Environmental Energy and Economic Research 2021 5(3): S015
DOI 10.22097/EEER.2021.249645.1170

Research Article

Design and Optimization of Smart Central Heating Units for Homes; Energy and Environment Nexus

Atila Fazeli [a], Alireza Pardakhti [b,*], Mohammad Ali Zahed [c], Vahid Mirkhani [d]

[a] College of Environment, University of Tehran (Kish International Campus), Kish, Iran
[b] School of Environment, College of Engineering, University of Tehran, Tehran, Iran
[c] Faculty of Biological Sciences, Kharazmi University, Tehran, Iran
[d] Department of Physics, Auburn University, Auburn, AL, USA

Received: 1 August 2020 /Accepted: 15 February 2021

Abstract

Due to urban extension, air pollution is continuously getting to be a vital issue in present day social orders, particularly in metropolitan zones. Owing to the tremendous characteristic gas assets in Iran, a significant number of residential, commercial and industrial sectors use the central heating unit (CHU) as a source for warming. Emission of pollutants from these sources not only increases environmental degradation and energy consumption, but it also decreases the working life of heating systems and the safety factor. Thus, planning and improvement of inventive frameworks in this division can result in noteworthy diminishment of pollution and increment of energy consumption productivity. In this paper, a smart CHU has been designed and implemented, using an innovative intelligent network with the aim of optimizing burner performance in a 2250 square meter residential building. Furthermore, carbon monoxide (CO) emission and fuel consumption were analyzed and reduced simultaneously. The use of software and hardware elements in the design has reduced the working hours of the burner and improved its performance according to the required heat capacity at different times of the day. The result of this innovation showed a reduction in CO emission by 28% and an increment in energy saving by 25%, in comparison to the initial state. This study further indicates how intelligent control can significantly lower the pollution and optimize energy consumption.

Keywords: Central Heating Unit, Carbon monoxide, Boiler room Pollution, Burner

Introduction

Innovation headway for comforting to the needs of society comes about in the increment in fossil fuel consumption, and it has been demonstrated to cause destructive impacts on the environment such as excessive emissions of pollutants and significant reduction of energy sources (Clitan et al. 2021; Pfeiffer et al. 2021; Shayesteh et al. 2019). Hence, execution of strategies with trendy instrumentation in numerous segments to provide energy consumption management, reduction and control of the pollutants' emission has gotten to be a need of most of the developed and developing

---

[*] Corresponding author E-mail: alirezap@ut.ac.ir

nations (Li et al. 2020; Mahapatra et al. 2021). Air pollution in Iran, especially in the metropolis of Tehran is increasing dramatically (Zahed et al. 2010). Heating units in residential, commercial and office buildings consume 40% of the produced energy, and they have a substantial stake in pollution and energy consumption (Ravanshadnia and Jahromi, 2018). Among energy carriers consumed for building heating, natural gas has the most elevated share with 67%. Thus, with current infrastructures and the use of the boiler systems in cities, an endless sum of this asset is consumed by means of building segments within Iran annually (Khosroshahi and Sayadi, 2020). Since the natural gas resources are depleting at a high rate due to consumption and exploitation, creating strategic infrastructure and investment in economical consumption is an associate imperative matter. Central heating units in Iran face problems such as excessive energy consumption due to lack of seasonal thermostat settings and improper operation of the burner, which replaces the existing worn and dense infrastructure with various problems and heavy costs. Therefore, the discussion of replacing motorhomes with new heating systems in the country is impractical and purely abstract (Fazeli et al. 2020; Salimi et al. 2020). Due to the mentioned administrative and economic problems, the use of integrated energy systems through intelligent control has a decisive role in using the existing infrastructure as efficiently as possible with the aim of sustainable development (Kaczmarczyk, et al. 2020; Sabru, 2021).

