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A Comprehensive Review of Compressed-Air Vehicles: A Technological Advancement Towards Sustainable Development

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Abstract

Greenhouse gas emissions have become an essential environmental issue with far-reaching effects on ecosystems and societies worldwide. Around 20-30% of air pollution is caused by harmful gas emissions, mostly by automotive vehicles. The consumption of fossil fuels in vehicles and other utilities is responsible for the depletion of natural resources. The excessive use of fossil fuels has increased energy costs and intensified competition for different resources, posing economic issues in several nations. This has led to risks to energy security and increased geopolitical conflict between countries. However, the drawbacks of using fossil fuels have made it necessary to discover alternate energy sources, ideally, the ones that don't endanger the environment. A compressed air vehicle (CAV) is a resilient transportation solution that utilizes compressed air as a power source instead of fossil fuel and reduces greenhouse gas emissions. This energy source has great potential for sustainable development. Along with sustainable energy, the fabrication of such vehicles with the use of polymers plays a vital role in the development and boosting of this industry. This paper represents a comprehensive overview of compressed air as a fuel source, along with the various technological innovations made by various researchers, scientists, and energy enthusiasts. During this study, rotor casing diameter, pressure angle, number of wings, and angle parameters were considered to enhance the capabilities of CAV.

Keywords: Compressed-air vehicle (CAV), Air engine, Air pollution, Air motor, Zero-emission, Sustainable energy, Energy density

INTRODUCTION

Fossil fuel was responsible for 82% of the overall primary energy source in 2011. Most of the air pollution generated is due to the burning of fossil fuels, which is necessary in industries, transportation, electricity generation, etc. Air pollution has been linked to the mortality of numerous children under the age of five [1]. Air pollution has become a major health risk, responsible for approximately 8.1 million fatalities worldwide in 2021. Nearly 90% of the diseases caused by air pollution are non-communicable diseases, such as respiratory diseases, lung cancer, diabetes, heart disease, and stroke. In 2022, roughly 8 billion metric tons of carbon dioxide equivalent ($GTCO_2e$) were generated; this amounts to 14% of all emissions worldwide. After the industrial facilities, transportation is responsible for producing the second-highest amount of CO_2 emissions worldwide, having grown by around 80% since 1990 [2]. Natural resource scarcity positively correlates with agriculture, forestry, fishing, fossil fuel energy consumption, and total greenhouse gas emissions. However, the combustion of fossil fuels causes the depletion of natural resources that can

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influence climate change and acid rain, further contaminating water reservoirs [3]. In the transportation sector, road vehicles account for the majority of emissions up to 70%. By 2050, it is possible that greenhouse gas emissions could reach 60%. A shift to low-carbon transport is urgently needed, as worldwide CO_2 emissions must decrease by about 20% by 2030 to meet net-zero targets for the transportation sector [4]. A considerable move towards electric vehicles and other low-emission technologies might help achieve these targets. The eco-friendly automobile market worldwide is starting to focus on electric vehicles. Pollution and habitat damage are the two detrimental environmental effects that may arise from the fabrication of batteries used for electric vehicles. If rare elements are not extracted ethically for making batteries, it can result in major environmental problems [5].

Another alternative fuel source that will soon be more popular in the automobile sector is hydrogen. However, improper containment can result in the discharge of nitrogen oxides, which makes it mandatory to undertake exhaust gas treatment to lower NO_x emissions [6]. Extensive studies are being conducted to build environmentally friendly, non-polluting vehicles.

Another industry has emerged that uses the energy stored in compressed air for vehicles. It might seem that this technology has been developed recently, but the use of compressed air in automobiles was implemented centuries ago. This study gives a summary of the numerous developments in compressed air technology over the years as well as its potential growth in the automobile industry.

Historical Development

Several research studies on utilising air as a power source for automobiles began in the 17th century. Denis Papin, a British physicist, invented the pressure cooker in 1679 and proposed the idea of the first cylinder and piston steam engine in 1687. Even though the idea was impractical, other engineers and researchers were able to enhance the design, and this later resulted in the development of the steam engine, which made a significant impact on the Industrial Revolution [7, 8]. Thomas Savery underwent numerous improvements in his design and constructed a steam-driven suction pump to remove water from coal mines. Figure 1 shows the prototype model of Newcomen's pump situated at Glasgow University. Later in 1712, Thomas Newcomen developed the first engine driven by air that could be lucrative and continually deliver power to a machine. This study laid a foundation for utilising steam as an energy power source [9]. James Watt improvised the functionality of the Newcomen engine in 1776 by adding a separate condenser to the design. The piston was lifted by the pressure of the steam, and by condensing the steam, the piston was brought to the original state [10] (insert Figure 1).

However, more significant advancements began after the 19th century. In 1816, the first Stirling engine was created by Robert Stirling, where the engine was used as a functional pump that forced water into a quarry in 1818. With the assistance of his brother, James, it was the first air engine to have been used as a practical machine; an external combustion thermal engine for non-automotive usage [11, 12].

In England, Bompas created the first-ever compressed-air locomotive in the year 1828 with two separate storage tanks and standard cylinders [13]. Andraud and Tessie of Motay from France were the first known to construct a compressed-air vehicle in 1838, and tested their vehicle in 1840 in Chaillot, France, using a pneumatic motor [14]. Charles B. Hodges went on to make significant advancements in this field in 1869, and it became successful in the mining industry, selling hundreds of units. Several additional researchers constructed, tested and had considerable success with their creations during that period [15].

When the Mekarski engine was employed for road transport in the year 1870, it established one such noteworthy name, which is shown in Figure 2. A Polish engineer named Louis Mekarski created the model of the Mekarski air engine and tested it in Paris in 1876. The engine was operated by increasing the gas enthalpy after passing it through hot water. Mekarski's trams operated on lines in several French cities starting in 1879 and eventually vanished from La Rochelle's streets in 1929 [16, 17]. Robert Hardie advanced the idea even further in 1882 by implementing an improved re-heating system for the engine that recovers engine brake energy. In the Hoadley-Knight system, a multi-stage air-powered engine was created to increase the locomotive's working range before requiring system recharge. Between 1880 and 1900, two air compressor stations were built in New York, USA, with 1500 horsepower steam-powered air compressors providing compressed air for the Hoadley-Knight and Mekarski systems [8,17,18]. The above-mentioned developments date back to the 19th century (insert Figure 2).

Figure 1. Thomas Newcomen’s suction pump [9].

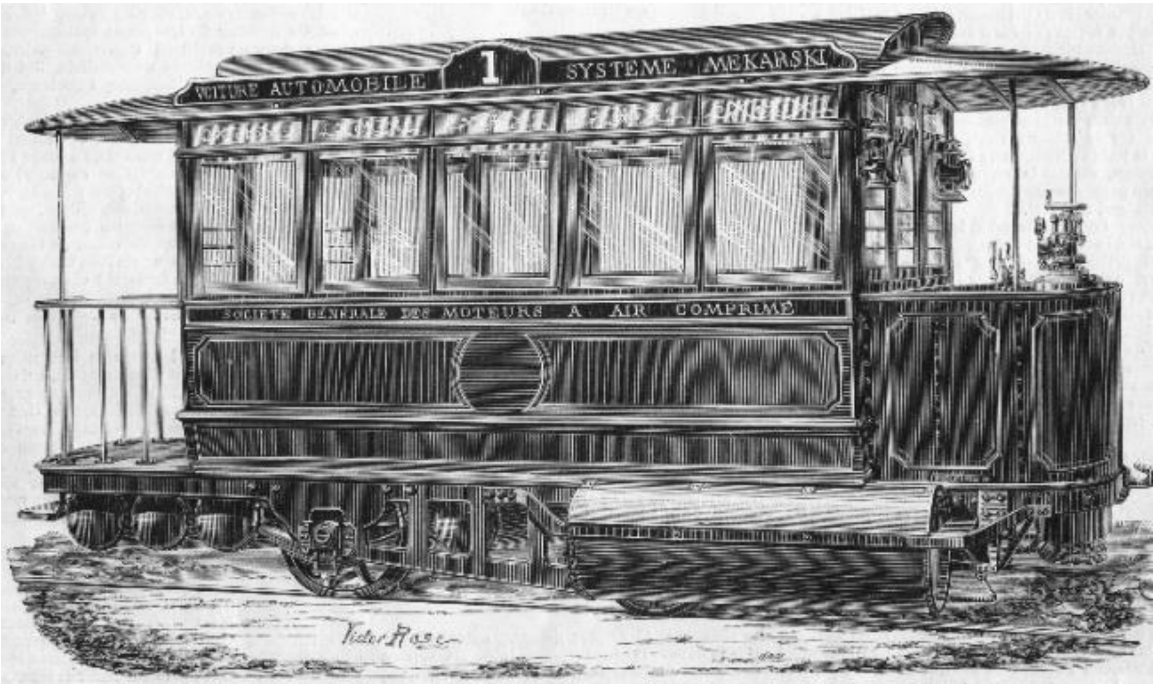

Figure 2. Mekarski trams powered by compressed air [18].

