RESEARCH AND REVIEWS IN SUSTAINABILITY

The Impact of Climate Change Induced Temperature Rise on Compression Power and CO_2 Emissions: A Theoretical Approach

TECHNICAL ARTICLE

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ABSTRACT

This study investigates the impact of rising ambient temperatures, driven by climate change, on compression power requirements and the resulting CO_2 emissions in compression systems. Using a theoretical model based on air as the compressed medium and assuming ideal gas behavior, the analysis quantifies the non-linear relationship between temperature increases and compression power demand. At a base/ambient temperature of 30°C, a 1.0°C rise leads to a 0.0885 MW increase in compression power, which scales with higher base temperatures. The increased energy demand from higher temperatures directly correlates with higher CO_2 emissions, with a 1.0°C rise resulting in a projected increase of 205.6 metric tons of CO_2 emissions, when powered by natural gas, annually per compressor. At higher base temperatures, the compression power and CO_2 emissions increases become even more pronounced, demonstrating the escalating environmental cost of rising temperatures due to climate change. The study findings underscore the urgent need for operational optimization and efficiency improvements, particularly in industries reliant on air compression systems in regions where temperatures are projected to rise sharply in the coming decades.

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KEYWORDS:
Compression power; Air compression systems; Ambient Temperature Effects; Climate Change Impact

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NOMENCLATURE

η	Polytropic efficiency	y	Work
k	Isentropic exponent	Z	Compressibility factor
M	Molar weight	ρ	Density
$\dot{m}$	Mass flow rate	**Subscripts**	
n	Polytropic exponent	0	At sea level
P	Power	1	Suction (atmospheric)
p	Pressure	2	Discharge
R	Gas constant	p	Polytropic
T	Temperature	u	Universal, $R_u = 8314.47 \frac{J}{kmol * K}$
v	Volume specific		

1. INTRODUCTION

As global temperatures continue to rise because of climate change (World Meteorological Organization, n.d.), industries worldwide face growing challenges related to energy consumption and environmental sustainability. compression systems are among the many processes impacted by rising temperatures (Compressed Air & Gas Institute, 2022).

1.1 THE ROLE OF COMPRESSION SYSTEMS IN INDUSTRY

Air Compression systems are essential to a wide range of industry applications such as gas processing, air conditioning, and power generation. They function by increasing the pressure of gases or air to meet specific process requirements, whether for storage, transport, or use in downstream processes. These systems are energy-intensive, often consuming a substantial portion of a facility's total electricity (Vittorini and Cipollone, 2016), which makes them a focal point for energy efficiency programs.

Ambient temperature plays a critical role in the performance of compression systems, as it directly affects the density of the air or gas being compressed (Compressed Air & Gas Institute, 2022). At higher temperatures, the air or gas becomes less dense (Legg, 2017), meaning the compressor must work harder to achieve the same level of pressure. This results in increased power consumption. While many studies have addressed the performance of compressors under varying loads, fewer have examined the specific impact of climate-induced temperature increases on compression power requirements.

1.2 CLIMATE CHANGE AND RISING TEMPERATURES

The world is currently on a path to exceed the 1.5°C global temperature increase limit set by the Paris Agreement (World Meteorological Organization, n.d.; United Nations Climate Change, 2015), with many regions already experiencing significant warming. According to the Intergovernmental Panel on Climate Change (IPCC), the average global temperature is projected to rise by 1.0°C to 1.5°C above today's levels between 2030 and 2052 (Intergovernmental Panel on Climate Change, 2018). This increase is expected to lead to more frequent and intense heatwaves, which will disproportionately affect industries dependent on ambient temperature-sensitive equipment like compressors.

As temperatures rise, the energy required to maintain industrial processes will increase. This is particularly true for systems like compressors, where power consumption is sensitive to even small changes in ambient conditions (Compressed Air & Gas Institute, 2022). Higher temperatures will not only increase operational costs but also contribute to higher greenhouse gas (GHG) emissions, thus continuing a vicious cycle of warming.

1.3 THEORETICAL FRAMEWORK FOR COMPRESSION POWER AND TEMPERATURE

In this study, a theoretical model is developed to quantify the relationship between ambient temperature and compression power. The model is based on air as the compressed medium.

