Effects of Improved Energy Performance of Buildings on Air Quality over the Greater Athens Area

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Abstract. Air pollution episodes are common in the Greater Athens Area (GAA) because of its pollutant source concentration, complex topography, and regional meteorology. For the GAA, over 90% of the existing building stock is classified below energy class B, so the effects of upgrades on energy savings are obvious and have been widely discussed. The present study focuses on the potential effects that a realistic level of implementation of the EPBD will have on the air quality over the GAA. Three renovation scenarios were examined with an implementation rate of 20%. Numerical simulation of primary pollutants’ dispersion over the GAA was performed using the CALPUFF modelling system. Ground level concentrations of SO\textsubscript{2}, NO\textsubscript{x}, CO and PM10 were calculated, taking into account pollutant releases from major roads and highways, passenger ports and cargo transport, residential heating installations and major industrial installations. The required source data was taken from National and European statistics, demographics and local topography while the Weather Research and Forecasting (WRF) model was implemented for the required high resolution meteorological field data. The modelling system was first successfully validated by comparison with available measurements of pollutant concentrations and then applied to case studies of EPBD implementation. Reductions up to ~6% were found in the ground level concentrations of major pollutants.

1. Introduction
Around one quarter of Europeans currently living in urban areas are exposed to air pollutant levels exceeding some EU air quality standards [1]. These urban areas are often subject to ongoing development projects as well as conforming to new legislation related to energy efficiency, such as the Energy Performance of Buildings Directive [2], whose effect on air quality is multi-parametric and difficult to evaluate [3]. Many efforts have been made to study the conditions which can cause an air pollution episode as well as air pollutants’ accumulation and long-term exposure [4]. Air quality dispersion models have been widely applied to provide for a deterministic relationship between emissions and concentrations of pollutants, considering meteorological conditions and topography [5]. Modeling air quality under different scenarios can lead to a better understanding of the observed concentrations and an evaluation of future environmental strategies [6], [7].

The Greater Athens Area (GAA) is an area with complex topography, located near an irregular coastline and surrounded by high mountains to the east, west and north. The Saronic gulf is situated in the south, the industrial area of Thrassion Plain to the west and Mesogia Plain to east. It is the biggest and most populated area in Greece, hosting 3.8 million people [8] in an area of approximately 450 km\textsuperscript{2} with a population density up to 17,000 people per km\textsuperscript{2}. The climate is Mediterranean with wet mild winters and hot dry summers. Daily mean temperatures range from 10°C in the winter to 26°C in the summer and the dominating winds blow from NE and SW, directions which coincide with the geographical axis of the basin [9]. The combination of topography, meteorology (temperature inversions and sea breeze) and anthropogenic activities such as traffic, residential heating, shipping and industrial emissions [10] has caused air pollution episodes in the past [11],[12]. Like most metropolitan areas, the GAA is facing challenging air pollution problems since air quality limits are often exceeded, especially during the summer [12] even though the ongoing economic recession has...
influenced pollution sources leading to lower concentrations of pollutants [13]. The EPBD may potentially contribute positively but it is difficult to quantify.

The EPA recommends the use of CALPUFF modelling system [14] for applications on long range transport of pollutants (distances > 50 km) or over complex terrain in order to account for the spatial and temporal variability of flow fields. CALPUFF is a non-steady state Lagrangian puff model designed to estimate transport, chemical transformation and removal of pollutants while considering time- and space-varying meteorological conditions [15]. There is a growing trend in combining Numerical Weather Prediction (NWP) models with dispersion models in order to better describe regional winds and sea breeze [16]. In the present study, concentrations of primary pollutants are estimated using CALPUFF coupled with the Weather Research and Forecasting (WRF) NWP model. Emissions and concentrations of relevant pollutants from road transport, residential heating, navigation and industrial facilities have been estimated. Different emission scenarios were also studied to account for the implementation of the Energy Performance of Buildings Directive (EPBD). The performance of CALPUFF is evaluated through comparison with measurements from air quality monitoring stations which are operated by the Hellenic Ministry of Environment & Energy. There have been a number of studies that address air pollution over the GAA [17], [18], [19] but, to the authors’ knowledge, this is the first attempt to combine emission estimation and dispersion simulation with detailed reference to the effects on air quality of the enactment of the EPBD.

