PNEUMATIC AS A FUTURE OR ALTERNATIVE ENERGY STORAGE SYSTEM

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July 2021

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfillment of the requirement to graduate with honors degree in
BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

Declaration

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Acknowledgement

This thesis is successfully be completed with the assistance from a lot of people. First and foremost, I would like to thank my supervisor, Assoc. Prof. Khairudin Bin Mohamed for all his helps, knowledge, ideas, encouragement, and guidance throughout the year. Even there is some problems about the initial project title, he immediately suggested me a new project title that is suitable to be run during the pandemic. I would be having a lot of problems if there is no aid from him. Furthermore, a big thanks to all the assistant engineer of School of Mechanical Engineering for their helps. One of them is Encik Mohd Ali Shahbana Mohd Raus who has explaining to be about the required component for a compressed air system and guide me to find for the required materials for the project. Moreover, I would like to recognize the aid from both of my friends which are Mohd Danial Bin Mohd Shukry and Ahmad Asri Bin Harith in helping me to look for the required components needed for the project. Also, I am so grateful for the continuous supports from my family in encouraging me to keep on studying and complete the degree for this course. Plus, it will be a shame to forget all the knowledge provided from all lecturers from the School of Mechanical and because of them, I am able to reach until this point in the university. Lastly, I also like to give a huge appreciation to the coordinator of this course, Dr Muhammad Fauzinizam Bin Razali for handling the students efficiently and giving the students his best in order to help us pass this course.

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List of Abbreviations

CAES	Compressed Air Energy Storage
USA	United State of America
AC	Alternating Current
DC	Direct Current
CPRC	Cost for Power-Related Plant Components
CESC	Cost for the Energy Storage Components
ST	“Typical” Hours of Storage for a Plant
TC	Total Cost
R&D	Research and Development
I-CAES	Isothermal Compressed Air Energy Storage
TES	Thermal Energy Storage
AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
DSW	Deep-Sea Water
PET	Polyethylene Terephthalate
FOS	Factor of Safety
LHS	Left Hand Side
BOM	Bill of Materials
LED	Light-Emitting Diode

Abstrak

Sistem penyimpanan tenaga pneumatik adalah sistem yang mengaplikasikan udara termampat sebagai input untuk menghasilkan output yang dimahukan seperti tenaga mekanikal dan tenaga elektrik. Terdapat beberapa kilang penyimpanan tenaga udara termampat di Amerika Syarikat dan Jerman, tetapi bukan bagi Malaysia. Melalui projek ini, sistem tenaga penyimpanan udara termampat berskala kecil dan mudah akan dibina dengan menggunakan barangan yang boleh digunakan semula dan lama sebagai sebahagian daripada sistem ini. Sistem ini akan difokuskan pada kawasan luar bandar yang bermaksud bahawa mekanisme atau undang-undang saintifik yang kompleks tidak digalakkan. Pada mulanya, turbin angin telah dicadangkan untuk memberikan input tetapi diganti dengan pam udara kereta elektrik ekoran terdapat pelbagai halangan di sepanjang pandemik yang berlaku kini. Terdapat beberapa reka bentuk yang dicadangkan untuk projek ini dan konsep reka bentuk dilukis di kertas untuk memberikan gambaran yang jelas mengenai setiap reka bentuk. Salah satu daripada reka bentuk tersebut akan dipilih mengikut kebaikan dan keburukan mereka. Setelah fabrikasi sistem selesai, sistem akan diteruskan dengan eksperimen untuk mengumpulkan data yang diperlukan. Hasilnya diperoleh, dianalisis dan kesimpulan telah dibuat. Kecekapan sistem sangat rendah kerana beberapa batasan dan kelemahan sistem yang wujud, di mana turbin tidak dilindungi dengan kawasan tertutup, kecekapan rendah yang rendah oleh turbin dan wujudnya kebocoran mikro pada tangki udara yang menyebabkan sistem kehilangan kuasa yang banyak.

Abstract

Pneumatic energy storage system is a system that benefits compressed air as the input to produce desirable output such as mechanical energy and electrical energy. There are several of CAES plants in USA and Germany, but Malaysia is not quite familiar with it. Through this project, a simple and small-scale compressed air storage energy system will be built by using old and reusable things as a part of the system. The system will be focusing on the rural areas which means that any complex mechanism or scientific law are not recommended. Initially, a wind turbine is suggested to provide the input, but it is replaced with an electrical car air pump because of some obstacles during the pandemic. There are several designs have been issued for the project and the design concepts are sketched out to provide a clear picture of each design. One of the designs will be chosen according to the pros and cons of the design. After the fabrication of the system done, the system will proceed to the experiment to collect data needed. The results are obtained, analyzed and the conclusion has been made. The efficiency of the system is very low due to some restrictions and weaknesses of the system which is the turbine is not secured with a closed region, the low efficiency of the turbine and the presence of micro-leaks on the air tank which lead to high power loss.

Chapter One: Introduction

1.1 Research Background

Huntorf, Germany, created the first utility-scale compressed air energy storage (CAES), which is still active today [1]. While the Huntorf CAES plant was designed with a load balancer for fossil-fuel-generated electricity in mind, the global move to renewable yet highly intermittent energy sources (e.g. photovoltaics, wind) has rekindled interest in CAES systems [2]. In addition, another CAES plant is at a McIntosh plant in Alabama, the USA. The efficiencies of the CAES plants in both Huntorf and McIntosh are 42% and 54% respectively [3]. Both plants are applying thermodynamic reaction using pure gas for combustion to compress the air [1].

However, this project is focusing on building a CAES system that is not applying any thermodynamic law but, just converting renewable energy into mechanical or electrical energy, but with compressed air energy being collected and stored as the intermediate stage of the system. Adding to that, the main purpose of the project is to use all sort of renewable energy form that available at the houses' surrounding which is wasted up until now because of poor management towards the available energy. Hence, this project will be performed with a small scale as the target location is somewhere around the rural areas where the residents can gain the benefits of using an available energy.

1.2 Problem Statement

It shows that several studies have been done on the study of the compressed air energy storage system according to the literature review. However, most of the system applied the thermodynamic law to complete the cycle of the system.

Therefore, as an alternative application, the compressed air which came from renewable sources like water, wind, or solar energy that stored in a reservoir tank as a power source to be delivered to a motor. The motor then produces mechanical energy before converting it back to electrical energy as our desired usage and this system does not require any complex thermodynamic law.

