

Original Research

Air Pollution Control Engineering in Urban and Congested Areas

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Received: February 04, 2025**Accepted:** July 07, 2025**Published:** July 11, 2025**Abstract**

The study aims to evaluate the progressive increase in energy systems pollutant emissions due to the efficiency loss and continuous deterioration in the energy conversion process. The paper analyzes the GHG, nitrous oxide, sulfur dioxide, and fine particle emissions from vehicles, residential and commercial heating systems, public buildings, health centers, and industrial conglomerates, with the servicing time and degradation level. The analysis applies to various emitting gases or small particle systems, which generate environmental impact or cause human health problems. The paper proposes a detection method based on an engineering system to determine the real emissions rate of an energy conversion system, establishing an obsolescence threshold beyond which the system requires a replacement or refurbishment to achieve an admissible pollutant emissions rate. The proposed engineering solution uses sensors that detect individual or collective pollutant-emitting sources like vehicles, heating exhaust pipes, or industrial chimneys. The engineering solution uses a control system to prevent excessive pollutant emissions by managing the operational process and adjusting parameters to maintain the pollutant emissions below a selected threshold. The study represents an advance in fighting against reaching the critical pollution level in urban and congested areas where the incidence of GHG, nitrogen oxides, fine particles (PM), and other contaminant elements is more relevant. The principal novelty of the present study is its adaptability to all types of combustion processes and emission rates, providing a powerful



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tool for pollutant emission managers. The study also represents a significant advance in managing the combustion process to regulate GHG emissions.

Keywords

Air pollution; control engineering; energy systems; GHG, nitrous oxide, and fine particles emissions; energy efficiency

1. Introduction

The pollution level increase represents nowadays one of the critical challenges that modern society should face [1]; the continuous growth of greenhouse gasses (GHG), nitrox oxides, and fine particle emissions to the atmosphere has reached a dangerous threshold, generating climatic changes at a planetary level, and causing natural disasters with human and material losses of dramatic proportions [2-5].

In past decades, supranational, national, regional, and local authorities encouraged changes in human habits regarding energy use and promoted alternatives to the current energy systems, aiming to reduce fossil fuel consumption [6-8]. The political decisions pursue implementing more efficient energy conversion systems, requiring lower power demand and preserving the environment due to lower pollutant emissions [9-13].

Among the many measures taken by politicians, imposed through laws, regulations, and various rules, restrictions, or banning specific energy systems' utilization are the most widely implemented in our society [14-17]. Vehicle fleet electrification, banning fossil fuel combustion systems for heating or air conditioning, or promoting biofuel use are good examples of changes in the energy conversion systems [18-23].

Restrictions and bans establish a threshold beyond which the energy system cannot be commercialized or operated any longer. This threshold limits the use of obsolete or highly pollutant systems in congested areas or urban zones where pollution effects are more relevant, especially for human health [24, 25].

The energy system manufacturing industry has adapted to these limitations by developing more efficient and less pollutant devices, fulfilling the laws and regulations to certify their product as feasible for human consumption. This compliance, however, does not guarantee the fulfillment of gas and particle emissions below the threshold for the system lifespan since the progressive degradation of the device components results in a lower efficiency operation, requiring higher fossil fuel demand and generating more pollutant emissions [26-29].

Degradation or deterioration of device components results from continuous use and lack of maintenance, a problem derived from low purchasing power or lack of environmental awareness [30-33]. Periodical inspections to evaluate the fulfillment of pollution emissions level contribute to limiting the environmental impact caused by energy systems operating out of bounds for a long period, but do not eliminate the pollutant emissions excess from the time the system overpasses the pollution emitting threshold until the inspection date [34-38].

Pollutant emissions can increase due to the degradation of a combustion system. This is because the combustion process is inherently a source of pollutants, and when the system degrades, it can lead to incomplete combustion and the release of more pollutants. Here's why and how [39, 40]:

- **Incomplete Combustion:**
When a combustion system is not working properly, it may not be able to burn the fuel completely. This can lead to the release of pollutants like carbon monoxide (CO), particulate matter (PM), and nitrogen oxides (NO_x).
- **System Degradation:**
Factors like aging, wear, poor maintenance, or improper operation can cause a combustion system to degrade. This can affect the efficiency of the combustion process, leading to increased emissions.
- **Example: Older Stoves:**
Older stoves, for example, are often less efficient and may produce more particulate matter (PM) compared to newer ones. This is due to factors like fuel blockages, soot buildup, and other degradation issues.
- **Example: Diesel Engines:**
Diesel engines, especially older models, can contribute significantly to nitrogen oxide (NO_x) and particulate matter emissions.
- **Fuel Type and Combustion:**
Even with a well-maintained system, the type of fuel used can also impact emissions. For example, some studies have shown that burning biomass in stoves designed for coal can lead to higher carbon monoxide (CO) emissions.
- **Impact on Air Quality and Climate:**
Combustion emissions have significant impacts on air quality and climate change. Greenhouse gas emissions from transportation, for example, are a major contributor to climate change.
- **Mitigation Strategies:**
To reduce pollutant emissions from combustion systems, it's important to prioritize system maintenance, ensure proper operation, and consider switching to more efficient or cleaner technologies.

A continuous survey of pollutant components generation and emissions to the atmosphere is mandatory if we intend to preserve air quality and reduce environmental pollution levels; nevertheless, we cannot leave this type of practice in the user's hands due to a lack of knowledge, neglect, or simply rejection of the imposition of controls.

This work proposes an engineering system to continuously control the GHG, nitrous oxide, and fine particle emissions in urban traffic, building exhaust pipes, and industrial chimneys. The control system regulates the energy system operation by adjusting parameters to reduce pollutant emissions below the setup threshold or warning the user of excess emissions if the energy system cannot operate under modified working parameters.

The paper intends to cover an existing gap in GHG emissions detection by predicting the combustion system performance regarding pollutant emissions under the influence of lack of maintenance and operating time degradation, which are parameters currently ignored in the combustion gas emissions control. A detailed literature review shows that the proposed methodology is not considered a key factor for predicting the pollutant emissions level in combustion systems.

2. Pollutant Emissions

2.1 Types, Effects, and Contribution

The atmospheric pollution level depends on many components, contributing to reducing the air quality. The most important ones are greenhouse gases (GHG), which affect the environment and cause climatic changes and global warming, and the pollutant elements affecting human health, like sulfur dioxide, nitrogen oxides, and fine particles (PM). Among the GHGs, we can mention the water vapor, the carbon dioxide, the ozone, and the methane [41, 42]. Although the principal effect of GHG is an environmental impact, it also affects human health, generating lung and heart affections, headaches, dizziness, trembling, convulsions, coma, vision loss, and death [43, 44]. The ozone is responsible for pulmonary affections like lung irritation, asthma aggravation, and lung disease chronification [45-47]. Methane also affects lung function by reducing pulmonary capacity, increasing asthma, and reducing immune system efficiency [48]. Although water vapor contributes to rainfall, it may affect pulmonary functioning, especially in people with lung diseases or respiratory problems.

Breathing high levels of nitrogen oxides can cause rapid burning, spasms, and swelling of the throat tissues and upper respiratory tract, reduced oxygenation of body tissues, fluid buildup in the lungs, and death [49]. Scientific studies link PM exposure to a variety of health impacts, including eyes, nose, and throat irritation, worsening of symptoms of coronary and respiratory diseases, and premature death in people with heart or lung disease [50-52].

The climatic change and global warming because of GHG emissions have not a direct impact on human health but generate dramatic effects on people due to natural disasters that cause human deaths beyond material destruction; therefore, we must consider that all pollutant elements are harmful to life on the planet [5, 53, 54].