Smartening in CHUs is often designed and implemented by improving operating conditions by considering consumption habits. Inadequate burner performance, poor quality of the burners and the lack of optimization of the operating conditions cause that CO emissions in a number of active engine rooms in Iran are six times higher than the world standard (Aghamolaei and Ghaani, 2020; Ahmadi et al. 2020). Various scenarios have been predicted and investigated to improve burner operating conditions. Preheating the inlet air to the burner is one of the effective solutions in this field (Wang et al., 2019). Concurring to the energy surveys conducted in CHUs, the complete combustion of fuel requires the appropriate stoichiometric mixture of fuel and Oxygen (λ) in the combustion chamber (Kotb and Saad, 2018). If the amount of air is less than required, combustion is incomplete and lower the productivity of the CHU (Denev et al., 2017). On the other hand, excess air volumes beyond the permitted level can cause heat loss (He et al., 2021). In expansion, the amount of produced CO gets increased if the amount of the excess air is more than 80% (Shu et al. 2019; She et al. 2020). In this regard, one of the solutions to improve the performance of the burner and its accessories is to adjust the amount of excess air by using sensors for complete combustion of the fuel; where with the data acquired from this sensor, the air intake of the boiler's burner can be adjusted (Moein et al. 2018; Dai et al. 2020; Pichler et al. 2021).

Optimization of burner operation time at different hours of the day based on consumption habits is one of the determining indicators in environmental and energy parameters (Sovacool and Del Rio, 2020). Lu et al. (2010) used sensors to determine the presence of people in the building. Due to the information received from these sensors and the improvement of engine room performance, they were able to reduce the energy consumption of the building's heating system compared to the previous state. In a study examining the consumption behavior and patterns of households in southern Germany, especially for older buildings and households with a lot of free time, Nägele et al. (2017) found that intelligent heating control by using sensors and programmable thermostats reduced energy consumption by at least 21 percent over a 14-month period.

Hot water is controlled manually in existing boiler rooms, and the adjusted temperature of the thermostat does not change in diverse seasons and hours of the day. Also, in numerous nonresidential buildings such as educational, commercial, and offices, the buildings are not used permanently and only operate at specific hours of the day, so there is no need for the CHUs to run out of the operating hours. This could impressively increase the amount of pollution and energy consumption. In this paper, a smart CHU has been designed and implemented, using an innovative intelligent network with the aim of optimizing burner performance in a 2250 square meter residential building. Furthermore, carbon monoxide (CO) emission and fuel consumption were analyzed and reduced simultaneously.

2. Methods and Materials

Case study

This study provides an overview and quantitative evaluation efficiency of a smart CHU for a 2250 square meter residential building located in Tehran-Iran. In this plan, in addition to the indicators determined in the way of smartening, by identifying the equipment in the engine room, including cast iron burners and boilers and the type of operation and their capacity in the system, the type of control equipment and actuators are selected (Table 1).

Table 1. Technical specifications of the studied engine room

Characteristic	Details
Building specifications	Residential building / 2250 square meter
Number and type of boiler	8-blade turbo cast iron boiler with a nominal capacity of 243,000 kcal
Thermal capacity	55000 kcal
Number and type of burner	Iran Radiator Burner with 260000 kcal capacity
Control tools	Micro Controller ATMEGA328P-PU Actuator Carbon Monoxide detection sensor MQ-7 Thermal Sensor NTC

Applied methods

First step in optimizing the effective parameters to decrease pollution and increase efficiency in the boiler's room is the deployment of software and hardware components. Amid this analysis, an actuator is installed on the burner to regulate the inflow of air to the intake of the burner in conjunction with a control circuit designed and installed to control the flow of air.

Next, a CO sensor is installed in the burner’s exhaust vent and a thermometer was installed inside the hot water pipeline, creating a network of CO and temperature gauges connected to the air valve control. The required amount of heat for heating the building is programmed into the burner in reference to the data received from the software and hardware elements. The required amount of inlet air to the burner is continuously calculated, through the data acquired by the sensors, in such a way that energy consumed by the burner is differed by the hours of day and the required heating capacity.

To simultaneously optimize the pollution index and efficiency of the CHU in the study, the data acquired by the installed sensors are recorded first, while the air valve is adjusted for the lowest CO outflow. By this data, the amount of consumed O_2 is extracted, and consequently the amount of λ in the lowest amount of CO emanation is calculated. In the following process, with the acquisition of data by the smart network and the actuator, the amount of air valve of the burner in the studied heating system is balanced based on λ=1 and the amount of emission CO in this setting is measured.