1.3 Objectives

The specific objectives of this research are:

a. To study the CAES system applications and their efficiency.
b. To investigate the way to apply available surrounding factors to create CAES system and obtain any desired output.

1.4 Scope of Research

This project is restricted to only used objects, but some items still need to be bought since they are so rare to be available at surrounding. Therefore, they are an exception for this project. The project also will not be focusing on the CAES that apply Thermodynamic Law as the system is simple and produce for low scale application. The focus area of the project is in the rural village or a place that is far away from the main city.

Chapter Two: Literature Review

The purposes of reviewing the literatures are to grasp a better understanding on the reasons for the compressed air energy storage (CAES) are needed, the CAES mechanism in action and to analyze on the progress of (CAES) system as pneumatic energy storage system until now.

2.1 Overview of Batteries, Pros and Cons as Energy Storage

Since 1800, human have been using batteries as the main power source for their creations such as machines, gadgets and so on [4]. The first true battery is invented by Volta that known as voltaic pile [4]. However, the problem is they are created with toxic and harmful substances where the electrolyte contained in the battery can cause burns and dangers to our eyes and skin, eat holes in clothing and even etch on the concrete floor if they are exposed to the surrounding and they also release hydrogen gas, which is combustible and, if concentrated in a tiny space, may start a fire or blast. [5].

2.1.1 Pros and Cons as Energy Storage

The ordinary batteries are categorized as non-renewable energy which means they have limited period of lifetime unlike the rechargeable [6] one but rechargeable battery contain lithium which can produce toxic gases [7]. Another problem is most of the electrical circuit system is not provided with proper energy storage system which will lead to waste of over generated energy and destruction of the electrical circuit connection in the system or machine. For example, wind turbines that available now are using electric generator to produces 60-cycle AC electricity; it is usually an off-the-shelf induction generator and motor to powers the yaw drive [8]. In terms of future applications, using the chemical energy storage system is not efficient and not eco-friendly to be applied for example in electrical transportation.

Other than that, the wind energy cannot be controlled and this will lead to problems like the wind turbine system will burnt out because of overloading powers as the turbines do not operate at wind speeds above about 55 mph because they may be damaged by the high winds [8]. Therefore, instead of using batteries as the main energy storage system or not using any proper storage system at all, this project tends to build a pneumatic energy storage system by utilizing compressed air energy to be collected and stored so that they can be used for any desired amount of output later. The CAES system uses compressed air to store energy provided at one time for later usage [9].

2.2 Introduction to CAES

In general, compressed air energy storage system is mainly using electrically driven compressor to compress air from the environment via wind turbines into a reservoir that can withstand outstanding pressure from the compressed air [10]. The suitable properties for a small scale reservoir can be determined through calculations by considering important factors such as desired compressed air volume, the required amount of pressure that the reservoir can hold including during expansion process due to changes of temperature and the mechanical properties and the lifespan of the materials as it will be used for a long period of time.

If large-scale CAES systems are to be built, huge air storages are necessary [11]. Therefore, the key factor is fabricating large storage containers. Hence, underground caverns have been used as storage for the current operational CAES plants, or to be specific, the salt caverns. From recent research, suitable geological formations include underground salt layers, underground hard rock layers, and underground porous rock layers. In Table 1, the capital cost of an air reservoir for various storage media and plant configurations are listed [11].

Abbreviations: CPRC, Cost for Power-Related Plant Components; CESC, Cost for the Energy Storage Components; ST, “Typical” hours of Storage for a Plant; TC, Total Cost.

Reservoir	**Size (MWe)**	**CPRC ($/kW)**	**CESC ($/kWh)**	**ST (h)**	**TC ($/kWe)**
Salt	200	350	1	10	360
Porous Media	200	350	0.1	10	351
Hard Rock	200	350	30	10	650
Surface Piping	20	350	30	3	440

Table 2.1: Various storage media and plant configurations of air storage reservoir

The compressed air from the reservoir will be released and reconverted to electricity by means of a turbine generator [10]. The way of compressed air energy storage system in bigger scale works in supporting power network operation, is accomplished by compressing air to a strong pressure employing compressors amid times of minimal electricity energy supply, and then unleashing the compressed air to operate an expander for power production throughout maximal supply intervals, as illustrated in Figure 1 [11]. The reservoir is usually an old mining cavern. Electricity is lowest priced late at night, and while air compressors are operating, 750 psi air can be pressed into a cavern or chamber (compression process). At daytime, when electricity is highly priced, the compressed air will be heated up using the heat collected and conserved during compression, and then implemented to operate a turbine [12].

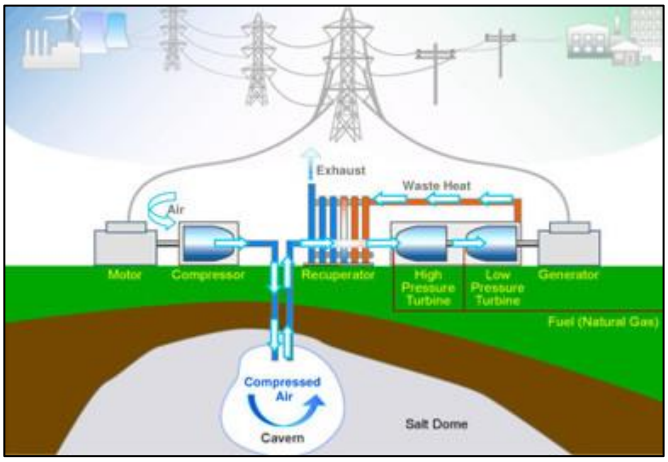


Figure 1: Compressors use off-peak electricity to fill the cavern with compressed air. For peak demand, the compressed air is withdrawn from the cavern and used to power a wind turbine [12].

2.2.1 Chronology of CAES Establishment

The idea to store electrical energy by using compressed air originally dates to the early 1940s and the application of the generated idea was going slow until by the mid-1970s where the general interest in CAES technology began to rise back, stimulated by the Huntorf project. After that, the growth of CAES application was rapidly increasing and eventually the first CAES plant, Huntorf was completely built and the intensive start for CAES R&D in the US began at the late of 1970s. Starting by the early of 1980s, there are many of other CAES plants were built in US even in Europe up until now. CAES R&D and industrial activities chronology where the projects are not thorough and are restricted to the biggest establishments can be observed in Figure 2 [10].