LITERATURE SURVEY

In the 20th century, many research papers emphasised the challenges faced by researchers to compete in the commercial market dominated by conventional gasoline internal combustion engine technologies [19]. Terry Miller implemented a multi-stage expansion with four stages in the year 1979. The rising expense of petroleum goods caused compressed air technology to pick up speed once more in 1979 [18]. Low energy density and low compression efficiency were among the main problems with compressed-air-powered systems. An outline of the advancements made in this sector with the aid of contemporary technology can be found below. Armando Regusci has made a substantial contribution in this area since 1984. One of his most notable inventions was a four-wheeled vehicle with a 100 km range on a single tank, powered by a pneumatic engine is shown in Figure 3 [20, 21] (insert Figures 3 and 4).

Figure 3. Testing took place in maldonado [21].

Figure 4. Improving the simple expansion motorcycle.

A chain was dragged by the piston instead of a rod which created the torque necessary for the movement. The piston slowly descended after the upstroke to draw the chain once more. Using a mechanism akin to that of a mountain bike, the chain with a stretcher attached to the wheels rotated the gear. This fix made the engine start on its own, but it prevented the car from moving at a constant speed. Later, he created a compressed air-powered motorcycle and a moped and as shown in Figure 4. Further research expanding to include engines driven by sugar cane ethanol and methods for producing hydrogen [21].

An Italian designer, Angelo Di Pietro, who formerly worked as a researcher at Mercedes-Benz, worked on the piston-less rotary Wankel engine in 1969 and 1970. After moving to Australia, he founded his own engineering company, EngineAir, and he designed a rotary motor that could run on compressed gas, naming it the "Angelo Di Pietro Rotary Positive Displacement Air Engine" in 1999 claiming its efficiency to be 94.5% which is more efficient than the products made by other competitors. This work reveals that the engine could rotate at one pound of pressure due to the engine's lack of a conventional crankshaft, and the gearbox could be controlled by pressure differences that allowed a smooth control of rotational speed as well as torque [21, 22] (insert Figure 5).

The air motor was constructed using a simple cylindrical rotary piston rotating on the inner side of the cylindrical stator without any friction. With the use of pivoting dividers, the area between the shaft driver and stator was separated into six expansion chambers. The motor shown in Figure 5 is effectively a 6-cylinder expansion motor. More research is still being conducted to increase the Di Pietro air motor's performance and efficiency [23]. Much other research was also carried out for developing other air motors, and efforts were made to improve their respective efficiency.

Figure 5. Di Pietro motor 6-cylinder expansion motor [23].

Figure 6. AirPod by TATA Motors and MDI.

Since the 1990s, Guy Negre, a former Formula One engineer, founded a Luxembourg-French-based company, Motor Development International (MDI). The company created numerous air-powered vehicles in 2012 [24]. The first air-powered vehicle prototype, known as AirPod, was created by MDI in 1998. Many lightweight materials, including glass fibre, carbon fibre, and composites were utilised for the car's body, etc. to make the final product lightweight and durable, weighing only 220 kg. The 175-litre air storage tank holds around 350 bar of pressure and is tested up to 700 bar, and its top speed is 70 km/h. The three-wheeled air-powered vehicle could cover 220 kilometres on a full single air tank for as little as 1.10 euros as shown in Figure 6 [25] (insert Figure 6).

MDI studied and implemented a multi-stage expansion air-powered engine (APE) idea. The compressed air from the tank expands in three stages in three separate cylinders and heat exchangers, and the heat exchangers between the stages assist in obtaining energy from the surroundings. As a result, the efficiency is increased, and the expansion is considerably closer to an isothermal process [21] (insert Figure 7).

An electromagnetic air distribution system is installed in the MDI Cars as shown in Figure 7 that controls the supply of air to separate cylinders, therefore enabling an effective way to utilise energy. The use of heat exchangers heats the air, which is cooled before resulting in its expansion. Heating air could be one of the solutions to improve the engine’s performance. From the processes explained above, the air temperature after leaving the engine is often observed between 0ºC to −15ºC, and so, the after-products do not pose any harm to health, nor do they affect the environment negatively.

In addition to AirPod, MDI has created the CityCat and MiniCat, two more noteworthy air-powered vehicles. One of MDI's innovative cars is the CityCat, which is intended for use in metropolitan areas. With a maximum speed of 110 kmph, it provides a normal urban traffic range of about 200 km. Conversely, the MiniCat bears a striking resemblance to the CityCat in many aspects and is positioned as a small air-powered vehicle intended for urban environments. In normal use situations, the car has a range of about 150 km, and it can reach up to a maximum speed of 110 kmph which is comparable to that of the CityCat [26]. The engine of MDI vehicles has been designed to cut off briefly when the vehicle is stationary. Furthermore, the pneumatic system can recover 13% of the energy expended during braking.

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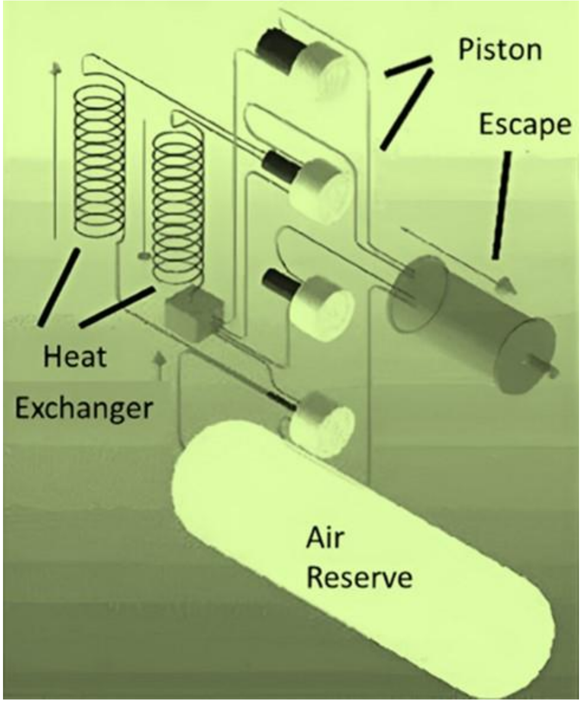


Figure 7. The air distribution system in MDI cars [21].

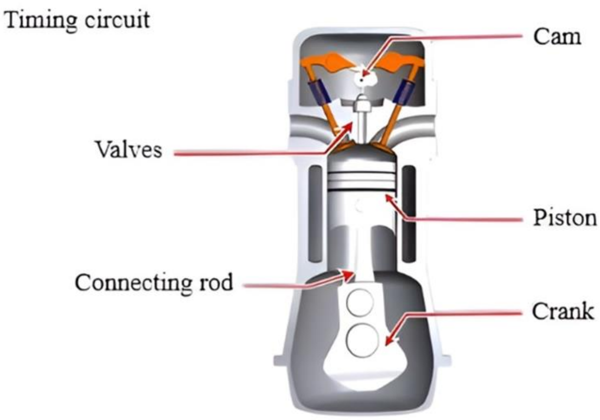


Figure 8. 4-stroke SI engine [27].

Patel revealed that it was possible to create an air-powered engine through internal combustion engine (ICE) modification and is shown in Figure 8. He developed the system's cam and swapped out the ICE's spark plug for a pulsed pressure flow control valve. A programmable logic controller (PLC) timing circuit operated the pulsed firing valve. This modification led to a lower temperature at the exhaust, reducing the risks of global warming. Compressed air technology was guaranteed to be a "Futuristic Mode of Transport" by his research [27] (insert Figure 8).

Dr. B. R. Singh and Dr. O. Singh have made a significant contribution to the advancement of compressed air technology. Their primary concerns were the escalating costs of fossil fuels and the pressing need to find an affordable and sustainable alternative energy source for automobiles. The best option for an energy source, they thought, was compressed air. Therefore, their primary goal was to create a practical air-powered engine with a turbine running on air that could produce 6.85 to 7.50 hp at 500 to 2000 rpm. This will satisfy the operating requirements of a motorbike. Their next goal was to store compressed air in a storage tank with a minimum capacity for the initial stage of operation for 30 minutes with a maximum pressure of approximately 200-300 psi [28]. The performance was investigated for the fundamental parameters, likely speed, torque and amount of air consumed to enhance the performance of the system (Figures 9 and 10).

It can be attributed from Figure 9 that the torque of the turbine decreases gradually with an increase in the speed and from Figure 10, the air would be rapidly consumed with an increase in speed. The fundamental function requirement to drive the system was the speed and the required speed to start the turbine would be 500 rpm at a minimum of 5 bar pressure (insert Figure 11).