The theoretical model used in this study allows for the calculation of compression power increases across a range of base temperatures, from 0°C to 55°C by 5C increments. By calculating the required compression power increase for a 1.0°C and 1.5°C temperature rise at different base temperatures, the study provides an understanding of how climate change will affect industrial energy consumption in the coming decades.

1.4 LINKING COMPRESSION POWER TO CO_2 EMISSIONS

Increased energy consumption from compression systems not only raises operational costs but also has significant environmental consequences. In many regions, industrial facilities are powered by fossil fuels, which emit CO_2 when burned. The link between compression power and CO_2 emissions is direct: as more energy is required to power compressors due to higher temperatures, more CO_2 is released into the atmosphere (U.S. Energy Information Administration, 2024).

This study quantifies the CO_2 emissions associated with the increased energy demand resulting from rising ambient temperatures.

The primary goal of this study is to explore the relationship between ambient temperature increases and compression power requirements and to quantify the associated CO_2 emissions using a defined theoretical model. This paper examines how compression power grows with rising temperatures and links this growth to the corresponding rise in energy consumption and emissions.

2. METHOD

This study follows a three-step approach to investigate how rising ambient temperatures impact compression power requirements and related CO_2 emissions in air compression systems. First, a theoretical model was developed specifically for air as the compressed medium to calculate compression power under varying ambient temperatures. Second, this model was used to evaluate the system's temperature sensitivity by determining how much temperature needs to increase to cause a specific rise in compression power (e.g., 0.1 MW), and then estimating the compression power increase for fixed temperature rises (1.0°C and 1.5°C) across a range of base temperatures. Third, the additional compression power was translated into annual energy consumption and associated CO_2 emissions using an emission factors relevant to three fossil fuels-based electricity (natural gas, coal & petroleum).

2.1 MODEL DEVELOPMENT

The compression power requirements in this study were estimated using a polytropic compression model, which more accurately represents industrial compressor behavior compared to simplified isentropic formulations (Oldrich, 2012; Brun and Kurz, 2019). All thermodynamic calculations follow the framework set out in ISO 5389, the internationally recognized standard for performance testing of turbo compressors. ISO 5389 provides equations and correction methods used in both industry and research to determine compression power for turbo compressors under defined conditions (ISO 5389:2005).

The model was applied to a single-stage, steady-flow compression process without intercooling, operating under fixed discharge pressure and variable inlet temperature. This configuration was chosen deliberately to maintain generality and isolates fundamental thermodynamic trends. Industrial compressors vary widely in design, and selecting a single real-world configuration (such as multistage with inter cooling) would narrow the relevance of the findings as they will introduce many additional site-specific variables such as intercooler effectiveness, cooling source and control strategy which can significantly affect results. Also, the warming increments of +1.0 to +1.5°C applied in this study reflect global mean climate projections. Since the exact magnitude of climate-driven temperature rise at a specific site is uncertain and may deviate from the global averages, a generalized approach provides broader applicability for several applications such as service and instrument air compressors, typically operating at ≤10 bar gauge (Nowacki, 1974).

2.1.1 Used Equations

$$P = \dot{m} * y_p \tag{1}$$

$$y_p = \frac{R * Z * T_1}{\eta} * \frac{n}{n-1} * \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \tag{2}$$

$$R = \frac{R_u}{M} \tag{3}$$

$$p * v = Z * R * T \tag{4}$$

$$n = \frac{1}{1 - \frac{k-1}{k * \eta_p}} \tag{5}$$

$$M = \frac{\rho * Z * R * T_1}{p_1} \tag{6}$$

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \tag{7}$$

Air is represented in the model as an ideal gas. This was not chosen to simplify the analysis, but because it is a technically valid approximation in the studied operating range. Studies demonstrated that deviations between real-gas and ideal-gas density remain <1% at 5 bar across 0–105°C, and <1–2% at 10 bar between 0–25°C (Vestfálová and Šafařík, 2018). Since this study examines 0–55°C and assumes pressures up to 10 bar, the ideal gas representation is justified and supported by empirical thermophysical analysis.

Several operating parameters were assumed to represent typical industrial compressor conditions, including pressure ratio, mass flow rate, polytropic exponent, and compressor efficiency (summarized in Table 1).