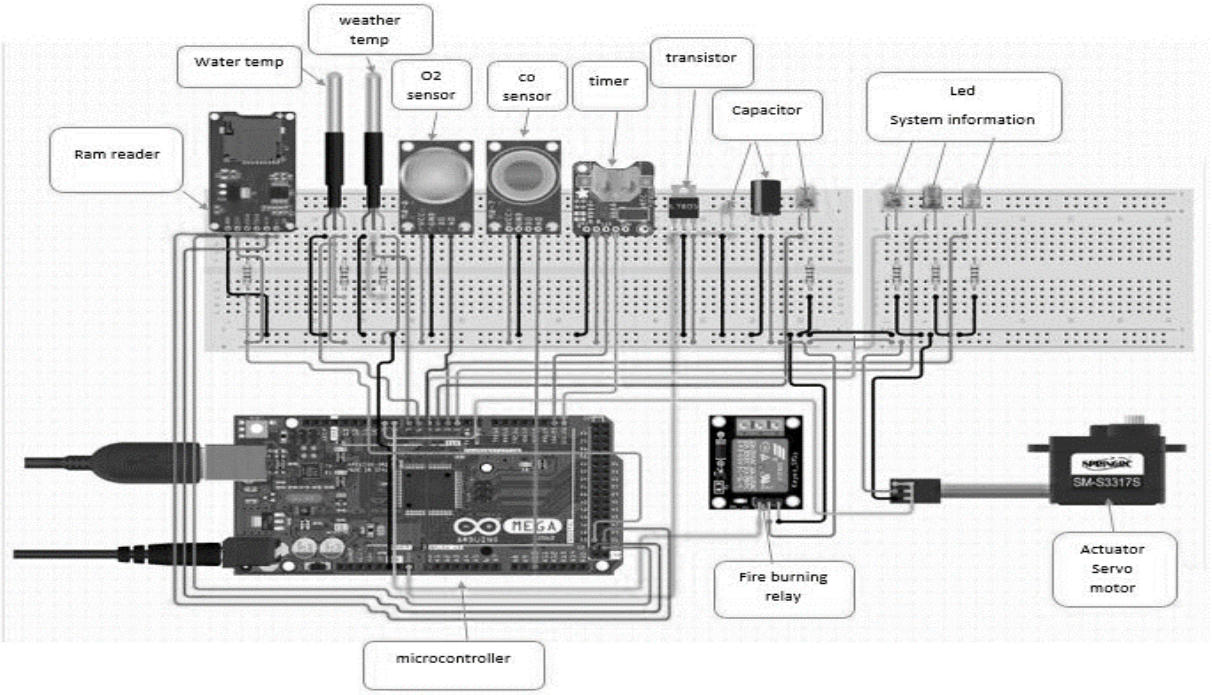

Figure 1. Smart Control Module installed in the study unit

After analyzing the acquired data to the micro-controller, the air valve is adjusted for the lowest CO emission and the best fuel consumption rate, and the software program for the micro-controller and the designed network is programmed accordingly. Therefore, in each step the average of input data is first received and after that, the air valve is adjusted every 5 minutes according to the data and conferring to the required parameters.