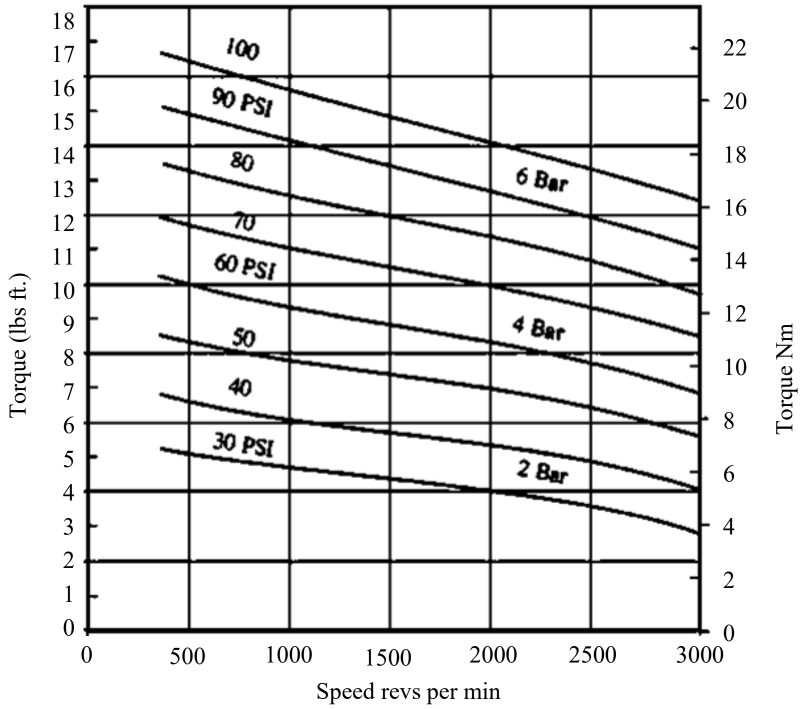


Figure 9. Torque vs speed [28].

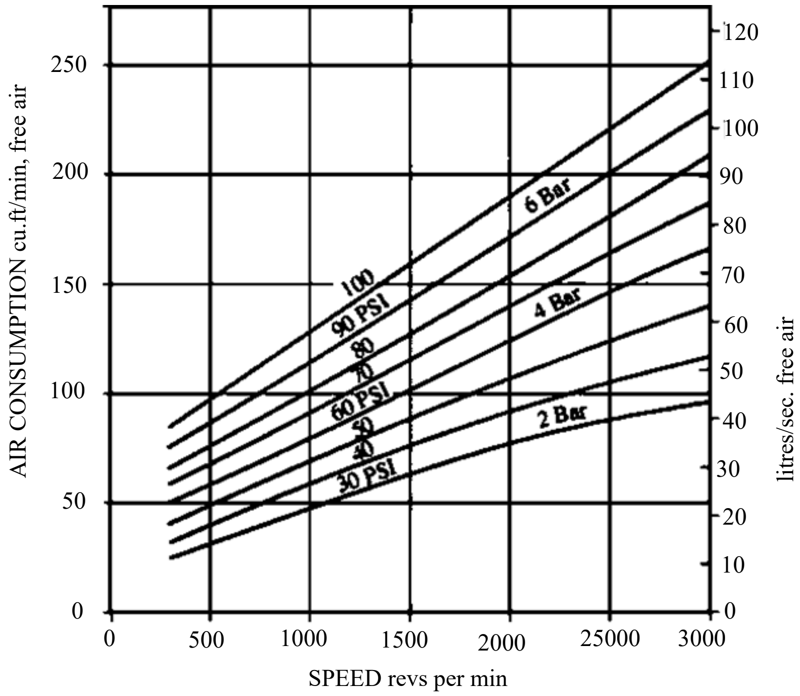


Figure 10. Air consumed vs speed [28].

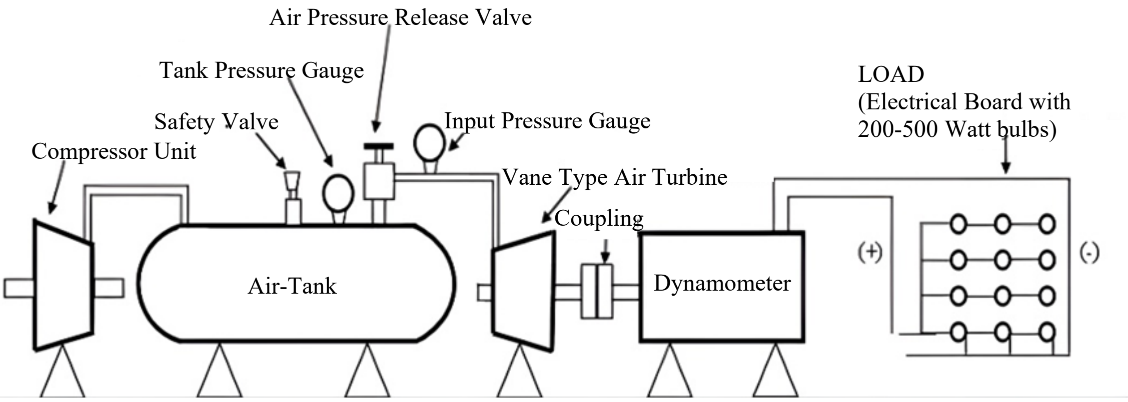


Figure 11. Test set-up representation [28].

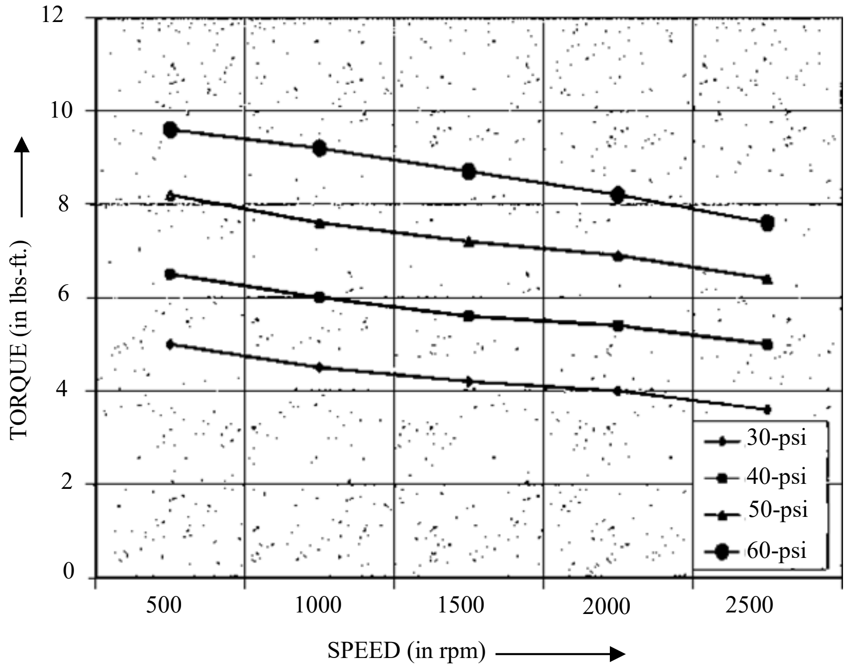


Figure 12. Torque vs speed [28].

To achieve the initial starting torque, high air pressure at low speed is required. At 2-3 bar air pressure, a 2000 r/min speed was obtained, leading to less air consumption. The following are the design considerations utilised for the commercial commitments preferably 7.2 hp.

Air pressure: 2.75-6.20 bar (assumed)
Speed: Approximate 500–750 r/min
Torque: Approximate 9.6 to 10 Nm
P–V ratio: 4/5

The theoretical calculation was made and the same was verified with the performance of experimental trials. During the comparative framework, it was observed that there is a slight error reported within the range of 15-20%. Also, variations in the mechanical losses were reported which result in less torque. (insert Figures 12 and 13)

Figure 12 and 13 represent 'torque (lb.-ft) versus speed (r/min)' and 'air consumption (ft^3) versus speed (r/min)' respectively.

It is observed that compressed air might work out to be a more practical and affordable option than a prime mover or engine powered by fossil fuels [28]. Additional studies were carried out to improve and optimize the vaned-novel air turbine design. Further study continued to optimize the rotary vaned motor, looking at several factors that impact the motor's performance [28-36], and constructed a compressed-air engine (CAE) prototype motorbike engine powered by compressed air [37] (insert Figure 14).

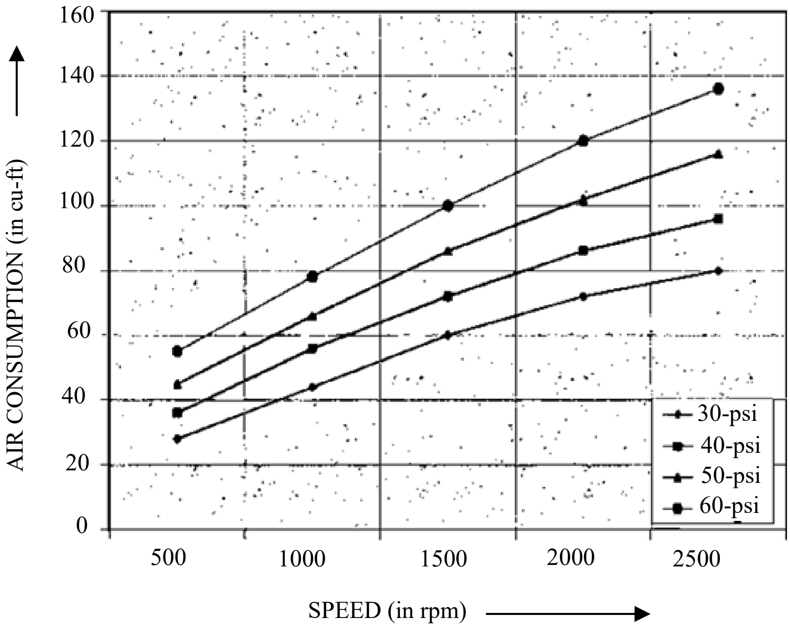


Figure 13. Air consumption vs speed [28].