These values provide a practical baseline for the calculations. It is important to note, however, that while varying these parameters would change the absolute magnitude of compression power, they do not alter the study's core findings. The analysis is focused on the relative difference in compression power between temperature points (e.g., +1.0°C and +1.5°C warming), which remains valid regardless of the specific parameter values selected.

To evaluate the effect of ambient temperature on compression power, calculations were performed across a temperature range of 0°C to 55°C, using 5°C increments. For all cases, ISO standard conditions were assumed for ambient pressure (1.01325 bar abs) and relative humidity (60%). This provided a consistent baseline for comparing results while isolating the effect of temperature as the primary variable. Under these fixed conditions, variations in ambient temperature directly influence inlet air density and thus affect the power required for compression.

PARAMETER	SYMBOL	UNIT	VALUE(S)	NOTES
Ambient/Base Temperature	T_1	°C	0–55	5°C increments are used (0,5,10,15, 20….)
Relative Humidity		%	60	Standard ISO Condition
Inlet Pressure	p_1	Bar_{abs}	1.01325	At Sea level/Standard ISO Condition
Polytropic Efficiency	η	%	80	Assumed
Outlet Pressure	p_2	Bar_{abs}	11	Assumed value
Universal Gas Constant	R_u	*J/(kmol.K)*	8314.47	Constant for Air
Compressibility Factor	Z		1	Ideal Gas Behavior
Air Mass Flow Rate	$\dot{m}$	*Kg/s*	50	Assumed Value
Isentropic Exponent	k		1.4	For Dry Air
Avg Temperature Increase		°C	1.0–1.5	As a result of climate change (Intergovernmental Panel on Climate Change, 2018)
Fuel Types & their CO_2 emissions per kwh	Natural Gas		0.44 Kg/kwh	U.S. utility-scale net electricity generation and resulting CO_2 emissions (U.S. Energy Information Administration, 2024)
	Coal		1.0478 Kg/kwh	
	Petroleum		1.11584 Kg/kwh	
Availability Factor	60%			Conservative Assumption (Saidur et al., 2010)

Table 1 Study Input values.

The resulting dataset was fitted with a second-order polynomial regression, yielding a compact analytical expression to quantify temperature sensitivity:

$$P(T) = aT^2 + bT + c$$

where T is ambient/base temperature in °C, and a, b, and c are the regression coefficients. This fitted equation formed the basis for the next step: quantifying temperature sensitivity that is, determining how much of a temperature increase is needed to drive a given increase in compression power.

2.2 QUANTIFYING TEMPERATURE SENSITIVITY

While the increase in compression power due to a fixed temperature rise (e.g., 1.0°C or 1.5°C) can be calculated directly using the polynomial model developed in the first step, an alternative approach was used here to provide additional insight. Instead of calculating compression power increase for a given temperature rise, this step reverses the process: it determines the temperature increase (ΔT) required to cause a fixed increase in compression power (e.g., 0.1 MW) at different base temperatures. This method makes it easier to visualize how the system becomes more sensitive to temperature changes as the ambient temperature rises.

The procedure involved evaluating the polynomial equation at incremental temperature values to identify the temperature at which compression power increased by 0.1 MW relative to a selected base point. The difference between this new temperature and the original base temperature was recorded as the required ΔT. This process was repeated across the full range of modeled base temperatures (0°C to 55°C, in 5°C increments).

Once the ΔT values were obtained, they were inverted to calculate how much compression power increase would occur for a standardized 1.0°C and 1.5°C rise in ambient temperature at each base point. The resulting values represent a practical measure of temperature sensitivity, showing how much more compression power is expected to be consumed as climate-induced temperature rises occur.

These temperature sensitivity values were later used to estimate energy consumption and CO_2 emissions associated with different climate scenarios, forming the basis for the final step of the method.

2.3 CO_2 EMISSIONS ESTIMATION

In the final step, the additional compression power requirements calculated for standardized temperature increases (1.0°C and 1.5°C) at various base temperatures were converted into annual energy consumption and then into CO_2 emissions.

To determine annual energy use, it was assumed that the compressor operates at 60% availability (220 days per year, running 24 hours per day). The additional compression power (in MW) was multiplied by this annual operational duration to estimate the increase in electrical energy consumption (in kWh) for each temperature scenario.