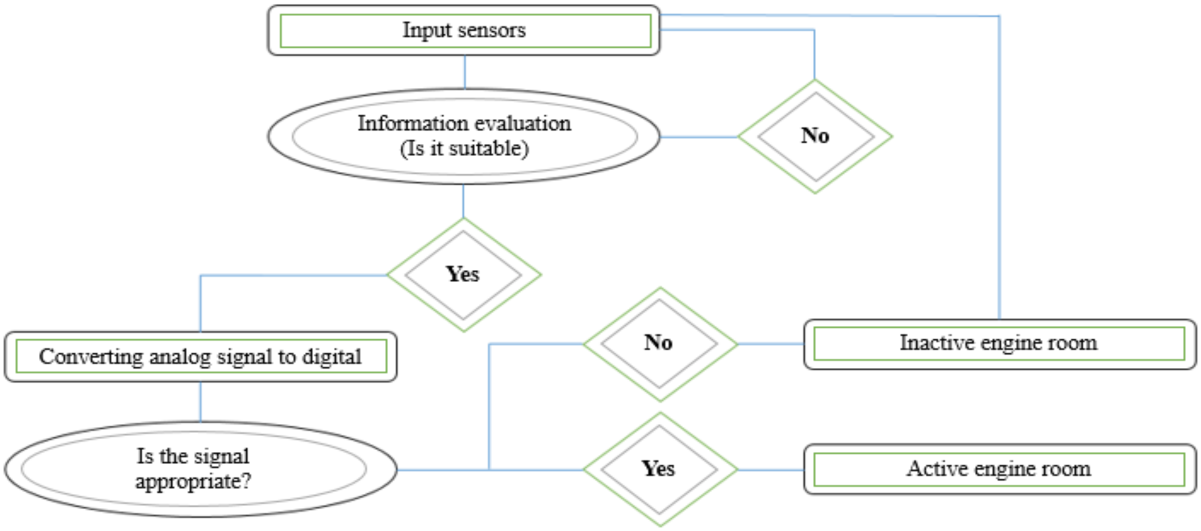

Figure 2. Flowchart of control program designed in the CHU

Analysis

Energy consumption measurement

Effects of the temperature parameter on the efficiency of the system is examined through the installation of observation devices and analysis of the combustion byproducts in the burner of the boiler's room. Due to the control of the heating capacity produced by the burner, the temperature of hot water is measured by the sensors before and after the utilization of the smart system as depicted in figure 2.

Figure 3 shows the temperature changes recorded for water flow, with respect to the optimization of burner performance compared to the initial state. Also, the maximum temperature recorded during different hours of the day is 76 (°C) as shown in figure 4.

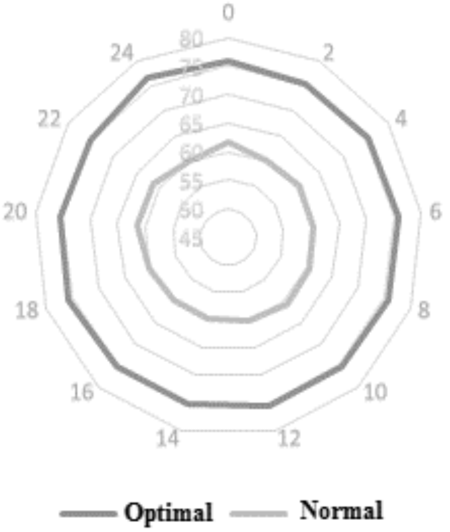

Figure 3. Water Temperature (°C) comparison in CHU during the day

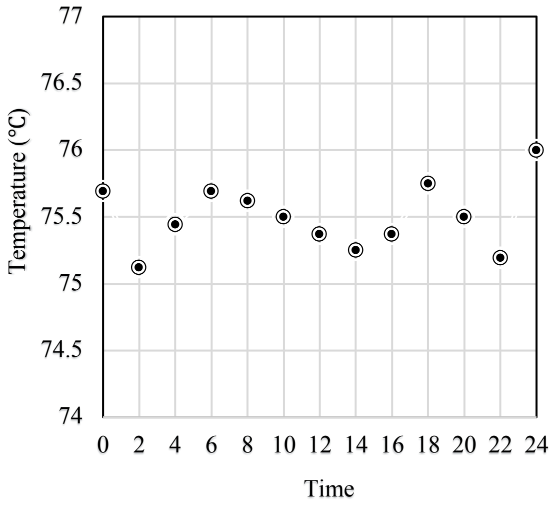

Figure 4. Water Temperature (°C) in optimized setting during the hours of day

The heat generated by the burner in the combustion chamber, causes the increase in temperature of the heat transfer medium and results in the transfer of heat to the water in the pipe. Therefore, considering the study system as a control volume, the energy conservation equation can be written as (Sowayan, 2020):

$$\dot{E}_{Fuel} = (\dot{E}_{out} - \dot{E}_{in})_{NG} + \dot{E}_{stored} \tag{1}$$

In the right hand of the equation (1), $(\dot{E}_{out} - \dot{E}_{in})_{NG}$ shows the required heat to warm up the natural gas flow in the burner and $\dot{E}_{stored}$ shows the required heat to increase the temperature of the heat transfer medium from the lowest to the highest operating temperature during a cycle which is calculated from the following equation (Amid et al. 2021; Ferioli and Buckley, 2006):

$$\dot{E}_{stored} = \int_{0}^{t_{ON}} m_{WF} C(\frac{dT}{dt}) dt \tag{2}$$

Where m_{wf} is the mass of the heat transfer medium, C is the heating capacity of the heat transfer medium, dT/dt is the rate of water temperature change over time and t_{ON} is the time frame of heat transfer to the water in the pipeline (when the burner is on).

