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EMISSION FROM STATIONARY COMBUSTION SOURCES AS THE DETERMINANT OF ENERGY AIR QUALITY INDEX

The energy air quality index (EAQI) is proposed as an essential criterion for evaluation of air quality in urban areas. EAQI connect the air quality with the structure of energy consumption and with conditions of emission resulting from urban development structure. The method of determination of EQAI connected with stationary combustion sources, along with defining the toxicity equivalents of emitted pollution, has been presented. Classification specifying potential threat to air quality based on the EQAI value is hereby proposed and an example of calculation the index value for a real urban area is shown.

1. INTRODUCTION

Air quality in urban areas is influenced by natural and anthropogenic factors. There exists a possibility for improvement of air quality through shaping the latter. Urban complex is a concentrated recipient of direct energy. It is assumed that for an urban complex, without essential participation of onerous industry and insignificant (in the general balance) value of flow of pollution from outside of the complex, the most essential anthropogenic factor with dynamic influence on air quality is combusting fuels in stationary and mobile sources. An important anthropogenic factor with static influence on the air quality is the urban structure. That is why energetic and ecological analyses of combusting sources and processes, consistent with the principle of sustainable development, should be a vital element of evaluation of air quality. Such approach to the subject, even though it should relate to the whole urban complex, is particularly foreordained to areas characterised by dense residential quarters with a considerable number of individual stationary combustion sources and with admitted combustion engine vehicle traffic.

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2. METHOD OF CALCULATION OF THE ENERGY AIR QUALITY INDEX

2.1. DEFINITION OF THE ENERGY AIR QUALITY INDEX

The energy air quality index (EAQI) is proposed as an essential criterion for evaluation of air quality in an urban area. EAQI is defined by equation connecting air quality with structure of energy consumption and with emission conditions resulting from buildings structure:

$$\text{EAQI} = \text{EAQI}_s + \text{EAQ}_t = E_{sFR}Y_{WH} + E_{tFR}Y_{WC} \quad (1)$$

The coefficients Y_{WH}, Y_{WC} as well as E_{sFR} are defined in Eqs. (6), (10), (12). The coefficients: $\overline{W}_{EEUA}$ (Eq. (7)) and W_{Qd} (Eq. (8)) are adopted as additional criteria. Separate determining of the values of EAQI_s (connected with stationary emission sources) and EAQI_t (connected with traffic emission sources) allows a detailed analysis of factors influencing the air quality.

Based on the results of analyses of six hypothetical urban areas with homogeneous heat supply structure [1–3], a classification of air quality has been proposed (Table 1) for determining potential threat based on the EAQI_s values.

Table 1

Air quality dependent on the EAQI_s value

EAQI_s [mg/(m^2·h)]	Air quality
0–400	1 – very good
401–1500	2 – good
1501–3500	3 – moderate
3501–6000	4 – unhealthy
Above 6000	5 – hazardous

EQAI does not take into account meteorological phenomena as independent of humans. Neither does it take into account the wind direction and its velocity, as in the areas of compact settlement considerable fluctuations of these parameters occur with general velocity reduction. Due to great variances of concentrations of species in the areas behind buildings and in street canyons, the values of E_{sFE} and E_{tFE} are approximated in time and space.

2.2. DETERMINING THE SURFACE AREA STRENGTH FOR A POLLUTANT EMITTED FROM STATIONARY ENERGY LOW SOURCES

Calculation of the E_{sFE} coefficient based on the structure of heat supply and values of W_{Qd} and $\overline{W}_{EEUA}$ comprises the following steps:

1. Determining of the usable energy value Q_{us} for recipients (buildings) along with defining its components and the direct energy value Q_d.

2. Determining of the primary energy value Q_p for these components of Q_{us} for which energy is consumed in the analyzed area (or adjacent areas).