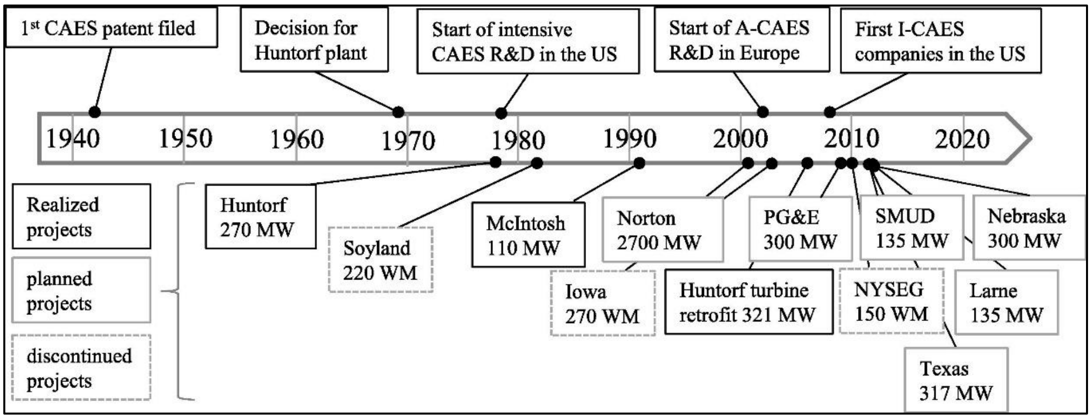


Figure 2: CAES R&D and industrial activities chronology where the projects are not thorough and are restricted to the biggest establishments.

2.3 Past Research for CAES

2.3.1 Design, modeling and experimental validation of a novel finned reciprocating compressor for Isothermal Compressed Air Energy Storage applications

Based on the first studies, Traditional CAES (Diabatic CAES) and Isothermal CAES (I-CAES), which accomplishes near-isothermal process employing heat exchanger or liquid spray in the process of energy storage and energy release, thus enhancing system efficiency [13]. Traditional CAES necessitates the use of compressors, compressed air storage, combustion chambers, expanders, and motors or generators. There are now two traditional CAES power stations in commercial operation. As mentioned before, the first CAES plant is the Huntorf power plant, which has been in operation since 1978 and has a total efficiency of 41.73 percent. It uses natural gas to enhance combustion in the energy release process [1].

The other is the McIntosh power plant in Alabama, which is in the United States. Waste heat is recovered with a total efficiency of 54 percent, and equipment is employed to recycle exhaust heat [14], [15]. Using thermal energy storage (TES) in the traditional system, the idea of advanced adiabatic CAES (AA-CAES) is also introduced, which has gotten a lot of interest and is an important direction of future CAES technological growth. This research reveals how CAES systems have evolved from traditional to advanced CAES systems that can be constructed in the future.

2.3.2 Hydro-Pneumatic Energy Storage System

While for the second studies, the patent that have been reviewed, stated that the source of the energy for the compressed air energy system is sea water. A deep-sea water (DSW) hydro-pneumatic energy storage system is detailed. A floating assistance framework, a floating assistance framework and a floating air tank over the floating assistance framework make up the system [16]. In the floating air tank, compressed air is contained. Furthermore, the patent states that the electrical power generator utilized by renewable energy from existing offshore turbine technology that employs wind, wave, or tidal turbine is expensive at offshore sites [16].

In addition, wind, wave, and tidal turbine energy cannot be stored and supplied in a timely manner [16]. All of these difficulties can be addressed by offering a strictly controlled release of high pressure deep-sea water and integrating deep offshore floating turbine technology with equipment for collecting energy to address the intermittent supply of natural energy [16]. Adding to that, the potential energy of high pressure deep-sea water can be transformed into electrical energy by enabling it to pass through a hydraulic turbine linked to an electric generator [16]. In overall, this patent explained in detail on how the potential energy from the pressurized deep-sea water can converted more efficiently compared to using wind, wave, and tidal energy if the site is located far away at the middle of deep-sea area [16].

2.3.3 Process design, operation and economic evaluation of compressed air energy storage (CAES) for wind power through modelling and simulation

The next research paper examines the process design, operation, and economic evaluation of compressed air energy storage (CAES) for wind generating using modelling and simulation. This research aims to evaluate the design and operation of a CAES system for wind power at design and off-design conditions using process modeling [17]. According to this study, rising usage of renewable energy such as wind and solar power in many countries has raised substantial environmental issues, resulting in greenhouse gas emissions from conventional power plants (greenhouse effect) [18], [19]. Moreover, wind power generation accounted for 3% (or 435 GW) of worldwide energy output in 2015 and is anticipated to rise to 14.8 percent (6145 TWh) in 2050 from 11.6 percent (3599 TWh) in 2030 [20], [21].

In addition, the growing usage of renewable energy is producing a demand-supply imbalance, which is a new challenge that we must handle. This is due to the intermittent nature of renewable energy, which is largely dependent on local environmental conditions and unpredictable weather [4], [8]. One of the most notable findings of this study is that the CAES system for wind power has greater performance at variable shaft speeds than at consistent shaft speeds. This is because, in variable shaft speed mode, the CAES system may consume more extra wind energy (49.25 MWh), store more compressed air (51.55 103 kg), generate more electricity (76.00 MWh), and provide a longer discharging time [17].

2.3.4 Development of a micro-compressed air energy storage system model based on experiments

This research so far is the most like the proposed project because of the targeted scale for the compressed air energy storage system (CAES) is in small scale. One of the interesting points is CAES technology is better suited to bigger units in the 50–300 MW range, however smaller CAES units may be of interest [22]. As the pressure in such systems varies from 2.5 MPa to 3.5 MPa, sealed air storage tanks can easily sustain this pressure because a small-scale CAES would not require an underground air storage vessel [23]. In the literature, the need for a deep underground cavern is recognized as a serious drawback in the CAES technology [24]. Figure 1 shows the setup for the small scale CAES system [23].