According to the acquired data by the software (figure 3), the amount of water flow temperature has increased compared to the initial state. By using equation (3) the amount of energy efficiency has increased between 22% and 28%. Figure 5 shows the rate of increase in productivity at different hours of the day by using the intelligent CHU.

$$\frac{\dot{E}_{stored_2}}{\dot{E}_{stored_1}} = \frac{dT2}{dT1} \tag{3}$$

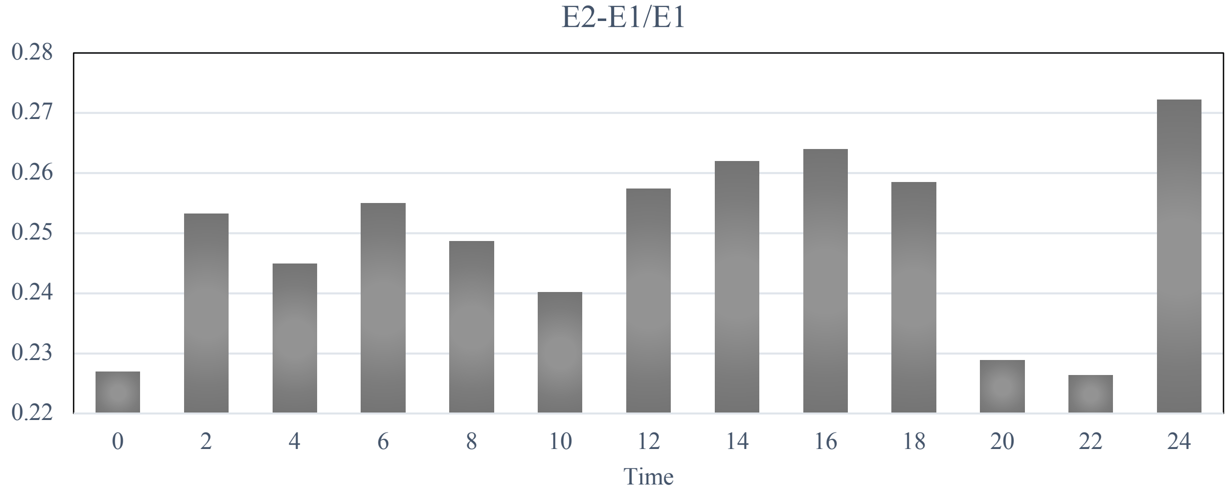

Figure 5. Amount of increase in performance in the different hours of the day

Due to the control of inlet and outlet water temperature by sensors during different hours of the day, the average temperature increase has been calculated to be 25%. The effect of heating in the water flow of the system has significantly reduced energy loss. The rate of increase in energy efficiency during different hours of the day has increased compared to the initial state and the maximum and minimum productivity increase, which is due to the difference between inlet and outlet water temperatures, has occurred at 24 o'clock and 22 o'clock, respectively.

Analysis of Pollutants emission

Figure 6 shows the amount of CO emissions in the CHU before and after CHU optimization, by improving the performance of the system at different times of the day and reading the data measured by the CO sensors. Figure 7 depicts the recorded amount of oxygen consumed by the oxygen sensor at different hours of the day.

According to the information in Figure 7, the amount of oxygen consumption in the optimal state is increased by up to 3 times by the inlet air regulation subsystem. This allows the combustion in the system to be more efficient and prevents the release of excess carbon monoxide into the environment. The amount of carbon monoxide emissions at different hours of the day was decreased by 28% compared to the initial state, based on the following equation (Stavropoulos et al. 2005).

$$\overline{X} = \sum \left(\frac{X2-X1}{X1} \right) * 100 \tag{4}$$

In the above relation, x_1 and x_2 are the concentration of CO_2 before and after using the system, and $\overline{X}$ is the mean percentage of change in pollutants in the optimal state.