3. Calculation of the factor of the local energy costs of the energy supply structure for the analyzed area according to the dependence:

$$W_{QUA} = \frac{Q_{pUA}}{Q_{us}} \tag{2}$$

3a. If all energy sources (heat and electrical energy both for living and technological needs) are beyond the area or if they have high stack, then:

$$W_{QUA} = 0$$

which means that the urban strength for a pollutant emitted from stationary (point) energy sources

$$E_{sFE} = 0$$

and the only emission from the buildings is anthropogenic heat emission:

$$W_{Qd} > 0$$

3b. In the case of heat supply structure totally based on local heating and (or) boiler houses with short stacks

$$W_{QUA} > 1\ \mathrm{GJ_p/GJ_{us}} \quad \text{and} \quad E_{sFE} > 0$$

generally

$$W_{QUA} = (1.1 - 1.8)\ \mathrm{GJ_p/GJ_{us}}$$

4. Calculation of the value of the emission of i-th species from the analyzed area, for each of n components of Q_{us}, connected with Q_p consumption, and based on defined factors of pollution emission for heat supply structures W_{Ei}

$$E_{iUA} = \sum \left(Q_{us} W_{EiUA} \right)_n \tag{3}$$

where the emission E_{iUA} concerns fuels combusted in sources situated in the analyzed area.

5. Calculation of the equivalent pollution emission rate based on the defined toxicity equivalents k_{Ui} of the analyzed pollution (Sect. 2.4):

$$E_{EUA} = \sum \left(k_{Ui} E_{iUA} \right) \tag{4}$$

6. Calculation of the strength on the surface area F_U for a pollutant i emitted from low stationary energy sources:

$$E_{sFi} = \frac{E_{iUA}}{F_{UA}} \tag{5}$$

and equivalnt emission rate from low stationary energy sources:

$$E_{sFE} = \frac{E_{sEUA}}{F_{UA}} \tag{6}$$

7. Calculation, of the cost coefficient of the ecological energy supply, an average for the analyzed area, which takes into account the equivalent pollution load E_{sEUA}

$$\bar{W}_{EEUA} = \frac{E_{sEUA}}{Q_{us}} \tag{7}$$

8. Calculation of the strength of the urban area for a direct energy consumption Q_d

$$W_{Qd} = \frac{Q_{dUA}}{F_{UA}} \tag{8}$$

2.3. FACTORS TAKING INTO ACCOUNT EMISSION CONDITIONS IN A URBAN STRUCTURE

Complexity of urban systems as well as variety of architectural structures do not allow complete consideration of their influence on substance dispersion, especially in the compact settlement areas. The purpose of introducing the urban factors to EAQI formula is to take into account relative deterioration of the dispersion conditions of emitted pollution, as an outcome of unfavourable technical conditions of emission.

The factor of technical conditions of emission W_H and the street canyon factor W_C were considered particularly important:

1. Factor of technical conditions of emission W_H

$$W_H = \frac{h_s}{H_{Bav}} \tag{9}$$

is the ratio of the emitter height h_s to the average height of residential buildings H_{Bav} in the range of cavity region of a building, that is up to $x = 6H_B$. The value $W_H < 2.0$ (2.5) characterizes low emitters. The W_H factor for an analyzed area is determined as the weighted average with respect to the equivalent emission rate from short stacks.

An average value of Y_{WH} for $W_H = 1$ was determined based on experimental investigations of the author [1]. The value Y_{WH} for $1 < W_H < 2.5$ was determined based on Elterman's dependence [4] with concentrations of emission for low stacks [5, 6]. Dependence of the EAQI$_s$ value on the W_H factor for $1 \le W_H < 2.5$ is given by the following equation:

$$Y_{WH} = \frac{\bar{C}}{C_{WH=2.5}} = 70.9\exp(-1.72W_H) \quad (10)$$

From the equation, the average value of the relative concentration of a species in the area of aerodynamic cavity region may be estimated on the leeward side of building, in a vertically limited space: by leeward wall and surface $x = 5H_B$, and horizontally by surfaces $z = 0.1H_B$ and $z = 0.4H_B$. It has been assumed that it is a space, where people are especially vulnerable to emission from low point sources. The concentration reference point $C_{WH=2.5}$ is the pollutant concentration in the described space when $h_s = 2.5H_B$, i.e. when the stack can be treated as a high one.