2. Materials & Methods

2.1. Model description
CALPUFF is a multi-layer, multi-species, non-steady state dispersion model. Its puff formulation enables it to address spatial variability of meteorology, non-uniform land use patterns, dry deposition, wet scavenging and turbulence based on dispersion coefficients derived from either similarity theory or observations [5]. It is suitable for modeling domains ranging from tens of meters to hundreds of kilometers from a source and for predictions for averaging times from one-hour to one year. It can operate with different source types: point, line, area and volume using an integrated puff sampling function. The sampling scheme can employ either radially symmetric Gaussian puffs or non-circular puffs (slugs). The first scheme was chosen since it is more suitable for far-field applications [15]. CALMET is the meteorological pre-processor of CALPUFF used for the computation of meteorological parameters. Its diagnostic field generator contains objective analysis and parameterizes treatments of slope flows and kinematic terrain effects among others, as well as a divergence minimization procedure. For the computation of the wind fields, an initial guess field is adjusted to obtain the Step 1 wind field. Then, an objective analysis procedure introduces observational or prognostic data to create the final wind field. Its input can be either data from meteorological stations or gridded prognostic wind fields from a mesoscale model, which may better reproduce regional flows and sea breeze and have no data gap [20]. The WRF model was run daily on three nested grids at 45 vertical levels: 12x12 km over Greece, 6x6 km over Attiki, 1.5x1.5 km over greater Athens. The 1.5x1.5 km resolution was used as input to CALMET.

2.2 Emissions estimation and spatial allocation
For the evaluation of air quality over the GAA, for February 10th-16th, 2018, we estimated emissions of nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO2), sulphur dioxide (SO2) and particulate matter (PM10) from road transport, residential heating, ship navigation and industry.

Emissions from stacks and national highways were estimated explicitly as point and line sources, respectively. All other emissions were allocated to a spatial grid and modeled as area sources. The grid resolution was 1.2 km for all pollutants. For the area sources the domain was split into 64 subdomains, each covering an area of 23.04 km and containing 16 grid cells. Line sources were simulated using a sequence of coordinates, enough to provide for a sufficient resolution of the road path. The study area
can be seen in figure 1. The grid is shown in red, the 64 areas in blue, the area of Piraeus port in green, industrial facilities in purple and finally highways in orange.

Figure 1: The study area of the GAA, Greece. Subdomain grid depicted in blue, grid cells in red, highways as orange lines, industrial facilities as purple dots and the area of Piraeus port outlined in green.

2.2.1 Road transport. Road transport is accountable for approximately 20% of total CO$_2$ emitted in Europe. While these emissions are dropping (e.g. by 3.3% in 2012), they are still 20.5% higher than 1990 [21]. While examining air quality related to vehicle emissions, because of differences in engine operation, it is a common practice to designate roads as urban, rural or highways [6]. Directly applicable data for road traffic emissions in Attica during the simulation period were not available but the European Monitoring and Evaluation Program (EMEP) has provided sector data for Greece for the year 2016 [22]. According to a road transport inventory for Greece and Attica for 2006-2010 [10], 40% of national CO$_2$, CO and 30% of NOx and particles are emitted in Attica. Emissions from urban roads were estimated and spatially allocated using:

\[ E_{i,x} = E_i \cdot \frac{\text{pop}_{i,x}}{\text{pop}_{\text{total}}} \]  \hspace{1cm} (1)

where \( E_{i,x} \) is the emission of pollutant \( i \) in the area \( x \) (tonnes), \( E_i \) is the annual total emission of pollutant \( i \) (tonnes), \( \text{pop}_{i,x} \) is the population in cell \( x \), \( \text{pop}_{\text{total}} \) is the total population for the entire domain. Population data were obtained from ELSTAT [8] and emissions from national roads were estimated based on hourly traffic count [23]:

\[ E_i = \sum_j (HTL \cdot L) \cdot e_{ijk} \]  \hspace{1cm} (2)

where \( E_i \) is the emissions (tonnes) of pollutant \( i \), \( H.T.L. \) is the hour traffic link (vehicles), \( L \) is the road segment length (km), \( e_{ijk} \): emission factor [24] for pollutant \( i \), vehicle type \( k \) and engine technology \( j \) (tonnes/km/vehicles). The types of vehicles included are passenger cars, light commercial vehicles, heavy duty vehicles, buses, and motorcycles. The two national highways can be seen in figure 1 and since the GAA is an urban area [25], rural emissions were not considered. Annual emissions from road transport for Greece and Attica, are shown in Table 1.

