is too intermittent to match demand on the grid. Having a facility in place to store this power when it is available affords the grid an on-demand source of electricity while reducing fossil fuel usage and taking advantage of renewable resources.

It is also possible to envision a configuration in which the CAES facility could be bypassed when conditions allowed for the renewable energy source to provide power to the grid directly. Further study of methods and configurations is required, and is ongoing to better quantify this relationship. This has been partially addressed in the literature [6,7,8]. By increasing renewable generation penetration, CAES can reduce reliance on fossil fuels and increase overall efficiency of our electricity generation system.

### 2.1.3 Existing CAES Facilities

Two CAES facilities are currently in operation worldwide, both utilize similar design and operating principles, as well as storage media. Several other proposed CAES projects are in various stages of completion. The operation of existing CAES facilities provides prior work from which a 2nd generation CAES facility could be developed in Ontario.

#### 2.1.3.1 CAES at Huntorf, Germany

This 290 MW CAES facility was built in 1978 and is used to provide spinning reserve power to the German grid [9]. It is co-located with the Unterweser nuclear power plant and provides power to the grid during peak demand. It is designed to provide full rated power for 2 hours. This time limitation is a function of storage capacity. The Huntorf facility utilizes two solution-mined salt domes with a total volume of approximately 300 150 $m^3$ (10.6 million $ft^3$). This facility is designed to go to idle power in 2.5 minutes, followed by a 90MW/minute increase to full rated capacity. Information about the geologic stability and site selection of this facility can be found in [10], further information on the history of this facility can be found in [11].

#### 2.1.3.2 CAES at McIntosh, Alabama

Like the Huntorf facility, the McIntosh facility utilizes a solution-mined salt cavern for energy storage. Unlike Huntorf, it is rated to provide 110MW and has a total capacity of 2600MWh before requiring the cavern to be recharged. During testing in August 1992, the plant ran in generation mode continuously for 26 hours. The total volume of the storage cavern at this facility is approximately 538 000 $m^3$ (19 million $ft^3$) [9].

This facility is capable of being brought from start to full load in less than 15 minutes. More information on the geology of this facility can be found in [12] further information on the history of this facility can be found in [13].

#### 2.1.3.3 Proposed and Planned CAES Facilities

There are currently five CAES facilities planned in North America. The first is being sited in Norton, Ohio. This is planned to be a large capacity facility (approximately 600MW). The second facility, the Iowa Stored Energy Park (ISEP) is planned for construction in Dallas Center, Iowa. Discussions are underway about a third, fourth, and fifth facilities in Texas, New York, and California respectively although planns for these facilities are in their early stages [9].

### 2.1.4 The Ontario Electricity Market and Development of Renewable Energy Resources

Between 2006 and 2009, over 1080 MW of wind generation capacity were installed in Ontario. With another 50 MW scheduled to come online in Quarter 4 of 2010 and 860 MW scheduled between Quarter 1 of 2011 and Quarter 2 of 2012 [5] Over 2009 and 2010 the average hourly power demand in Ontario was 16.1 GW. While Ontario's installed wind power capacity is relatively high, solar photovoltaic installations are only slowly being introduced.

The Ontario Power Authority (OPA) is planning for an increase in Ontario's renewable energy generation capacity (wind, solar and biomass) to 13% by 2018, from 3% today. While the OPA's plan requires a large increase in renewable energy generation, OPA's plan also includes a reduction in total demand by 28 TWh by 2030 [14].

With the large increase in renewable energy's contribution to electricity generation in Ontario's electricity market, the intermittency of these energy sources needs to be addressed. While the contribution from solar photovoltaics is relatively predictable based on prevailing weather conditions, the output of wind farms is highly variable and hardly disptachable. Some element of energy storage will be required by the electricity system operators in order to act as a buffer [15], allowing this power to be dispatched and reducing Ontario's reliance on simple-cycle and combined-cycle gas turbines for peak power generation.

### 2.2.0 Geologic and Geographic Considerations for CAES in Southwestern Ontario[1]

The abbreviated account of general geology is taken from the work of Shidahara, Hutt, Langer, Sanford, Smith, and Dryer [12,16,18,19,23-30]; the synthesis of relevant economic geology is sourced from Langer, and Sanford [25,27,28].

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[1] Portions of the geologic analysis have been contributed by Dr. Frank Simpson from the Department of Earth and Environmental Science at the University of Windsor.

Sedimentary strata with CAES potential attain a maximum thickness on the order of 1,400 m in the Sarnia area and under central Lake Erie. The strata rest on a basement of crystalline Precambrian rocks and thin northeastwards to pinch out along the southern perimeter of the Precambrian Shield. The sedimentary rocks of the area range in age from Upper Cambrian to Upper Devonian. In general, they thicken from the central part of Southwestern Ontario west and northwestward toward the Michigan basin and also east- and southeastward in the direction of the Appalachian (Allegheny) basin. Strata with reservoir potential – and closely related CAES potential – occur throughout the sedimentary sequence. The Silurian part of the succession contains the carbonate reefs of the Guelph Formation and the overlying salt-bearing strata of the Salina Formation, both of which have CAES potential [24,25,27-29].

#### 2.2.1 Bedded Salt Deposits

Solution-mined caverns in salt have proven successful for storage in existing CAES facilities like Huntorf and McIntosh [9,31,32]. This indicates particular promise for parts of Southwestern Ontario, where solution-mining operations already exist. Bedded salt deposits, referable to the Salina Formation, occur over large areas of Southwestern Ontario. The main salt-bearing strata occur in the Salina A-1, A-2, B, D, E and F units, in which rock salt is interbedded with dolomite, anhydrite and shale. These salt units are found along the western margin of the Michigan basin, from Amherstburg northward to Kincardine.

At both existing CAES facilities, the salt caverns were mined for the purpose of storing air for CAES. Although this is feasible in Ontario as well, the existence of previously-mined salt caverns provides an economically more attractive option. Solution mining of new caverns has the potential to add cost and time to construction of CAES facilities in Ontario. There are also salt-mining operations in the Windsor area and at several locations between Courtright and Kincardine. These include both producing and abandoned brining operations, as well as the producing mines at Windsor and Goderich.

### 2.2.2 Reservoir Storage

Commercial quantities of hydrocarbons have been discovered throughout the sedimentary sequence of Southwestern Ontario. The Cambrian strata, the Gull River, Coboconk, Kirkfield, Cobourg and Sherman Fall strata (Ordovician), the Whirlpool, Grimsby, Thorold, Irondequoit, Guelph, Salina A-1 and Salina A-2 strata (Silurian) and the Dundee Formation (Devonian) yield natural gas. The Cambrian, Sherman Fall, Whirlpool, Grimsby, Guelph, Salina A1, Lucas and Dundee strata contain commercial accumulations of crude oil. All of these reservoir units offer potential storage media for CAES facilities.

Configurations of strata, prospective for hydrocarbons and also potentially suitable for CAES applications, occur (1) along the western margin of the Appalachian basin, (2) on the eastern edge of the Michigan basin, and (3) on the Findlay arch. The pinnacle and patch reefs of the Silurian Guelph Formation hold particular promise for CAES, both as depleted hydrocarbon reservoirs and as trapping mechanisms, devoid of oil and gas. The Salina A-1 and A-2 carbonate traps are located directly above Guelph reefs, which in many cases occur along the crests of tilted, fault-bounded blocks. Secondary recovery is widely employed in oil and gas exploitation in Southwestern Ontario. This process uses water flooding with a line drive or five-spot and nine-spot patterns of wells. Accordingly, reservoir performance has been extensively documented for many pools. However the penetration of producing reservoirs by recovery and injection wells may limit their potential for adaptation to CAES use. It is worth noting some of the Devonian reservoirs were damaged by poor production practices [25,28,29].

The planned Iowa Stored Energy Park (ISEP) is slated to utilize an aquifer for storage of compressed air. However there are many unknowns with the utilization of this geology. It is possible that residual water in an aquifer could prevent airflow and restrict the number of paths that air can take when entering and exiting the reservoir. As the air is cycled through the cavern, the available paths could change as water migrates throughout the porous structure. The effects of air cycling on aquifer structure require further study before usage of specific aquifers is determined to be suitable for CAES in a particular location [19].