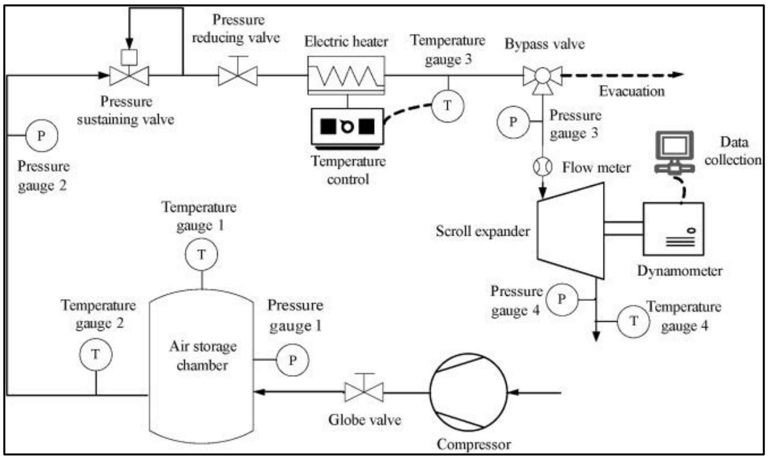


Figure 3: The small scale CAES system setup [20]

The single-stage system's efficiency is limited, according to the findings, in part because of reduced expander efficiency and shorter discharge time when the expander's inlet air pressure is higher [23]. Reduced expander input air pressure, on the other hand, results in decreased output power [23]. The former can be addressed by increasing the air storage chamber's maximum pressure, while the latter can be addressed by using more expansion stages in the discharging process. When the structure was altered from a single-stage to a triple-stage A-CAES, the maximum system efficiency increased from 25.52 percent to 60.04 percent [23].

Chapter Three: Research Methodology

3.1 Design Concept

In the earlier stage of the project, there are several ideas for the design of the simple CAES. The ideas are then being illustrated in sketches to give a clear view for each design. The consideration of the design is involving in the selection of the suitable materials with the restriction to only used items, the ease of finding them and the availability for the total of expenses for the project.

3.1.1 Initial Project Diagram

This is the diagram of the project at the earlier stage of the research. At this stage, the component involved are expected to be available by neglecting the other factors such as the current availability of the required components and the required cost.

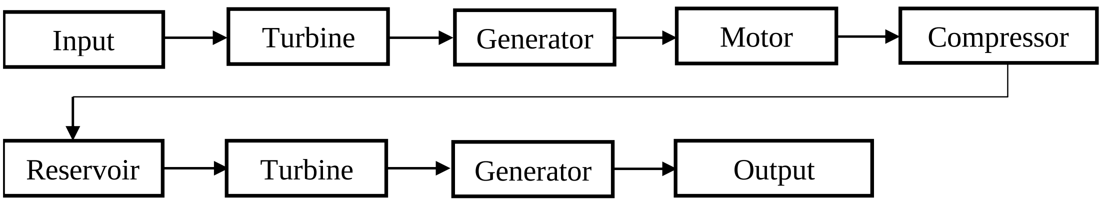


Figure 4 Initial Project Diagram

3.1.2 Final Project Diagram

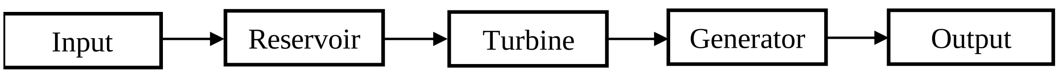


Figure 5 Final Project Diagram

3.1.3 Design Ideas/Evolution

At the earlier stage, the original idea is to use two wind turbines, one is placed after the input while the other one is at the place where electrical energy need to be generated to produce the output. Meanwhile, four 1.5L carbonated drink bottles will be used for the reservoir. However, the original idea or the initial setup requires a lot of components thus the required cost is high. This is because if one of the wind turbines is placed after the input, a motor and compressor are needed. It is quite hard to find an old compressor that still can be operated safely at the surrounding and if the compressor is personally made or bought, it also requires a lot of budget. Considering the bottles can only be used for low capacity to contain compressed air, some modification for the idea has been made. As a result, the wind turbine that need to be placed after the input, the motor and compressor are removed. An old electrical air pump will be replaced in exchange to provide the input or the compressed air directly into the reservoir. One different type of bottle will be used as the entrance which is Pepsi bottle as it is longer, and it will be easier for the tip of the valve to reach the electric car air pump.

Initial setup:

- Input: Wind energy. A wind turbine needs to be placed at an area with high and constant wind current.
- Compressor: It may be possible to buy or create them personally.
- The turbine, generator, and motor: Need to be bought
- Reservoir: Three 1.5L Coke bottles and one Pepsi bottle will be used as they can withstand high pressure and quite tough.
- Output: Electrical energy

Final setup:

- Input: Compressed air. An old air pump will be used to provide compressed air directly into the reservoir.
- Compressor: Compressor is not needed anymore
- The turbine, generator, and motor: No need to buy the motor anymore. While for turbine, only one will be used for generating the output.
- Reservoir: Three 1.5L Coke bottles and one Pepsi bottle will be used as they can withstand high pressure and quite tough.
- Output: Electrical energy

3.2 Design Sketches/Illustration

The key of choosing the right design is mainly focused on the design of the reservoir itself as the other components like the turbine, generator, wires and LED will be placed at the same position which is at the end of the reservoir's exit.

3.2.1 Design 1

At the middle, the bottles are connected directly through the car tubeless valves by facing the bottles' bottom parts altogether.

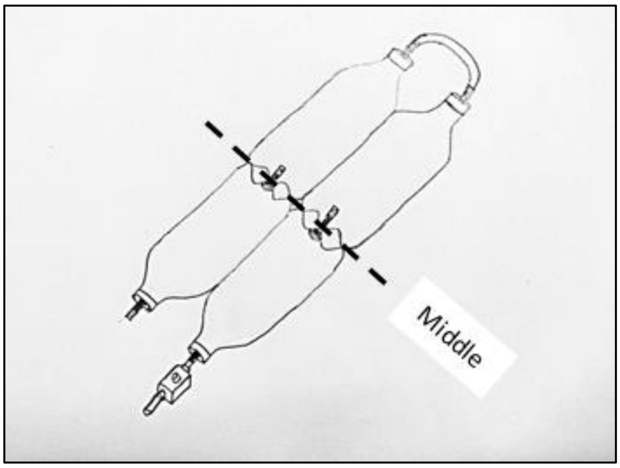


Figure 6: Design 1 for Reservoir

3.2.2 Design 2

At the middle, the bottles are connected directly through the car tubeless valves and pneumatic tubes by facing the bottles' top parts altogether.