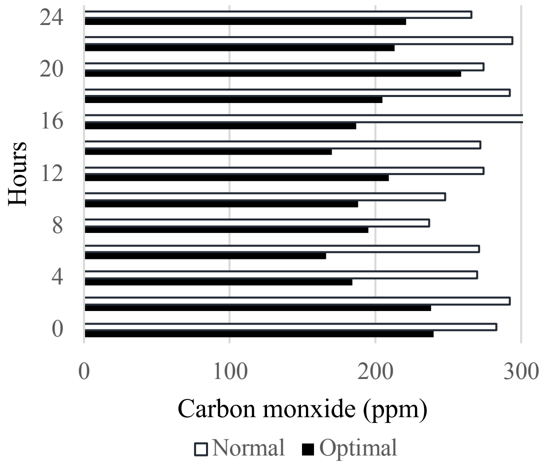

Figure 6. CO emissions in the CHU during a day

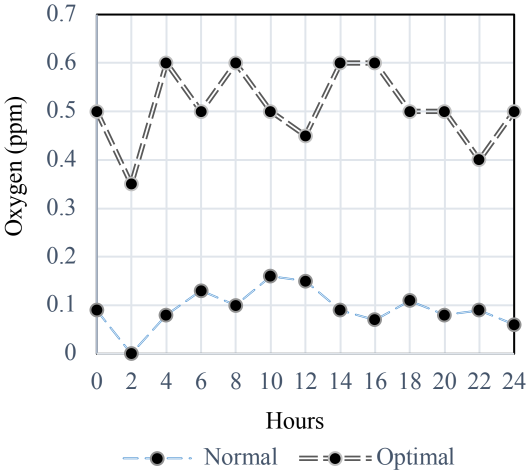

Figure 7. Amount of measured consumed oxygen during a day

Statistical Analysis

For each unit of fuel and 17.67 units of air, the coefficient of lambda equals to one (λ=1). The combustion process of the CHU is only stable if the fuel-air ratio is in the appropriate range. the combustion equation is generally obtained from Equation 5 (Li and Morgans, 2016):

$$C_xH_y + a\,(O_2 + 3.76N_2) \rightarrow x\,CO_2 + (y/2)\,H_2O + 3.76aN_2 \tag{5}$$

$$4/76\ \text{Air} \equiv O_2 + 3.76\ N_2 \tag{6}$$

$$a = x + y/4 \tag{7}$$

$$\lambda = \frac{\mathrm{m\ (fuel)}}{\mathrm{m\ (air)}} \tag{8}$$

Table 2. Amount of CHU Combustion Coefficients

Coefficient	**Calculated Amount**
a	2
x	1
y	4

Optimization in the field of energy and the environment is done simultaneously. In equation 6, It is assumed that air consists only of O_2 and N_2. The ratio of the mole number of O_2 in the reactants to that of fuel is illustrated by equation 7. x and y represent the chemical formula of the fuel used thus, the parameter a could be considered as a constant in the study. the system has been validated 24 hours a day using embedded sensors. Based on the results, lowest emission of carbon monoxide occurred when the amount of oxygen (m_{air}), air consumption by system and λ, is 0.59, 2.8 and 1.12 respectively. In terms of reducing energy consumption, matching to recorded data, the highest energy saving has been made at a temperature of 75.6 degrees Celsius and this temperature occurs in Lambda between 1.1 and 1.15. According to the trend of changes in carbon monoxide emissions with the lambda coefficient in Figure (8), the CO emission rate first had a downward trend, and after reaching a certain limit of the lambda coefficient, it reached its minimum (λ =1.12) and finally took an upward trend. As claimed by the analysis, it can be observed that the inlet air regulation subsystem has the greatest impact in the field of productivity and environment. By and large, comparing the measured parameters before and after the installation of the smart CHU, the amount of energy savings and reduction of carbon monoxide (CO) emissions are 25% and 28%, respectively, compared to the initial state.

Table 3. The amount of the measured parameters in the optimal system

Parameters	**Amount of measured parameter**
CO (ppm)	167
O_2 (ppm)	0.59
T(°C)	75.6
Air	2.8
Lambda (λ)	1.12