### 2.2.3 Guelph Reefs

The carbonate mounds of the Guelph Formation occur as pinnacle reefs, with relief of up to 165 m, in a band 16-32 kilometers wide, to the south of Lake Huron, and as patch (incipient) reefs, with relief generally in the range of 10-30 m and located to the south and east of the others. The pinnacle reefs are elongate in plan, with average lateral dimensions of 1500m long by 650m wide. The enveloping rocks are the evaporite-bearing strata of the lower part of the Salina Formation. The Guelph patch and pinnacle reefs and overlying Salina A-1 and A-2 carbonate traps are the most productive in the area. Depleted hydrocarbon reservoirs in reef carbonates of the Guelph Formation have been converted for the underground storage of natural gas in Lambton County. Because Guelph reefs are potential hydrocarbon reservoirs, the hydrocarbon content must be known before adding compressed air to the reservoir.

### 2.2.4 Mechanics of Porous Rock

While Guelph reefs comprise the majority of viable porous-rock type formations available in Southwestern Ontario, additional work has been done to characterize the air flow in these and other types of porous-rock. Azin et al [17], Allen et al [18], and Kushnier et al [19] recognized the importance of these reservoir types. Their characterizations provide a basis for further work on the types of reservoirs which may be available in Ontario. These types of reservoirs, while more abundant, may provide challenges to designers of next-generation CAES facilities which were not seen by those developing facilities utilizing open-cavern storage media.

### 2.2.5 Locations of Viable Wind Resources in Southwestern Ontario

Data regarding average wind speeds was acquired from the Ontario Ministry of Natural Resources, an example of the data is shown in Figure 2.4. This data shows average wind speeds at a height of 80 m above ground level (AGL), and data is available at 20 m intervals. Additionally, the location of existing wind and solar resources is also shown. When co-location of CAES and wind farms is discussed, the location of viable winds in relation to appropriate geology for CAES could be a critical factor for selecting a location for the CAES facility. Therefore it is necessary that this data is readily available for a first approximation of a CAES/wind site. In areas with already high levels of wind energy penetration, CAES could facilitate further development of wind resources [3].

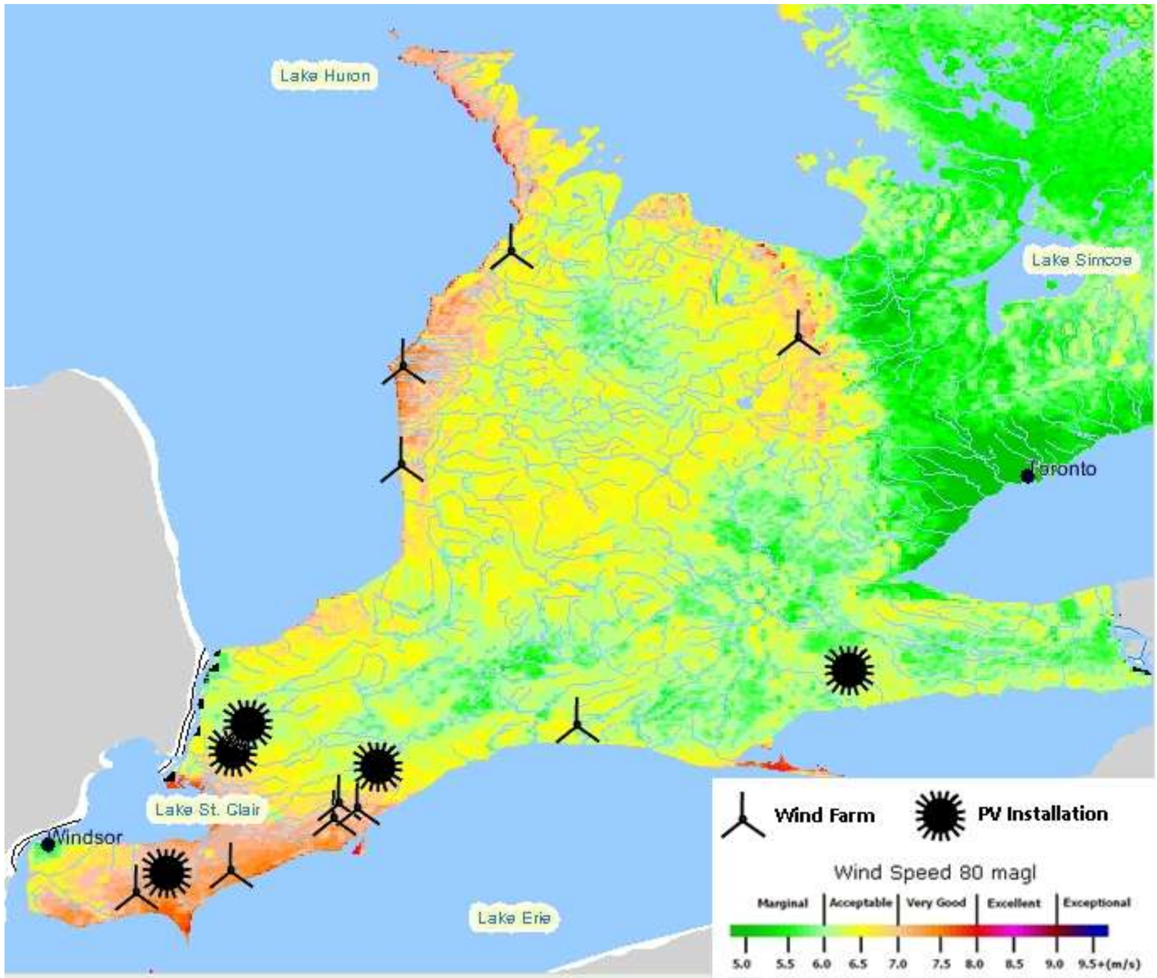


**Figure 2.4 – Wind Speed at 80m AGL and Renewable Energy Resources [33]**

### 2.2.6 Economic Considerations

In petroleum exploration the term "geologic success, economic failure" describes geology that would normally be expected to contain trapped hydrocarbons, but for some reason does not. Often these formations consist of porous rock which has a history of gas storage. In terms of CAES, this geology may be an economic success if it were found suitable for use as a compressed air reservoir.

In addition to aforementioned geological considerations, the cost of excavating caverns or solution-mining salt needs to be considered in any economic model. This cost is non-trivial especially for the very large reservoirs required to support base load sized plants.

As discussed in the previous sections regarding the geology and geography of Southwestern Ontario, viable wind resources that are already being exploited coincide with appropriate geology for CAES across this area of the province. The Sarnia area is considered particularly viable for development of a CAES facility due to the existing power generation and petroleum recovery infrastructure. The existence of porous rock-type geology which may have the required wellhead infrastructure already in place could significantly decrease the cost of developing underground volume for a CAES facility.

Further, work already completed on the economics of similar storage systems for natural gas [20] can provide an economic basis with which electricity system operators can make correct decisions when it comes to operating a CAES facility. The work of Thompson et al [21] and Zhao and Davison [22] on economic control of power plants in market economies could strongly influence the actions of a potential operator of a CAES facility.

### 2.3.0 Conclusions and Recommendations

This brief overview of the state of CAES technology and development of CAES facilities shows the potential for further development in the Ontario electricity generation market. As an enabling technology for higher penetration of renewable resources, CAES can provide the necessary storage medium to supplant the intermittency and lack of "dispatchability" in wind generation. As a standalone technology, it is evident how a

CAES facility could operate for profit and assist with grid balancing by conducting energy arbitrage.

In either case, CAES technology has the potential to reduce overall fuel usage and assist electricity generators in better utilizing existing resources while reducing emissions at the same time. Higher levels of renewable energy generation enabled by CAES will also assist in achieving these goals.

Through careful analysis of existing CAES facilities, an optimized solution for the Ontario electricity market could be conceived. The results of this research create a basis for a feasibility study of CAES in Ontario. By understanding the underlying geological and geographical constraints, a site selection study could proceed as the first phase, followed by engineering and economic evaluation and a subsequent optimization of the facility. The completion of this prefeasibility examination provides the impetus to further consider the potential of CAES to serve as an enabling technology to assist the province of Ontario and other interested parties in meeting their renewable energy generation goals in the near term.