2. Street canyon factor W_C:

$$W_C = \frac{H_{Bav}}{W} \quad (11)$$

is the ratio of the average height of buildings delimiting the canyon at the length $L > 2.5H_B$ to the total width of the street W. Depending on its value, three types of flow, perpendicular to the canyon symmetry axis, can be classified [7, 8]:

- skimming flow, for $W_C > 0.9$, is characterized by significant reduction of air exchange inside the canyon,
- wake interference flow, for W_C from 0.30 to 0.9, when alongside stream circulation inside the canyon, cleansing of a part of pollution and transporting it (mainly within the wake region) to adjacent canyons exists,
- isolated roughness flow, for $W_C < 0.30$, when the influence of reciprocal interaction of the canyon walls on the flow interference can be ignored.

The value of W_C factor has a decisive influence on diffusion of pollution from traffic sources but also from adjacent low stationary sources [9, 10].

Based on the investigations of Chang et al. [10] and Sini et al. [11] an equation determining the dependence of the EAQI$_t$ value on W_C has been developed:

$$Y_{WC} = \frac{C}{C_{WC=0.25}} = 0.7\exp(1.3W_C) \quad (12)$$

with the following boundary conditions:

a) for $W_C > 0.9$, $Y_{WK} = 2.5$ – skimming flow,

b) for $0.30 > W_C > 0.9$ – wake interference flow

c) for $W_C < 0.3$, $Y_{WC} = 1.0$ – isolated roughness flow – EAQI$_m$ does not depend on W_C.

Based on Eq. (12) an average value of relative concentration in the region of leeward wall may be estimated, horizontally restricted by planes $z = 0.1H_B$ and $z = 0.4H_B$. Concentration reference point is pollutant concentration in the area under investigation for $H_{Bav} = 0.25W$, i.e. when the influence of a canyon can be neglected.

2.4. TOXICITY EQUIVALENTS OF EMITTED POLLUTANTS IN EVALUATION OF AIR QUALITY

Toxicity equivalents of emitted pollutants k_{Ui}, with regards to the reference substance, are determined for primary pollution taking into account the following factors:

- direct influence of the pollutant on living organisms (especially on humans),
- the range of pollutant interaction also with various components of the environment,
- life span of emitted pollutant,
- physicochemical processes involving the pollutant,
- secondary impacts arising from pollution.

The toxicity equivalents thus differ from the toxicity coefficients which are determined based on ambient air quality standards.

Values defined in the Life Cycle Assessment (LCA) procedures have been accepted as the basis for determining the toxicity equivalents of pollutants emitted from combustion processes. They concern pollution emission and take into account the factors listed. The following categories of environmental impacts have been selected [12]:

- human toxicity potential (HTP),
- photochemical ozone creation potential (POCP).

The following ambient air quality standards were also analyzed:

- permissible concentration of pollutants in EC with regards to human heath [13],
- air quality standards according to NAAQS, US EPA [14],
- air quality standards according to WHO [15],
- air quality standards according to NAAQOs, Canada [16],
- permissible concentration of air pollutants in Poland [17].

Sulphur dioxide SO_2 is (traditionally) assumed the reference. Other references in the LCA procedure are also used (3,4 dichlorobenzene for HTP, ethylene for POCP). This fact was taken into consideration. The method of calculation of toxicity equivalents for analysed pollutants has been presented elsewhere [1].

The value of k_U has also been calculated for CO_2 as pollution which, due to the magnitude of emission from burning processes, influence air quality in areas with restricted diffusion. As the basis for determination of the toxicity equivalent of CO_2 with respect to SO_2, their concentrations in the air of medium sized cities (according to European Standard for Ventilation EN 13779) have been assumed. The determined values of k_{Ui} are given in Table 2.