Atmospheric pollution levels derive from variable sources, natural or anthropogenic; natural contamination is generated by phenomena such as forest fires [55-56] or volcanic eruptions [57-59], while anthropogenic contamination is caused by human activities, mainly fossil fuel combustion [60, 61].

Fossil fuel combustion in the European Union is associated with road traffic (23.8%), building heating (11.9%), industrial activities (20.3%), agriculture (10.8), or power plants (27.4%); additional activities like international shipping, flights, residues management, and other combustion processes agglutinate the remaining 5.8% [62]. A similar distribution occurs in the USA, with 29% for transportation, 30% for industry, 31% for commercial and residential, and 10% for agriculture [63].

The combustion produces different pollutant components depending on the burned fossil fuel. The highest pollution emissions level among the GHG corresponds to carbon dioxide, around 81.6% in the USA and 80.6% in the European Union, with a lower contribution for methane (12.1%), nitrox oxides (5.3%) and fluoride gasses (2%). Carbon monoxide contribution is irrelevant, lower than 0.1%. We include CO emissions due to the lethal effects on human health despite the negligible contribution of carbon monoxide to atmospheric pollution [64].

The pollutant impact on human health and the environment is the GHG emissions from combustion boilers and other systems burning fossil fuels. Its control may produce significant benefits by preventing excessive emissions above healthy levels. On the other hand, the predictive methodology may show if the combustion processes will fulfil the legal requirements, or the process

requires additional measurements to reduce GHG emissions to maintain the level below a specific threshold. The predictive methodology may also show if a reduction in the pollutant emissions results from applying advanced techniques to the combustion process.

2.2 Detection Systems

Because of the different chemical structures of pollutant gases and fine particles, the detection system and sensors vary. Based on sensing wavelength, we can detect the presence of pollutant gases (Figure 1).

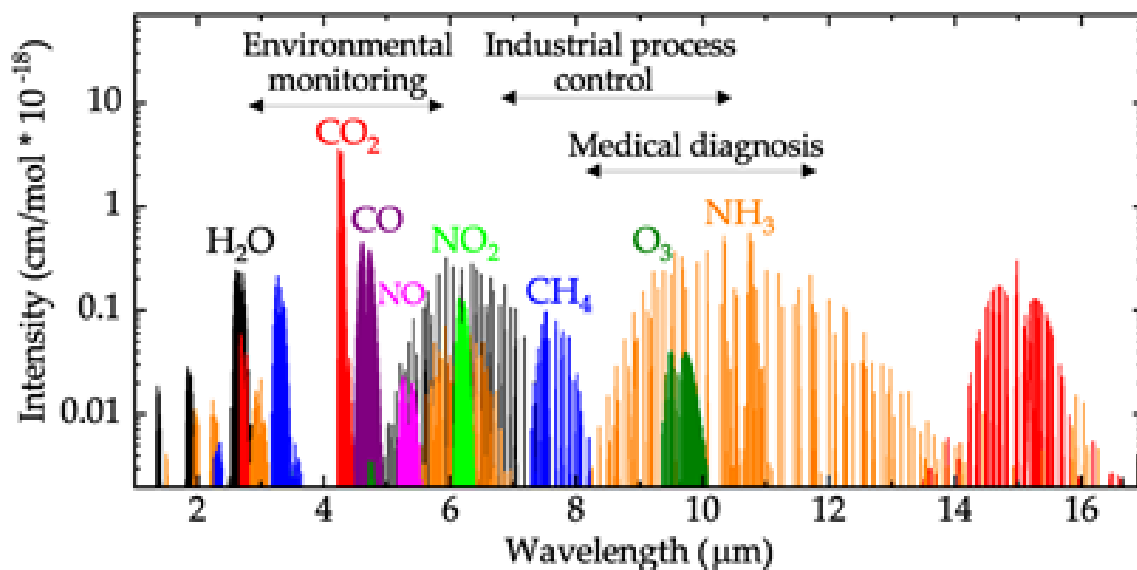


Figure 1 Mid-infrared absorption spectra of some gasses [65].

Carbon dioxide detectors utilize non-dispersive infrared sensors (NDIR), which operate on a spectroscopy measurement basis. Domestic and professional sensor devices can measure CO₂ concentration anywhere (Figure 2).



Figure 2 Carbon dioxide detector: domestic (left) [66] and professional (center) [67]. NDIR (right) [68].

While detectors are designed for wall mounting either for direct reading (domestic) or remote control recording (professional), using a moderate space (10 cm × 10 cm), the NDIR is smaller,

currently less than 1.5 cm in diameter, allowing insertion in heating, ventilating, and air conditioning ducts, or in exhausting pipes (Figure 3).

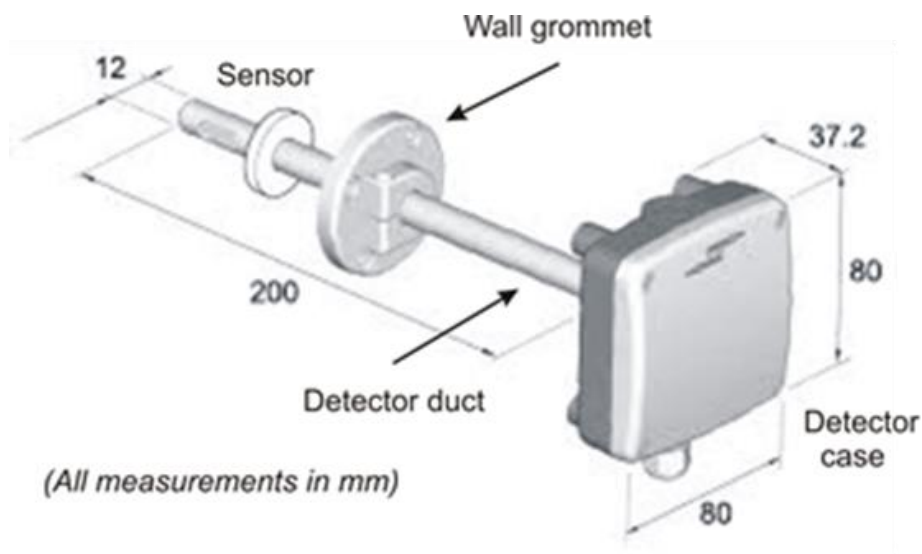


Figure 3 Schematic representation of CO₂ sensor insertion.

Carbon monoxide detectors are similar to CO₂ ones, both domestic and professional models (Figure 4). The carbon monoxide sensor insertion in a duct or exhausting pipe is similar to the one shown in Figure 3 for the carbon dioxide.



Figure 4 Carbon monoxide detector: domestic (left) [69] and professional (center) [70]. Electrochemical sensor (right) [71].

The primary method for measuring NO₂ is a continuous chemiluminescence analyzer. During this process, air is drawn in and nitrogen monoxide (NO) is caused to react with ozone. This produces NO₂ in a chemical reaction that also releases light. IR analyzers for NO can also measure NO₂ if equipped with a NO₂ to NO converter.

As with carbon monoxide and dioxide, nitrous oxide analyzers can be portable or desktop units (Figure 5). Depending on the installation type, one of the two devices is more convenient than the other.



Figure 5 Nitrous oxide detector: domestic (left) [72] and professional (center) [73]. Chemical sensor (right) [74].

The in situ measurement of methane emissions uses infrared optic technology, although alternative techniques like confinement chambers, tracking techniques, “sniffing” techniques, and portable laser methane detectors are also suitable. For automatic measurements, infrared or laser detectors are the most suitable (Figure 6).



Figure 6 Methane detector: domestic (left) [75] and professional (center) [76]. Infrared sensor (right) [77].

Both nitrous oxide and methane sensors can be attached to the measuring device system shown in Figure 3 for the CO₂. This structure utilizes a gas flow to detect the emissions of selected components, including CO₂, CO, NO_x, and CH₄, by inserting the appropriate sensor into the gas stream.