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# CHAPTER III

# EXERGY ANALYSIS OF THE MCINTOSH, ALABAMA COMPRESSED AIR ENERGY STORAGE FACILITY

## 3.0 Introduction

Compressed air energy storage (CAES) technology has been identified as an enabling technology for high levels of renewable energy generation. While the technology has been employed since the late 1970s for emergency "spinning reserve" and power smoothing [1], it has yet to be employed as a buffer between renewable energy sources and the rest of the power grid. With the increasing efforts to improve efficiency in the electricity generation industry, and the potential looming change in power demand with the advent of various types of plug-in electric vehicles, it will become increasingly important to maximize efficiency in all stages of power generation and distribution. While second-generation advanced adiabatic CAES has been proposed and studied [1-3] , a thorough analysis of the feasibility of this technology is still required. To this end, an exergy-based analysis of one existing first-generation CAES facility in McIntosh Alabama is considered here, with particular emphasis placed on the recoverable exergy from intercooling processes within the compressor train, the ultimate goal of this research being the development of an optimization scheme for second-generation Advanced Adiabatic CAES (AACAES).

The development of second-generation CAES is of specific interest when discussing the use of CAES as a buffer between renewable energy resources and the grid; because first-generation CAES still requires significant amounts of natural gas to run efficiently. For this reason, underground pumped-hydroelectric energy storage (UPH) has been suggested by Pickard et. al. [3] as a potentially less-costly alternative to second-generation CAES. The analysis presented by Pickard et. al. provides a wide range of possible reasons that CAES and UPH have not yet been utilized, mainly focusing on economic shortfalls. AACAES does provide certain engineering challenges with regard to thermal energy storage, and the first step to understanding these design challenges is to determine the exergy destruction characteristics of existing CAES facilities. Considering the sub-surface space requirements for both technologies, as well as the location of existing and planned renewable energy infrastructure development, it is postulated that CAES will have a role to play in the future of renewable energy development. While general analyses of theoretical CAES facilities have been attempted [2,4], to the author's knowledge, no comprehensive analysis of the two existing facilities has been completed. To this end, an analysis of the exergy destruction characteristics of the McIntosh, Alabama CAES facility is presented here.

### 3.1 Analysis Method

The motive air flow diagram for the Alabama CAES facility is shown in Figure 3.1. Notation for all system diagrams is as follows: LP – low pressure, IP – intermediate pressure, HP – high pressure. The system was analyzed in two segments. First, the compression cycle was considered, in which the compressor train is driven and air is compressed into the cavern. Second, the cooling process in the cavern between compression and generation stages was analyzed. Finally, the generation process was considered with the facility running at full rated power (110 MWe) including recuperator operation. During all phases of analysis, air and the combustion products were considered to behave as ideal gases, and liquid water was considered incompressible. Both inlet and stored air are considered dry gases because the inlet gas stream contains a water separator. Although work has been done to consider the effects of humidifying the compressed air stream [5], such effects are not considered here.

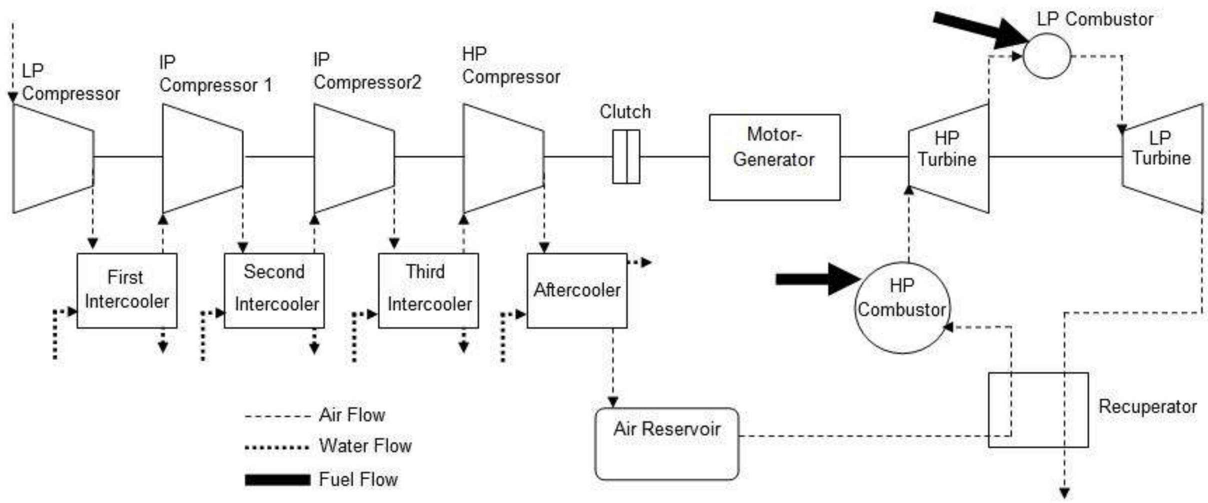


**Figure 3.1 – Alabama CAES Facility Diagram**

The dead (reference) state was set at $T_0$ = 295K, $p_0$ = 99 kPa, which are the atmospheric conditions at which cycle data was available [6,7]. All processes are assumed to be at steady-state with no mass accumulation in turbomachinery, however mass does accumulate in the cavern during the fill process.

The compression process is analyzed at full power during a complete 41.7 hour compression cycle. Figure 3.2 depicts the system as it functions during the compression cycle. While compressing air, the compressor train shaft is driven with 47.4 kW, with 15.6 kW driving the first-stage axial compressor, and the remaining power driving the three centrifugal compressors as a unit. During storage, the air in the cavern is assumed to cool to ambient underground temperature (308K) through a constant-pressure heat removal process.

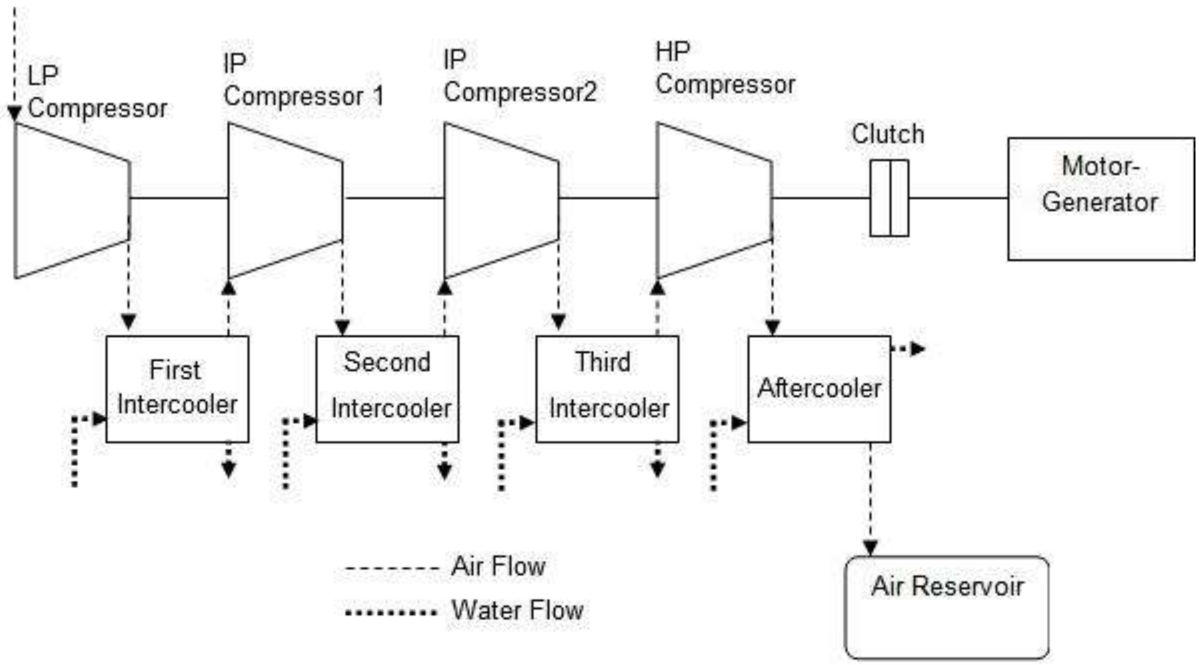


**Figure 3.2 – Compressor Train System**

Throughout the generation process, the electrical output of the generator is considered to be 110 MWe, while the shaft output of the expander train is 113.9 MW. The system during generation is depicted in Figure 3.3. For analysis of the generation process, the fuel was considered to be pure methane ($CH_4$) with a molar exergy of 824348 kJ/kmol [8].