Table 2

Toxicity equivalents of emitted pollutants k_{Ui}

Pollutant	SO_2	NO_2	CO	PM_{10}	benzene	VOC	CO_2
Equivalent k_{Ui}	1	8.5	0.25	8.3	75	5.0	$1.5 \cdot 10^{-5}$

3. AN EXAMPLE OF DETERMINING OF THE $EAQI_S$ VALUE (CONNECTED WITH STATIONARY EMISSION SOURCES) FOR REAL URBAN AREAS

Based on the stocktaking of stationary emission sources connected with covering of energetic demand and those of heat energy recipients in Jeżyce district in Poznań [18], the $EAQI_s$ was determined taking into consideration low stationary sources for real conditions. The analyzed district of the surface area of F = 4 028 000 m^2 was divided into nine areas of similar urban structure. The analysis comprises the regions:

- with compact settlement (from the beginning of the 20th century) with significant contribution of individual heating (coal, gas, electric energy) and built-in boiler houses (regions: A2A, A2C, A2D),
- with multi-family apartment building development (from various periods of the second half of the 20th century) with built-in boiler houses, either local or supplied by city heating network (regions: A2B, A2E, C11A, C11C),
- with detached single family development with green areas, with built-in boiler houses (regions: C11B, C11D).

Next to the residential buildings there are also administrative, educational, commercial, service and manufacturing facilities in the district. Stacks of individual heaters and boiler houses are short what compared to W_{Hav} values (Table 4).

In accordance with the method presented in Sect. 2.2, energetic and ecologic factors defining $EAQI_{s.}$ have been assigned to individual subareas. The analysis was conducted for average climate conditions of three winter months with the lowest outside temperature (December, January, February), related to 60 min. The results are shown in Figs. 1–3 and Tables 3 and 4.

The analyzed part of the city is diversified both in terms of urban development and structure of energy consumption. Values of the local energy costs $W_{QUA} > 1$ (Fig. 1, Table 4) point to a dominant contribution of individual heating and built-in boiler houses. This pertains to sub areas A2D, C11B, and C11D. Contribution of these sources is also relatively large (W_{QUA} = 0.75) in the sub area A2C. The values of the ecological costs coefficient W_{EEUA} (Table 4) result from properties of fuel, being energy carriers. Large values W_{EEUA} of in the sub areas A2D, C11B, A2C, and C11D indicate a dominant or significant contribution of coal as a fuel.

$EAQI_s$ values which take into account not only energetic and ecological costs but also the concentration of sources, along with urban structure, point to the potential occurrence of given states of air quality. A specific case is the subarea A2D (Fig. 3, Table 4) for which $EAQI_s$ = 4698 mg/(m^2·h), belonging to the „unhealthy class" of air quality (Table 1). The causes for this state, apart from high W_{QUA} and W_{EEUA} coefficients, are compact settlement and small values of W_{Hav} (Table 4). Dense building development and high W_{QUA} and W_{EEUA} coefficients are the reason for classifying subareas A2A and A2C to the third class of air quality (moderate). Sub areas C11B and C11D, despite large W_{QUA} and W_{EEUA} coefficients, are ranked as follows:

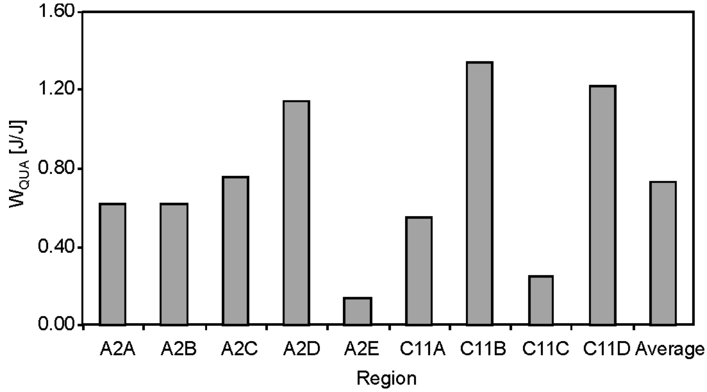

Fig. 1. Factors of energy costs of the energy supply structure W_{QUA} for the sub areas

