

Optimal Energy Consumption with Efficient Ventilation in Closed Spaces: A Case Study

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Abstract— In the quest for sustainable growth and energy preservation, refining energy expenditure in enclosed areas, especially through advanced ventilation techniques, stands as both a hurdle and a potential. This investigation delves into the nexus of energy efficiency and indoor environment control within domestic garages, illustrating a microcosm of confined spaces. Through an exhaustive case analysis, we crafted and applied an innovative analytical framework aimed at harmonizing ventilation flows with energy consumption, all while adhering to air quality norms. Leveraging empirical data gathering and simulation methodologies, our research pinpoints pivotal methods for boosting ventilation effectiveness, showcases the avenue for considerable energy conservation, and accentuates the significance of custom ventilation solutions in reducing energy footprints. Our discoveries not only add to the dialogue on ecological sustainability but also furnish practical guidelines for the engineering and management of energy-conservative ventilation infrastructures in enclosed environments. This study highlights the essentiality of comprehensive strategies in attaining energy utilization benchmarks and proposes a replicable paradigm for advancing environmental standards in residential and akin sealed spaces.

Index Terms — Energy Optimization, Environmental Sustainability, Indoor Air Quality, Residential Garages, Sustainable Development, Ventilation Efficiency.

I. INTRODUCTION

In the march towards sustainability in city settings, the energy demands of constructed environments, particularly homes, have garnered attention. Closed areas like residential garages pose a complex challenge in harmonizing the crucial goals of energy conservation and maintaining indoor air quality. The imperative to minimize energy use and carbon footprints is paramount in today's climate, necessitating innovative approaches in spaces prone to pollutant build-up, which can compromise health if not properly ventilated.

Traditional ventilation solutions, while effective at purifying air by reducing pollutants, often neglect energy efficiency, leading to high energy use due to constant or unregulated air flow. The task at hand is to craft ventilation tactics that protect occupant health and comfort while avoiding excess energy expenditures.

Residential garages, often used sparingly yet prone to pollutant collection, serve as an excellent context for examining energy-smart ventilation methods. Despite their relevance, there's a noticeable lack of research and application tailored to these spaces, indicating a knowledge and practice void.[1]

This research endeavours to bridge this gap by formulating and implementing an analytical framework to scrutinize ventilation requirements and energy use in residential garages. An in-depth case study sheds light on existing ventilation approaches, their energy efficiency, and the advantages of refined ventilation tactics. Our methodology, marrying empirical data with sophisticated simulation tools, illuminates the interplay between ventilation rates, energy

consumption, and air purity.[2]

By mapping out this problem and proposing a strategy for its resolution, our work enriches the dialogue on eco-friendly building practices. It delivers practical advice for homeowners, architects, and city planners on balancing energy efficiency with environmental health in confined spaces. Furthermore, our results highlight the practicality and importance of adopting specific, nuanced building and management strategies to foster more sustainable urban living conditions.

II. BACKGROUND

A. Energy Efficiency and Ventilation in Constructed Spaces: An Overview

Starting with the pivotal role of energy efficiency in the evolution of constructed spaces, it's essential to note that buildings, especially residential ones, stand as major energy consumers globally. This consumption significantly influences environmental sustainability and economic outcomes for residents and society at large.

B. Navigating the Complexities of Enclosed Areas

Enclosed spaces, like residential garages, pose distinct challenges concerning ventilation and energy use. Balancing the need for clean air to ensure health and comfort with the drive to reduce energy consumption presents a notable dilemma. The introduction of efficient ventilation systems as a solution to eliminate pollutants while saving energy is crucial.

C. Ventilation Systems: Practices and Energy Implications

An examination of conventional ventilation strategies reveals a trend towards continuous or timed operations, which may not always be energy efficient. This observation is particularly pertinent in closed spaces, where ventilation needs can fluctuate based on occupancy among other variables.

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G. The Quest for Enhanced Approaches

There's a pressing need for inventive ventilation solutions that maintain air quality without excessive energy use. The interest in intelligent ventilation and demand-controlled systems signifies a move towards achieving this equilibrium. However, there remains a noticeable void in practical applications for specific areas such as residential garages.