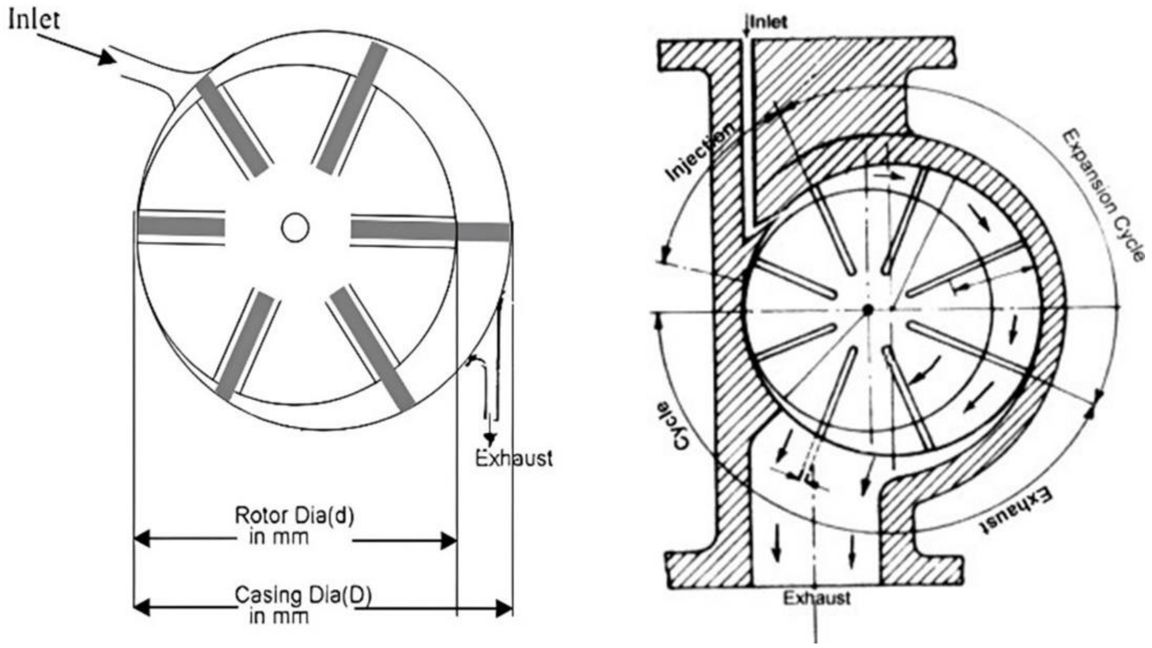


Figure 14. Air turbine-diagram and model [29].

After development, the experimentation has been continued to the effects of varying injection pressures ranging from 2, 3, 4, 5 and 6 bars fixed at injection angles Ø = 30^o, 45^o, and 60^o at a rotational speed of the turbine is 2500 rpm having any impacts on the expansion work, its flow and overall work output of the air turbine (insert Figures 15–17).

The performance was evaluated on the basis of rpm. It can be revealed from Figure 15 that the overall power output vs rotation speed observed at injection angle φ=30º, where the optimal shaft input obtained is at vane angle θ=60º for 6 vanes. Also, Figure 16 reveals that the total power output vs speed of rotation at injection angle φ=45º, where the optimal shaft input is obtained at either θ=45º or 51.4º for 8 to 7 vanes. At 60º injection angles, the power output for the shaft is observed to be maximum and represented in Figure 17 [29]. The correspondence between the injection angle and the vane angle is crucial for achieving the best air turbine output, and the application of different injection angles does have a substantial impact on the overall shaft power output.

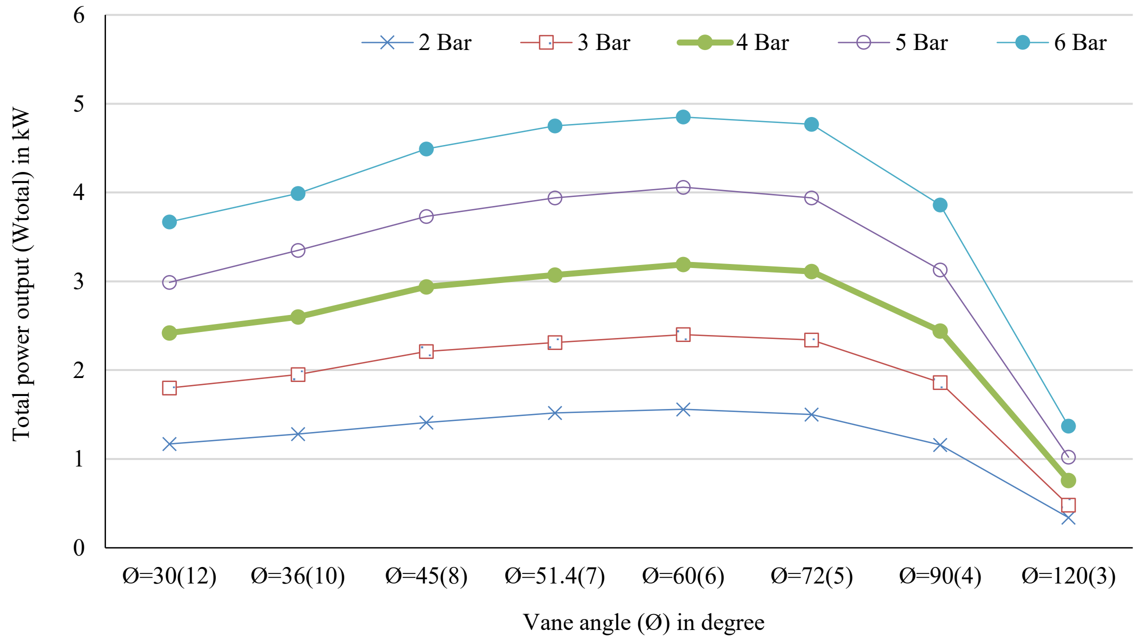


Figure 15. Ø =30º, rotation speed=2500 rpm [29].

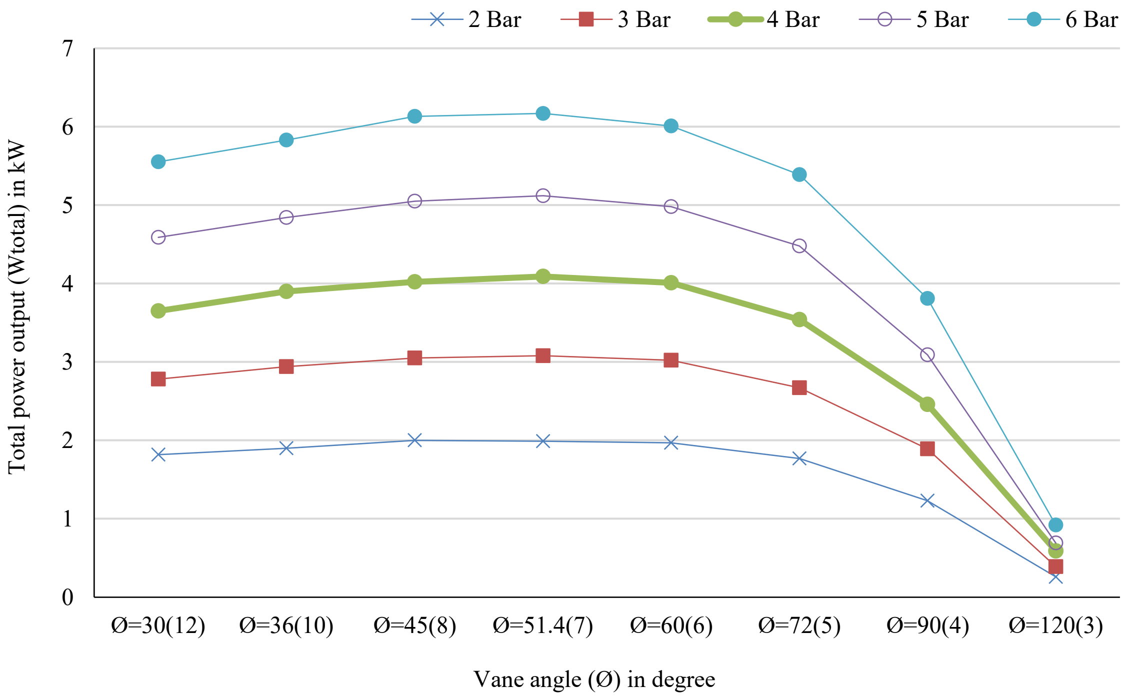


Figure 16. Ø =45º, rotation speed=2500 rpm [29].