| Emissions [tonnes/year] | NO$_x$  | CO    | SO$_x$ | CO$_2$   |
|-------------------------|---------|-------|--------|----------|
| Greece                  | 6.91E+05| 2.48E+06| 1.14E+03| 2.11E+08|
| Attica                  | 2.78E+04| 9.61E+04| 4.56E+01| 8.50E+06|
2.2.2 Small Combustion. This category was sub-divided into five different groups, following EMEP/EEA [24] classification: open fireplaces using wood, small size boilers (< 50 kWth) using oil, medium size boilers (50 kWth - 1MWth) using oil, boilers using natural gas and finally stoves using natural gas. Although open fireplaces in houses situated in urban areas are designed to be mainly decorative, the declining income in Greece has led to their extensive use as means for domestic heating [26]. GAA in particular has experienced formation of residential wood burning smog during winter months [27]. The emissions of relevant pollutants (SO$_2$, NOx, CO and PM10) were determined using a technology specific approach [24] based on the equation:

$$E_i = \sum_{j,k}EF_{i,j,k}A_{j,k}$$

where $E_i$ is the annual emission of pollutant $i$ (g), $EF_{i,j,k}$ is the default emission factor of pollutant $i$ for source $j$ and fuel $k$ (g/GJ), $A_{j,k}$ is the annual consumption of fuel $k$ in source type $j$ (GJ). The annual consumption of thermal energy in a typical Greek household was taken according to ELSTAT [28] and the share of fuels used for residential heating in Attica is given by Eurostat [29]. Spatial allocation of emissions was possible using population and housing data [8] so each area of the grid corresponded to a number of households. Table 2 shows boiler and fuel type emission factors.

### Table 2: Emission factors for residential heating by technology and fuel used [24]

| Pollutant | Fuel Oil | Natural Gas | Wood |
|-----------|----------|-------------|------|
|           | Medium boilers (50-1000 kWth (g/KWh)) | Small boilers (<50 kWth (g/KWh)) | Stoves (g/KWh) | Boilers (g/KWh) | Open fireplaces (g/KWh) |
| SO$_2$    | 5.04E-01 | 2.84E-01    | 0.18E-02 | 0.11E-02 | 0.40E-01 |
| NOx       | 3.60E-01 | 2.48E-01    | 18.0E-02 | 15.1E-02 | 1.80E-01 |
| PM10      | 0.11E-01 | 0.11E-01    | 0.18E-02 | 0.07E-02 | 30.2E-01 |
| CO        | 1.44E-01 | 0.65E-01    | 10.8E-02 | 7.92E-02 | 144.8E-01 |

2.2.3 Navigation. Ship emissions in port account for a small percentage of the total emissions from ship activity [30]. Nevertheless, the most noticeable part of ship emissions takes place in ports and port-cities [31]. There is a limited number of studies focusing on emission in ports and only a few for the port of Piraeus [17], [32]. Emission from the passenger and container port of Piraeus were estimated for the main ship exhaust pollutants (SO$_2$, NOx, PM10) & GHG (CO$_2$). Depending on the available data for the ships at port, emissions can be estimated through a default approach (Tier I), a technology-specific approach (Tier II) and a ship movement methodology (Tier III) [24]. For the passenger port of Piraeus, detailed ship movement data and engine data were available and thus Tier III was applied using the following equation:

$$E_{Trip,i,j,m} = \sum_p[T_p \sum_e(P_e \times LF_e \times EF_{e,i,j,m,p})]$$

where $E_{Trip}$ is the emission over a complete trip (tonnes), EF is the emission factor (kg/tonne) depending on type of vessel, LF is the engine load factor (%), P is the engine power (kW), T is time (h), $i$ is the pollutant, $e$ is the engine category (main or auxiliary), $j$ is the engine type (slow-, medium-, and high-speed diesel, gas turbine or steam turbine), $m$ is the fuel type (bunker fuel oil, marine diesel oil/marine gas oil, gasoline) and finally $p$ is the different phase of trip (manoeuvring or at berth). The Hellenic Ministry of Shipping and Island Policy announces departures from coastal ships from the port of Piraeus daily [33]. To obtain data on the engines of ships, their names and types were collected and features from Elliniaki Aktoploia [34] on each of those ships were utilized. The engine load factors and the emission are shown in Table 3 [35],[24]. All ships in port were driven by medium speed diesel (MSDs) and used LSFO fuel (Low Sulphur Fuel Oil, containing maximum 1.5% Sulphur content by mass, as required by EU Directive 2005/33/EU) for their main engines. From the 21 ships found at port, 14 used diesel-electric engine configuration and 7 were driven by diesel engines while their
auxiliary engines burnt medium diesel oil (MDO - 1% S). To calculate manoeuvring time, information on the destinations of the vessel was required to locate its position at berth. Manoeuvring time is calculated by dividing the distance traveled from entry to berth by the ship’s average in-port speed plus 6 minutes to dock and 3 minutes to undock. Inbound speed is on average 9.26 km/h and outbound 14.82 km/h while an average time at berth of 8h was assumed for each ship [17].

Table 3: Emissions factors for passenger ships at Piraeus port [24]

| Engine      | Ship Movement | Load Factor | NOx | SOx | PM | CO | CO2 |
|-------------|---------------|-------------|-----|-----|----|----|-----|
| Main        | Manoeuvring   | 0.2         | 10.2| 6.6 | 0.9| 1.7| 710.0|
|             | Berth         | 0.0         | 0.0 | 0.0 | 0.0| 0.0| 0.0  |
| Auxiliary   | Manoeuvring   | 0.6         | 13.5| 4.3 | 0.3| 1.61| 690  |
|             | Berth         | 0.3         | 0.0 | 4.3 | 0.3| 1.61| 690  |

Entry distance varied between 0.3 and 1.9 km with docking and undocking lasting an average of 9 min and manoeuvring times for entry and exit varying between 2-12 min at 9.3 km/hr and 1-8 min at 14 km/hr, respectively. The area and layout of Piraeus port is shown extracted in figure 1. Tier III [24] approach was also applied for the estimation of emissions from the container terminal of Piraeus, using data from Marine Traffic [36], which provides the number and type of ships located in ports. Depending on the type of ship and the fuel used, estimated main engines power, average cruise speed, average duration for in-port activities and emission factors were obtained from EEA’s guidebook [24] (Table 3). Fuel type for each ship category was chosen based on the percentages of installed main engine power by engine type/fuel class found in the guidebook. We assumed that all ships belonging to a certain category use the dominant fuel/engine type in that category. The ship categories present at the port during the week of simulation were liquid bulk carriers (LBC), dry bulk carriers (DBC), containers (C), general cargo (GC), Ro-Ro cargo, tugs (T) and others (O). For all of them, main & auxiliary engine load factor while manoeuvring was 0.5. At berth, it was 0.2 for the main engines, 0.6 for LBC’s auxiliary engines and 0.4 for all others’ auxiliary engines. Engines vary from slow speed diesel (SSD) to medium speed diesel (MSD) and to high speed diesel (HSD) while fuel types are either bunker fuel oil (BFO) or marine diesel oil – marine gas oil (MDO – MGO).

2.2.4 Industry. Industrial activity data are available from European Pollutant Transform and Release Data Registry [37] for the year 2016. The register contains annual data reported by more than 30,000 industrial facilities covering 65 economic activities within the following 9 industrial sectors: energy, production and processing of metals, mineral industry, chemical industry, waste and waste water management, paper and wood production and processing, intensive livestock production and aquaculture, animal and vegetable products from the food and beverage sector, and other activities. A facility is required to report data under E-PRTR if it releases pollutants that exceed thresholds specified for each medium - air, water and land. For the area modelled, six facilities met the criteria. Emissions were allocated in cells using the coordinates of each facility and data required by the model concerning stack height and stack diameter, exit velocity and exit temperature of pollutants were gathered from various sources [38], [39]. The location of those industries can be seen in figure 1.