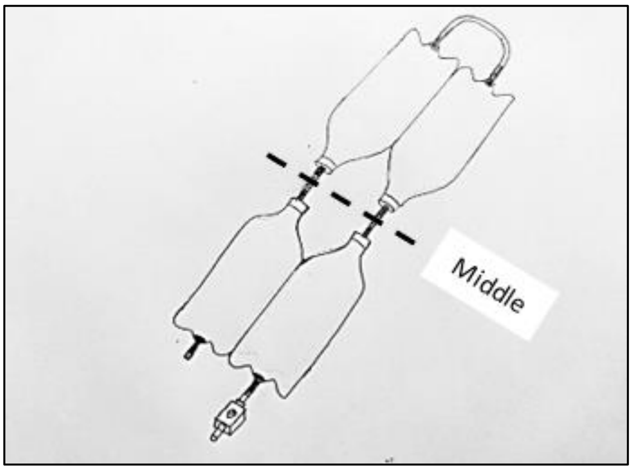


Figure 7: Design 2 for Reservoir

3.2.3 Design 3

All bottles are connected independently through car tubeless valves and pneumatic tubes.

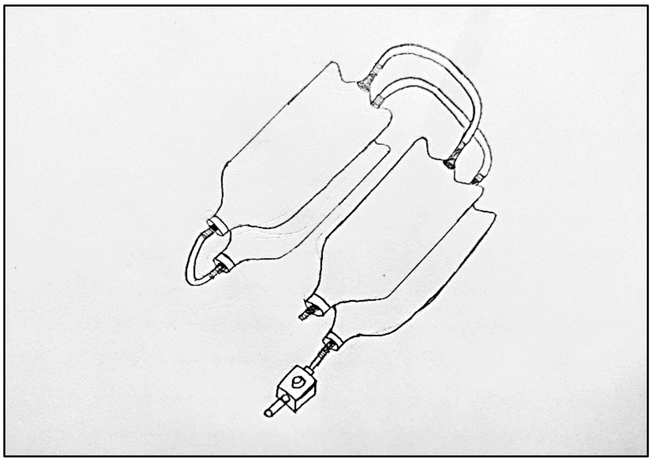


Figure 8: Design 3 for Reservoir

3.2.4 Pros and Cons for Each Design

Design	Pros	Cons
1	The overall structure of the design is sturdy because at the middle of the design, the bottles are connected directly with the valves which is not elastic.	Very high risk of leaking at the middle of the connection between bottles through the valves if both of valves' end are not sealed properly.
		Two different sizes of holes need to be drilled because of varies diameter size throughout the valves structure. Thus, the crafting process will be riskier to be handled.

		A long wooden plank is needed to act as the base which will lead to unnecessary cost of materials
2	Low risk of leaking as the bottles are connected through valves secured by pneumatic tubes.	The bottles are connected to pneumatic tubes at the middle; hence, the overall design is not sturdy as the pneumatic tubes will bend over due to their elasticity.
		Hard to be placed as the design will require large spaces due to the length of the pneumatic tube at the middle.
3	Low risk of leaking as the bottles are connected through valves secured by pneumatic tubes.	The bottles need to be installed with frames over a platform or secured inside a box as the housing to prevent them from moving.
	Easy to place the air tank including the housing because only moderate space is needed.	

Table 3.1: Pros and Cons for Each Proposed Design

3.3 Chosen Design

The selected design is determined carefully by considering important factors such as the risk of leaking, the ease of fabrication and the space required for storage purpose of the prototype. After all the important factors are being considered, Design 3 is the most suitable to be undergo the fabrication process. Adding to that, a housing has been introduced for holding the bottles in their place and protection for the users if the bottles explode unexpectedly due to some circumstances. A mineral water box will be used for that application as it is easy to be obtained and operated; plus, it is lightweight too. Hence, the bottles will be placed inside the box.

3.4 Impact Test

It is rare to find research papers or thesis in Google Scholar, Scopus and ScienceDirect explaining about carbonated drink bottles used as air tank. However, there are many ideas applying the bottles as air tank in other platforms such as YouTube and Reddit. The impact test for a specific type of bottle should be done personally but there are problems like site of experiment, the instrument needed and lack of resources for project. Moreover, there is also no explanation available about the maximum pressure of a 1.5 L carbonated drink bottle can withstand in research papers. However, there is a bit explanation about the 2 L carbonated drink bottle such as it burst at pressures around 1.07 MPa or 155 psi through an experiment shared in a website [25]. Since, the maximum pressure of 1.5 L bottle cannot be determined experimentally, a calculation for the maximum pressure is being made.

As mentioned before, there are two types of bottles being used which are the Coke and Pepsi bottles. The dimensions of the bottles like their diameters and wall thicknesses need to be measured. In addition, the type of material used for manufacturing both bottles also need to be identified to take note the yield strength of the material for calculation purpose. By placing the bottles upright, the base diameters are being measured. If the base diameter is smaller than the middle, the diameter of the middle part of the bottle will be taken. The details of the calculation for both bottles will be explained further below. Furthermore, the bottles are produced with the same material which is Polyethylene terephthalate (PET) that has a yield strength of 125 MPa. The pressures exist in each bottle are in form of stresses which are the longitudinal stress in the wall of the bottle, $\sigma_{longitudinal}$ and hoop stress in the wall of the bottle, σ_{hoop}. A failure criterion for the yield of ductile materials known as von-Mises criterion states that if the energy of distortion gains the equal energy, a failure will happen for yield or failure in uniaxial tension. The von-Mises criterion will be applied to find the maximum pressure or stress for each bottle before it began to fail. The allowable stress can be calculated through the Factor of Safety (FOS) equation by determining the FOS value of the air tank. Air tank which is also known as pressure vessel has a FOS value ranged from 3.5 to 6 [26] based on Figure 3.6. The maximum value of FOS for pressure vessels will be used in the calculation which 6.

Equipment	Factor of Safety - *FOS* -
Aircraft components	1.5 - 2.5
Boilers	3.5 - 6
Bolts	8.5
Cast-iron wheels	20
Engine components	6 - 8
Heavy duty shafting	10 - 12
Lifting equipment - hooks ..	8 - 9
Pressure vessels	3.5 - 6
Turbine components - static	6 - 8
Turbine components - rotating	2 - 3
Spring, large heavy-duty	4.5
Structural steel work in buildings	4 - 6
Structural steel work in bridges	5 - 7
Wire ropes	8 - 9

Figure 9: Factor of Safety for Equipment [26]

3.4.1 Pressures/Stresses Calculation for The Bottles

For Coke bottles:

- Diameter of the bottle, $D_1 = 95$ mm
- Thickness of the bottle, $t_1 = 0.5$ mm
- Factor of safety value, FOS = 6