Finally, the fine particle concentration, PM 2.5 and PM 10, is measured using a laser beam to scan the particle density in a specific volume or gas flow (Figure 7). Among the fine particles, we can mention microscopic aerosols, air-suspended powders, and heavy metal particles. The most dangerous are the ultrafine particles, specifically PM 2.5, which correspond to particles with a diameter of less than 2.5 micrometers, because the human pulmonary filtering system is unable to retain them before they enter the lungs.



Figure 7 Fine particles detector: domestic (left) [78] and professional (center) [79]. Laser sensor (right) [80].

3. Environment

Pollutant emissions proceed from different sources which can be classified in three groups: first, building installations, including residences, commercial centers, institutional buildings, hospitals, education centers, and similar; second, industrial facilities, and third, transportation, public and private.

The GHG emissions and other pollutant components like SO₂, NO_x, and PMs derive from the fossil fuel combustion used for services, such as water heating, room air conditioning, industrial processes, and vehicle driving.

Combining groups and services, we obtain the following categories (Table 1):

Table 1 Classification of pollutant emissions sources by group and service.

	Water heating	Air conditioning	Industrial processes	Vehicle driving
Building installation	C1	C2	n.a.	n.a.
Industrial facility	n.a.	n.a.	C3	n.a.
Transportation	n.a.	C4	n.a.	C5

n.a. applies for not applicable, null or negligible contribution.

Fossil fuel combustion for water heating typically uses natural gas, propane, or butane, although in some cases, electricity serves as the power source.

Air conditioning is variable depending on the system adopted for heating and cooling. Room heating may use wall radiators, radiant floor, forced convection, aero thermal units, or heat pumps; the first two systems burn gas to generate hot water that circulates through the wall radiators or radiant floor ducts to heat the room, while the last three ones consume electricity for heating air or water used for space heating. The air conditioning for transportation in internal combustion engine (ICE) cars represents a singularity, as it utilizes the thermal energy from fossil fuel combustion to operate the air conditioning unit. In any of the cases mentioned above, there is a fossil fuel combustion process, directly in the air conditioning burning chamber or indirectly through the fossil fuel combustion in power plants to generate electricity. An exception occurs when electricity is

derived from renewable sources, such as solar photovoltaic or wind energy, although this situation continues to represent a minor contribution today.

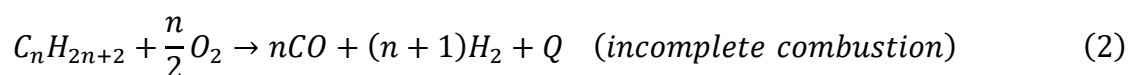
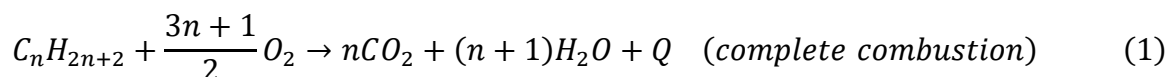
Industrial processes operate under thermodynamic cycles, currently Rankine or similar, to generate electricity or manufacture industrial products. The required energy for running the thermodynamic cycle comes from fossil fuels, such as gas, petrol, or coal.

The transportation sector can be divided into two categories: ICE (Internal Combustion Engine) and electric vehicles. Hybrid cars are included in the ICE group, as they use a fossil fuel combustion engine to propel the car for part of the driving time.

Pollutant emissions for the five configurations shown in Table 1 depend on various factors, including the type of fuel, combustion process technology, and power generation efficiency. Although they currently operate with specific fuels and technological processes to achieve the highest performance.

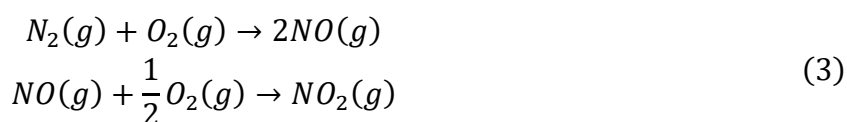
4. Energy Process and Performance

The pollutant emissions can be determined applying to any energy process the specific emission rate for every component emitted during the fossil fuel combustion. If we consider an energy conversion process to generate heat or electricity, requiring fossil fuel combustion, the pollutant emissions amount is given by:



n is the number of reacting moles and Q the combustion heat power.

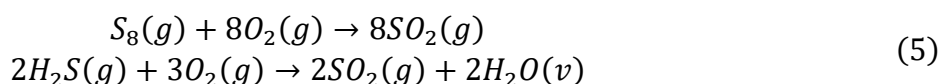
On the other hand, the combustion at high temperature may produce nitrogen dioxide according to:



The methane formation is the result of a chemical reaction between carbon and hydrogen as in:



The sulfur dioxide derives from the combustion of sulfur and hydrogen sulfide according to:



Sulfur is a natural component of crude oil; therefore, it is found in gasoline and diesel. When burning these fuels, sulfur emissions such as sulfur dioxide (SO₂) or sulfate particles occur. Coal also contains sulfur in the form of pyritic sulfur and sulfates.

Fine particle generation is the reaction product of nitrogen oxides or sulfur dioxide at high temperatures, although other human activities, such as grinding, crushing, or material abrasion, may also produce fine particle emissions.

If the required energy for heat or electricity power generation in the combustion process is ξ , we can determine the pollutant emissions through the expression:

$$m_{p,i} = \frac{\xi}{(HHV)_j} \frac{1}{\rho} \frac{r_{p,i}}{\eta_c} \quad (6)$$

m_p is the pollutant emissions mass, HHV is the fossil fuel higher heat value, ρ is the emission gas density, η_c is the combustion process efficiency, and r_p is the specific component pollutant emissions rate. Subscripts i and j account for the pollutant component and the type of fossil fuel.

Provided the required energy is constant for a specific process, and considering HHV , ρ , and r_p remain steady as well, the pollutant emissions mass depends inversely on the energy efficiency; therefore, if the efficiency decreases, the pollutant emissions mass increases.

Energy efficiency changes depending on operating conditions; nevertheless, in current practice, combustion processes are designed to operate at maximum efficiency to optimize process performance. Factors influencing energy efficiency are variable; however, two of the most relevant ones are working temperature and oxygen content. The oxygen content varies with ambient pressure when using atmospheric air for fossil fuel combustion.

Other important factors influencing the energy efficiency in combustion processes are the energy losses and the power demand rate. With time, the combustion system increases energy losses due to deterioration or degradation of elements, resulting in a reduction in energy efficiency. Changes in the power demand rate produce a double contribution to the energy efficiency variation; on one side, if the power demand increases, the fossil fuel consumption is higher, increasing the pollutant emissions; on the other side, a deviation from the optimum working point because of the power demand change may cause a decrease in energy efficiency.

Since the influence of ambient pressure and temperature changes on energy efficiency in combustion processes does not depend on the user, we focus on the system aging and power demand rate as the relevant factors that modify the energy efficiency value in combustion processes, thereby affecting the pollutant emissions rate.

Determining the influence of aging on combustion system efficiency is complex, as it depends on many factors, such as working time, operational mode, and maintenance. Therefore, we should integrate all these effects into the energy efficiency value as a generic factor, f_{ag} .

The most accurate way to model system degradation evolution over time is with a quadratic pattern base and random fluctuations (Figure 8).