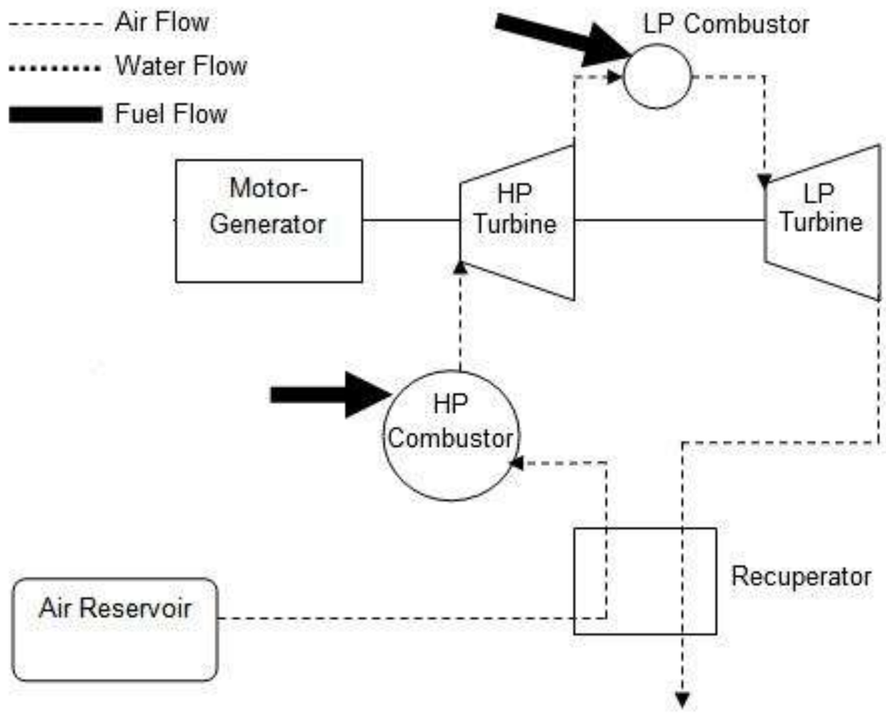


**Figure 3.3 – Expander Train System**

For ease of comparison, the exergy analysis has been completed in rates [kW] rather than absolute exergy [kJ]. The exergy rate (availability) in the cavern has been based on a 26-hour generation cycle to arrive at cavern availability.

## 3.2 Exergy Analysis

The flow (stream) exergy of an ideal gas as shown by Bejan et al [8] is:

(1) $$\psi = C_P T_0 \left\{ \left[ \frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right] - \ln \left( \frac{P}{P_0} \right)^{\frac{(k-1)}{k}} \right\}$$

Where ψ is the flow exergy, $C_p$ is the constant pressure specific heat capacity of the working fluid, T is the absolute temperature, $T_0$ is the reference temperature (295K), P is the absolute pressure, $P_0$ is the reference absolute pressure (99 kPa) and k is the ratio of specific heats for the working fluid (sometimes denoted γ).

Similarly, the non-flow (closed system) exergy, φ, of an ideal gas from Bejan et al [8] is given as:

(2) $$\phi = C_P T_0 \left\{ \frac{T}{T_0} - 1 - \ln\frac{T}{T_0} + \frac{k-1}{k}\left[\ln\frac{P}{P_0} + \frac{T}{T_0}\left(\frac{P_0}{P} - 1\right)\right]\right\}$$

Equation 2 is utilized only to calculate the exergy of the cavern when the inlet and outlet valves are closed and air is being stored over a period of time. In this scenario, the closed system exergy is the only component of exergy considered.

Exergy transfer due to heat is given by Cengel and Boyles [9] in Equation 3 and is used to quantify exergy loss in the cavern during the storage process.

(3) $$\dot{X}_{heat} = \left(1 - \frac{T_0}{T}\right)\dot{Q}$$

Where $\dot{X}$ is the total exergy rate (in kW) due to heat transfer and $\dot{Q}$ is the heat transfer rate in kW.

The combustion process in the high pressure combustor is assumed to be complete with excess air as shown:

(4) $$aCH_4 + bO_2 + 3.76bN_2 \rightarrow\ aCO_2 + 2aH_2O + (b-2a)O_2 + 3.76bN_2$$

The combustion process in the low pressure combustor is assumed to be complete with excess air as shown:

(5) $$dCH_4 + (b-2a)O_2 + 3.76bN_2 + 2aH_2O + aCO_2 \rightarrow\ (a+d)CO_2 + (2a+2d)H_2O + (b-2a-2d)O_2 + 3.76bN_2$$

Chemical exergy of the combustion process can be calculated from standard chemical exergies of a substance given in Bejan et al [8] as:

(6) $$\dot{X}_{ch} = \dot{m}x_{ch}$$

Where $x_{ch}$ is the standard chemical exergy of the substance, $\dot{m}$ is the mass flow rate of that substance and $\dot{X}_{ch}$ is the total chemical exergy rate.

For a chemical reaction, the exergy destruction can be calculated as:

(7) $$\dot{X}_{chemical,destroyed} = \sum_{reactants} \dot{m}_i x_{i,std,ch} - \sum_{products} \dot{m}_i x_{i,std,ch}$$

Total exergy for a flow stream is the sum of all discussed exergy components:

(8) $$x_{total} = x_{mechanical} + x_{heat} + x_{chemical} + \psi$$

The units for $x_{total}$ are kJ/kg. By multiplying by the mass flow rate, we can arrive at the physical exergy rate in kW which allows us to compare the facility's input and output.

(9) $$\dot{X}_{total} = \dot{m}x_{total}$$

For analysis of the water side (incompressible) of the air/water intercoolers, the standard definition for flow exergy shown by Cengel and Boles [9] and Bejan et al [8] is used:

(10) $$\psi = (h - h_0) - T_0(s - s_0)$$

Where h is enthalpy, $h_0$ is enthalpy at the reference state, s is entropy and $s_0$ is entropy at the reference state. The units of $\psi$ are kJ/kg.

The entropy term ($s$-$s_0$) is defined in this case by Cengel and Boles [9] as:

(11) $$s - s_0 = C_{avg} \ln \frac{T}{T_0}$$

Where $C_{avg}$ is the average specific heat capacity of the substance.

Second-law efficiency is defined as:

(12) $$\eta_{II} = \frac{X_{output}}{X_{input}}$$

## 3.3 Results

The system was analyzed as two processes: a storage (filling) process and a generation process. During the fill process, mass accumulates in the cavern as it is brought from its initial pressure of 5205 kPa to a final pressure of 7791 kPa[10]. The mechanical power input to the compressor train during the fill process is assumed to be measured at the output shaft of the electric motor. The motor delivers a total shaft power of 47.3 MW over the 41.7-hour filling process. The mechanical exergy input to the system is given as the shaft power measured at each compressor.

Exergy destruction is the removal of the ability to do useful work from the system. This is an important concept because it identifies which components of a complex system are contributing most to lowering its efficiency. By reducing exergy destruction, overall efficiency is increased.

The first stage compressor operates at a pressure ratio of approximately 4 to 1 and is an axial-type compressor. It consumes 15.6 MW of shaft power and imparts 13.9 MW of exergy to the air flow. It operates at a second law efficiency of 89 %. The isentropic efficiency of the first stage compressor is 81%. The first stage intercooler causes 3.4 MW of this exergy to be destroyed during the cooling of the gas stream, and operates at a second law efficiency of 75%. The flow exergy of the water increases by 429.6 kW, the importance of this value will be explained further in the analysis section. Table 3.1 details the results of the compressor train analysis. Figure 3.4 shows exergy destruction rates of each component of the compressor train system and Figure 3.5 shows the second-law efficiencies of each component of the compressor train. The input data from [6] are detailed in Appendix A.