- The longitudinal stress in the wall, $\sigma_{\text{longitudinal 1}}$:

$$\sigma_{\text{longitudinal 1}} = P_1D_1/4t_1$$

$$= P_1 \text{ (95 mm)/ (4*0.5 mm)}$$

$$= 47.5\ P_1$$

- The hoop stress in the wall of the bottle, $\sigma_{\text{hoop 1}}$:

$$\sigma_{\text{hoop 1}} = P_1D_1/2t_1$$

$$= P_1 \text{ (95 mm)/ (2*0.5 mm)}$$

$$= 95\ P_1$$

- Von-Mises criterion for principal stress of $\sigma_{\text{longitudinal 1}}$ and $\sigma_{\text{hoop 1}}$, while the stress levels are acceptable if:

$$\text{sqrt } (\sigma_{\text{longitudinal}}\text{^}2 - \sigma_{\text{longitudinal}} * \sigma_{\text{hoop}} + \sigma_{\text{hoop}}\text{^}2) < \text{yield strength}$$

  By expanding, collecting the LHS and substitutes all values, the equation can be simplified as below. As mentioned before, P_1 is the maximum value of pressure or stress when the bottle starts to fail. Hence, P_1 will be replaced with $P_{\text{fail 1}}$ to make it clearer for FOS calculation later:

$$82.272\ P_{\text{fail 1}} < 125*10^6 \text{ Pa}$$

  Therefore, after solving the equation, the value of $P_{\text{fail 1}}$ that is obtained is:

$$P_{\text{fail 1}} < 1\ 519\ 350.45 \text{ Pa or } 220.36 \text{ psi}$$

  By manipulating the equation of FOS for allowable stress design, the allowable pressure or stress, $P_{\text{allowable 1}}$ is determined:

$$\text{FOS} = P_{\text{fail}}/ P_{\text{allowable}}$$

$$P_{\text{allowable 1}} = P_{\text{fail 1}}/ \text{FOS}$$

$$= 1\ 519\ 350.45 \text{ Pa / 6}$$

$$= 253\ 225.08 \text{ Pa or } 36.73 \text{ psi}$$

For Pepsi bottles:

- Diameter of the bottle, $D_2 = 91$ mm
- Thickness of the bottle, $T_2 = 0.5$ mm
- Factor of safety value, FOS = 6

- The longitudinal stress in the wall, $\sigma_{\text{longitudinal }2}$:

$$\sigma_{\text{longitudinal }2} = P_2D_2/4t_2$$

$$= P_2\ (91\ \text{mm})/\ (4*0.5\ \text{mm})$$

$$= 45.5\ P_2$$

- The hoop stress in the wall of the bottle, $\sigma_{\text{hoop }2}$:

$$\sigma_{\text{hoop }2} = P_2D_2/2t_2$$

$$= P_2\ (91\ \text{mm})/\ (2*0.5\ \text{mm})$$

$$= 91P_2$$

- Von-Mises criterion for principal stress of $\sigma_{\text{longitudinal }2}$ and $\sigma_{\text{hoop }2}$, while the stress levels are acceptable if:

$$\text{sqrt}\ (\sigma_{\text{longitudinal}}\text{\^{}}2 - \sigma_{\text{longitudinal}} * \sigma_{\text{hoop}} + \sigma_{\text{hoop}}\text{\^{}}2) < \text{yield strength}$$

  By expanding, collecting the LHS and substitutes all values, the equation can be simplified as below. As mentioned before, P_2 is the maximum value of pressure or stress when the bottle starts to fail. Hence, P_2 will be replaced with $P_{\text{fail }2}$ to make it clearer for FOS calculation later:

$$78.808\ P_{\text{fail }2} < 125*10^6\ \text{Pa}$$

  Therefore, after solving the equation, the value of $P_{\text{fail }2}$ that is obtained is:

$$P_{\text{fail }2} < 1\ 586\ 133\ \text{Pa or } 230.05\ \text{psi}$$

  By manipulating the equation of FOS for allowable stress design, the allowable pressure or stress, $P_{\text{allowable }2}$ is determined:

$$\text{FOS} = P_{\text{fail}}/\ P_{\text{allowable}}$$

$P_{allowable\ 2} = P_{fail\ 2} / FOS$

$= 1\ 586\ 133\ Pa / 6$

$= 264\ 355.57\ Pa$ or 38.34 psi

- The Total of Allowable Pressure for The Bottles:

$P_{allowable\ 1} = 253\ 225.08\ Pa$ or 36.73 psi

$P_{allowable\ 2} = 264\ 355.57\ Pa$ or 38.34 psi

It is safe and recommended to assumed that the allowable pressure, $P_{allowable}$ for all bottle is the minimum allowable stress of the bottles is 253 225.08 Pa or 36.73 psi.

The total allowable pressure, $P_{allowable\ total}$ for 3 Coke bottles and 1 Pepsi bottles is:

$P_{allowable\ total} = 253\ 225.08\ Pa * 4$

$= 1\ 012\ 900.32\ Pa$ or 146.91 psi

3.4.2 Adjustment on The Final Total Allowable Pressure

Unfortunately, the total allowable pressure for all bottles is very high for a small-scale experiment. Moreover, the bottles have been tested one by one by filling the compressed air inside them before connecting them together with pneumatic tube. Shockingly, each of the bottles become as hard as a rock when the total pressure inside it reach only 68947.6 Pa or 10 psi. This is maybe due to the modification applied on them such as inserting the valves and pneumatic tube. The modification maybe caused their yield strength to become lower as their overall structure are affected by the it. Considering the safety measure as a high level of experience is needed to operate highly pressurized air, the total allowable pressure for the bottles will be reduced into a very safe level. The new allowable stress, $P_{new\ allowable}$ will become the average of only for each 2 bottles:

$P_{new\ allowable} = (68947.6\ Pa * 4) / 2$

$= 137\ 894\ Pa$ or 20 psi

3.5 CAD Design

All the required materials are then being illustrated from 2D into 3D using Solidworks to give more clearer view for the project. Their dimensions are recorded beforehand using a measuring tape for bigger parts of the materials rather than a ruler to obtain more precise measurements. Vernier caliper is only restricted to smaller parts because of the instrument's measuring scale limitation. The diagrams shown below are the parts involved in the project (the wires and led are excluded).