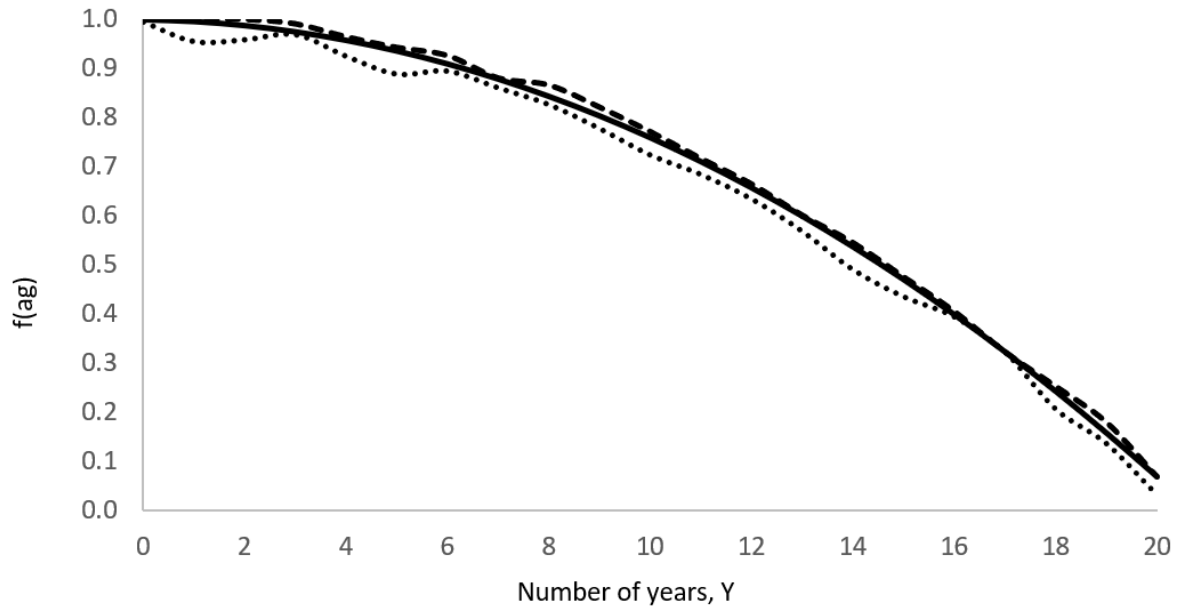


Figure 8 Estimation of combustion system energy efficiency aging factor evolution.

The Figure 8 graph responds to the following algorithm:

$$f_{ag} = 1 - (aY^2 + bY + c) \quad R^2 = 0.9992 \quad (a = 0.00225; b = 0.0015; c = 0.001) \quad (7)$$

The random fluctuation is in the (+0.025; -0.050) range. Y represents the number of operating years.

On the other hand, the power demand rate relates to energy efficiency as in:

$$\eta_c = 1 - \frac{\dot{Q}_L}{P} \quad (8)$$

$\dot{Q}_L$ is the power thermal losses, and P is the power generation.

Since the combustion system cannot operate at 100% efficiency, Equation 8 should reformulate as in:

$$\eta_c = \eta_c^o - \frac{\dot{Q}_L}{P} \rightarrow \eta_c = f_\eta \eta_c^o ; f_\eta = 1 - \frac{\dot{Q}_L}{\eta_c^o P} \quad (9)$$

η_c^o is the attained maximum efficiency by the system, and f_η is the efficiency correction factor due to changes in operational conditions.

Thermal losses depend on temperature change according to the following expression:

$$\dot{Q}_L = U_L(T_{op} - T_{amb}) \quad (10)$$

U_L is the global thermal loss coefficient, and T is the temperature, with subscripts op and amb accounting for operational and ambient conditions.

As the power demand rate increases, the system's energy efficiency decreases due to two causes: irregular temperature exchanges prevent the system from achieving the operating pressure in a

timely manner, and thermal exchange occurs at higher temperatures, resulting in higher thermal losses.

Combining all factors, and replacing in Equation 6:

$$m_{p,i} = \frac{\xi}{(HHV)_j} \frac{1}{\rho} \frac{r_{p,i}}{f_{ag} f_{\eta} \eta_c} = \frac{1}{\rho} \frac{\xi}{(HHV)_j} \frac{P}{\eta_c^o P - \dot{Q}_L} \frac{r_{p,i}}{1 - (at^2 + bt + c)} \quad (11)$$

5. Engineering Design

The technology control and methodology of GHG emissions and air pollutants have been previously studied [81-83]. In our case, applying the schematic structure drawn in Figure 3, we can measure the gas emissions using the corresponding sensor inserted in the duct through which the gas flows (Figure 9 and Figure 10). There are as many sensors as pollutant gasses detection are required.

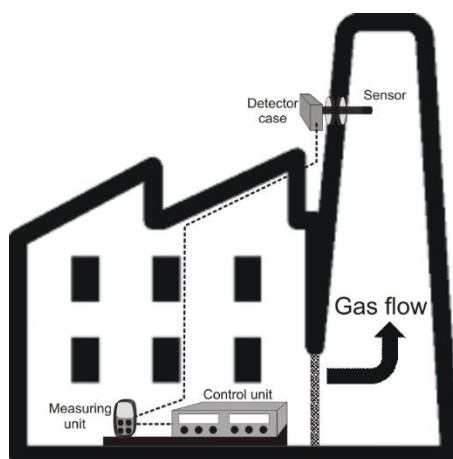


Figure 9 Schematic view of the gas detection and control of the pollutant gasses for building installations.

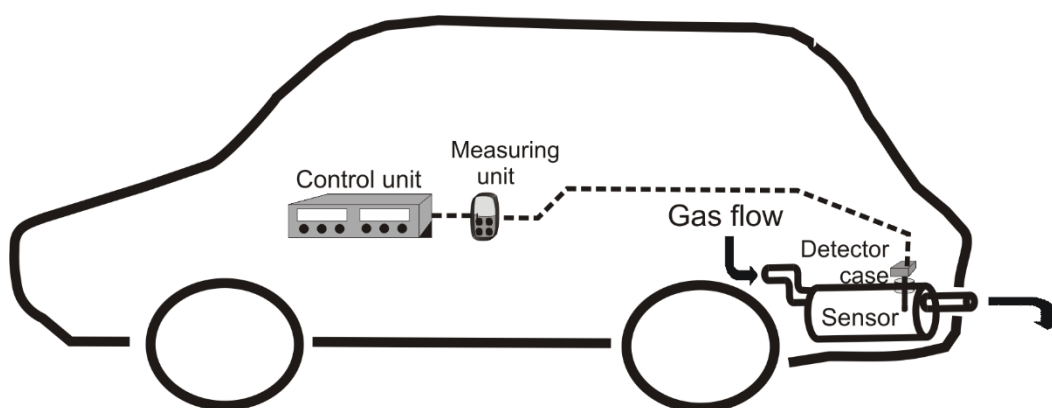


Figure 10 Schematic view of the gas detection and control of the pollutant gasses for vehicles.

The gas sensor detects the presence of pollutant emissions and sends a signal to the detector case, which converts the received signal into an electric current proportional to the pollutant gas concentration in the gas flow.

The detector case amplifies the signal and sends it to the measuring unit, which transmits the measured value to the control unit.

For simplicity, Figure 9 and Figure 10 show a single sensor, whereas in current practice, we have one sensor per detected gas inserted into the exhaust pipe. Depending on the configuration, the measuring unit is a multifunctional device that can measure all types of selected gases or a multi-device unit with a single measuring device for each detected gas. In building installations, with no space limitations, this second option is the most suitable, as the single device may have higher accuracy. However, in mobile systems like vehicles, where the space for measuring devices is limited, the first option is more suitable. The control unit is unique, although the one installed in cars is smaller in size. The measuring unit is currently wall-mounted in building installations, while in cars it is integrated into the dashboard control panel.

Figure 11 and Figure 12 show the control panel in building installations and the vehicle dashboard control panel.

