IMPLEMENTATION OF A MODEL FOR A WIND TURBINE SYSTEM IN ENERGYPLUS

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ABSTRACT

A model for computing electricity production of wind energy conversion systems has developed and added to a building energy simulation program (EnergyPlus). This paper describes an environmental analysis of local wind conditions and the simulation algorithms for modelling horizontal axis as well as vertical axis wind turbine systems. To verify the capabilities of the model, results predicted by the model with different type and scale wind turbine systems were validated against the power curves manufactures provide. Energy performance and environmental impact in three different buildings in two different locations have been analyzed, and the results are discussed. Wind turbine systems have the potential to impact electric energy consumption and costs as well as the environment, producing electricity and reducing the peak electric demand in buildings with no pollution.

INTRODUCTION

Wind power is one of the fatest growing sources of renewable power generation that produces electricity with no fuel consumption and no air pollution. To date, there have been many buildings that have implemented wind energy conversion systems even though large wind farms have been more prevalent due to the dependence of surrounding wind condition. However, there has been no systematic method for looking at wind turbines in conjunction with building energy analysis. A whole building energy simulation such as EnergyPlus needs to have ability to model these systems so that they are able to be considered as a potential design solution.

The model discussed in this paper factors in not only the physical configuration of the wind turbine such as the rotor speed, the height, and the number of blades but also the overall performance of the wind turbine through the tip speed ratio and the power coefficient. Almost all the other models in energy simulation tools do not incorporate these vital parameters. Instead, existing models use the average power production, which causes inaccuracies in the computational predictions under different wind conditions since almost all data for the power curves in the literature are obtained at a specific location. In addition, the model includes an algorithm that predicts local wind speeds at the particular height of the system. Accurate prediction of wind data is critical because the wind speed is the single most important factor affecting the power production. To obtain accurate wind data, the model adjusts the typical meteorological year (TMY) wind data and factors differences between the TMY wind data and the local wind data at the location where the wind turbine system is installed. As a result, the model improves wind speed predictions and thus better models wind energy conversion systems.

This paper will discuss the development of the model to predict the electrical power production from wind energy conversion systems. An algorithm for analyzing local wind speed and calculating the power production will also be discussed. In addition, the model validation against empirial data published in the manufacturer's literature will be provided in order to verify the capability of the model as implemented in EnergyPlus. An analysis of the potential energy saving of these systems in various buildings and locations will also be presented.

MODEL DESCRIPTION

Overview

The wind turbine model in EnergyPlus is intended to estimate the production of electric power for both horizontal and vertical axis wind turbine systems. Due to the cubic relationship between the wind speed and the power production of wind energy conversion systems, the performance of these systems is highly dependent on local wind conditions. The model starts with wind data obtained from a standard TMY weather file which is selected for the location where the building is located. To minimize uncertainties due to inaccurate wind data, the model estimates the air density and wind speed at the particular height of the system and then factors differences between the wind speed from the TMY weather data and the local wind speed. EnergyPlus also has functions that calculate wind speed at a given altitude and terrain as described in ASHRAE Handbooks, so that the wind speed is altered based on the height and local terrain. These wind power conversion systems are typically installed at a height where the airflow is not disturbed by the building geometry itself. The model thus does not include adjustments due to building geometry. The model also requires inputs for both an annual average wind speed that represents a more accurate wind profile at the location than TMY wind data and the height where this annual average wind speed was measured to adjust the wind speed data obtained from the TMY file.

The model calculates the power production by both horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) from generic mathematical equations. It includes two different types of dynamic power control, fixed speed fixed pitch (FSFP) and variable speed fixed pitch (VSFP). It does not include an algorithm for modeling pitch control such as fixed speed variable pitch (FSVP) and variable speed variable pitch (VSVP). If the control type of the wind turbine system is either FSVP or VSVP, the control type of VSFP will be assumed. The model assumes constant power generation at the rated power and the rated wind speed when the ambient wind speed is between the rated wind speed and cut out wind speed. Models for the individual subsystems, such as rotors, shafts, generators, and inverters, of wind energy conversion systems are available. However, the model does not attempt to model individual subsystems due to computational convergence, time, and usability. Instead, the total system efficiency handles any conversion losses during the DC-AC-DC conversion processes and delivery losses to buildings. Since the biggest uncertainties are likely to be inaccurate TMY wind data, these assumptions would be appropriate to the precision of the model within building-integrated systems in that the control of these systems attempts to achieve the maximum power production and to protect against damage under severe conditions.