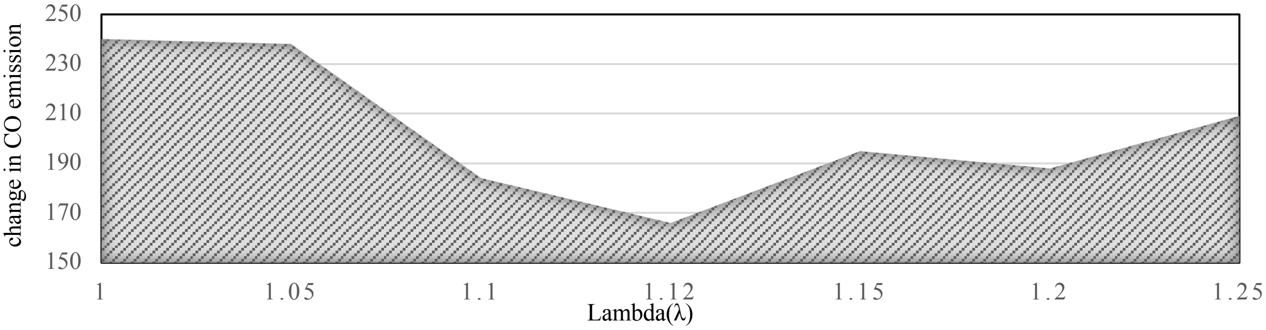

Figure 8. changes in emitted CO (ppm) per Lambda coefficient (λ)

Conclusion

An innovative network was designed in order to create a smart CHU. Moreover, the optimum operating conditions of the smart system were investigated with the aim of optimizing the energy and environmental indicators. Various subsystems were used to control the water temperature of the system, adjust the amount of air required by the burner and regulate the operating time of the burner at different times. The implementation of various sensors improved the energy and environmental indicators of the project so that the rate of reduction of energy consumption and emissions of pollutants were measured 25% and 28%, respectively, in the optimal condition. According to the results, utilization of energy systems with intelligent control should be prioritized in order to strive for sustainable development.

References

Aghamolaei, R., and Ghaani, M. R. (2020). Balancing the impacts of energy efficiency strategies on comfort quality of interior places: Application of optimization algorithms in domestic housing. Journal of Building Engineering, 29, 101174.

Ahmadi, S., Fakehi, A. H., Vakili, A., & Moeini-Aghtaie, M. (2020). An optimization model for the long-term energy planning based on useful energy, economic and environmental pollution reduction in residential sector: A case of Iran. Journal of Building Engineering, 30, 101247.

Amid, S., Aghbashlo, M., Tabatabaei, M., Karimi, K., Nizami, A. S., Rehan, M., et al. (2021). Exergetic, exergoeconomic, and exergoenvironmental aspects of an industrial-scale molasses-based ethanol production plant. Energy Conversion and Management, 227, 113637.

Clitan, I., Muresan, V., Abrudean, M., and Clitan, A. F. (2021). Distributed Heating System for Residential Homes. International Journal of Modeling and Optimization, 11(1).

Dai, B., Qi, H., Dou, W., Liu, S., Zhong, D., Yang, H., et al. (2020). Life cycle energy, emissions and cost evaluation of CO2 air source heat pump system to replace traditional heating methods for residential heating in China: System configurations. Energy Conversion and Management, 218, 112954.

Denev, J. A., Dinkov, I., and Bockhorn, H. (2017). Burner design for an industrial furnace for thermal post-combustion. Energy Procedia, 120, 484-491.

Fazeli, A., Pardakhti, A. R., and Zahed, M. A. (2020). Economic and environmental analysis of a new intelligent central heating system based on optimizing pollutant emissions. New Science and Technology, 2(2), 188-199.

Ferioli, F., and Buckley, S. G. (2006). Measurements of hydrocarbons using laser-induced breakdown spectroscopy. Combustion and Flame, 144(3), 435-447.

He, Y., Du, Y., Guo, H., Yang, J., Sun, Y., Wang, Z., et al. (2021, January). Design and Research of Intelligent Building Control System. In IOP Conference Series: Earth and Environmental Science (Vol. 632, No. 4, p. 042023). IOP Publishing.

Kaczmarczyk, M., Sowiżdżał, A., and Tomaszewska, B. (2020). Energetic and environmental aspects of individual heat generation for sustainable development at a local scale—A case study from Poland. Energies, 13(2), 454.

Khosroshahi, M. K., and Sayadi, M. (2020). Tracking the sources of rebound effect resulting from the efficiency improvement in petrol, diesel, natural gas and electricity consumption; A CGE analysis for Iran. Energy, 197, 117134.

Kotb, A., and Saad, H. (2018). Case study for co and counter swirling domestic burners. Case studies in thermal engineering, 11, 98-104.

Li, J., and Morgans, A. S. (2016). Simplified models for the thermodynamic properties along a combustor and their effect on thermoacoustic instability prediction. Fuel, 184, 735-748.

Li, Y., Ding, Z., Shakerin, M., & Zhang, N. (2020). A multi-objective optimal design method for thermal energy storage systems with PCM: A case study for outdoor swimming pool heating application. Journal of Energy Storage, 29, 101371.