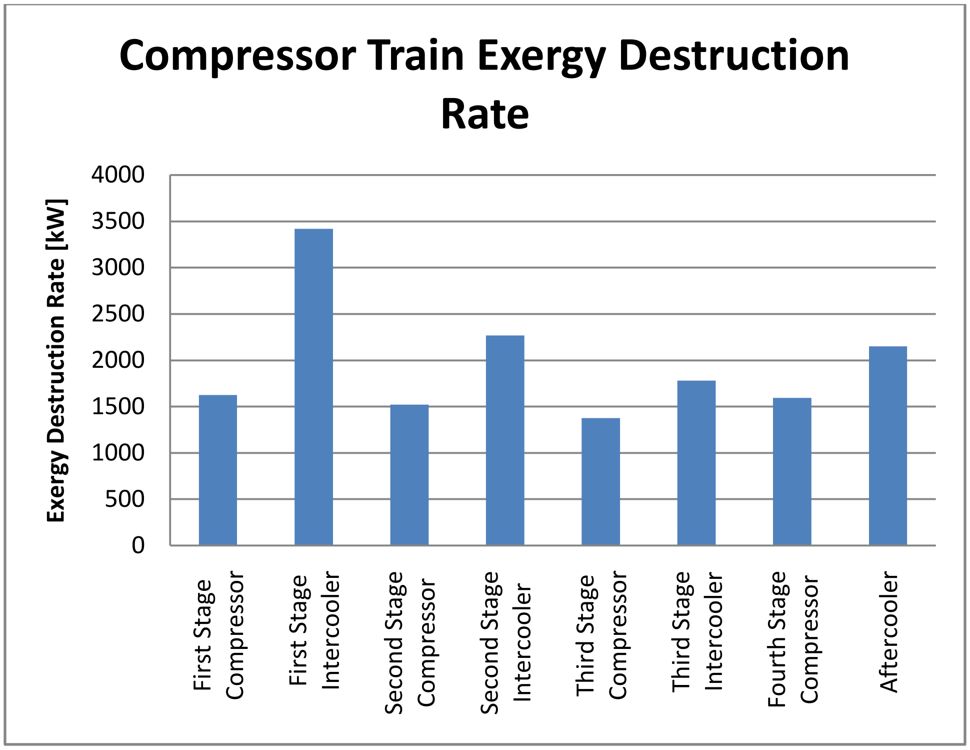


**Figure 3.4 – Compressor Train Exergy Destruction Rates**

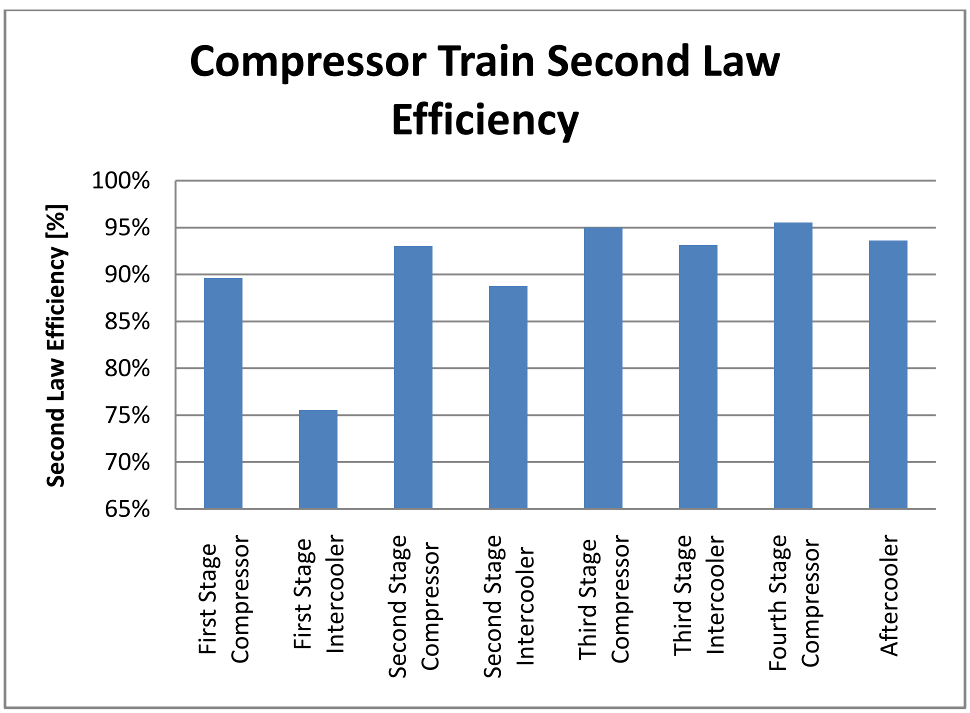


**Figure 3.5 – Compressor Train Second Law Efficiency**

The compressor system operates at an overall second-law efficiency of 66.52%. This accounts for all exergy destroyed in the compression and intercooling processes. The absolute exergy losses are most prevalent in the first and second stage intercoolers as seen in Figure 3.4. The remaining system components all have non-trivial but similar exergy losses. The significantly lower second-law efficiency found in the first stage intercooler can be attributed to the higher compression ratio of the first stage compressor and the increased water flow through the intercooler.

The expander train includes a recuperator which is an air to air heat exchanger. The recuperator pre-heats the air coming from the cavern with combustion products from the exhaust of the low-pressure turbine. It operates at a second law efficiency of 88%. The combustors, however both operate at approximately 53% second law efficiency. This is the major source of inefficiency in the generation process.

The high pressure turbine operates at 90% efficiency and the low pressure turbine operates at 85% efficiency. The overall second-law efficiency of the generation process is 45% when operating at steady-state and full rated power. Figure 3.6 shows the exergy destruction rates of the expander train. It clearly shows the significant amounts of exergy destroyed in the combustion process, which is consistent with the results showing in analyses of similar systems [11]. This analysis accounts for the amount of chemical exergy converted to physical exergy and used to drive the turbines to generate power. Figure 3.7 shows the second-law efficiencies of the expander train during steady-state operation.