The wind turbine system is modeled in EnergyPlus as a generation component that produces electricity and delivers it directly to buildings. Wind turbine components are executed at the beginning of each time step called by the HVAC manager, so that the electric load for the whole building will be corrected with the result of the electricity production by these systems. The model calculates electricity production from HAWTs and VAWTs by using generic mathematical equations. The model then passes the electricity estimated to the electric load center in EnergyPlus at each HVAC system time step. The electric load center then determines the whole building electrical demand, deducting the power output by wind turbine system along with power productions by any other operating generators from the total electrical demand of the building. Any electric production from wind turbine generators that exceeds the building electrical demand is either sold or stored as specified by the user.

Simulation algorithm

The wind turbine model calculates the local wind speed in order to determine accurate power production of the system. During the model initialization, the program reads the annual average wind speed from a statistical weather file if the user attaches a weather data file. This annual average wind speed is then adjusted to a wind speed at the height at which the local annual average wind speed is measured and factored into the model using the following equation:

$$V_{L_{TMY}} = V_{Avg_{Annu}} \left(\frac{\delta_{met}}{H_{met}} \right)^{a_{met}} \left(\frac{H}{\delta} \right)^{a} \quad (1)$$

$$F_V = \frac{V_{L_{TMY}}}{V_L} \quad (2)$$

Note that the wind speed factor F_v of 1.0 is assigned, if the user does not input the local wind conditions, or no weather data file is attached to the simulation.

The model adjusts the local air density as well as TMY wind speed at the height of the system by using the following EnergyPlus built-in and psychrometric functions:

$$T_L = OutDryBulbTempAt(Z) \quad (3)$$

$$P_L = OutBaroPressAt(Z) \quad (4)$$

$$\omega_L = PsyWFnTdbTwbPb(T_L, T_{wb}, P_L) \quad (5)$$

$$\rho_L = PsyRhoAirFnPbTdbW(P_L, T_L, \omega_L) \quad (6)$$

$$V_Z = WindSpeedAt(Z) \quad (7)$$

The local wind speed at the height (V_L) of the wind turbine is thus determined as:

$$V_L = \frac{V_Z}{F_v} \quad (8)$$

The tip speed ratio (TSR) of the rotor can then be expressed as:

$$\lambda = \frac{\omega R}{V_L} \quad (9)$$

- Horizontal Axis Wind Turbine (HAWT)

Once the local wind speed and air density are determined, the model calculates the electrical power production of the wind turbine system according to the rotor type. For HAWT systems, two different approximations are available. For more accurate predictions, the model uses an analytical approximation (Siegfried Heier, 2006) when the user inputs all six empirical coefficient parameters C_1 through C_6. The equations that define the analytical approximation are:

$$C_p = C_1(\frac{C_2}{\lambda_i} - C_3\theta - C_4\theta^x - C_5)e^{-\frac{C_6(\lambda,\theta)}{\lambda_i}} \quad (10)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \quad (11)$$

The model alters the rotor speed at the maximum TSR at each time step when the predicted TSR is greater than the maximum. Similarly, the predicted power coefficient is also set to the maximum, if the maximum is smaller than the predicted. Assuming the maximum for the rotor angle, i.e. zero, the power production of the wind turbine can be obtained from the kinetic equation (Siegfried Heier, 2006):

$$P_W = \frac{1}{2}\rho_L A_R V^3 C_p(\lambda,\theta) \quad (12)$$

The model assumes the simple approximation, if any of all six empirical power coefficient parameters are unavailable. The power production of wind turbine is then directly determined from the equation (12) above using the user inputs as well as the air density and local wind speed.

Here, the model defines the wind turbine power production as rated power output at the rated wind speed, if either the predicted power production or local wind speed is greater than the rated power or rated wind speed, respectively. The power coefficient in this particular case is thus recalculated as:

$$C_p = \frac{P_W}{0.5\rho_L A V_L^3} \quad (13)$$

The overall power production of the HAWT system, which includes conversion loss and delivery loss is thus:

$$P = \eta P_W \quad (14)$$

- Vertical Axis Wind Turbine (VAWT)