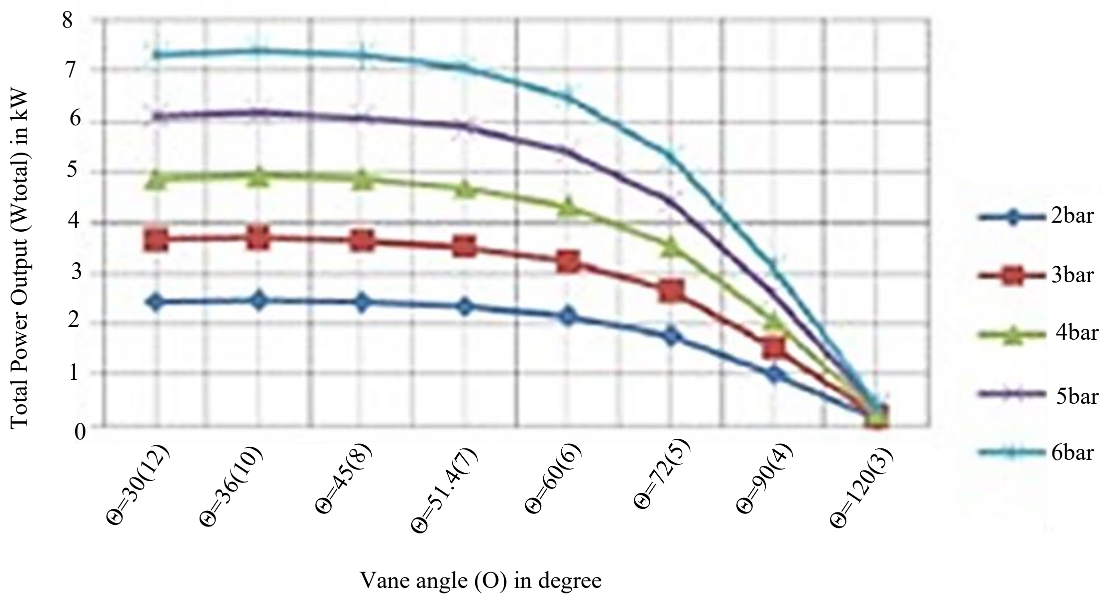


Figure 17. Ø =60º, rotation speed=2500 rpm [29].

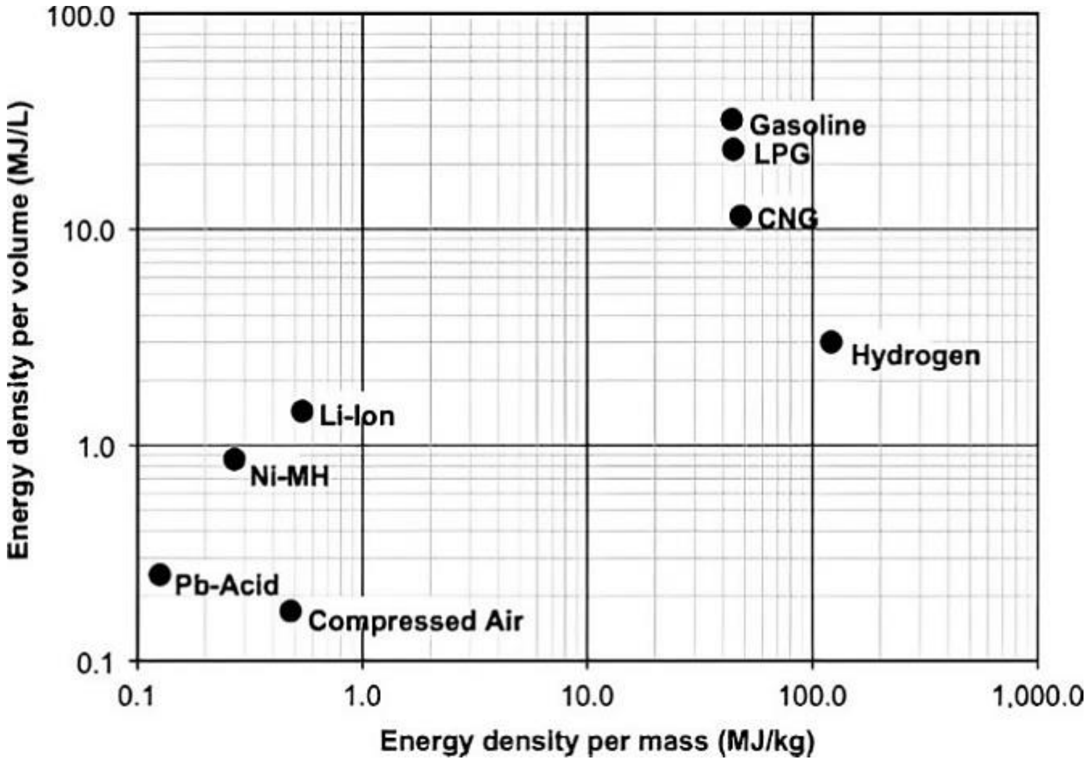


Figure 18. Comparison of Energy density of various fuels [38].

In 2010, Papson, Creutzig and Schipper analysed vehicle performance in terms of drive-cycle patterns, environmental effects and economic costs through the comparison of various fuels.

The energy densities of different energy sources such as batteries, compressed air, petrol, hydrogen, etc., were also examined (insert Figures 18 and 19).

Figure 18 shows the representation of energy density per unit volume with per unit mass of various energy sources. The carbon emissions of the CAV are higher than those of petrol and electric vehicles, as seen in the accompanying Figure 19. The carbon footprints of a CAV and an electric vehicle differ depending on the fuel combination because they both run on electricity. The air-powered vehicles (APV) emissions per mile are 1.6-2.6 times higher than those of petrol vehicles due to the compressors. Furthermore, in every scenario they compared: fuel economy, range and fuel costs; the CAV emits 4.3 times more emissions than the electric car. However, this statistical data was examined ten years ago, back when the compressors could run on both electricity and fuels like diesel and petrol [38]. Numerous technological advancements have undergone over the years making it feasible to reduce the carbon footprints generated by APVs.

Extensive trials were conducted to examine the operation of an air engine operated by a piston and a systematic diagram shown in Figure 20. Chih-Yung Huang with his colleagues conducted research by modifying a 100 cm3 ICE into an air engine. In the experiment, a high-pressure sensor with a 400 L buffer tank and 5-9 bar of pressure was used in place of the spark plug [39] (insert Figures 20 and 21).

The comparison of torque vibration, pressure and valve lifts is represented in Figure 21, and it is observed that variation in pressure changes the crank angle with a change in the torque. The inlet pressure had reduced slightly as the intake valve opened, increasing the cylinder pressure at a crank angle of 60º. The torque seemed to increase at the compression and expansion stroke at around 120º. The inlet pressure in the cylinder was regained at 6.7 bar after the intake valve closed, reducing the pressure within it to 2.5 bar after the exhaust valve opened completely. The total power output was reduced due to the compression process recurring within the cylinder chamber due to an increase in pressure. However, there was a rapid reduction in the cylinder pressure as well as the torque when the exhaust valve opened gradually. With a low outlet pressure throughout the cycle, a maximum deviation was observed at the exhaust stroke. With all the modifications in the working of cam and crank angles, 0.95 kW was the maximum power obtained at 1320 rpm and 9 bar, with 9.99 Nm maximum torque at 465 rpm at that pressure. The split-cycle engine's output pressure rose by 0.75 bar, more than 1.5 bar at 500-2000 rpm, respectively.