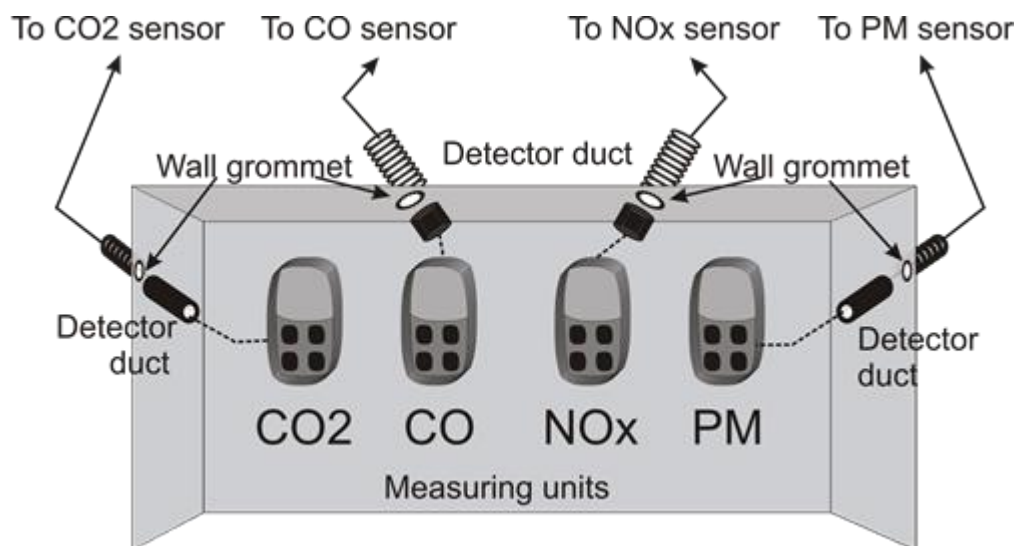


Figure 11 Layout of wall mounted measuring units in building installation.

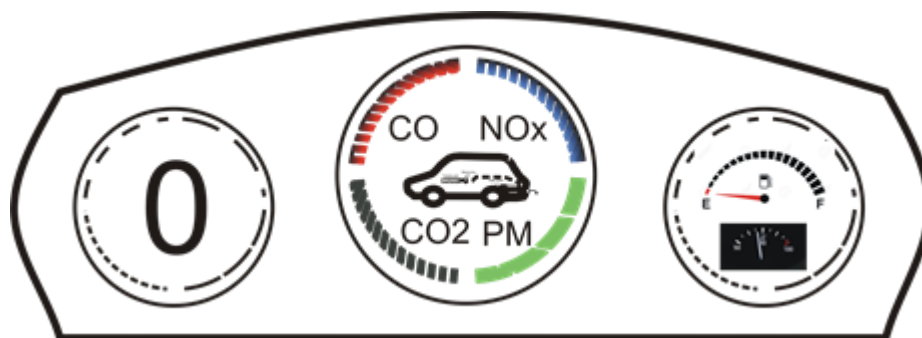


Figure 12 Layout of car dashboard control panel measuring unit.

6. Control Operation

We may control pollutant emissions by regulating fossil fuel consumption to accommodate the emissions rate to a set value. Considering negligible the gas density variation with operating

temperature change, and because the higher heat value and specific component pollutant emissions rate are constant, expressing the energy in terms of setup power generation, we have:

$$\dot{m}_{p,i} = C_o \left[\frac{1}{P_{MAX} - U_L(T_{op} - T_{amb})} \frac{1}{1 - (aY^2 + bY + c)} \right] \quad (12)$$

With:

$$C_{o,i} = \frac{r_{p,i} P^2}{\rho(HHV)_j} ; P_{MAX} = \eta_c^o P \quad (13)$$

Therefore, the pollutant emissions rate depends on working temperature and system degradation; if working or ambient temperature changes, the pollutant emissions rate changes too, increasing or decreasing as the temperature differential between the combustion process and the ambient decreases or increases.

On the other hand, as time goes by, the pollutant emissions rate increases due to the combustion system's time degradation. We should fulfill the following mathematical condition to maintain the pollutant emissions rate constant considering both effects:

$$[P_{MAX} - U_L(T_{op} - T_{amb})][1 - (aY^2 + bY + c)] = K_p \quad (14)$$

K_p represents the operational constant to maintain the pollutant emissions rate unchanged.

Equation 14 applies to any pollutant emissions rate by simply changing the value of the K_p constant. Indeed, combining Equations 12 and 14:

$$\dot{m}_{p,i} = \frac{C_{o,i}}{K_p} \rightarrow K_p = \frac{C_{o,i}}{\dot{m}_{p,i}} \quad (15)$$

We observe that any change in the $\dot{m}_{p,i}$ value modifies the K_p value automatically and vice versa.

6.1 Control Operation Protocol

The protocol to regulate the K_p value, maintaining the pollutant emissions rate, follows the diagram (Figure 13).

The operational protocol works as follows:

- The system designer introduces reference parameter values for emissions gas density (ρ), fossil fuel higher heat value (HHV), maximum power generation (P_{MAX}), pollutant emissions specific rate for every component ($r_{p,i}$), maximum operational efficiency (η_{co}), global thermal losses coefficient (U_L), and combustion system aging coefficients (a, b, c) in the database.
- The measuring unit collects information about operational and ambient temperature.
- The control unit claims for the required power generation (P) obtained from the energy demand.
- The control unit calculates the K_p -coefficient value for every pollutant component.
- The control unit determines the pollutant emissions for every component ($\dot{m}_{p,i}$).
- The control unit compares the amount of pollutant emissions with the maximum allowed ($\dot{m}_{p,i})_{MAX}$ for every component. The maximum value may correspond to the highest value

permitted by current regulations or to a user's custom setting value. A control regulator allows manual changes in the $(m_{p,i})_{MAX}$ value.

- If the comparative analysis results in a positive answer, the power generation process continues without any changes in the operational parameters; if not, the control unit evaluates the process efficiency, comparing the retrieved value from the database to the maximum introduced by the system designer.
- If the current efficiency is lower than the maximum, the control unit proceeds to calculate the aging factor; otherwise, the power generation process continues.
- Once the control unit determines the aging factor, it calculates the corresponding efficiency, $\eta_c(Y)$, and compares the value with the reference power efficiency, η_c , retrieved from the database.
- If the efficiency does not match, the control unit increments the year number, Y , and repeats the process until the calculated efficiency matches the reference value.
- The control unit compares the last Y value with the obsolescence threshold, Y_{MAX} , set up by the manufacturer or the system designer.
- When the Y value meets the obsolescence threshold, the control unit issues a warning signal, advising the user to cease operations of the combustion system. If it does not match the threshold, the unit reduces power generation by a predetermined interval, ΔP , and resets the process to the K_p calculation step.