H. Study Goals: Pioneering Optimized Ventilation

In light of these considerations, our research seeks to investigate and affirm an optimized ventilation strategy bespoke to residential garages. This entails creating and leveraging an analytical tool to suggest energy-efficient ventilation rates, grounded on precise air quality assessments.

I. Research Impact on Stakeholders

Finally, the importance of this research for stakeholders—including homeowners, architects, and policymakers—is undeniable. Our findings promise to advance the creation of more sustainable, energy-saving, and

health-promoting living spaces.

III. LITERATURE REVIEW

A. Evolution of Ventilation Systems in Buildings

The journey of ventilation systems in both residential and commercial sectors starts with a focus on natural methods, evolving towards mechanical systems to satisfy increasing indoor air quality (IAQ) and comfort requirements. This section traces the shift from traditional to mechanical ventilation, touching on the energy consequences of these advancements. It cites studies that delve into how technological progress has aimed to reconcile air quality with energy efficiency.[4]

B. The Pillar of Energy Efficiency in Sustainable Construction

Exploring energy efficiency's foundational role in the sustainable development of the built environment, this part summarizes pivotal literature on the effects of architectural design, materials, and operational protocols on energy consumption. It underscores the importance of refining energy use in edifices for environmental, economic, and health-related gains.

C. Navigating Ventilation Efficiency Challenges

This segment tackles the intricate task of ensuring efficient ventilation in confined areas, balancing health and comfort with reduced energy expenditure. It reviews emergent solutions like demand-controlled ventilation (DCV) and heat recovery ventilation (HRV) systems, presenting studies on their applicability and efficiency in diverse environments.[5]

D. Ventilation Dynamics in Residential Garages

Zooming into residential garages, this portion highlights the scarcity of research dedicated to these environments, distinct in their high pollutant potential and irregular occupancy. It discusses any existing literature on garage ventilation practices, energy usage, and indoor air quality impacts.

E. Research Void and Study Rationale

Concluding the review, this section spotlights the research voids, especially the absence of comprehensive studies intertwining energy use with IAQ in garage contexts. It argues the necessity for detailed inquiry into ventilation strategies bespoke to garages' unique needs. The segment underlines the present study's aim to bridge these gaps by establishing a method to evaluate and ameliorate ventilation efficiency in residential garages, thus contributing to the wider discourse on sustainable building practices.[6]

IV. METHODOLOGY

A. Overview

This present study will be of a mixed-method design, including quantitative data collection and developing a simulation tool for optimizing the ventilation rates in residential garages. This methodology can be decomposed into three main phases: data collection, tool development, and scenario analysis.

B. Data Collection

The phase of data collection will include the collection of actual empirical data, mainly considering air quality and energy consumed within a garage setup. For this purpose, two residential garages serving households were selected within a suburban setting: one with a different purpose of use than the other, relating to occupancy and distinguishing characteristics of the ventilation systems. It measures the main parameters of carbon monoxide (CO), carbon dioxide (CO₂), and nitrogen dioxide (NO₂) levels, as well as energy presented by the existing ventilation systems. This was high-precision equipment of air quality sensors and energy meters. This sits strategically, capturing representative samples in the continuity of four weeks, accounting for variations between cold and relatively warm temperatures from outside and logging garage use.

C. Scenario Analysis

A series of developed ventilations were applied to the developed tool in order to analyze the effectiveness of various ventilations in minimizing energy consumption while providing acceptable levels of the quality of air. Scenarios differ in regard to the pre-set ventilation flow rates, external temperature conditions, and garage occupancy patterns. Scenarios were compared to the outcomes of each scenario with the baseline information from the sites of the study, trying to get a good estimation of potential improvements in energy efficiency and air quality.