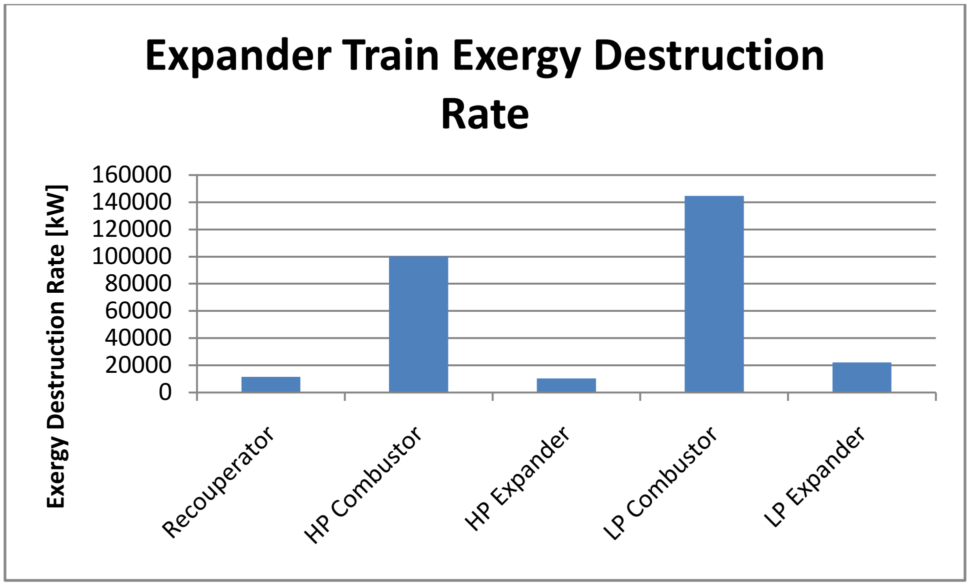


**Figure 3.6 – Expander Train Exergy Destruction**

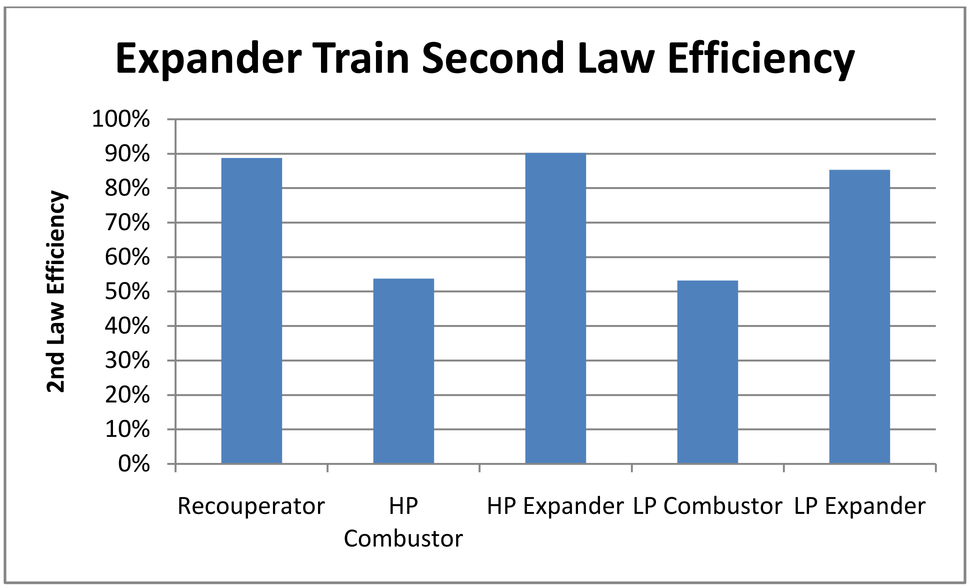


**Figure 3.7 – Expander Train Second Law Efficiency**

## 3.4 Analysis and Conclusions

The exergy analysis of the compressor train reveals a potentially recoverable exergy of 1.2MW in the form of increased exergy in the cooling water. In the presented analysis these values are contained within the exergy destruction values shown in Table 3.1. They are obtained by calculating the exergy increase in the water side of the intercoolers. It must be noted that this is in a system which is not optimized for exergy recovery in the compression stage. The analysis shows that the potential does exist, with a properly designed system, for second-generation CAES to provide an efficiency increase over traditional first-generation CAES.

While the compressor and expander trains were analyzed as separate systems, they are interconnected. Were a compression train designed specifically to maximize heat recovery from the intercoolers, the potential does exist for reduction of fuel usage in the expander train. Analysis of the expander train reveals an important fact: the highest exergy destruction occurs in the combustors. As the goal of second generation CAES is to reduce the amount of fuel used by a CAES facility, the efficiency increase that is possible comes from reduction of fuel usage. While complete elimination of the combustors is considered impractical, a reduction in fuel usage would allow for a reduction in exergy destruction, and therefore result in an increase in overall system efficiency. This may be achieved by modifying the compressor designs to increase recoverable exergy in the intercoolers. Careful analysis is required, however, in order to maximize the potential for heat recovery in the compressor train.

The next step is to optimize a theoretical second-generation CAES facility based on the exergy methods outlined in this paper. While some of this work has been done in a very general sense [2] a second-law based optimization algorithm for second-generation CAES is the ultimate goal of this work.

### 3.5 Data Tables

**Table 1 – Compressor Train Exergy Analysis**

| Component | Low Pressure Compressor | Low Pressure Intercooler | Intermediate Pressure Compressor 1 | Intermediate Pressure Intercooler 1 | Intermediate Pressure Compressor 2 | Intermediate Pressure Intercooler 2 | High Pressure Compressor | Aftercooler |
|---|---|---|---|---|---|---|---|---|
| Flow Exergy Input [kW] | 0 | 13,984 | 10,564 | 20,168 | 17,900 | 25,994 | 24,213 | 33,651 |
| Mechanical Exergy Input [kW] | 15,608 | 0 | 11,125 | 0 | 9,470 | 0 | 11,030 | 0 |
| Total Exergy Input [kW] | 15,608 | 13,984 | 21,689 | 20,168 | 27,371 | 25,994 | 35,243 | 33,651 |
| Exergy Output [kW] | 13,874 | 10,564 | 20,168 | 17,900 | 25,994 | 24,213 | 33,651 | 31,499 |
| Exergy Destruction [kW] | 1,623 | 3,420 | 1,521 | 2,268 | 1,376 | 1,781 | 1,592 | 2,151 |
| 2$^{nd}$ Law Efficiency [%] | 89% | 75% | 93% | 88% | 94% | 93% | 95% | 93% |

**Table 2 – Expander Train Exergy Analysis**

| Component | Recuperator | High Pressure Combustor | High Pressure Turbine | Low Pressure Combustor | Low Pressure Turbine |
|---|---|---|---|---|---|
| Flow Exergy Input [kW] | 103848 | 78949 | 105620 | 84817 | 151302 |
| Chemical Exergy Input [kW] | 0 | 137807 | 10878 | 224025 | 12875 |
| Total Exergy Input [kW] | 103848 | 216757 | 116498 | 308843 | 164177 |
| Mechanical Exergy Output [kW] | 0 | 0 | 26473 | 0 | 87403 |
| Chemical Exergy Output [kW] | 0 | 10878 | 10878 | 12875 | 12875 |
| Flow Exergy Output [kW] | 92192 | 105620 | 68838 | 151302 | 41641 |
| Total Exergy Output [kW] | 92192 | 116498 | 106189 | 164177 | 141919 |
| Exergy Destruction [kW] | 11655 | 100258 | 10309 | 144665 | 22258 |
| $2^{nd}$ Law Efficiency [%] | 88% | 53% | 90% | 53% | 85% |

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# CHAPTER IV

# FUTURE WORK

At the current stage of CAES development a "black box model", shown in Figure 4.1, has been established to demonstrate relationships between the principal components of CAES facility optimization and design. A complete determination of the discrete inputs to each section of the model is still required.

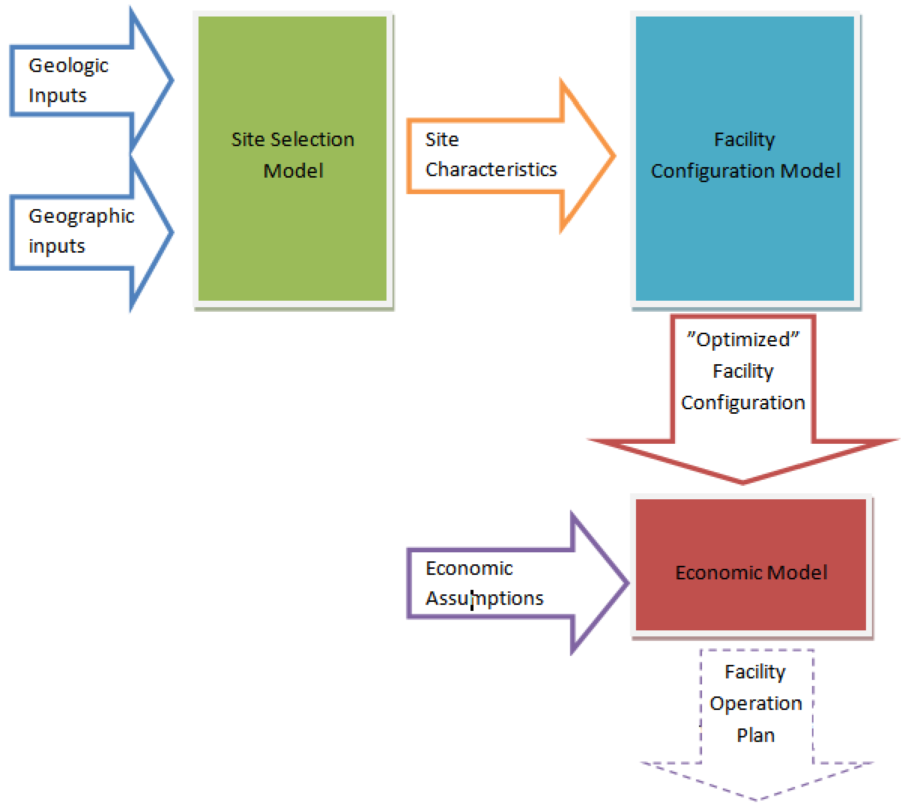


**Figure 4.1 – A "Black-Box" Model for CAES in Ontario**

Completion of the work contained in this thesis is a necessary enabling step towards a fully comprehensive feasibility study for CAES in Ontario. In this vein, the feasibility study will be broken down into three major sections as follows:

1. Geology and Geography
2. Facility Design and Configuration
3. Economic and Operations Analysis

The output of the geology and geography portion of the CAES facility model should include such features as: an interactive Geographic Information System (GIS) mapping model which contains information which would affect the optimization and design of a CAES facility.  The output of this model will aid any potential user in selecting a site for a CAES facility by providing relative site-selection scores based on all of the factors listed.  The GIS model will then provide the inputs for a CAES facility design optimization model which is the second portion of the feasibility study.