3.5.1 The Parts Involved In The Project

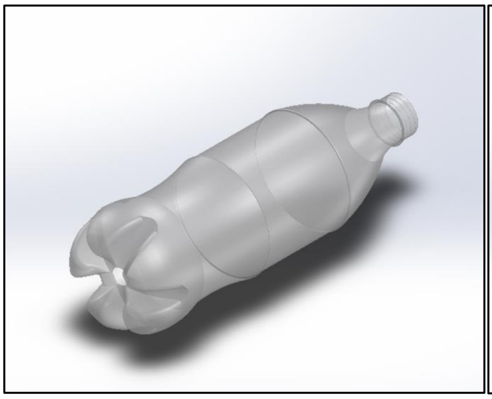


Figure 10: Coke Bottle with Hole

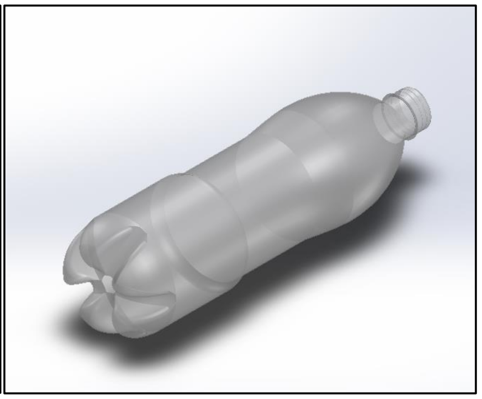


Figure 11: Pepsi Bottle with Hole

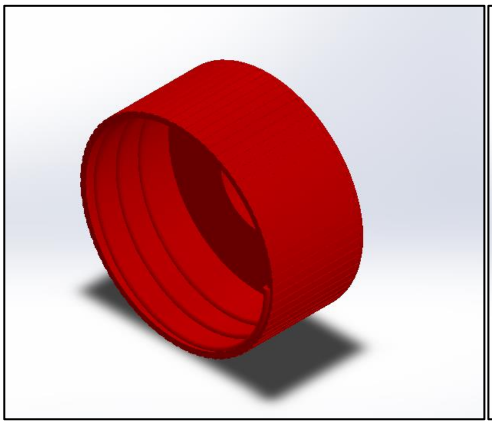


Figure 12: Bottle Cap with Hole

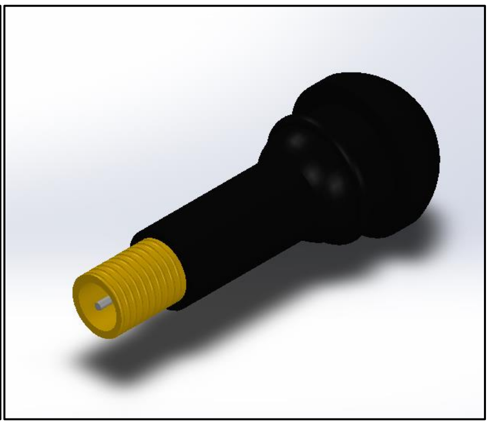


Figure 13: Car Tubeless Valve

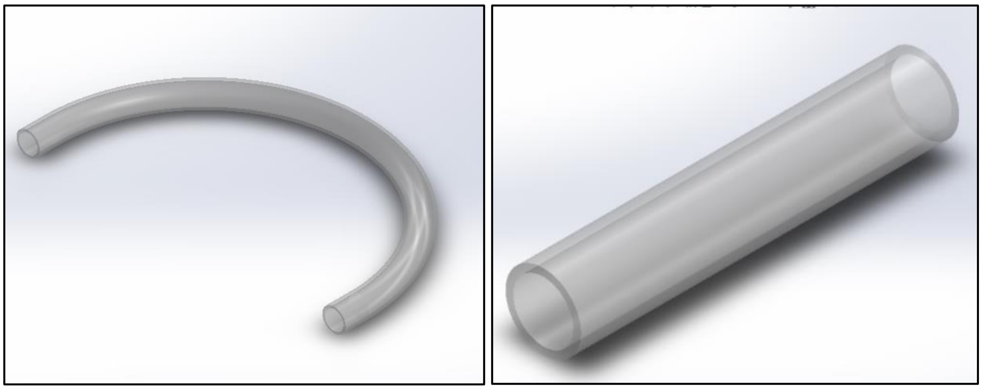
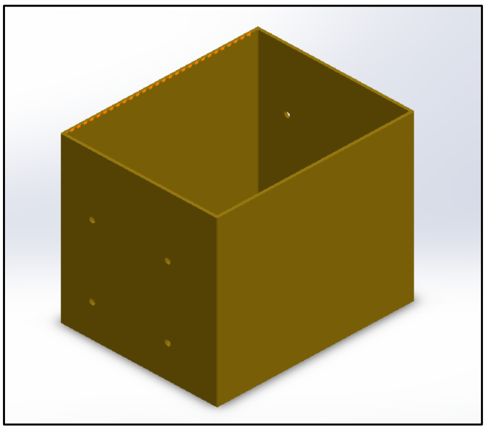


Figure 14: Pneumatic Tube



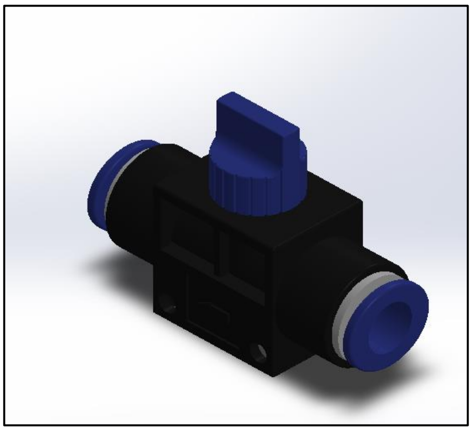
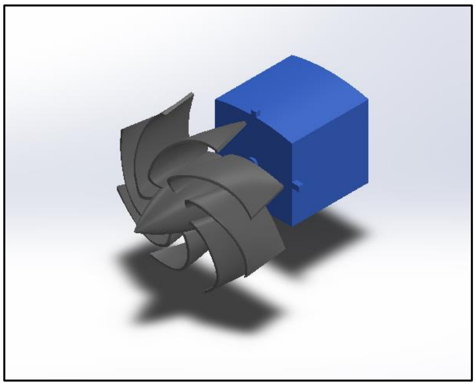