The model employs general mathematical expressions for the aerodynamic analysis of straight-bladed Darrieus-type VAWTs to predict the power production of VAWTs. If the predicted TSR at the time step is greater than the maximum, the model estimates the actual rotor speed from the following expression:

$$\omega R = \lambda V_{Local} \quad (15)$$

Assuming quasi-steady state, the induced wind speed incident on the rotor and the non-dimensional angle of attack (α) with no consideration of blade pitch are defined as:

$$V_a = \frac{2}{3}V_{Local} \quad (16)$$

$$\alpha = \tan^{-1}\left[\frac{\sin\theta}{(\omega R/V_L)/(V_a/V_L) + \cos\theta}\right] \quad (17)$$

The chordal velocity (V_c), normal velocity (V_n), and relative flow velocity (W) as shown in Figure 1 can be defined as following expressions:

$$V_c = \omega R + V_a\cos\theta \quad (18)$$

$$V_n = V_a\sin\theta \quad (19)$$

$$W = \sqrt{V_c^2 + V_n^2} \quad (20)$$

The tangential and normal force coefficients are expressed as:

$$C_t = C_l \sin\alpha + C_d \cos\alpha \quad (21)$$

$$C_n = C_l \cos\alpha + C_d \sin\alpha \quad (22)$$

The net tangential and normal forces are obtained from the following expressions:

$$F_t = C_t \frac{1}{2} \rho_{Local} A_c W^2 \quad (23)$$

$$F_n = C_n \frac{1}{2} \rho_{Local} A_c W^2 \quad (24)$$

The average tangential force on a single blade can be defined as:

$$F_{ta} = \frac{1}{2\pi} \int_0^{2\pi} F_t(\theta) d\theta \quad (25)$$

Substituting the equation for F_t and arranging F_{ta} on azimuth angle θ assumed as zero, equation (25) can be written as:

$$F_{ta} = \frac{1}{4\pi} C_t \rho_{Local} A_c \left(\int_0^{2\pi} (\omega R)^2 + \int_0^{2\pi} V_a^2 \right) \quad (26)$$

The expression of the total torque for the number of blades is defined as:

$$Q = N F_{ta} \quad (27)$$

The power production of wind turbine is thus:

$$P_W = Q\omega \quad (28)$$

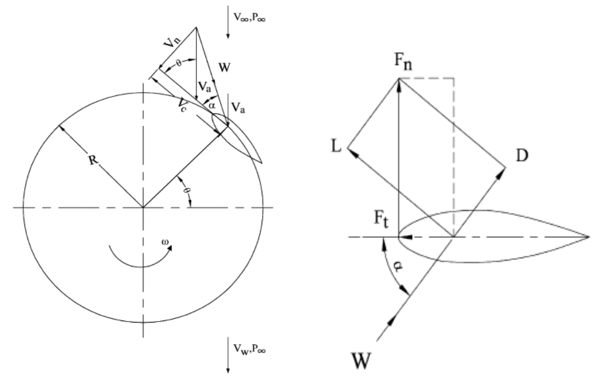

Figure 1 Flow and force diagram of a blade airfoil (Adapted from Mazharul Islam et al., 2008)

MODEL VALIDATION

As decribed in the previous sections, small variations in the wind speed can significantly change the overall power production of the wind energy conversion system. The power curve published in the manufacturers' literature is typically measured in a specific area thus a particular wind condition. Due to the dependency of surrounding environmetal conditions, uncertainties in computational predictions of the power production of wind turbine systesms are always involved. These uncertainties include experimental errors, power curve reading errors, using mean values, incorrect measurement of wind profile and physical dimension of the system, power control types, and calculation algorithm within the model. Particularly, the TMY wind data typically attached to the simulation is the largest source of the uncertainties. The validation of the model is thus difficult.

The model implemented in EnergyPlus is primarily intended to predict the performance of medium or small-scale HAWTs as well as VAWTs that are either grid-connected or building-connected wind energy conversion systems. It also models large-scale wind turbine systems with the electricity capacity of above 1000kW. To validate the model, a 55kW medium-scale HAWT, a 100kW large-scale HAWT, a 11kW small-scale H-rotor type VAWT, and a 4kW small-scale curved-blade, which is a modified curved-blade Darrieus-type VAWT, were chosen for testing with the model in EnergyPlus. The characteristics of each wind turbine system such as physical configuration, operational condition, and rated information of the four different wind turbine systems are indicated in Table 1. In addition, HAWT simulations were run using the simple approximation algorithm for the medium-scale HAWT and the analytical approximation with EnergyPlus default values of the six empirical coefficients for the large-scale HAWT.