3. RESULTS

This section presents the outcomes of the theoretical modeling and analysis, including (1) the relationship between ambient temperature and compression power, (2) the temperature sensitivity of the compression system, and (3) the resulting increases in energy consumption and CO_2 emissions for projected temperature rises of 1.0°C and 1.5°C.

3.1 COMPRESSION POWER VS. AMBIENT TEMPERATURE

The results of the model calculations (presented in Table 2), show a non-linear increase in compression power with rising ambient temperatures (as shown in Figure 1).

A second-degree polynomial regression was fitted to the calculated data points over the 0°C to 55°C range using 5°C increments (shown as a dotted line). The curve shows that as temperature increases, the rate of change in compression power increases. The curve fit demonstrated strong agreement with theoretical values, with a high coefficient of determination (0.99), indicating that the polynomial equation reliably represents the trend across the selected temperature range.

3.2 TEMPERATURE SENSITIVITY ACROSS THE OPERATING RANGE

The second part of the analysis focused on quantifying the system's sensitivity to temperature increases.

AMBIENT/BASE TEMPERATURE (°C)	AIR DENSITY (ρ_1, kg/m^3)	MOLAR WEIGHT (*M, g/mol*)	R, $\frac{J}{kmol*K}$	POLYTROPIC WORK y_p	COMPRESSION POWER (*P, MW*)
0	1.288	28.877	287.931	295,882.443	**14.794**
5	1.263	28.830	288.398	301,787.014	**15.089**
10	1.238	28.767	289.027	307,882.446	**15.394**
15	1.213	28.683	289.870	314,232.606	**15.712**
20	1.188	28.573	290.989	320,919.261	**16.046**
25	1.162	28.429	292.463	328,046.856	**16.402**
30	1.135	28.243	294.393	335,748.604	**16.787**
35	1.107	28.004	296.902	344,194.637	**17.210**
40	1.078	27.701	300.147	353,603.213	**17.680**
45	1.046	27.320	304.331	364,256.534	**18.213**
50	1.012	26.846	309.713	376,523.739	**18.826**
55	0.975	26.259	316.635	390,895.294	**19.545**
Reference, Equation	Professional Quality Psychrometric Calculator	ISO 5389:2005, Eq. (6)	ISO 5389:2005, Eq. (3)	ISO 5389:2005, Eq. (2)	ISO 5389:2005, Eq. (1)

Table 2 Compression power requirement – Model output.