The facility design and configuration section of the feasibility study should consist of optimizing the configuration of a CAES facility in Southwestern Ontario based on the chosen geology/geography (from the GIS model outputs).  Outputs from this model will then feed the economics analysis or re-feed the geology/geography model for further refinement of the site selection.  Based on the information presented in this thesis, an exergy-based optimization model is preferred, especially when considering construction of an Advanced Adiabatic CAES facility.

The economic analysis of presented would then use inputs generated from the facility optimization model.  The outputs of the economic model would then be used to further refine the facility configuration and then finally to produce an economically-viable operating plan in order to support renewable energy electricity generation.

Development of an exergy-based optimization method of CAES facilities should be the focus of the design optimization phase.  The ultimate goal of this research being a dynamic model which would enable CAES facility designers to specify the prevailing conditions relevant to plant configuration such as ambient air conditions, power available from renewable sources, and cavern capacity and conditions.  Utilizing these prevailing conditions and a variation of the exergy methods presented in Chapter 3 and Appendix A, the iterative tool would then be used to specify the number and approximate power of compressor and turbine stages as well as any heat recovery or recuperation devices.

Utilizing the geologic and economic models to further increase the fidelity of this approach will allow designers of future CAES systems the ability to produce the most efficient system to couple with renewable energy generation resources.

APPENDIX A

ALABAMA CAES FACILITY OPERATING DATA[2]

| State | Pressure [kpa abs] | Temperature [K] | Mass Flow [kg/s] |
|---|---|---|---|
| **First Compressor Inlet** | 100 | 295 | 89 |
| **First Intercooler Inlet** | 410 | 460 | 89 |
| **Second Compressor Inlet** | 402 | 305 | 89 |
| **Second Intercooler Inlet** | 1073 | 424 | 89 |
| **Third Compressor Inlet** | 1058 | 305 | 89 |
| **Third Intercooler Inlet** | 2454 | 407 | 89 |
| **Fourth Compressor Inlet** | 2433 | 305 | 89 |
| **Aftercooler Inlet** | 6267 | 423 | 89 |
| **Aftercooler Outlet** | 6236 | 322 | 89 |

**Table A.1 – Compressor Train (Air) Operating Data**

| Intercooler | Inlet Water Temperature [°C] | Outlet Water Temperature [°C] | Mass Flow [kg/s] |
|---|---|---|---|
| First Stage | 26.1 | 42.8 | 230 |
| Second Stage | 26.1 | 41.7 | 185 |
| Third Stage | 26.1 | 42.8 | 138 |
| Aftercooler | 26.1 | 42.8 | 132 |

**Table A.2 – Intercooler Water-side Operating Data**

| Location | Temperature [K] | Pressure [kPa abs] | Mass Flow [kg/s] |
|---|---|---|---|
| **Recuperator Inlet (Cavern Side)** | 308 | 4482 | 143 |
| **High Pressure Combustor Inlet** | 559 | 4351 | 146 |
| **High Pressure Turbine Inlet** | 811 | 4309 | 146 |
| **Low Pressure Combustor Inlet** | 654 | 1627 | 147 |
| **Low Pressure Turbine Inlet** | 1144 | 1517 | 147 |
| **Recuperator Inlet (Exhaust Side)** | 641 | 105 | 147 |
| **Recuperator Outlet** | 407 | 102 | 147 |

**Table A.4 – Expander Train Air Data**

[2] All data was obtained from EPRI TR-101751-V2 "History of First U.S. Compressed-Air Energy Storage (CAES) Plant (110 MW 26h) Volume 2: Construction". Original data was presented in Imperial units, for full citation information, see Chapter 3 Reference [6].

APPENDIX B

SR-30 TURBOJET ENGINE DEMONSTRATOR EXERGY ANALYSIS

## B.1 Introduction

The SR-30 turbojet demonstrator is used for classroom and laboratory demonstrations of the principles of turbojet engine operation to undergraduate and graduate engineering students. The turbojet, along with the attached MiniLab control and data acquisition system allows for investigation into the operating parameters of the turbojet system. The SR-30 turbojet can be depicted as a Brayton-cycle machine with a nozzle as depicted in Figure A.1.

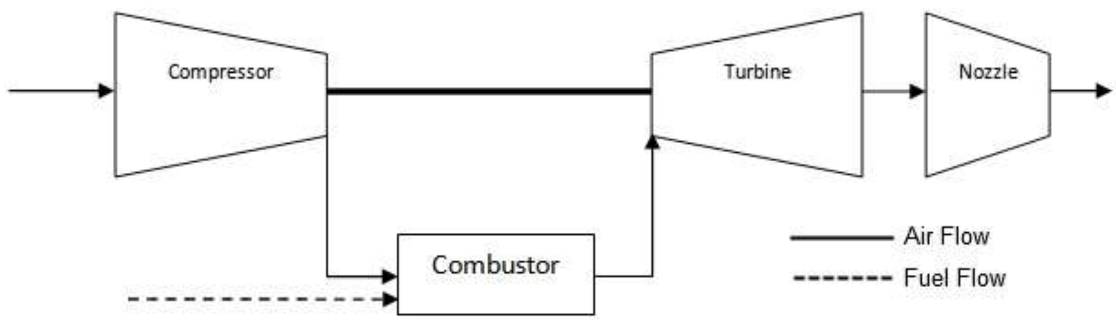


**Figure B.1 – SR-30 System Diagram**

Hot gases flowing from the combustor drive the turbine which then drives the attached compressor wheel, feeding more air through the combustor inlet. Jet-A fuel is fed to the combustor at a rate between 2 and 5 gallons per hour. From the MiniLab system, five sets of sensors are placed at each of the points labeled 1 to 5, at each point temperature and pressure are measured.

The start sequence of the turbojet begins with the introduction of compressed air at 100psi to the system, this causes the main shaft to spin to approximately 10000RPM, at this point the fuel pump activates and fuel begins to flow to the combustor; once fuel is burning in the combustor the turbine spools to approximately 43000RPM. The shutdown sequence consists of deactivation of the fuel pump and allowing the turbine to come to rest. For these reasons, any operating data collected below 45000 RPM and/or 2.0gpm of fuel flow have been removed as outliers as the turbine is not operating at a steady-state.

## B.2 Data Analysis Method

An exergy-based analysis of the turbojet system allows identification of locations of high inefficiency relative to the amount of thermodynamically available power. An assessment of the exergy destroyed during a process gives an indication of how much potential energy is lost to heat generation and irreversibilities.