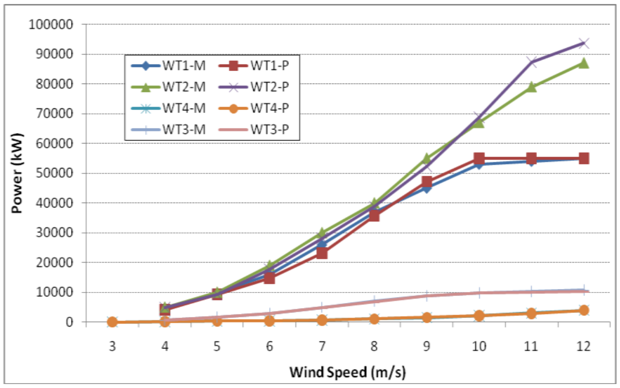

Figure 2 Variations of measured and predicted power output (P: predicted and M:measured)

The medium-scale HAWT (WT1) indicated a maximum difference percentage of 11.1% in power production between the measured output obtained from the power curves in the manufacturers literature, and predictions by the model at the wind speed of 7m/s, and a minimum of 0.53% at 4m/s. Relatively big differences appeared between 5m/s and 7m/s as 4.6% at 5m/s and 8.1% at 6m/s, while about 3.7% differences appeared between 8m/s and 11m/s. The maximum difference of the large-scale HAWT (WT2) was 10.5% at 11m/s, and the differences at the high wind speed ranges between 11m/s and 14m/s were greater than the low wind speed ranges. The maximum and minimum differences in the other wind speed ranges between 4m/s and 10m/s were 2.1% at 4m/s to 6.9% at 6m/s. In the small scale H-rotor type VAWT (WT3), the biggest difference of 9.5% appeared at 4m/s, and the minimum was 0.01% at 5m/s. The differences of the other wind speed ranges were 5.5% at 12m/s to 0.5% at 10m/s. The small-scale curved-blade VAWT (WT4) showed the maximum difference of 10.25% at 4m/s. The difference was also relatively big at 5m/s as 10.1%. However, the other ranges between 6m/s and 12m/s showed good agreements with the power curve as low as 0.1% at 7m/s and as high as 2.9% at 11m/s.

In the WT1 and WT2 cases, the differences between 5m/s and 7m/s were larger than the other wind speed ranges. The VAWTs cases showed larger differences which appeared between 4m/s and 5m/s while the other wind speed ranges were in good aggrements with the measured data. Note that the differences at the low wind speed may decrease if accurate empirical power coefficients of the rotors for HAWTs, and drag or lift coefficients of the blades for VAWTs are avaialble. With consideration of the frequency of the wind speed range and compensation of the under- or over-estimations throughout entire operational wind speed ranges, the computational predictions of the model for the performance of different types as well as scales of wind energy conversion systems were well agreed with the power curves published in the manufacture's literature.

CASE STUDY DESCRIPTION

Case studies were designed to estimate the potential energy savings in electricity and environmental impact due to the integration of wind energy conversion systems in three different types of buildings placed at different locations. Simulations were run in a pre-release version of EnergyPlus version 5.0 for an entire year with Chicago, IL TMY3 weather data. A time step of 15 minutes was chosen for all simulations. Three different bechmark models were chosen. The elementary school bechmark model is a single story 6,871 m^2 area building having 25 zones. Packaged VAV systems with hot water reheat coils are the main HVAC systems. Internal heat gains vary with the purpose of the spaces. The medium office benchmark model is a three story 4,932 m^2 rectangular building that has 15 controlled zones, and each floor is identical. The strip mall benchmark model is a single story 2,090 m^2 building divided into 10 zones. Packaged Single Zone Air Conditioner (PSZ-AC) and gas furnace are the main cooling and heating system.

Multiple small-scale vertical axis wind turbine systems with the capacity of 4kW and 11kW validated against the power curves were connected to the three different example buildings. Two different locations (city and suburban) were speficied for the simulations of each type of building. That is, each type of building was simulated in a city area as well as in a suburban area so that the wind power potential according to the locations can be described. In the elementary school, five 4kW wind turbine systems and five 11kW wind turbine systems were connected. The strip mall and medium office were specified with five 11kW wind turbine systems and three 11kW wind turbine systems, respectively. In fact, since the electricity rates and peak hours vary with location, season, and fuel types, all inputs required for the economic analysis were set to defaults and thus estimated automatically by EnergyPlus. For a more accurate analysis of the wind conditions at each location, the local annual average wind speed of 6.4m/s and the measurement height of the local wind speed of 50m were utilized. In addition, for the investigation of the environmental benefits, all the simulations specify environmental impact factors as carbon dioxide (CO2) emission factor for electricity of 341.7 g/MJ, and total carbon equivalent emission factors from CO2, nitrogen oxides (NOx), and methane (CH4) were set to 0.2727 kg/kg, 80.7272kg/kg, and 6.2727kg/kg, respectively.