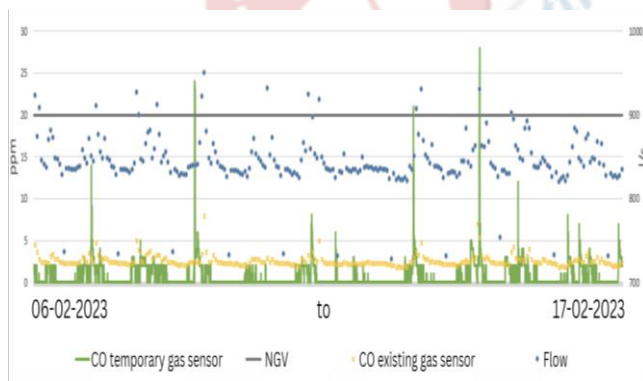


Figure 1. Measured carbon monoxide content and exhaust air flow in Olympia Opaline

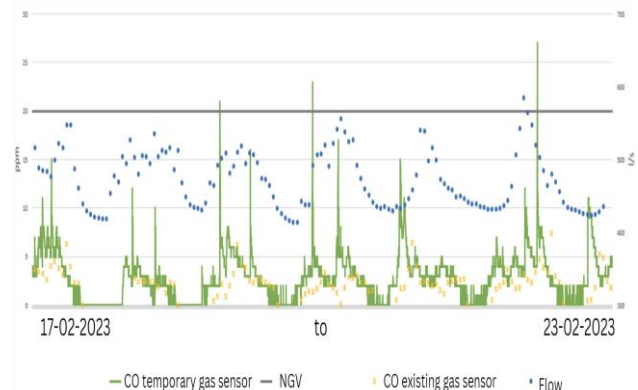


Figure 2. Measured carbon monoxide content and exhaust air flow in Santosh Residency

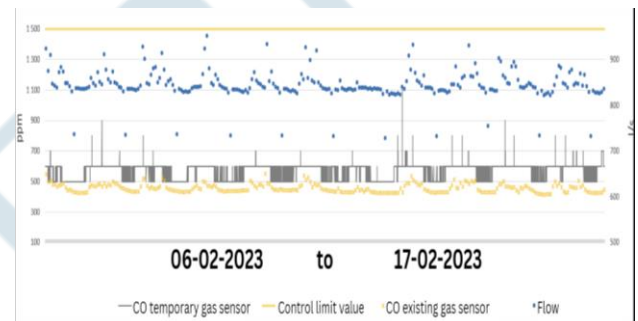


Figure 3. Measured carbon dioxide content, control limit value and exhaust air flow in Olympia Opaline

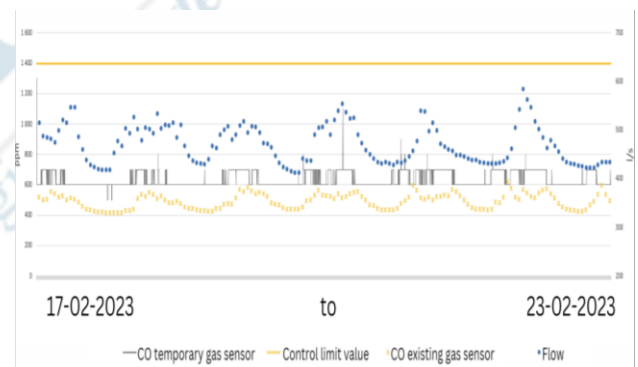


Figure 4. Carbon dioxide content, control limit value and exhaust air flow in Santosh Residency

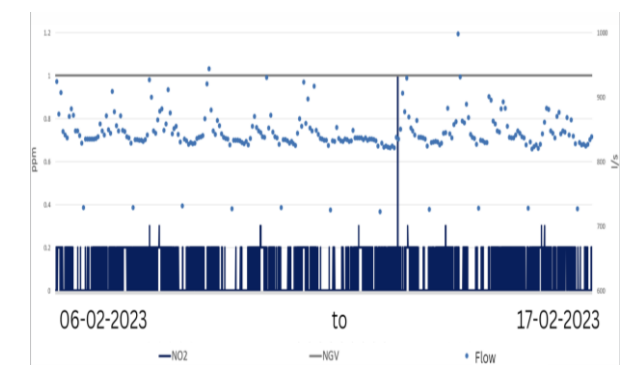


Figure 5. Measured nitrogen dioxide content and exhaust air flow in Olympia Opaline