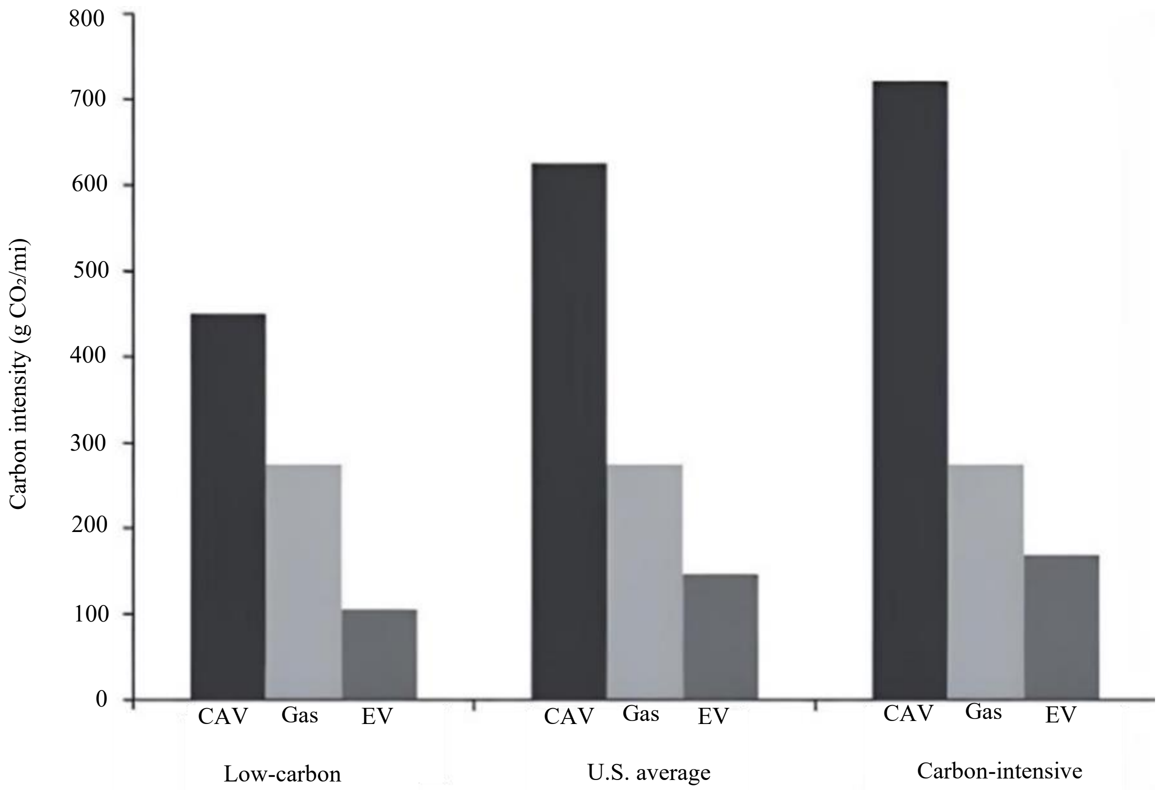
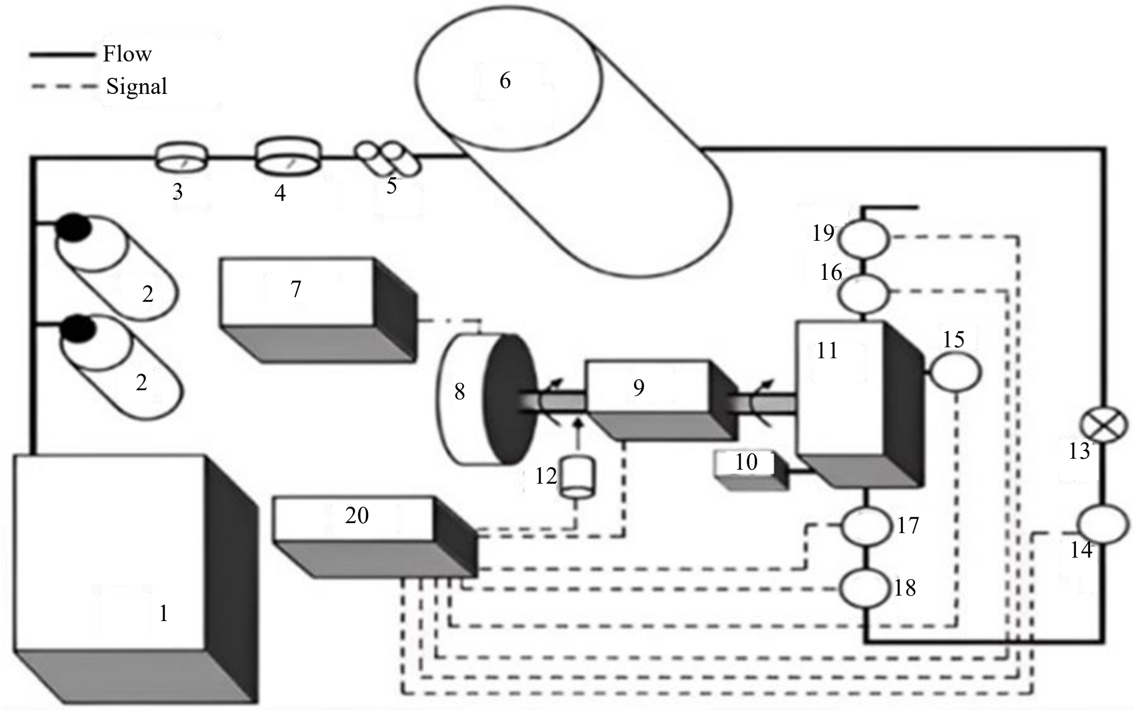


Figure 19. Comparison of vehicle carbon intensity [38].



1.Compressor
2. High pressure tank
3. High pressure regulator
4. Low pressure regulator
5. Water filter
6. Buffer tank
7. Power supply
8. Electromagnetic brake
9. Torque sensor
10. Starter
11. Engine
12. High pressure tank
13. Optical tachometer
14. Flow meter
15. Cylinder pressure
16. Outlet pressure sensor
17. Inlet pressure sensor
18. Inlet thermocouple
19. Outlet thermocouple
20. DAQ

Figure 20. Diagrammatic representation of their experimental setup [39].

This could be an indication that the compressed air energy can be recycled again through the addition of more cylinders. This study reveals that the CAE could produce more torque than an ICE, although it might not result in the same power output. The current air engine's low air consumption (flow rate), which was roughly 1050 L/min, restricts its power output. Adopting wider intake and exhaust valve apertures could further increase the overall power performance and torque output.

S.S. Verma gave a status report regarding the latest advancements in compressed-air technology till 2013 and gave a brief list of a few leading manufacturers working in this field. Table 1 represents the recent development in the era of compressed air vehicles (insert Table 1).

Polymers play a pivotal role in the advancement of compressed air technology due to their unique properties, such as lightweight, flexibility, and resistance to corrosion. These materials are commonly utilised in the manufacturing of seals, gaskets, hoses, and storage tanks, ensuring durability and efficiency in compressed air systems. The use of advanced polymer composites further enhances the thermal and mechanical performance of components, contributing to reduced energy losses and improved system longevity. Additionally, their versatility enables the development of innovative designs for compressed air storage and delivery systems, paving the way for sustainable and high-performance applications [40].

Table 1. Recent development of compressed air vehicles [41].

Company	Recent Development
Association Promotion Usages Quasiturbine (APUQ)	Developed an air-powered car that uses a quasi-turbine for rotary motion.
Motor Development International (MDI)	Developed several models of AirPods. Their foremost invention was the "active chamber", where the air is heated to improve the energy output.
TATA Motors collaborated with MDI	The main concern of air cars; lesser range and lower engine temperatures encouraged the company to produce for the Indian Market.
The Energine Corporation	Promised to develop assembled cars which will run on a hybrid system.
K'Airmobiles	The project has failed to secure the required funding. Meanwhile, the team has determined that using compressed air that has been kept on board is physically impossible because of the low energy in the air with the various losses that arise during expansion.
Engine-air	A small-scale industry situated in Australia that uses air-powered vehicles for their company's usage.
Honda	Presented the Honda Air concept car in 2010

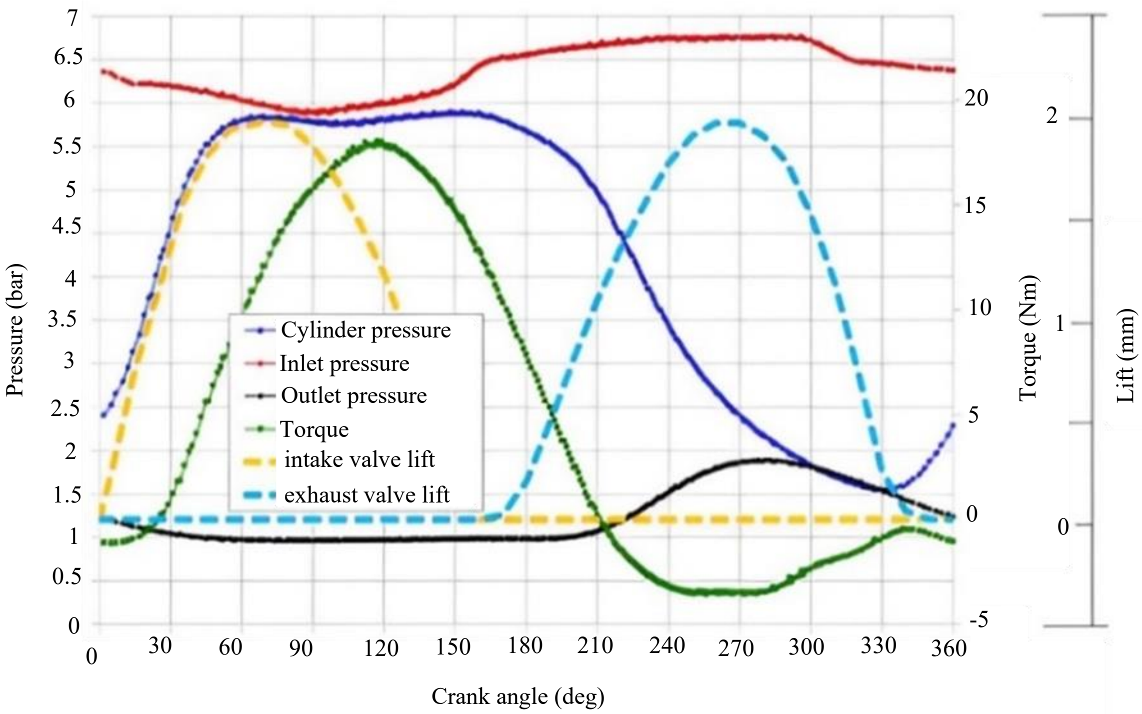


Figure 21. Comparison of pressures, torque variation and valve lifts [39].