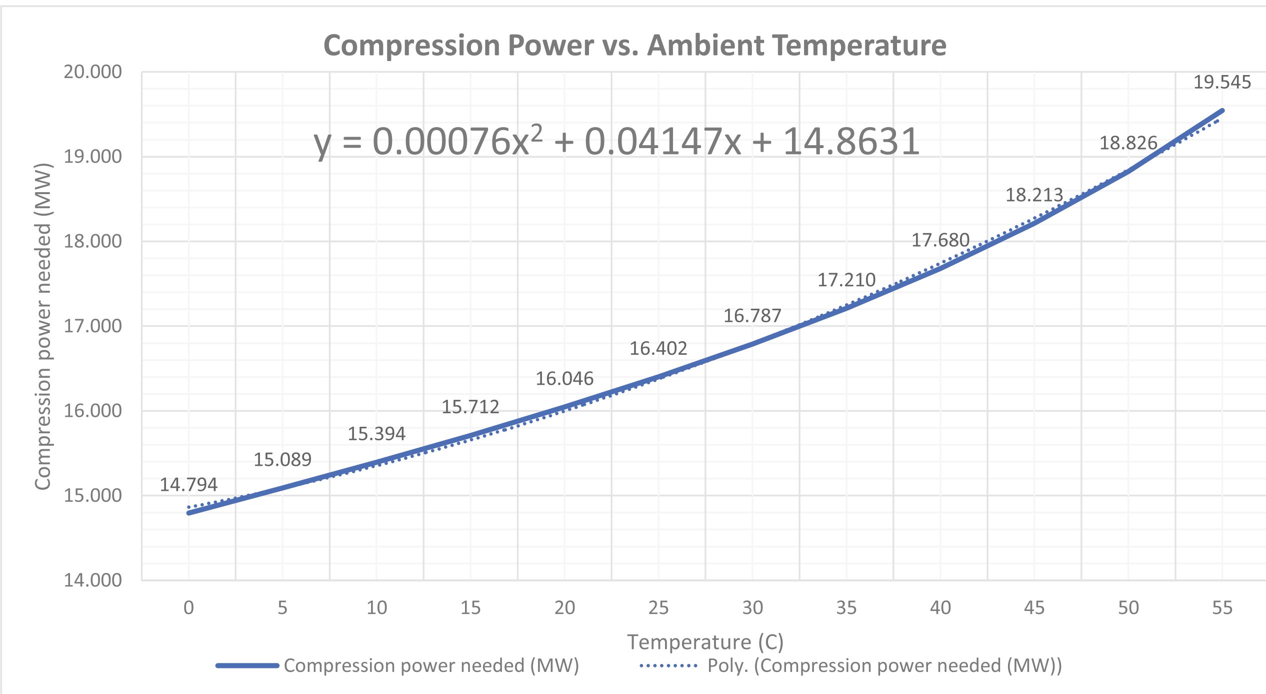

Figure 1 Compression Power vs. Temperature polynomial trendline represented by a second-degree equation.

Specifically, the model was used to determine the temperature increment (ΔT) required to cause a fixed compression power increase of 0.1 MW (100 kW) at various base temperatures. These values were calculated using the inverse of the fitted polynomial model.

As shown in Figure 2, lower base temperatures (e.g., 0–15°C) require relatively larger ΔT values to produce a 0.1 MW increase in compression power. In contrast, at higher base temperatures (e.g., 40–55°C), even small temperature rises below 1°C can result in the same 0.1 MW increase. This trend highlights the increasing sensitivity of the compression system to ambient warming as the climate warms.

3.3 ENERGY AND CO_2 EMISSIONS IMPACT

Based on the temperature sensitivity findings, the increase in compression power for standardized ambient temperature rises of 1.0°C and 1.5°C was calculated across the full range of base temperatures (0°C to 55°C, in 5°C increments). These power increases were then converted into annual energy consumption and corresponding CO_2 emissions, assuming continuous operation at 60% availability (i.e., 220 days per year, 24 hours per day) as illustrated in Table 3, and using CO_2 emission factors of 0.44, 1.0478 & 1.11584 kg CO_2/kWh, representative of natural gas, Coal & petroleum fired electricity generation respectively.

The results (illustrated in Figures 3 & 4), show that both energy consumption and CO_2 emissions increase more significantly at higher base temperatures, due to the system's growing sensitivity to temperature rise. For example, at a base temperature of 30°C, a 1.0°C increase leads to an additional 0.0885 MW of compression power, translating to approximately 528,000 kWh/year and 232.3 metric tons of CO_2 emissions annually. At 50°C, the same 1.0°C rise causes a power increase of nearly 0.119 MW, resulting in 627,264 kWh/year and 276 metric tons of CO_2.

These findings highlight two key trends: (1) compression power sensitivity accelerates at higher base temperatures, and (2) this leads to substantial increases in annual energy consumption and CO_2 emissions. The next section discusses the implications of these trends.

	FOR 1.0°C	FOR 1.5°C
AMBIENT/BASE TEMPERATURE (°C)	INCREASE IN ENERGY PER YEAR (*kwh*)	INCREASE IN ENERGY PER YEAR (*kwh*)
0	227,532.46	341,298.70
5	265,454.54	398,181.81
10	305,581.39	458,372.09
15	343,529.41	515,294.11
20	383,649.63	575,474.45
25	423,870.96	635,806.45
30	465,132.74	697,699.11
35	505,384.61	758,076.92
40	541,855.67	812,783.50
45	584,000.00	876,000.00
50	625,714.28	938,571.42
55	665,316.45	997,974.68

Table 3 Energy Increase (kWh/year) for 1.0°C and 1.5°C rises at various base temperatures.