Both the air and hot combustion product gases in the system are treated as ideal gases. This means that for this analysis the ideal gas law applies:

$$Pv = m\bar{R}T$$

The component dimensions of the SR-30 turbine are taken from Witkowski et al [3] and are summarized below:

| **Location** | **Description** | **Area [m$^2$]** |
|---|---|---|
| 1 | Inlet to compressor impeller. | 0.002522 |
| 2 | Outlet of compressor diffuser. | 0.002622 |
| 3 | Inlet to turbine stator. | 0.00299 |
| 4 | Outlet of turbine rotor. | 0.00299 |
| 5 | Nozzle exit.* | 0.00299 |
| * - The nozzle exit is assumed to have the same area as the turbine outlet. | | |

**Table B.1 – SR-30 Flow Area**

The physical exergy (or availability) of a fluid flow on a per mass basis is given by (Turgut 2006):

$$\overline{Ex}_{ph} = \bar{h} - \overline{h_0} - T_0(\bar{s} - \overline{s_0})$$

Because the velocity of the flow is small and the change in height through each component is negligible, the kinetic and potential exergy terms have been neglected. If all gases in the engine are assumed to be ideal, this can be simplified to:

$$\overline{Ex}_{ph} = c_p T_0 \left[ \left( \frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + \ln \left( \frac{P}{P_0} \right)^{\left( \frac{k-1}{k} \right)} \right]$$

Mass flow rate of air is calculated from:

$$\dot{m} = \rho V A$$

Assuming air is a dry gas, the density (ρ) of air can be calculated from:

$$\rho = \frac{P}{R \cdot T}$$

The velocity of air can be calculated from Bernoulli's equation (in one dimension, assuming all flow is perpendicular to the plane in which the sensors are located):

$$\frac{V_1^2}{2} + gz_1 + \frac{P_1}{\rho_1} = \frac{V_0^2}{2} + gz_0 + \frac{P_0}{\rho_0}$$

Assuming air to be still at the dead state and there is no gravitational potential term so the axial velocity at point one can be solved from:

$$V_1 = \sqrt{2\left(\frac{P_0}{\rho_0} - \frac{P_1}{\rho_1}\right)}$$

Continuity allows the solution for velocity at the compressor outlet to follow as the mass air flow rate is constant through the compressor. Continuing through the combustor, the mass flow rate increases by the amount of fuel introduced at the combustor. Additionally, the exergy balance must include the chemical exergy contained within both the air and fuel. Chemical exergy in turbojet engines has been mathematically modeled by Turgut et al [5] using exergy values from a model by Bejan et al [4]. The chemical exergy values used in this analysis are shown in Table 2.

| **Compound** | **Chemical Exergy [kJ/kmol]** |
|---|---|
| Nitrogen ($N_2$) | 640 |
| Oxygen ($O_2$) | 3950 |
| Carbon Dioxide ($CO_2$) | 14175 |
| Water vapour ($H_2O$) | 8635 |
| Jet-A Fuel ($C_{12}H_{23}$) | 45.8 **[MJ/kg]** |

**Table B.2 – Chemical Exergies of Substances**

The chemical exergy can be found from the following equation from Salto [2] and Bejan et al [4]:

$$\overline{Ex}_{ch} = \sum_i x_i \overline{ex}_i^{ch} + \bar{R}T_0 \sum_i x_i \ln x_i$$

For the combustion reaction, the volumetric composition of air is assumed to be 79% Nitrogen, 21% Oxygen and air is assumed to be a dry gas.

**B.3 Results**

While completing this analysis, significant issues with the experimental setup were discovered. In correspondence with the technical team at the manufacturer, it was discovered that at lower power settings, the flame front from the discharge end of the combustor tends to propagate into the turbine. This causes combustion of the fuel to continue through the turbine section, which is an thermodynamically undesirable condition. This condition is known to the manufacturer and is not considered to be an issue when the turbojet is used solely for demonstration to undergraduate classes.

It is interesting to note that this phenomenon is less prominent at higher power settings (fuel flows > ~4.5 gallons per hour). However, during analysis it was discovered that while the temperature trend across the turbine is in the proper direction at high power settings, without accounting for the additional heat generated by continued combustion, an exergy-based analysis of this system is not possible.

As can be seen in the data tables presented in Section A.5, this condition is indicated by a temperature rise between thermocouples 3 and 4. Thermocouple 3 is located at the combustor outlet/turbine inlet and thermocouple 4 is located at the turbine outlet/nozzle inlet. Significant time was devoted to determining how this problem could be solved without modification to the experimental setup.

### B.4 Further Work

While the initial analysis was unable to be completed, this analysis is still considered worthwhile and should be further pursued. Working with the manufacturer to modify the data acquisition system including moving the thermocouple stacks could result in better data fidelity which would allow an exergy-based analysis to continue. In addition, enabling the thrust measurement functions of the SR-30 would allow a more accurate analysis to be completed.

### B.5 Data Tables

| Fuel Flow | Speed | P1 | P2 | P3 | P4 | P5 |
|---|---|---|---|---|---|---|
| gph | RPM | kPa abs | kPa abs | kPa abs | kPa abs | kPa abs |
| 1.99 | 43076.51 | 100.25 | 144.19 | 143.84 | 103.81 | 102.41 |
| 2.30 | 48855.82 | 100.74 | 160.00 | 159.51 | 105.77 | 103.61 |
| 2.53 | 50147.98 | 99.81 | 162.71 | 162.59 | 105.16 | 102.87 |
| 2.73 | 53009.75 | 100.55 | 172.94 | 172.72 | 106.87 | 104.04 |
| 3.01 | 55443.78 | 100.48 | 181.70 | 181.74 | 107.80 | 104.49 |
| 3.27 | 59630.04 | 100.76 | 198.37 | 198.31 | 109.62 | 105.57 |
| 3.44 | 62980.34 | 100.44 | 211.68 | 210.75 | 110.18 | 105.83 |
| 3.79 | 64289.88 | 101.42 | 223.36 | 223.36 | 112.05 | 107.53 |
| 4.08 | 66926.61 | 101.35 | 235.10 | 235.39 | 112.73 | 108.15 |
| 4.30 | 69685.87 | 101.33 | 249.55 | 249.50 | 113.26 | 108.84 |
| 4.47 | 70888.36 | 100.87 | 254.79 | 255.03 | 113.13 | 108.71 |
| 4.94 | 77741.64 | 101.86 | 302.73 | 302.69 | 117.83 | 112.56 |

**Table B.3 – Pressure Measurements**

| Fuel Flow | T1 | T2 | T3 | T4 | T5 |
|---|---|---|---|---|---|
| gph | K | K | K | K | K |
| 2.16 | 295.58 | 393.79 | 872.79 | 897.18 | 699.91 |
| 2.58 | 293.76 | 415.83 | 853.48 | 903.18 | 739.10 |
| 2.81 | 293.62 | 395.63 | 855.67 | 911.17 | 745.76 |
| 3.20 | 294.31 | 405.62 | 864.39 | 910.13 | 744.56 |
| 3.31 | 294.00 | 414.29 | 865.71 | 904.28 | 743.34 |
| 3.55 | 293.39 | 429.39 | 861.08 | 891.18 | 742.67 |
| 4.01 | 295.12 | 451.78 | 870.23 | 880.58 | 749.95 |
| 4.29 | 293.11 | 447.97 | 866.24 | 891.72 | 748.47 |
| 4.33 | 293.20 | 449.19 | 864.09 | 890.94 | 748.98 |
| 4.60 | 293.32 | 466.34 | 872.22 | 869.60 | 752.45 |
| 4.94 | 295.12 | 468.12 | 883.35 | 876.69 | 759.29 |
| 4.97 | 293.88 | 493.71 | 910.11 | 855.54 | 765.62 |

**Table B.4 – Temperature Measurements**

## References


[1] Cengel, Y., Boles, M., (2006) Thermodynamics: An engineering approach, 5$^{th}$ Edition, McGraw Hill, Toronto, 2006

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[4] Bejan, A., Tsatsaronis, G., Moran, M. (1996) Thermal Design and Optimization. Toronto, ON. John Wiley & Sons.

[5] Turgut, E., Karakoc, T., Hepbasli, A., (2007) Exergetic analysis of an aircraft turbofan engine, International Journal of Energy Research, Vol. 31, No. 14, pp. 1383-1397, November 2007

# VITA AUCTORIS

James Konrad was born in 1986 in Windsor, Ontario. He graduated from Vincent Massey Secondary School in 2004. He obtained his B.A.Sc. in Mechanical Engineering from the University of Windsor in 2009. He is currently a candidate for the Master's degree in Mechanical Engineering at the University of Windsor and hopes to graduate in Winter 2011.