Figure 15: Mineral Water Box

Figure 16: Pneumatic Ball Valve



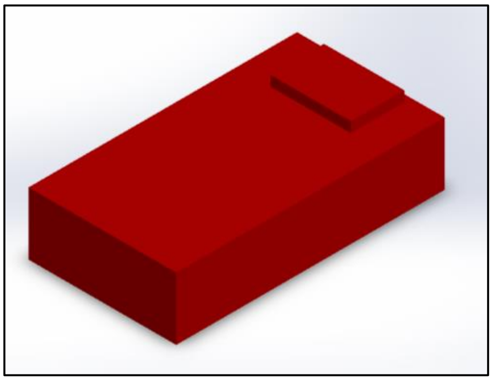


Figure 17: Turbine and Generator

Figure 18: Platform

3.5.2 Project Assembly

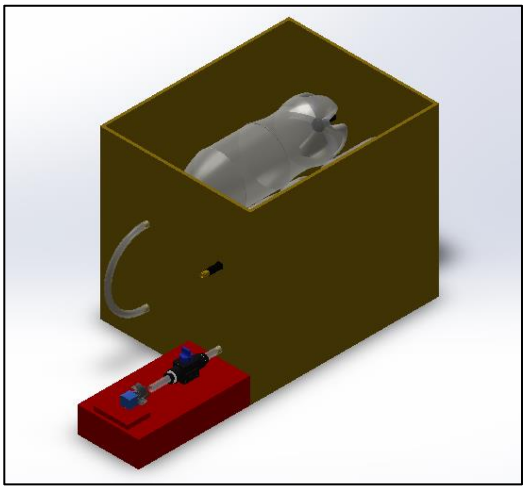


Figure 19: The assembly of the project

3.5.3 Exploded View and Bill of Materials (BOM)

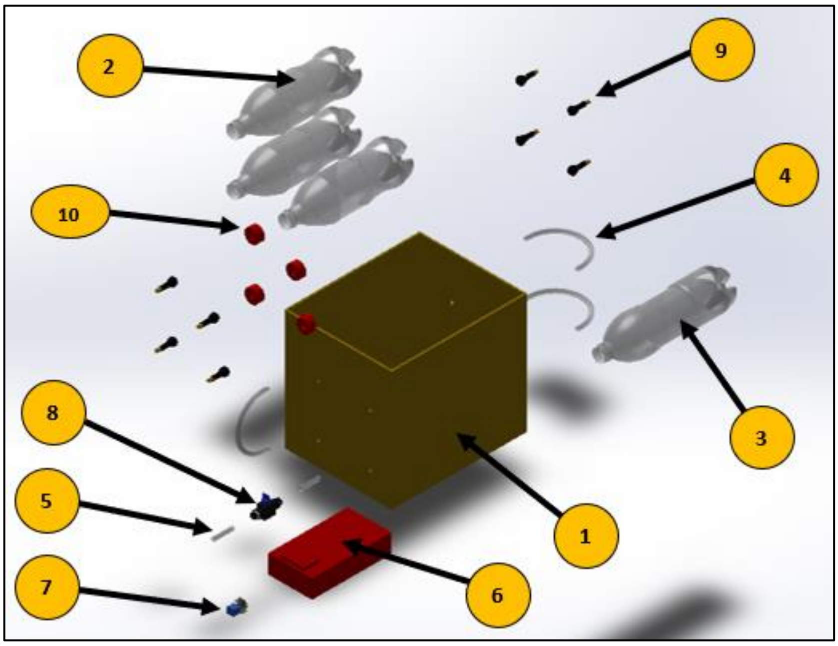


Figure 20: Exploded View of the Project

Item No.	Part Number	Description	Quantity
1	Mineral water box	NA	1
2	Coke bottle with valve no core		3
3	Pepsi bottle with valve		1
4	Pneumatic tube		3
5	Pneumatic tube straight		2
6	Platform		1
7	Turbine and generator		1
8	Pneumatic ball valve		1
9	Car tubeless valve		8
10	Bottle cap		4

Table 3.2: The Bill of Materials (BOM) of the project

3.6 Fabrication Procedures

First and foremost, the bottle caps from all bottles are removed and drilled with a driller using a 14mm-diameter drill bit to make holes. The location of the holes is supposedly to be at the center. Then, the bottom parts of all bottles are drilled with the same drill bit and the holes are also at the center of the bottles. The holes are made sure to be drilled carefully and slowly especially around the bottom parts of the bottles which are very hard to avoid any micro cracks as it will lead to leaking. It is also advisable to start with a smaller drill bit first to obtain a better result. After that, seven out of the eight car tubeless valves will have their valve cores removed by using a valve core remover tool. The valve cores are made sure to be removed carefully by rotating the tool in a counterclockwise direction. This is to prevent from damaging the valve cores, in case of reusing them in future.

Next, all the car tubeless valves are inserted through the holes of the bottle caps and the bottles themselves. For both bottle caps and the bottles, the head of the valves must always be at the inside of the caps and the bottles, while the tips are faced towards the outside. Then, the valve that still has its valve cores will be inserted at the bottle caps that is located at the entrance (where the input is applied). All the bottle caps are put back to the bottles and the caps is made sure to be closed tightly to prevent from the leaking. The bottles with the caps then will be soaked into a container or pail of soap water to check for any leaking presence. Moreover, if any soap bubbles appeared around the bottle cap or the bottles holes, a liquid rubber sealant is needed to be applied at that area. The use of other weak sealant like hot glue gun need to be prevented because the structure will fail in highly compressed air.

One of the bottles will be placed inside a mineral water box to make sure which side it can fit properly. Then, the position of the tips of both car tubeless valves at the bottle cap and the bottom part of the bottle are marked with a permanent marker at the center of the valve tips. The rest of the bottles may be placed temporarily inside the box to mark the other position and some spaces between the bottles in horizontally and vertically are to be made sure, to allow them expand freely without any disturbance when being filled with compressed air later. After that, the bottles are removed from the box and all the marked position on the mineral water box will be punctured with a sharp tool like scissors or knife carefully to keep clear of any injury.

Afterwards, all the bottle with the valves will be placed back inside the box and the tips all valves are inserted properly through the holes at the box. All valves except the ones at the entrance and the exit, then will be inserted to three long pneumatic tubes so that the bottles will be connected to each other. The pneumatic tubes can be screwed tightly through the thread from the valves' tips. Subsequently, a ball valve will be connected at the exit of the air tank through two short pneumatic tubes. A platform which is made from a shoe box will be placed under the ball valve and attached at the box wall to support the ball valve weight that could bend the pneumatic tubes. The turbine with a generator then will be placed at the new exit which is located at the end of the pneumatic tube that is connected to the ball valve. A certain distance between the turbine and the exit airways are to be made sure to reduce loss of compressed air applied towards the turbine.