CONSTRAINTS IN COMPRESSED AIR

During the evaluation of the performance of compressed air technology, researchers came across several constraints. The various parameters were considered during the study to enhance the performance of the system. The key parameters considered are input energy, temperature control, air storage capacities, etc.

Air storage and Refuelling:

The pressure vessel must follow the appropriate safety criteria in the design of the storage tanks. Installing modern, convenient, high-tech air pumps at petrol stations is necessary. However, it would be a challenging investment for station owners. CAVs would be more convenient overall, although refilling them would take longer.

Input Energy

For compressed air, less than 20% of the energy input is used by the car; the remaining 80% is paid for goes straight into the distribution network. This energy source comparatively contains a low energy density.

Temperature Control

When air is compressed, an adiabatic process occurs where the heat of compression is retained; no heat is exchanged, which results in zero entropy. This causes the compressed air to heat up significantly. The energy added to the gas by the compressor causes the compressed air to rise in temperature, which could be managed using various techniques. The heat in the gas must inevitably be removed for this to happen. Heat exchangers, also known as intercoolers, can be used to remove this heat from the compressor between stages.

Multi-stage Compression

The compression phase in the air engine tends to generate heat. Therefore, the temperature of the compressed air has to be reduced between the stages, which keeps the heat within the system, improving overall efficiency.

Energy Released

When compared to many other utilities, compressed air costs more per unit of energy delivered. As a result, the energy released by compressed air is quite significant, as there are variables which depend on it. (insert Figures 22 and 23)

Adiabatic Expansion

It can be attributed from Figure 22 that a linear relationship was observed in the energy release of isothermal expansion and adiabatic expansion with an increase in air pressure. The adiabatic expansion was found to be lower when compared with the isothermal expansion.

Also, temperature in adiabatic expansion decreases with an increase in the compressed air pressure, with a temperature of 300K as shown in Figure 23.

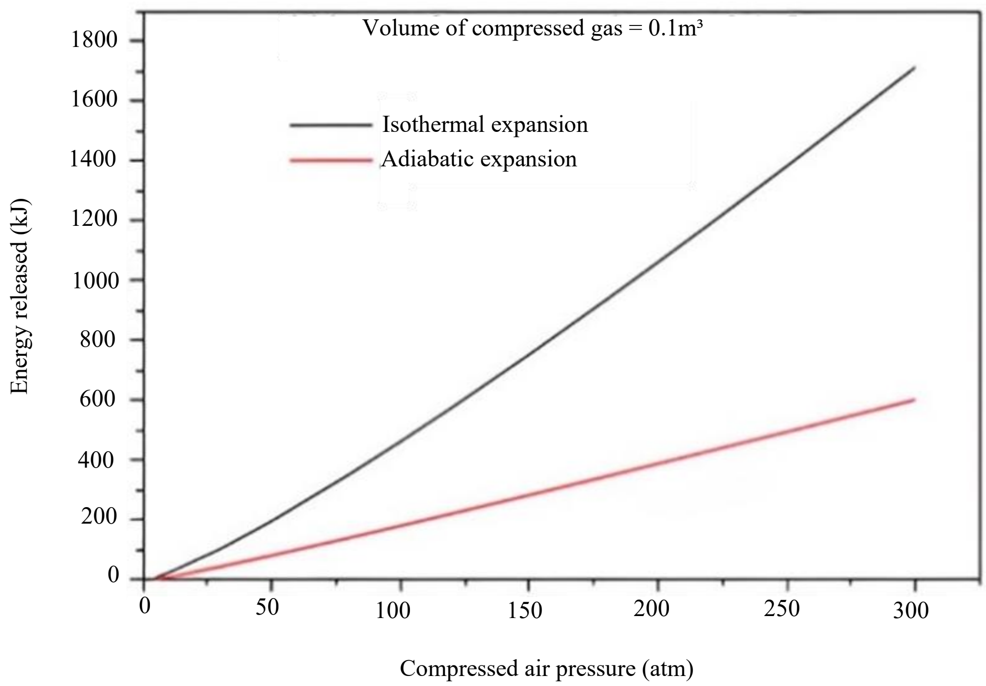


Figure 22. Isothermal & Adiabatic expansion [41].

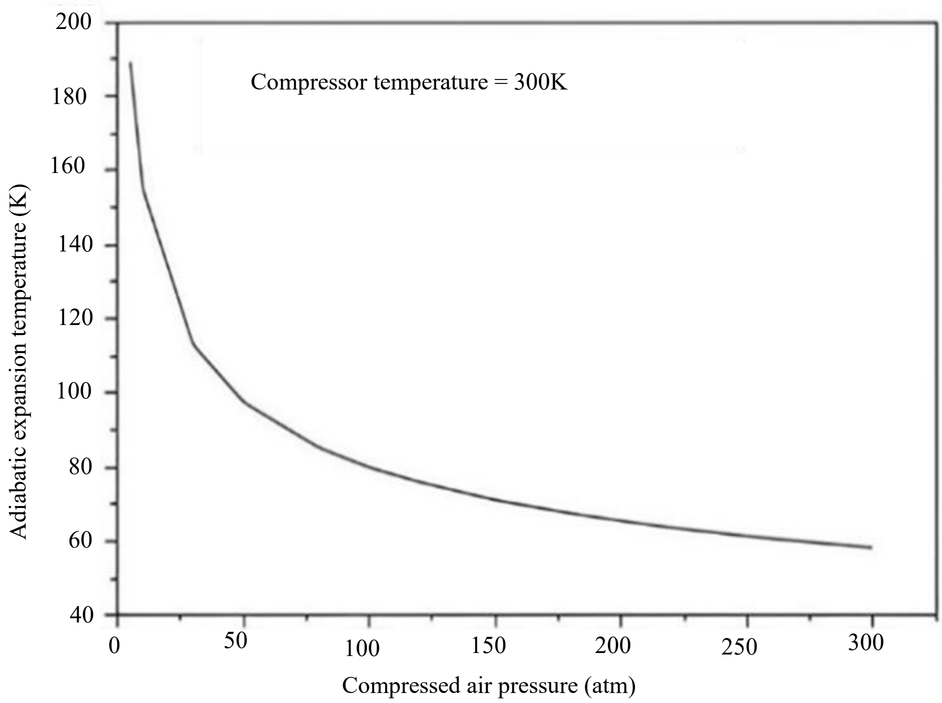


Figure 23. Compressed air-temperature [41].

Pollutant Emission

The air in the CAVs does not produce high air pollution as it is filtered initially before entering the compressor, but may contain lubricants. The emissions from these types of vehicles also depend on the air quality and the temperature of it stored in the storage tank. However, an excess temperature could lead to the dissociation of nitrogen components in the atmosphere and their reaction with $O_{2,}$ leading to the production of undesirable gaseous molecules such as NO and N_2O in substantial amounts. In comparison to the ICE, the compressed air-driven locomotive is safer because it does not produce a lot of heat or sparks when operating [41].

In recent development, Tamer Nabil developed a virtual prototype of an APE by modifying a Dayun petrol engine of 150 $cm^{3,}$ with the main objective was to modifying a 4-stroke SI engine to an APE. Therefore, he chose to develop a simulation of a prototype in MATLAB 8. During simulation, a solenoid valve replaced the spark plug and used infrared modules, which helped in managing the piston timing. For practical implementation, he also designed a special mechanism and auxiliary components for functionality (insert Figure 24).

A schematic diagram is shown in Figure 24 of the prime components of the system used in the development, including a compressor, storage tank, SI engine, solenoid valve, battery, throttle valve, pressure gauge, K-type thermocouples, etc., including the IR timing technique. The tank's supply pressure was set to 8 bar, and the crankshaft was adjusted to 0. The engine was started with the kick start, which applied the necessary initial thrust. Using the IR module to send signals to the solenoid valve, the timing for opening and closing the valves was set for the engine. The cycle was repeated till there was enough supply pressure in the tank. When the intake of the engine was opened, the piston made a power stroke, moving from the TDC to the BDC without opening the exhaust. The intake was kept closed just before the BDC. It is necessary to allow the pressurised fluid to expand and decrease the quantity of air consumed. The exhaust stroke of the piston forces the expanding air out of the cylinder. When the crank angle is at 355º, the exhaust is stopped, causing the residual air to be compressed and utilised to increase the restricted pressure. This method reduces the piston's output work while assisting the entering pressure in moving the piston with enough force (insert Figure 25).