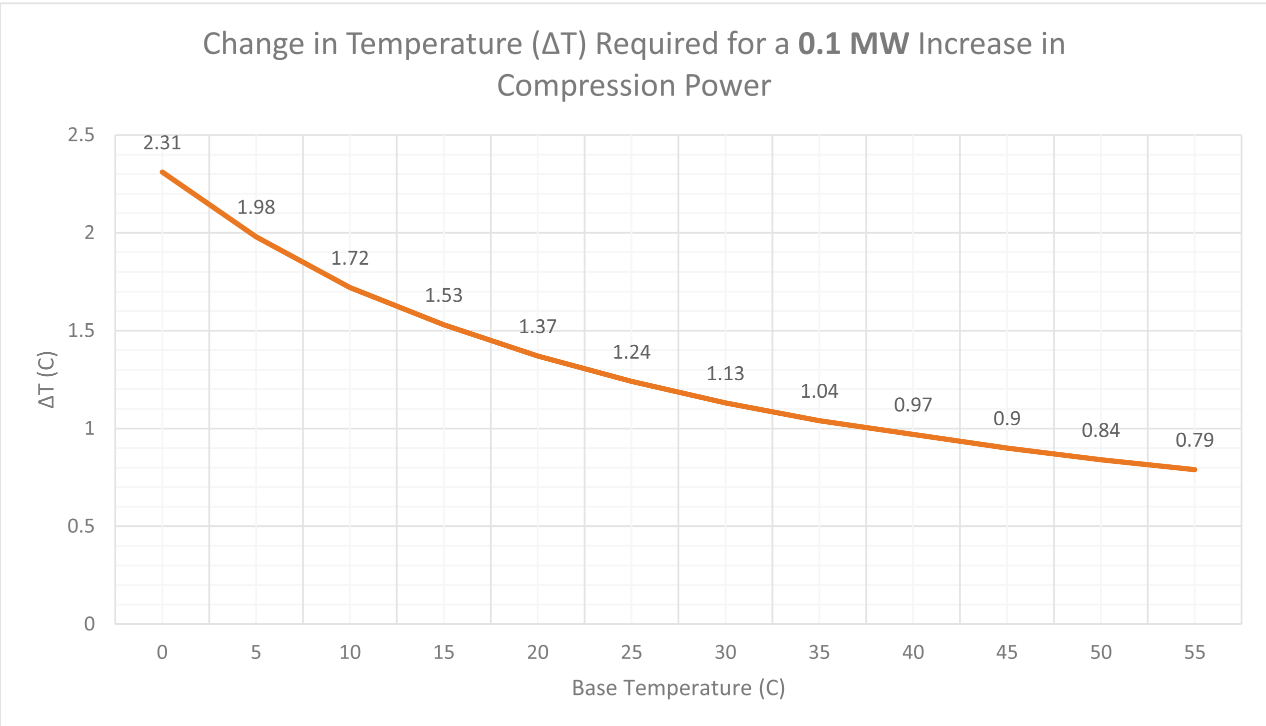

Figure 2 Temperature Sensitivity Across the Operating Range.