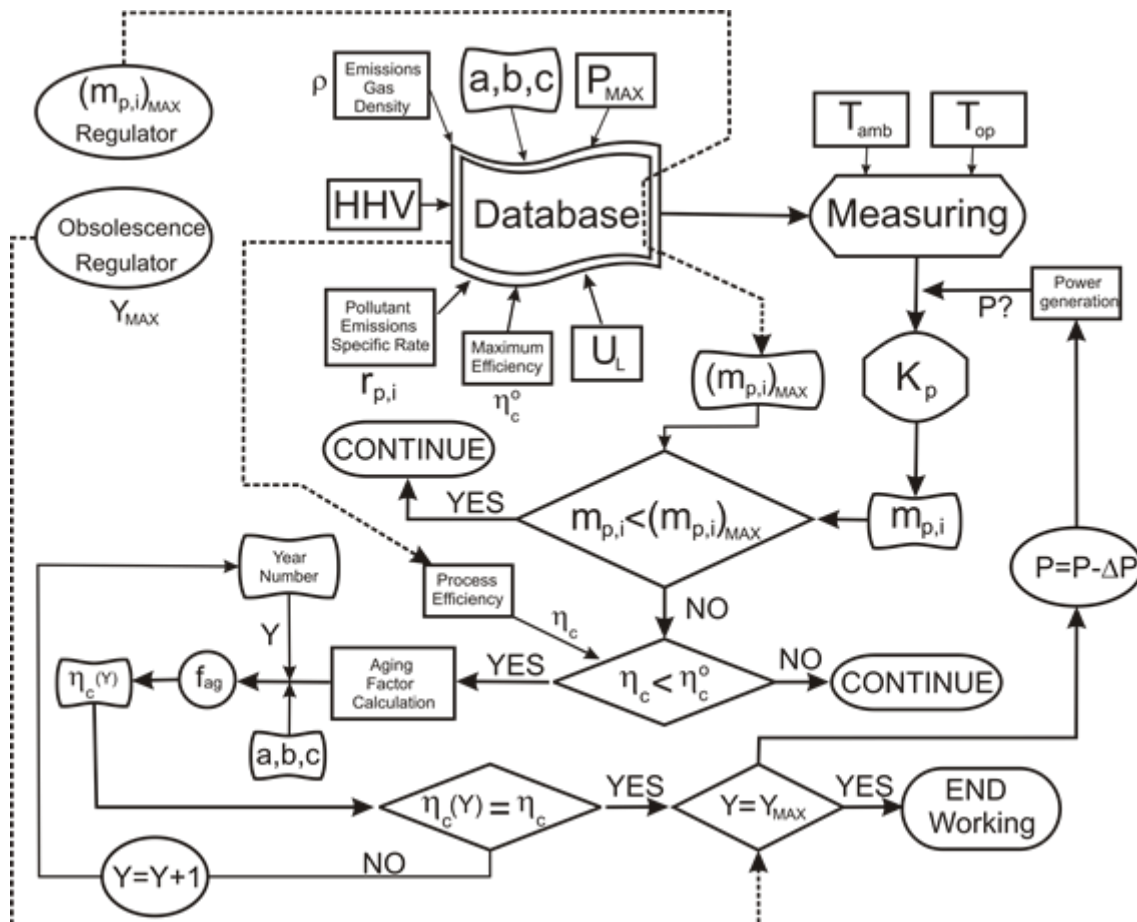


Figure 13 Operational protocol flowchart for pollutant emissions control.

The protocol is adaptive to different pollutant components, variable emissions rate threshold, and obsolescence by simply regulating the corresponding values to maximum emissions rate, according to current regulations or specific values set up by the manufacturer, the designer, or the user, and adjusting the obsolescence threshold to match a programmed lifespan or an estimated value to match a minimum efficiency making the operation energetically and economically reliable.

7. Applications

The developed protocol encompasses all sectors of society, including residential, commercial, industrial, institutional buildings, sanitary and leisure facilities, as well as automobile fleets. The protocol applies to any combustion process that produces pollutant emissions impacting the environment and human health.

Among the many protocol applications, we can mention domestic combustion boilers, gas or coal stoves, conventional power plants (fueled by gas, fuel, and coal), internal combustion engine vehicles, and industrial processes that burn fossil fuels, among others.

The continuous use of combustion engines results in a progressive deterioration of system components and a decrease in efficiency. Two consequences arise from the degradation of the combustion system: first, the need for a higher fossil fuel supply to compensate for the efficiency loss, and second, an increase in pollutant emissions resulting from higher fossil fuel consumption.

7.1 Case A: Building Heating

If we consider a generic combustion process for building heating, applying Equations 12 and 13, we have:

$$\dot{m}_{p,i} = \frac{r_p P^2}{\rho(LHV)_{fuel}} \left[\frac{1}{\eta_c^o P - U_L(T_{op} - T_{amb})} \frac{1}{1 - (aY^2 + bY + c)} \right] \quad (16)$$

Where the power generation derives from the thermodynamic expression:

$$P = S_o T_h \left[\left(\frac{\kappa}{e} \right) + h + T_h^3 \left(\frac{1 + f + f^2 + f^3}{f^3} \right) \right] \left(1 - \frac{1}{f} \right) ; f = \frac{T_h}{T_r} \quad (17)$$

κ and T_h are the thermal conductivity and Kelvin temperature of the heat transfer material, h is the convection coefficient, T_r is the room comfort Kelvin temperature, and S_o is the heat exchanger surface.

We use the lower heating value (LHV) since in this combustion process water contained in the fuel is not vaporized.

Combining Equations 16 and 17 and operating:

$$\dot{m}_{p,i} = \left[\frac{C_3 C_4 \left[(C_1 + C_2 T_h^3) S_o T_h \left(1 - \frac{1}{f} \right) \right]^2}{\eta_c^o (C_1 + C_2 T_h^3) S_o T_h \left(1 - \frac{1}{f} \right) - U_L(T_{op} - T_{amb})} \right] \quad (18)$$

With

$$C_1 = \left(\frac{\kappa}{e}\right) + h ; C_2 = \left(\frac{1 + f + f^2 + f^3}{f^3}\right) ; C_3 = \frac{r_p}{\rho(LHV)_{fuel}} ; C_4 = \frac{1}{1 - (aY^2 + bY + c)} \quad (19)$$

Operating at a specific short interval in the combustion system lifespan, the parameter Y is constant; since coefficients C_1 , C_2 , and C_3 are constant, provided the working parameters do not change, and considering that comfort and ambient temperature remain unchanged, the only variables in Equation 18 are T_h and T_{op} . If we reduce the T_{op} value, we should lower the T_h value to maintain the pollutant emissions rate and vice versa.

Let us suppose the operational temperature lowers by a factor f_{op} , so the new operating temperature is $T_{op}^n = f_{op}T_{op}$, with $0 < f_{op} < 1$; therefore, according to the previous statement, the heating temperature lowers too, let us say by a factor f_h , where $T_h^n = f_hT_h$, with $0 < f_h < 1$.

Applying this to the condition of constant pollutant emissions rate (Equation 18), we have:

$$f_{op} = \frac{1}{T_{op}} \left\{ T_{amb} + \frac{\eta_c^o}{U_L} \left[(C_1 + C_2 f_h^3 T_h^3) S_o T_h \left(\frac{f_h^2 - 1}{f_h} \right) \right] - \frac{C_3 C_4}{(\dot{m}_{p,i})_o} \left[(C_1 + C_2 T_h^3) S_o T_h \left(\frac{f_h^2 - 1}{f_h} \right) \right]^2 \right\} \quad (20)$$

$(\dot{m}_{p,i})_o$ is the constant value for the pollutant emissions rate.

Equation 19 represents the control algorithm to adjust operational conditions for maintaining the pollutant emissions rate constant.

7.2 Case B: Gas Cooking

A similar development applies to the gas cooking case with the only difference in the power generation expression, which for this case is:

$$P = \frac{1}{\eta_h} [(m_o c_o + m_b c_b) \Delta T] \quad (21)$$

η_h is the heating process efficiency, m is the mass, c is the specific heat, and ΔT is the temperature increase in the cooking process. Subscripts o and b account for the recipient and the body.