DISCUSSION

Energy performance

To analyze the energy performance of the three different buildings in different locations using wind turbines, various parameters were predicted such as total electricity end uses, wind power productions, peak electricity demands, total demands, energy charges, and percent reductions by wind turbine systems as shown in Table 2. The total electricity end uses of the elementary school in a city and in a suburban were 3632.29GJ and 3605.22GJ, and the total 10 small-scale VAWTs used by the building provided 196.63GJ in the city and 305.9GJ in the suburbs. Wind power generated by the wind turbine systems connected to the elementary school in the suburbs produced 55% more electricity than in the city. The wind turbine systems supplied about 5.41% and 8.48% of the total electricity end uses in this elementary school building. In terms of the peak electricity demand, these systems reduced the peak electricity demand by 2.79% in the city and 3.78% in the suburbs. As a result, the total electricity demands and the electricity energy charges estimated by using automatic cost analysis in EnergyPlus decreased about 5.49% in the city and 9.1% in the suburbs. In addition, due to the differences in peak electricity between the city and suburban, the total electricity end use in the city was about 0.74% greater than that in the suburbs.

Similarly, a larger total electricity end use of 971.91GJ in the strip mall building in the city was estimated in comparison to 960.34GJ in the suburbs. Due to relatively lower energy end use than the other two types of building, electric power generated by the five 11kW VAWTs connected to the strip mall yielded 17.95% electricity of the total electricity end use in the city and 27.41% of the total in the suburbs. The peak load reduction rates, 2.29% in the city and 3.47% in the suburbs, significantly decreased the total electricity energy charges estimation by 20.3% in the city and 34.68% in the suburbs, which is predictd by the automatic economic analysis function in EnergyPlus. The medium office building tied with the three 11kW wind turbine systems also had similar conditions to the other two buildings. The total electricity end use of 1719.96GJ in the suburban was about 0.24% less than that in the city. The wind turbine systems in the suburbs generated about 51% more electricity than the other. The reduction rates of the peak demand were 2.57% in the city and 3.53% in the suburbs, and these reductions contributed to the reductions in the total electricity energy charges of 6.22% in the city and 9.73% in the suburbs.

Environmental impact

Another advantage of a wind energy conversion systems is the environmental benefits. The reduction rates of CO2 emission and carbon equivalent emissions from three greenhouse gases such as CO2, Nox, and CH4 indicated the environmental-effectiveness of these wind energy conversion systems. In the elementary school, the total CO2 emission rates of 1414238kg in the city and 1346952kg in the suburbs were observed as shown in Table 3. The carbon equivalent emissions were predicted to be 597807kg in the city and 568688kg in the suburbs. As a result, integration of wind turbine systems to the elementary school reduced the total emission rates by 4.87% in the city, and this reduction rate increased to 7.62% in the suburbs. Similarly, the emission rates of the strip mall in the city were greater than in the suburbs, and the reduction rates of 14.01% estimated in the city increased to 20.51% in the suburbs. The medium office buildng using the wind turbine systems in the city reduced the total carbon equivalent emissions by 5.66%, and this reduction increased to 8.49% in the building in the suburbs. Note that the reduction shown in the table 3 below is the percent reduction of carbon equivalent emissions, and the percent reductions between carbon equivalent and CO2 emissions were very close each other.

CONCLUSION

A model for modeling wind energy conversion systems has been developed and implemented in EnergyPlus. The electric power productions predicted by the model from four different types of wind turbine systems were validated with the manufacture-supplied power curves. Case studies have been performed to evaluate the energy performance as well as the enviroinmental impact of the wind turbine systems for various types of building and locations. These components in suburban area produce about 50% more electricity than those in city. They are able to achieve more electricity cost savings than the power productions that the systems actually produce, decreasing peak electricity demand. The power production rates as well as pollutatnts emission rates of these systems in the suburbs was significantly increases in comparion with the city area. In conclusion, the model is capable of predicting the performances of various wind turbine systems regardless of scale, rotor type, and power control type, and the performance of these systems is better in the suburbs due to the higher availabilities of the wind.