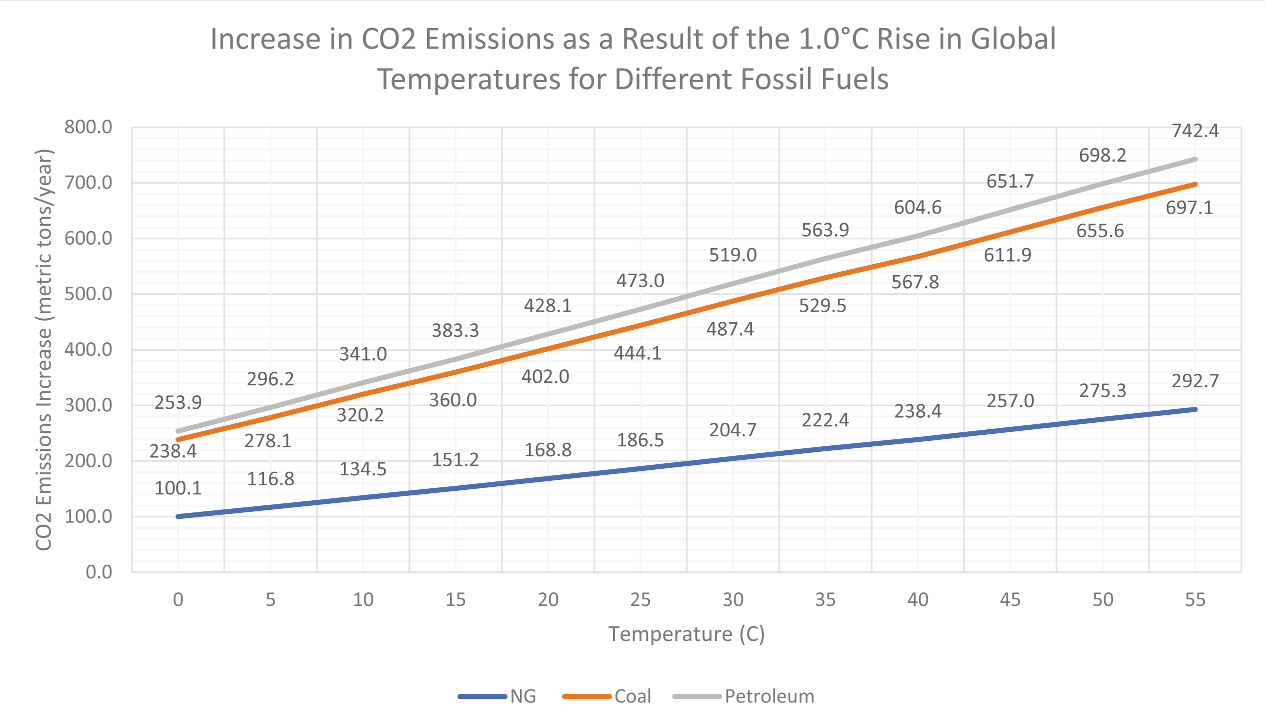

Figure 3 CO_2 Emissions Increase Across the Operating Range as a Result of the 1.0°C Rise in Global Temperatures.

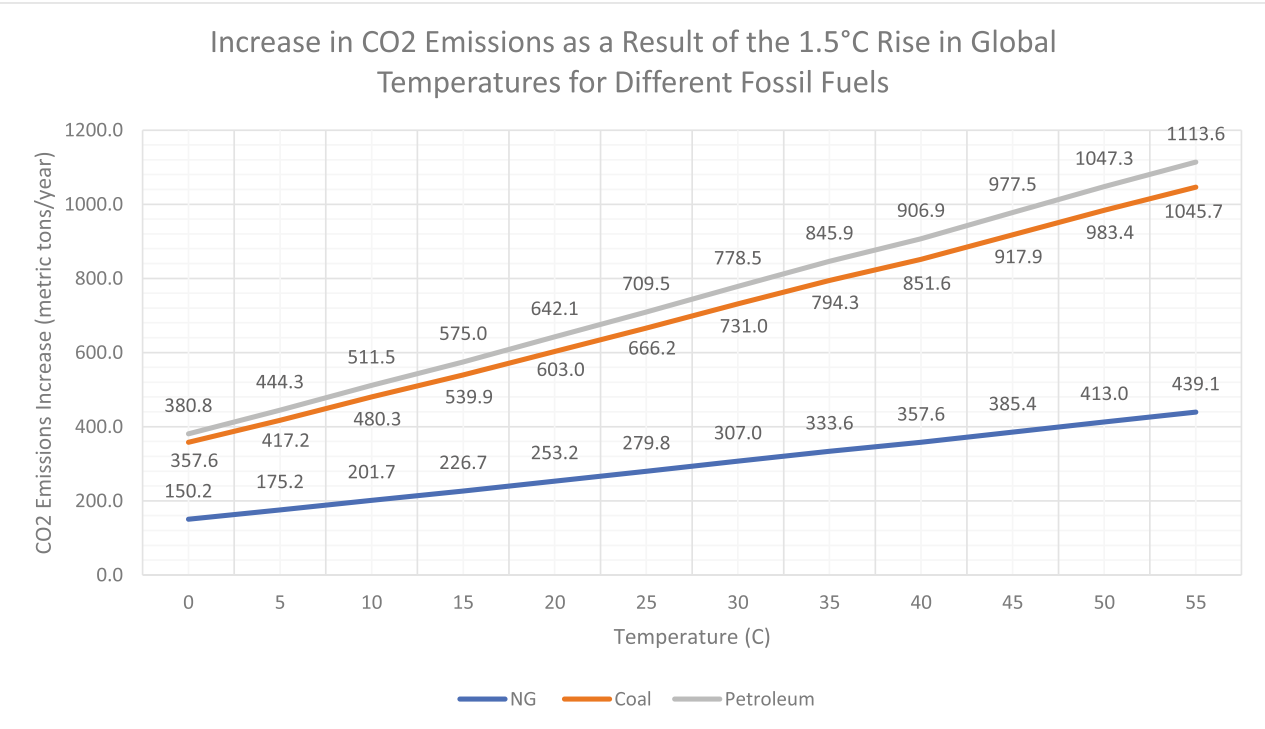

Figure 4 CO_2 Emissions Increase Across the Operating Range as a Result of the 1.5°C Rise in Global Temperatures.