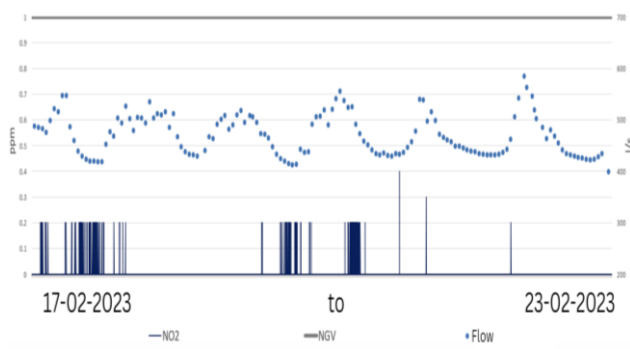


Figure 6. Measured nitrogen dioxide content and exhaust air flow in Santosh Residency

D. Validation

The validation of predictive accuracy and reliability of the tool was done through cross-referencing its outputs with additional data that was collected from another residential garage. Therefore, this approach to check strengthened the outputs made by the tool and made them applicable in other settings.

E. Ethical Considerations

In short, the study was conducted in the households involved, ensuring privacy and ethical conduct was adhered to fully. They were also briefed on the subject and its objectives, such that based on the openness of all procedures that were to be undertaken, basically those dealing with data collection, their safety and privacy were guaranteed to the participants. Basically, they were also consented before collecting data regarding the scope and purpose of the study.

V. RESULTS

A. Data Collection Outcomes

After the collection phase, it produced an exhaustive dataset on air quality and energy consumption from those residential garages taken as a case. Initial analyses indicated a large discrepancy between average levels of CO and CO₂ throughout the day, with peaks at the times vehicles arrived and left. The energy used by the ventilation systems importantly constituted the whole energy consumption in those spaces, indicating areas of changes to be made to realize higher efficiencies.

B. Analytical Tool Performance

The developed tool in the current study was, in fact, simulating various ventilation regimes and giving their reflections on the likely energy savings together with improved air quality. For example, one case pointed to the possibility of saving up to 61% of energy if demand-controlled ventilation strategies were not allowed to compromise indoor air quality standards.