NOMENCLATURE

A_R : swept area (m^2)
A_c : blade chord area of VAWTs (m^2)
a : site wind exponent, 0.22
a_{met} : wind exponent, 0.14

C_d : blade drag coefficient
C_l : blade lift coefficient
C_n : normal force coefficient
C_t : tangential force coefficient
$C_{1\text{-}6}$: empirical power coefficient parameters
F_n : normal force in radial direction (J)
F_t : tnagential force (J)
F_{ta} : average tangential force (J)
F_v : wind speed factor
H : height of local wind speed measurement (m)
H_{met} : height of TMY wind data measurement (m)
N : number of blades
P : overall power production (W)
P_L : local static air pressure (Pa)
P_w : wind turbine power production (W)
Q : overall torque (J)
R : rotor radius (W)
T_L : local air temperature (℃)
$V_{avg,annu}$: annual average TMY wind speed (m/s)
V_L : local wind speed at the roter height (m/s)
$V_{L,TMY}$: local TMY wind speed (m/s)
V_c : chordal velocity component (m/s)
V_n : normal velocity component (m/s)
V_z : adjusted TMY wind speed (m/s)
x : exponent, 1.5
λ : tip speed ratio, TSR
λ : tip speed ratio at the ith pitch
δ_{met} : wind boundary layer thickness
η : wind turine system efficiency

ACKNOWLEDGMENT

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under award number DE-FC26-06NT42768.

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Table 1 Main input parameters for the model validation

Performance	WT1	WT2	WT3	WT4
Type	HAWT	HAWT	VAWT (Curved)	VAWT (H-Rotor)
Height (m)	30.5	37	13.6	7.6
Number of Blades	3	3	3	5
Power Control	FSVP	VSVP	FSFP	FSFP
Rated Power (kW)	55	100	11	4
Rated Rotor Speed (rev/min)	41	59	130	160
Rated Speed (m/s)	10	14.5	11	12
Cut-in Speed (m/s)	3.5	3.5	4.0	3.0
Cut-out Speed (m/s)	25	25	25	25

Table 2 Energy performance in electricity of each type of buildings

Case	Electricity (GJ)	Wind Power (GJ)	Percent Electricity (%)	Total Demand (J)	Peak Demand (J)	Energy Charge ($)	Percent Peak Demand (%)	Percent Energy Charge (%)
E-C	3632.39	0		1009078	3455.55	46726.28		
E-C-WT		196.63	5.41	954454.4	3361.84	44293.32	2.79	5.49
E-S	3605.22	0		1001530	3415.84	46382.64		
E-S-WT		305.9	8.48	916551.3	3291.56	42513.63	3.78	9.10
M-C	971.91	0		269996	867.68	13076.61		
M-C-WT		174.44	17.95	221535.5	848.29	10870.25	2.29	20.30
M-S	960.34	0		266781.5	854.25	12930.26		
M-S-WT		263.24	27.41	193652.9	825.58	9600.79	3.47	34.68
O-C	1724.14	0		478965.1	1724.3	22590.77		
O-C-WT		104.67	6.07	449888.8	1681.15	21266.95	2.57	6.22
O-S	1719.96	0		477804.8	1720.21	22537.94		
O-S-WT		157.95	9.18	433927.6	1661.61	20540.25	3.53	9.73

Note: E - elemenatary school, M - mall, O - office, C – city, S – suburban, and WT - wind turbine

Table 3 Total gas emission and carbon equivalent emission rates from the building facilities

Case	CO2 (kg)	Carbon Equiv. (kg)	Reduction Rate (%)
E-C	1414238.88	597807.56	4.87
E-C-WT	1346952.98	568688.36	
E-S	1406164.25	594236.97	7.62
E-S-WT	1301702.38	548961.90	
M-C	385857.58	162542.77	14.01
M-C-WT	333315.4	139770.33	
M-S	382701.5	161105.22	20.51
M-S-WT	306450.5	128057.11	
O-C	633935.1	270844.71	5.66
O-C-WT	598585.8	255523.88	
O-S	633040.7	270410.55	8.49
O-S-WT	580067.4	247451.26	

Note: E - elemenatary school, M - mall, O - office, C – city, S – suburban, and WT - wind turbine