4. DISCUSSIONS

The results of this study reveal several important implications for the operation, energy efficiency, and environmental footprint of air compression systems in the context of a warming climate. The non-linear increase in compression power with rising ambient temperatures underscores a key vulnerability for industrial facilities operating in hot regions or during peak summer months. As shown in the model, the same increase in compression power (e.g., 0.1 MW) requires a much smaller temperature rise at higher base temperatures. This means that as global average temperatures continue to rise, the rate at which compression-related energy demand increases will accelerate an important consideration for long-term planning and infrastructure resilience.

From an operational standpoint, these findings highlight the need for more proactive thermal management strategies. In particular, the temperature sensitivity trends suggest that cooling air intakes becomes increasingly effective at higher ambient temperatures which can be used in identifying when cooling becomes operationally or economically justified. Even a modest reduction in intake temperature can result in measurable energy savings and lower operating costs. The quantified relationship between temperature rise and CO_2 emissions further supports this strategy, as it shows that reducing compression load through cooling also reduces the facility's carbon footprint. This could be particularly relevant for operators subject to emissions limits or sustainability reporting requirements.

The results also demonstrate the value of adopting climate-informed maintenance and energy strategies. For example, in locations where ambient temperatures are expected to rise by 1–2°C in the coming decades, operators can use the provided polynomial model to estimate the additional load and emissions burden on their systems, and plan upgrades accordingly. This could include re-evaluating the sizing of cooling systems, adjusting maintenance schedules, or investing in more efficient compressor units.

That said, several limitations should be acknowledged. The analysis was based on a single-stage, steady flow compression model without intercooling, which was intentionally chosen to highlight fundamental thermodynamic sensitivities but does not capture the performance distinctions of advanced systems such as multistage compressors. Air was modeled as an ideal gas, which is technically valid under the studied conditions (11 bar absolute, 0–55°C) where deviations from real-gas behavior remain negligible, but future extensions could incorporate real gas effects for higher pressures or humid conditions. Moreover, while the use of ISO 5389 grounds the methodology in internationally validated practice, no new empirical measurements were carried out. Looking ahead, the framework presented here offers a foundation for more detailed, site-specific evaluations. By calibrating the model with actual equipment specifications, site conditions, and electricity sources, operators and researchers can develop tailored estimates of energy and emissions impacts, enhancing both practical applicability and environmental insight.

Finally, the findings reinforce the broader message that rising ambient temperatures will not only affect cooling and air conditioning systems but will also impact core industrial processes such as air compression. Integrating climate impact assessments into operational planning is no longer optional, it is a necessary step for ensuring energy and emissions performance remains within acceptable bounds as environmental conditions continue to change.

5. CONCLUSION

This study demonstrates how rising ambient temperatures, driven by climate change, can significantly increase the energy demand and CO_2 emissions of air compression systems. Using a polytropic compression model under ideal gas assumptions, the analysis quantified the non-linear relationship between temperature and compression power, revealing that systems become increasingly sensitive at higher base temperatures. The resulting increases in energy consumption and emissions underscore the operational and environmental consequences of even small temperature rises.

Grounded in ISO 5389 and general operating conditions, the model provides a practical framework for, it provides a practical framework for identifying risk trends, guiding cooling strategies, and informing long-term planning. As global temperatures continue to rise, incorporating climate-aware insights into compressor operation and design will be essential for maintaining efficiency, reducing emissions, and improving overall system resilience.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author used ChatGPT for basic rephrasing to improve the readability and language of the manuscript. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

DATA ACCESSIBILITY STATEMENT

The calculation file supporting the findings of this study (spreadsheet containing the model and sensitivity analysis) is provided as supplementary material.

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COMPETING INTERESTS

The author has no competing interests to declare.

AUTHOR CONTRIBUTIONS

The author solely conceived, developed, and completed all aspects of the study, including conceptualization, modeling, writing, and revisions.

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