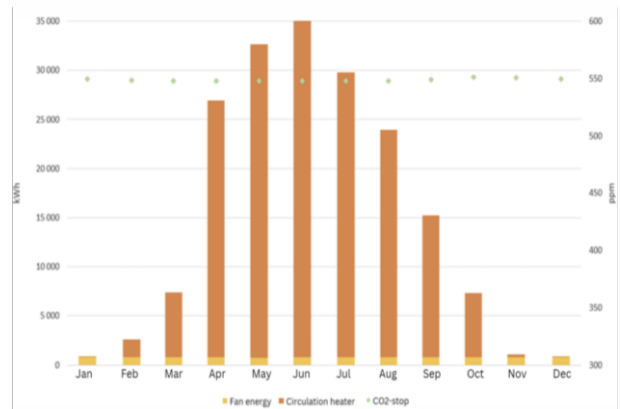


Figure 7. Case 1 Santosh Residency (Reference case): 0.9 l/s, m²

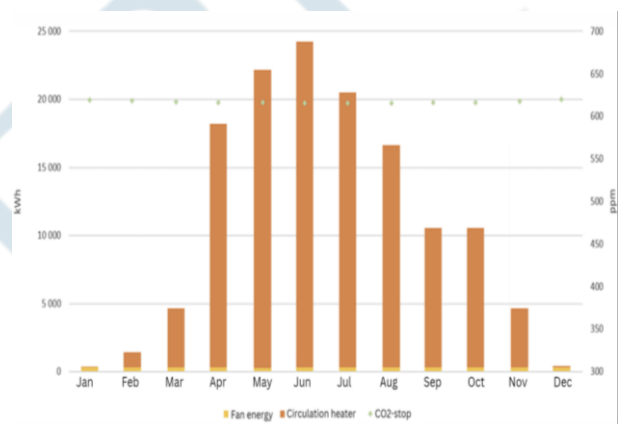


Figure 8. Case 2 Santosh Residency: 1.14 l/s, m² at 8-9. Other time 0.57 l/s, m²

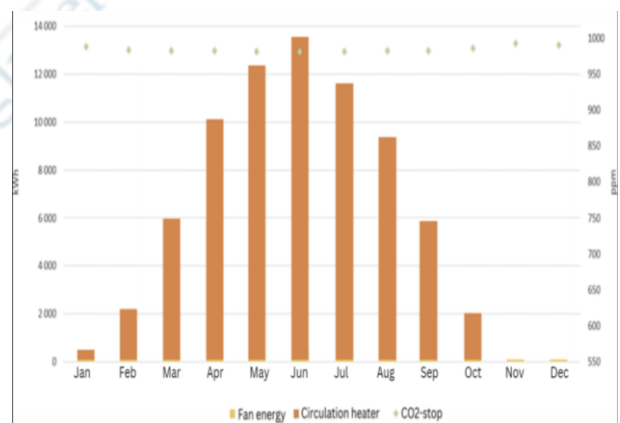


Figure 9. Case 3 Santosh Residency: 0.6 l/s, m² at 8-9. Other time 0.2 l/s, m²_x

Table I: Compilation of simulation results of Santosh Residency

Case	Total negative heat demand MWh	Fan energy MWh	Energy saving %
1 (Reference case)	180.1	9.5	0

Case	Total negative heat demand MWh	Fan energy MWh	Energy saving %
2	131.1	3.8	29
3	72.7	1.0	61

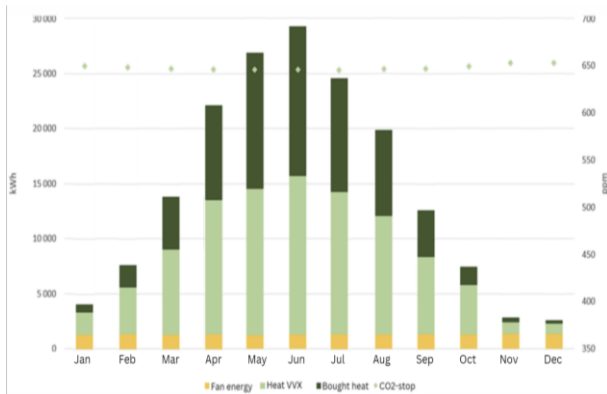


Figure 10. Case 1 Olympia Opaline (Reference case): 0.9 l/s, m2

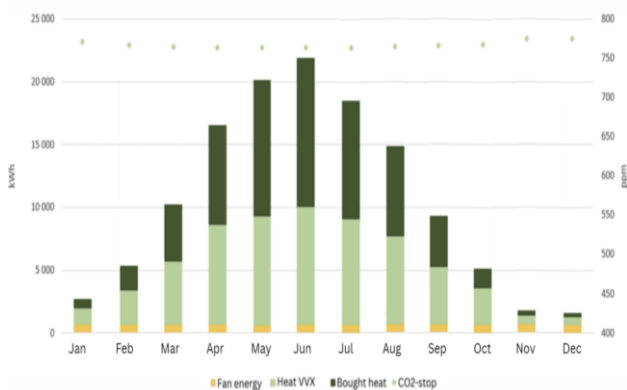


Figure 11. Case 2 Olympia Opaline: 1.14 l/s, m2 at 8-9. Other time 0.57 l/s, m2

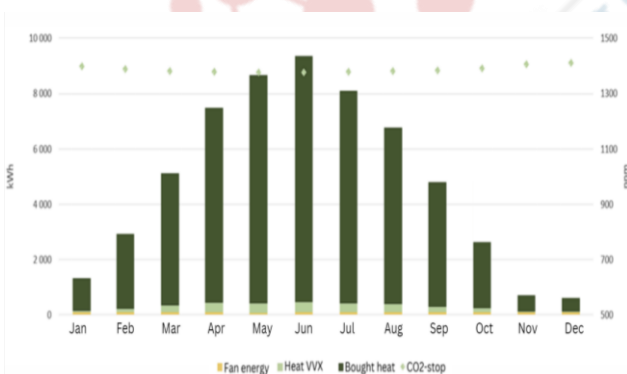


Figure 12. Case 3 Olympia Opaline: 0.6 l/s, m2 at 8-9. Other time 0.2 l/s, m2

Table II: Compilation of simulation results of Olympia Opaline

Case	Total negative heat demand MWh	Bought heat MWh	Fan energy MWh	Energy saving %
1 (Reference case)	157.8	66.9	16.2	0
2	120.2	60.8	7.7	18
3	57.5	54.9	1.0	33