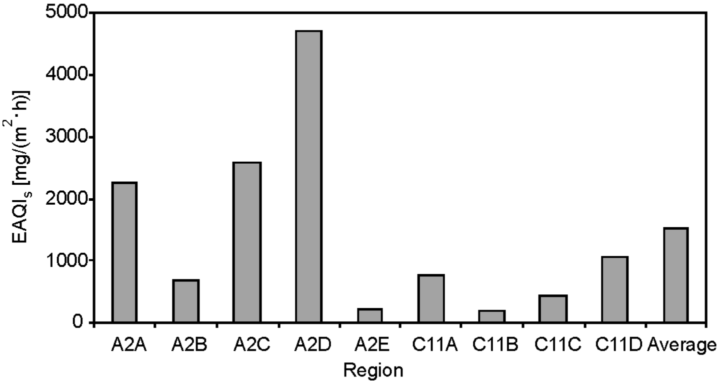

Fig. 2. Values of Energy Air Quality Index $EAQI_s$ for sub areas

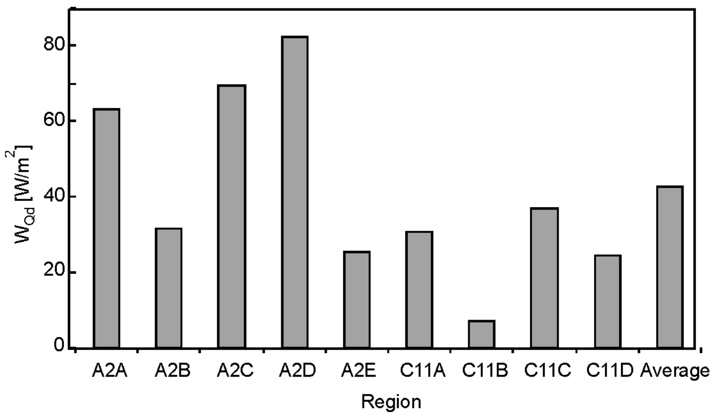

Fig. 3. The sub urban areas strength for direct energy consumption W_{Qd}

Table 3

Pollution emission from stationary energy sources for the analyzed regions

Region	Area F_U [$m^2 \times 10^3$]	E_s						E_{sEUA} [kg/h]
		SO_2 [kg/h]	NO_2 [kg/h]	PM_{10} [kg/h]	CO [kg/h]	VOC [kg/h]	CO_2 [Mg/h]	
A2A	419	10.79	2.08	5.89	10.30	2.44	3.47	92.20
A2B	553	3.11	1.70	1.67	3.16	0.76	2.23	36.09
A2C	425	15.55	2.59	8.53	14.82	3.48	4.57	129.56
A2D	561	29.67	6.03	16.09	28.20	6.76	9.80	255.47
A2E	340	0.77	0.18	0.42	0.75	0.17	0.29	6.86
C11A	274	3.26	0.73	1.80	3.16	0.74	1.18	28.91
C11B	375	1.60	0.42	0.88	1.56	0.36	0.64	14.66
C11C	535	2.59	0.45	1.43	2.57	0.59	0.78	21.70
C11D	547	5.01	2.14	2.80	5.14	1.17	2.99	53.57
Total	4028	72.33	16.32	39.52	69.66	16.48	25.96	639.02

Table 4

Values characterizing $EAQI_s$ for the analyzed regions

Region	$Q_{us\text{-}wint}$ [GJ/h].	W_{QUA} [GJ_p/GJ_{us}]	E_{sFE} [mg/($m^2 \cdot h$)]	W_{EEUA} [g/GJ_{us}]	W_{Qd} [W/m^2]	W_{Hav} [m/m]	Y_{WH}	$EAQI_s$ [mg/m^2h]	Air quality
A2A	79.1	0.62	219.88	1105.8	63.2	1.09	10.86	2387.3	3
A2B	56.5	0.62	65.23	615.7	31.5	1.07	11.26	734.4	2
A2C	83.6	0.75	305.21	1469.0	69.7	1.20	8.93	2725.1	3
A2D	121.3	1.14	455.63	1999.7	82.3	1.09	10.86	4947.1	4
A2E	30.0	0.14	20.20	217.3	25.6	1.07	11.26	227.4	1
C11A	30.9	0.55	105.38	889.5	30.7	1.30	7.64	805.5	2
C11B	7.1	1.34	39.11	1970.4	7.2	1.50	5.37	210.2	1
C11C	71.9	0.25	40.58	286.1	36.7	1.07	11.26	456.9	2
C11D	38.2	1.22	98.02	1343.9	24.2	1.07	11.26	1103.4	2
Average	518.5[a)]	0.73	158.65	1171.5	42.8	1.13	10.14	1608.8	3