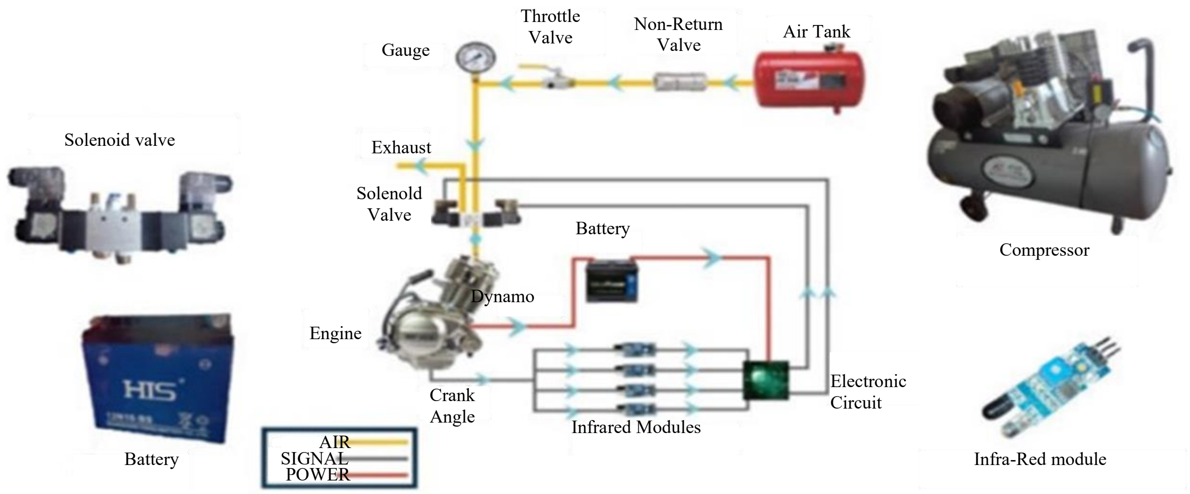


Figure 24. Description of the CA system to be developed [42].

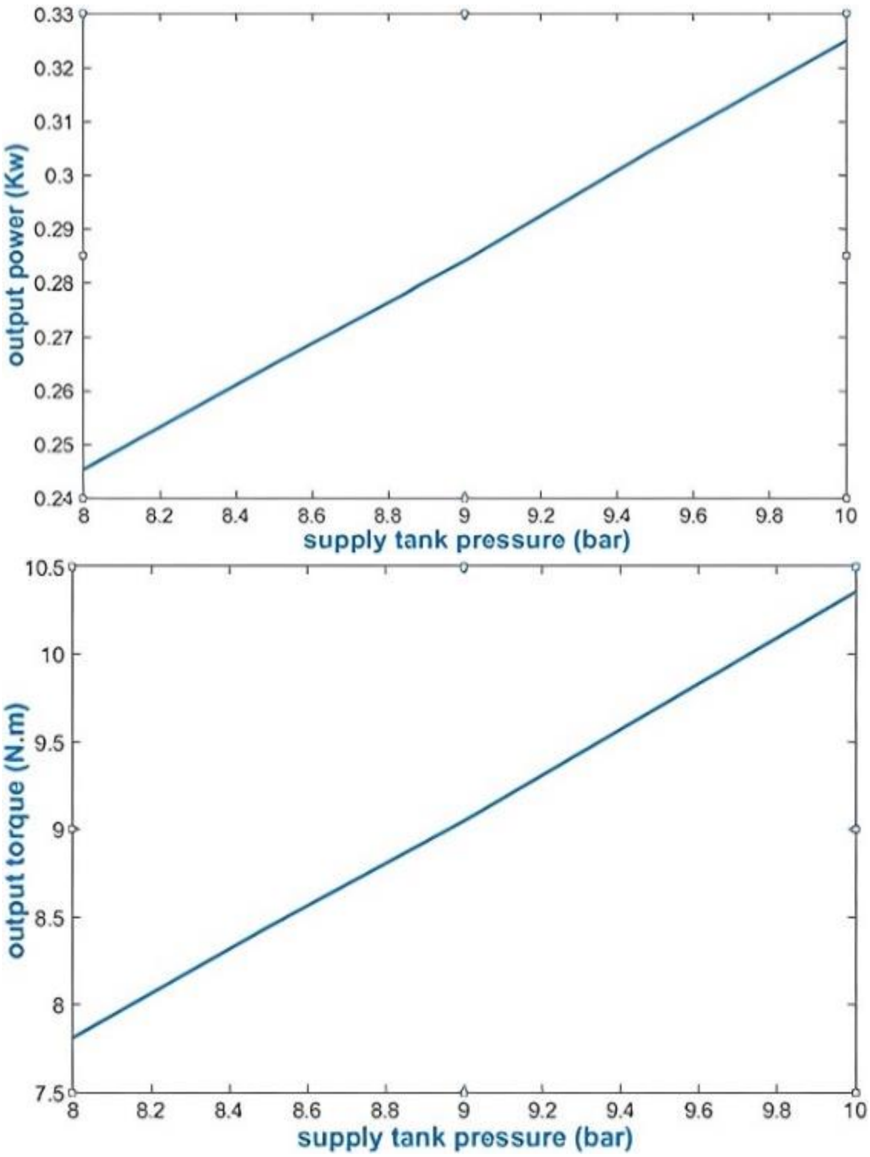


Figure 25. Output power and Output torque vs Supply tank pressure [42].

A linear relation between output power and supply tank pressure was obtained at 245 watts. Similarly, linear relationship was observed between output torque and supply tank pressure at 7.8 Nm and is shown in Figure 25. Since the engine needed to run at a high torque from the beginning, the torque and output power of the petrol engine are roughly 30% and 97% higher respectively, than those of the CAE. It attributed that the output of power and torque increases at equal rotation speeds after increasing the input tank pressure. They demonstrated how increasing supply tank pressure causes an increase in air pressure near the end of the expansion [42].

An extensive study has been conducted over the years towards establishing sustainable solutions and achieving net-zero targets for air pollution. Compressed air technology could be predicted as a futuristic advancement in the automotive sector on a large scale. If the challenges such as low range, low energy density, higher initial cost and low efficiency are overcome by technology, this could be the ultimate solution [43].

CONCLUSION

The overall air-powered vehicle market is expected to grow to $4.43 billion in 2031. The Compound Annual Growth Rate (CAGR) is predicted to be 57% in the upcoming years. There are obstacles in the way of compressed-air vehicle adoption, particularly the need for refuelling infrastructure and range constraints. Nevertheless, these issues will probably be resolved and the viability of CAVs in urban settings improved by continuing research and partnerships between the automotive industry and governmental organisations. Furthermore, when governments around the world step up their efforts to combat air pollution and lessen their reliance on fossil fuels, the adoption of CAVs may be aided by the establishment of legislation designed to promote low-emission vehicles.

This study considered various parameters towards a sustainable solution and to achieve a better performance system. Many researchers, energy enthusiasts, scholars, market competitors, and scientists are currently working towards a green environment and the sustainable development of society. It can be attributed that energy, system efficiency, compressed air pressure, and temperature are the key parameters will help to enhance the performance. Also, this study will enhance the forecasts for the market growth, technological developments, and significant environmental advantages to support the optimistic outlook for compressed-air vehicle technology. The ongoing development and incorporation of creative solutions in this industry portend a radical change in the way we view and use transportation [44,45,46].

Future Scope

The compressed-air technology can be a sustainable energy source with the security of an unlimited air supply, unlike conventional gasoline vehicles. The CAV can be a promising source with very low operating costs, eliminating the long-term threat caused by limited fossil fuels. The non-flammable nature of compressed air makes it a safer option when compared with all other alternative fuel sources, such as hydrogen, electric vehicles (with Li-ion batteries), biofuels, etc. Due to a lack of combustion, a negligible amount of air pollution is produced by CAVs, contributing to net-zero targets for the future.

Novelty of Work

The originality of this review is found in its thorough assessment of the development of compressed-air vehicles (CAVs) throughout history, technological developments, and comparative analysis. In contrast to earlier reviews, it also covers the benefits of polymer applications in CAV fabrication. This study is uniquely positioned as a useful resource for scholars and industry stakeholders due to its comprehensive approach to sustainability, materials, and energy innovation.

List of Abbreviations

CAV	Compressed-Air Vehicles

CAGR	Compound Annual Growth Rate
APV	Air-Powered Vehicle
CAE	Compressed-Air Engine
MDI	Motor Development International
APUQ	Association Promotion Usages Quasiturbine
APE	Air-Powered Engine
PLC	Programmable Logic Controller
ICE	Internal Combustion Engine

Declaration

Availability of data and materials. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request to represent review.

Ethical Approval

Not applicable. This study does not involve human participants or animals.

Conflict of Interest

The authors declare no conflict of interest related to this study.

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