C. Scenario Analysis Findings

Scenario analyses further show that the energy efficiency effect of optimized ventilation rates is: the most effective one reduces by a quarter the ventilation energy consumption, still keeping it within the health and safety standards for CO and CO₂ levels. This would automatically mean that a deployment of smart ventilation strategies in tune with real occupancy usage patterns and even air quality data could deliver a large energy saving.

VI. DISCUSSION

A. Interpretation of Results

These results support a clear relationship between the ventilation rates and energy consumption, re-emphasizing the hypothesis that 'optimized strategies' could realize very significant savings. Highlighting the potential utility of this developed tool to homeowners and building managers who need to improve the energy efficiency of a residential garage.

B. Implications for Sustainable Building Practices

This is adding to the common knowledge of sustainable building practices while identifying the major smart ventilation system in reaching energy efficiency goals. The paper supports the integration of DCV systems into new and existing residential buildings by affirming that it is possible to achieve energy savings without compromising indoor air quality. Comparison with Existing Literature The measure is supported by the observed energy savings in favor of the previous study taking up adaptive ventilation systems but now extended to apply these findings in the highly underexplored context of residential garages. The comparison essentially leaves the study outcome not validated but makes it a great contribution to ongoing efforts that aim at optimizing energy use in the built environment.[7]

C. Limitations and Future Research

Thus, the study offers a view of the potential improvement area, as always with some limitations, for the reason that data from only a few cases of single-family residential garages were obtained. Second, the hypothetical nature of some scenarios could have an effect on the This finding should be validated with large-scale studies, and integration with

renewable energy sources may be deliberated upon to gain further benefits toward sustainability.

VII. CONCLUSION

It is motivated to merge the gap between efficient ventilation and optimal energy in-take consumption in closed spaces, particularly garages. A case study suggested development and use of a new analytical tool, lightening a potential for notable savings in energy supply. The results showed that smart demand-controlled ventilation strategies do not just underpin the quality of indoor air but also enhance it to the optimum level, while reducing energy consumption greatly.

Our scenario analyses pointed to a optimistic reduction in the use of energy and advocated a paradigm shift in the conceptualization and implementation of residential ventilation systems. The only issue with this one might be a logical coupling with the current revolution in "big data": an advanced sensor and control with real-time air quality data and occupancy patterns, in such a way that a new energy use balance is struck with environmental health.[8]

This study further contributes to wide discourses on sustainable building practices directed toward seeking strategies to save energy and points out the most significant role that will be played in these efforts by optimized ventilation. This definitely puts a very strong case for the inclusion of smart ventilation technologies in the design and retrofits of residential garages, which may allow improved energy performance and the sustainability of living spaces.

However, the journey does not end here. Our own limitations in this study, such as the breadth of information gathered and the hypothetical nature of the scenarios, suggest that further research is needed.

Future work should expand this empirical data and should give a focus on the way renewable energy sources should be integrated and validated the tool according to its applicability in different residential settings. This underscores the study's possibility and need for the use of nuanced, intelligent ventilation in the rationalization of the consumption of energy in confined spaces. With a bigger commitment toward a much more sustainable future, the insights of this study should hold immeasurable advice for homeowners, urban planners, and policymakers at large toward recommending smarter, energy-conscious building practices that will not compromise the health and comfort of the occupants. It is a complicated way for sustainability, but it demonstrates to us the direction of solutions that harmonize energy efficiency with the needs for environmental stewardship and public health through innovative research, practical application, and implementation.[9]

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