[a]The value constitutes a sum

C11B – very good (large W_{Hav} value) and C11D – good, mainly thanks to detached building development and dispersion of emission sources. Values shown in Fig. 3 and Table 4 point to subareas A2D, A2C and A2A as to significant (W_{Qd} > 65 W/m^2) urban heat island (UHI) generation sources, which can influence periodical circulation of air masses linked with pollution transfer.

4. CONCLUSIONS

The analyses of the EAQI values and additional criteria (W_{QUA}, W_{EEUA}, W_{Qd} coefficients) not only indicate the areas with deteriorated air quality but also identify the reasons for this state, being the basis for the recovery program. The method for determination of EAQI, assumes isolating a city or its area from the whole energetic system. It gives a rationale for evaluation of the air quality inside a fixed balance protection, based on the analysis of an existing urban and energy structure. It also allows programming of the modernization activities of the structure aiming to improve air quality in the discussed area.

Energy air quality index is determined mostly for isolated areas within an agglomeration, with densely developed areas with stationary and mobile emission sources. It can also be calculated for other areas and as a mean value for a city. Determination of the EAQI factor may be vital for areas with existing continuous monitoring system of pollution concentrations, satisfying the conditions of measurement background. This may allow one to calculate relative $\mathrm{EAQI}_{UA}/\mathrm{EAQI}_{Bac}$ indexes and to determin correlations between used option of air quality index (AQI) and EAQI, suitable for a urban complex with specific geographical and climatic location.

LIST OF SYMBOLS

EAQI – energy air quality index, mg/(m^2·h)
EAQI_s – energy air quality index for stationary emissions sources, mg/(m^2·h)
EAQI_t – energy air quality index for traffic exhaust emissions, mg/(m^2·h)
E_{iUA} – emission rate of i-th pollution from the combustion sources in analyzed area UA, mg/s
E_{EUA} – equivalent emission rate from combustion sources in area UA, mg/s
E_s – mass emission rate of a pollutant, mg/s
E_{sFi} – strength for a pollutant i emitted from low sources on the surface area F, mass low emission rate per unit area, mg/(m^2·s) or mg/(m^2·h)
E_{tFE} – strength for an equivalent pollutant emitted from traffic sources on the surface area F, mg/(m^2·h) or g/(m^2·year)
E_{sFE} – strength for an equivalent pollutant emitted from stationary (point) energy sources on the sur face area F, mg/(m^2·h) or g/(m^2·year)
F_U – surface area UA, m^2
H_B – building height, m
h_s – geometric stack height (from the ground level), m
k_{Ui} – emissive toxicity equivalent of i-th pollution in relation to SO_2
Q_d – direct energy – total energy used in the building, J
Q_{pUA} – primary energy of fuels combusted in low sources, in the analyzed surface, J
Q_{us} – usable energy – total energy consumed by a building, J
W_{Ei} – emission rate of i-th pollution per unit usable energy, g/GJ$_{\mathrm{us}}$
$\bar{W}_{EEUA}$ – average area emission rate per unit usable energy (ecological costs coefficient for energy supply), g/GJ$_{\mathrm{us}}$
W_H – factor of technical conditions of emission, m/m
W_C – street canyon factor, m/m
W_{Qd} – urban area strength for direct energy consumption as the determinant for generating Urban Heat Island, W/m^2
W_{QUA} – factor of energy costs for the energy supply structure, J/J

Y_{WH} – coefficient taking into account technical conditions W_H of emission
Y_{WC} – coefficient taking into account the street canyon factor W_C

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