Therefore, applying Equation 16:

$$\begin{aligned} \dot{m}_{p,i} &= \frac{r_p [(m_o c_o + m_b c_b) \Delta T]^2}{\eta_h^2 \rho (LHV)_{gas}} \left[C_4 \frac{\eta_h / \eta_c^o}{[(m_o c_o + m_b c_b) \Delta T] - U_L (T_{op} - T_{amb})} \right] \\ &= C_4 C_5 \left[\frac{(\Delta T)^2}{C_6 \Delta T - U_L (T_{op} - T_{amb})} \right] \end{aligned} \quad (22)$$

With:

$$C_5 = \frac{r_p [(m_o c_o + m_b c_b)]^2 \eta_h}{\eta_h^2 \rho (LHV)_{gas} \eta_c^o} ; C_6 = (m_o c_o + m_b c_b) \quad (23)$$

An equivalent operational temperature change as the one accepted for the heating building produces a variation of f_g in the cooking temperature jump, so the new temperature increase is $f_g \Delta T$, and the control algorithm that rules the control unit protocol is:

$$f_{op} = \frac{1}{T_{op}} \left[f_g \frac{C_6}{U_L} \Delta T - \frac{f_g^2}{\dot{m}_{p,i}} \frac{C_4 C_5}{U_L} (\Delta T)^2 + T_{amb} \right] \quad (24)$$

7.3 Case C: Vehicle Fleet

Internal combustion engine cars are responsible for more than 30% of pollutant emissions in urban areas, severely impacting the environment and human health. Although modern regulations aim to prevent excessive pollutant emissions, the pollution level continues to concern local authorities and citizens. This situation stems from insufficient maintenance, aggressive driving habits, and inadequate use of theoretical non-polluting vehicles.

In past decades, the regulations about GHG, NO_x, and PM emissions from ICE cars have been tightened, adopting severe restrictions regarding the level of polluting emissions from new vehicles; nevertheless, the progressive degradation of the car engine, with null or low maintenance, generate an increase in the pollutant emissions due to lower engine efficiency. Another cause of increasing pollutant emissions is adopting an aggressive driving mode, which consumes more fuel and generates a higher pollutant emissions rate.

Modern policies want to replace ICE cars with hybrid electric vehicles, the most popular segment because of their reduced price compared to fully electric cars and lower dependence on recharging stations may suggest a significant change in the trend in terms of polluting emissions; however, their inadequate use increases fossil fuel consumption and pollutant emissions rate.

The proposed methodology for controlling pollutant emissions is particularly suitable for addressing the issues associated with car use in urban environments.

The power demand in a vehicle depends on car speed, v , and driving force, F ; therefore, the pollutant emissions rate equation adopts the form:

$$\dot{m}_{p,i} = \frac{r_p F^2 v^2}{\rho (LHV)_{fuel}} \left[\frac{1}{\eta_c^o F v - U_L (T_{op} - T_{amb})} \frac{1}{1 - (aY^2 + bY + c)} \right] \quad (25)$$

Because the driving force depends on four terms, inertial, drag, rolling, and weight, we may write:

$$F = F_a + F_d + F_r + F_w = ma + \kappa v^2 + \mu mg + mgsin\alpha \quad (26)$$

m , a , and v are the vehicle mass, acceleration, and velocity, κ and μ are the drag and rolling coefficients, and α is the road slope.

Only the inertial and drag force depends on the driving mode; therefore, we convert Equation 24 into:

$$F = ma + \kappa v^2 + F_o \quad (27)$$

F_o encompasses the rolling and weight terms.

Replacing in Equation 25 and grouping terms:

$$\dot{m}_{p,i} = C_3 C_4 \left[\frac{\kappa^2 v^6 + 2\kappa F_o v^4 + 2m\kappa a v^3 + (m^2 a^2 + F_o^2 + 2mF_o a)v^2}{\eta_c^o (ma + \kappa v^2 + F_o)v - C_7} \right] \quad (28)$$

With:

$$C_7 = U_L (T_{op} - T_{amb}) \quad (29)$$

We consider ambient and ICE operating temperatures constant.

The way to lower pollutant emissions in vehicle driving is reducing the car speed and acceleration; since the acceleration depends on the velocity change rate, we may consider the vehicle speed as the critical variable in lowering the pollutant emissions; therefore, Equation 28 transforms into:

$$\Delta \dot{m}_{p,i} = C_3 C_4 \left[\frac{(1 - f_v^6)\kappa^2 v^6 + 2(1 - f_v^4)(\kappa F_o v^4 + m\kappa a v^3) + [(1 - f_v^2)m^2 a^2 + F_o^2 + 2(1 - f_v)mF_o a](1 - f_v^2)v^2}{\eta_c^o [(1 - f_v)ma + (1 - f_v^2)\kappa v^2 + F_o](1 - f)v - C_7} \right] \quad (30)$$

f_v represents the vehicle speed reduction coefficient.

The control system uses the algorithm in Equation 30 to adjust the pollutant emissions rate in vehicle driving to the setup value.

7.4 Case D: Industrial processes

Since manufacturing industrial processes require specific energy consumption at fixed operational temperature, the reduction in pollutant emissions rate depends only on the aging factor; therefore, Equation 16 converts into:

$$\dot{m}_{p,i} = \frac{C_8}{1 - (aY^2 + bY + c)} \quad (31)$$

With:

$$C_8 = \frac{r_p P^2}{\rho(LHV)_{fuel} \eta_c^o P - U_L (T_{op} - T_{amb})} \quad (32)$$

There is no option to reduce pollutant emissions with system degradation progress since Y increases continuously. In this case, the protocol shown in Figure 13 applies to determine the obsolescence time at which the combustion system reaches its lifespan limit.

8. Comparative Analysis

The predicted gas emissions, excluding the effects of system degradation and lack of maintenance, depend on the required power generation and the fuel type used for combustion, as per Equation 6. If we consider the efficiency loss due to system aging and performance reduction because of a lack of maintenance, Equation 11 applies. Comparing the two equations, we determine the predicted difference in gas emissions, $\Delta m_{p,i}$, using the proposed methodology.

$$\Delta m_{p,i} = m_{p,i} - m_{p,i}^o = \frac{1}{\rho} \frac{\xi}{(HHV)_j} \frac{P}{\eta_c^o P - \dot{Q}_L} \frac{r_{p,i}}{1 - (at^2 + bt + c)} - \frac{\xi}{(HHV)_j} \frac{1}{\rho} \frac{r_{p,i}}{\eta_c} \quad (33)$$

$$= \frac{r_{p,i}}{\rho} \frac{\xi}{(HHV)_j} \left(\frac{P}{\eta_c^o P - \dot{Q}_L} \frac{1}{1 - (at^2 + bt + c)} - \frac{1}{\eta_c} \right)$$

Because the parameters involved in Equation 33 depend on the fuel and gas emissions type, system efficiency, power generation, and energy demand, it is hard to evaluate $\Delta m_{p,i}$ for a generic case; therefore, we must simulate variable conditions to obtain a numeric value rather than an analytic prediction.

We calculate the GHG emissions density based on the gas type and percentage in the combined gas emissions. The initial combustion boiler efficiency corresponds to the average value in the literature [84, 85]. The HHV value applies to natural gas [86].

Applying data for a gas power plant (Table 2), and considering an efficiency loss of 0.5% per year, we obtain the time evolution of the increasing GHG emissions factor shown in Figure 14. We define the factor as the ratio between the expected pollutant emissions from conventional determination and the predicted values with the proposed methodology. This factor represents the increase in GHG emissions due to efficiency loss (system degradation and lack of maintenance).

Table 2 Parameter values used for the simulation.