Lu J. Sookoor T. Srinivasan V. Gao G. Holben B. Stankovic J. Field E., and Whitehouse K. (2010). The Smart Thermostat: Using Occupancy Sensors to Save Energy in Homes. SenSys '10 Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems, pp. 211-224.

Mahapatra, R. P., Srikant, S. S., Rao, R. B., and Mohanty, B. (2021). Less Polluted Flue Gases Obtained with Green Technology During Precious Metals Recovery from Unwanted and Discarded Electrical and Electronics Components. In Intelligent Computing and Applications (pp. 715-720). Springer, Singapore.

Moein, M., Shamsaei, S., and Khebri, Z. (2018). A Study of Sensitivity of AERMOD Model in Relation to Physical Factors of Stack. Journal of Research in Environmental Health, 4(3), 185-193.

Nägele, F., Kasper, T., and Girod, B. (2017). Turning up the heat on obsolete thermostats: A simulation-based comparison of intelligent control approaches for residential heating systems. Renewable and Sustainable Energy Reviews, 75, 1254-1268.

Pfeiffer, C., Puchegger, M., Maier, C., Tomaschitz, I. V., Kremsner, T. P., and Gnam, L. (2021). A Case Study of Socially-Accepted Potentials for the Use of End User Flexibility by Home Energy Management Systems. Sustainability, 13(1), 132.

Pichler, M., Wesenauer, F., Jordan, C., Puskas, S., Streibl, B., Winter, F., and Harasek, M. (2021). Design and Simulation of Gas Burner Ejectors. Carbon Resources Conversion.

Ravanshadnia, M., and Jahromi, H. (2018). A Study of the Role of Building Management System in Simultaneous Reduction of Gas and Electricity Consumption in Heating System (Motor House) Office Buildings, 3rd International Conference on New Findings of Civil Architecture and Building Industry, Tehran, University of Tehran

Salimi, M., Faramarzi, D., Hosseinian, S. H., and Gharehpetian, G. B. (2020). Replacement of natural gas with electricity to improve seismic service resilience: An application to domestic energy utilities in Iran. Energy, 200, 117509.

Sarbu, I. (2021). Modelling, Optimisation and Modernisation of Heating Systems. In Advances in Building Services Engineering (pp. 87-208). Springer, Cham.

Shayesteh, A. A., Koohshekan, O., Ghasemi, A., Nemati, M., and Mokhtari, H. (2019). Determination of the ORC-RO system optimum parameters based on 4E analysis; Water–Energy-Environment nexus. Energy Conversion and Management, 183, 772-790.

Shi, C., Ji, C., Wang, S., Yang, J., Ma, Z., and Meng, H. (2020). Potential improvement in combustion behavior of a downsized rotary engine by intake oxygen enrichment. Energy Conversion and Management, 205, 112433.

Shu, J., Fu, J., Liu, J., Wang, S., Yin, Y., Deng, B., and Becker, S. M. (2019). Influences of excess air coefficient on combustion and emission performance of diesel pilot ignition natural gas engine by coupling computational fluid dynamics with reduced chemical kinetic model. Energy Conversion and Management, 187, 283-296.

Sovacool, B. K., and Del Rio, D. D. F. (2020). Smart home technologies in Europe: a critical review of concepts, benefits, risks and policies. Renewable and sustainable energy reviews, 120, 109663.

Sowayan, A. S. (2020). A Comparative Study of Solar Heat Transfer on Roof-Top Water Storage Tank Orientations in Saudi Arabia. Arabian Journal for Science and Engineering, 1-12.

Stavropoulos, P., Michalakou, A., Skevis, G., and Couris, S. (2005). Quantitative local equivalence ratio determination in laminar premixed methane–air flames by laser induced breakdown spectroscopy (LIBS). Chemical Physics Letters, 404(4-6), 309-314.

Wang, G., Tang, P., Li, Y., Xu, J., and Durst, F. (2019). Flame front stability of low calorific fuel gas combustion with preheated air in a porous burner. Energy, 170, 1279-1288.

Zahed, M. A., Pardakhti, A., Mohajeri, L., and Bateni, F. (2010). Wet deposition of hydrocarbons in the city of Tehran-Iran. Air Quality, Atmosphere and Health, 3(2), 77-82.