Parameter	r_p (kgCO ₂ /m ³ gas)	ρ (kg/m ³)	η^o (%)	HHV _{gas} (kWh/kg)
Value	0.008	0.964	0.945	14.5

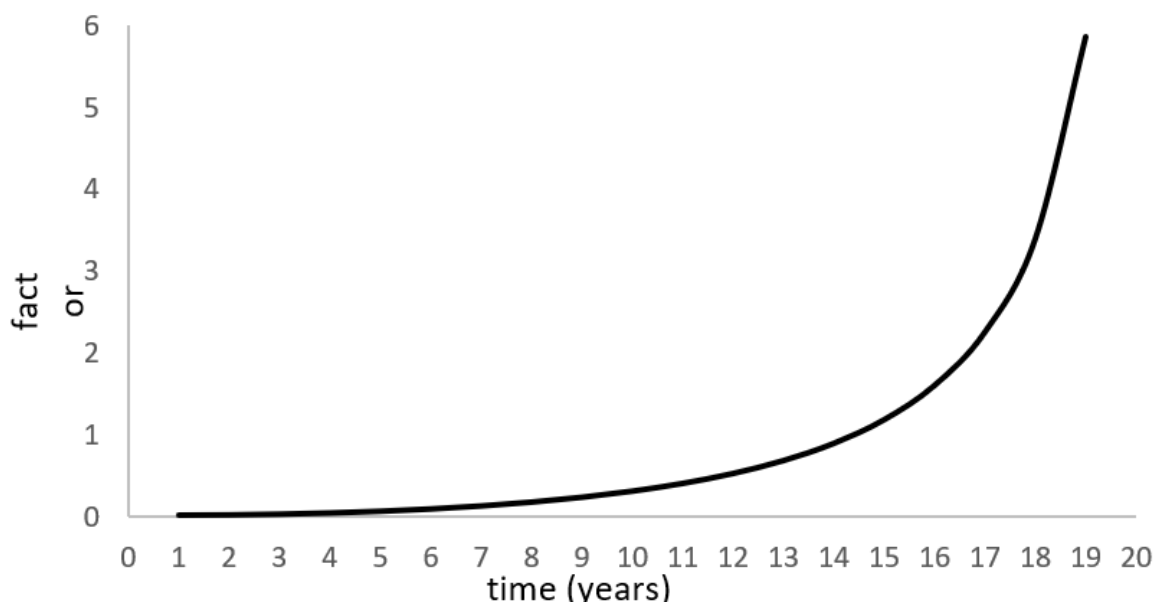


Figure 14 Yearly evolution of the increasing factor for the GHG emissions from a gas power plant due to efficiency loss.

The simulation results are independent of the output power and energy generation. We observe that the factor increases linearly with time for the first ten years with a regression coefficient of R^2

= 0.9, and a net variation of 31% at the ten-year operation, resulting in a yearly increase of 3% regarding the initial value, 1.8% at the end of the first operation year. Beyond this point, after ten years of operation, the factor rises rapidly, achieving a value of nearly 6.0 at 19 years of operation.

The simulation results show that the GHG emissions rate dramatically increases after 10 operational years. This situation is due to a significant drop in combustion process performance resulting from system degradation and/or inadequate maintenance. Therefore, a continuous survey of the materials and periodic maintenance labor is mandatory.

9. System Implementation

The proposed methodology requires the physical implementation of sensors and the installation of a control system to monitor the process. The implementation depends on the application because the required sensors and building structure vary for each case.

Regarding the four analyzed environments, building heating, gas cooking, vehicle fleet, and industrial processes, the following procedure applies:

9.1 Case A: Building Heating

Sensors should be installed in the exhaust pipe connecting the combustion boiler to the environment. This procedure requires modifications to the manufacturing process, including the integration of built-in sensors and a control system within the structure, or the insertion of sensors in the exhaust pipe, with the sensor connected to an external control unit (Figure 15).

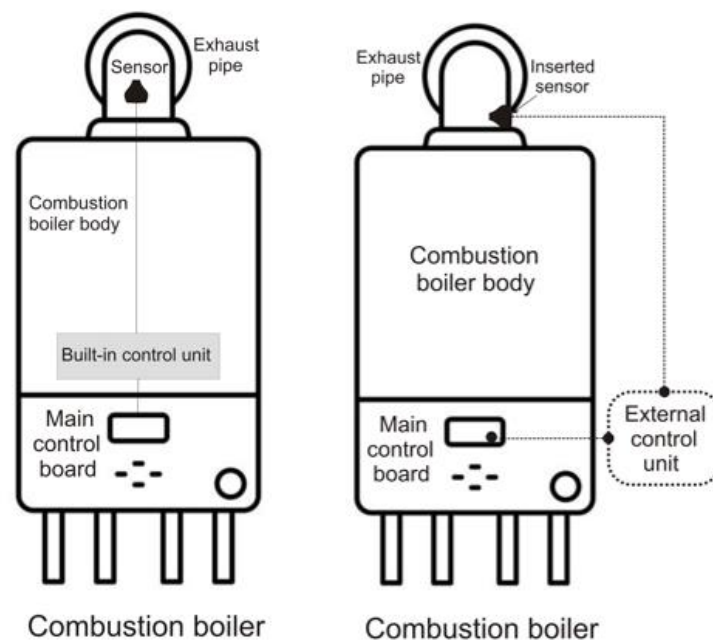


Figure 15 Schematic view of gas emissions control unit in a building heating system. Left side: manufactured built-in mode. Right side: coupled mode.

The built-in unit is included in the combustion boiler system provided by the manufacturer, while the coupled unit requires professional service for installation.

9.2 Case B: Gas Cooking

The control system implementation responds to a similar structure as shown in Figure 14. The only difference is the use of built-in or inserted miniaturized sensors due to the small dimensions of the exhaust pipe.

Figure 11 illustrates the layout of the control unit for detecting gas emissions from combustion boilers used in building heating or gas cooking.

9.3 Case C: Vehicle Fleet

The control unit implementation in vehicles (Figure 12) requires the system to be built during the car manufacturing process due to the complex control unit installation. Implementing the system in a manufactured car requires specialized professional services and is highly labor-intensive.

9.4 Case D: Industrial Processes

Figure 9 shows the engineering system that should be implemented in an industrial facility. Because industries are large installations, sensors and control units are easily adapted to existing infrastructure. The labor time and installation cost are of low importance compared with the benefits derived from the GHG emissions control.

9.5 Limitations

Technically, the system implementation has no limitations, as sensors and control units are current market items; however, the engineering may pose a problem depending on the facility's architectural configuration. In industrial facilities, implementing sensors and control units should be straightforward; however, in domestic and commercial environments, the lack of accessibility for installing sensors and the difficulties in wiring them to control units can lead to complex installations, increased costs, and a reluctance to proceed.

Regarding the facility type, the proposed system and methodology do not exhibit any limitations other than those derived from labor time and installation costs.

10. Future Research

The present study will proceed with an experimental part, focusing on collecting data from existing installations and designed prototypes to verify the validity of the proposed methodology. The data collection should involve all facility types; nevertheless, there is a limitation in the application field since only the industrial installation type has a similar configuration to our engineering design. To avoid this problem, we intend to install the proposed system in prototype installations, commercial and domestic, to extend the validation process. The implementation in the vehicle fleet poses a significant challenge because it requires changes to the manufacturing process, which must overcome the car manufacturer's reluctance.

11. Conclusions

The developed control protocol enables the reduction of pollutant emissions by controlling power generation in combustion systems.

The protocol utilizes algorithms tailored to each application, incorporating power generation and aging as key factors in determining the pollutant emissions rate.

The protocol applies to any combustion system, provided we know the operational parameters the protocol algorithm uses for pollutant emissions rate control. Additionally, the protocol is adaptable to variable pollutant emissions rates established by current regulations or set by the system manufacturer, designer, or user.

The control process allows for determining the system lifespan limit for specific pollutant emissions rates, warning the user to replace the combustion boiler to continue complying with emissions regulations.

The protocol adapts to any lifespan value through an obsolescence regulator, thereby extending the protocol's applicability to almost any system and operational condition.

The paper represents the first part of an ambitious project aimed at developing a protocol to regulate combustion processes and pollutant emissions rates, based on energy demand, fuel type, and installation. The future research direction aims to achieve this goal.

Author Contributions

The author did all the research work for this study.

Competing Interests

The authors have declared that no competing interests exist.

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