2.3 Concentrations estimation
To estimate ambient concentrations with high spatial resolution, non-steady state model CALPUFF was used and meteorological fields were obtained from the next-generation mesoscale NWP model WRF. The European Directive 2001/81/EC [40] establishes health-based standards for a number of air pollutants, since human exposure to those can have adverse health effects (Table 4). Pollutants’ estimated average concentrations were compared with those standards.
Table 4: Ambient concentration standards [40]

| Pollutant | Concentration | Averaging Period       |
|-----------|---------------|------------------------|
| CO        | 10 mg/m³      | maximum daily 8 hour mean |
| SO₂       | 350 µg/m³     | 1 hr                   |
| SO₂       | 125 µg/m³     | 24 hours               |
| NO₂       | 200 µg/m³     | 1 hr                   |
| NO₂       | 40 µg/m³      | 1 year                 |
| PM10      | 50 µg/m³      | 24 hours               |
| PM10      | 40 µg/m³      | 1 year                 |

2.4 Dispersion model

The aggregated emission field was split into three different categories, based on different input parameters. The individual categories and the quantity of distinguished sources in each category are: 6 point sources representing industrial facilities, 64 area sources, 4.8 km² each, one of which corresponds to the port of Piraeus and all of them are used for the spatial allocation of road transport and residential heating emissions, and 91 line sources representing the two national roads. The computational domain was divided into a homogenous grid with 1.2 km step size. Temporal resolution was 1 hour, corresponding to the available meteorological data. Pollutants concentrations were estimated for all hours between 10 to 16 February 2018 at the positions of 1024 gridded receptors. Chemical transformation was parameterized using the five species scheme (SO₂, SO₄=, NOₓ, HNO₃, and NO₃⁻) employed in the default reaction algorithm MESOPUFF II [15]. We compared the final estimated concentrations with available measurements at several monitoring stations operated by the Ministry of Environment & Energy [41]. Comparison included daily timeseries of concentrations for the entire week of simulation and, for selected pollutants, hourly timeseries during a specific day.

2.5 Scenarios - Impact of input parameters

In order to estimate the effects of different input parameters on emissions for the Attica region, three scenarios were constructed. Each one represents building interventions in relation to the implementation of the European Directive on Energy Performance of Buildings [2].

2.5.1 EPBD implementation. The Energy Performance of Buildings Directive [2] along with the Energy Efficiency Directive [42] promote the improvement of energy performance of buildings within the EU. One of the goals of the EPBD and its revision [2] is to promote the cost-effective renovation of existing buildings. EU states have 20 months to transpose the 2018 revision into national law [43]. We focused on the existing building stock and priority was given to energy performance improvement interventions related to the building envelope (thermal insulation of walls, windows, doors, ceiling, etc) and the equipment (more efficient heating, cooling systems, ventilation, etc). According to Greek law, a renovation is considered major when the total cost is higher than 25% of the value of the building, excluding the land value upon which the building is situated [44]. The Regulation on the Energy Performance of Building (KENAK) has set requirements in energy performance for new buildings and buildings undergoing major renovations. These set energy class B as a minimum unless it can be proven by a technical report that it’s functionally and economically not possible. For the GAA, it is found [45] that 78.66% of the existing building stock is classified below energy class B. Based on a report published by the Greek ministry for the environment [46] which studied different measures on the existing building stock and calculated thermal and electrical energy savings for each, we chose three different renovation scenarios with their respective effects:

- a. insulation of walls resulting in thermal savings ranging from 33% to 60%
- b. increase of boiler efficiency resulting in thermal savings up to 17%
- c. replacement of fuel oil boilers with natural gas boilers resulting in thermal savings up to 21%

We assumed an implementation rate of 20% as an optimistic projection of the future, even though the current rate doesn’t exceed 3% [47]. Renovation scenarios were limited to buildings that don’t belong to an acceptable energy efficiency class, namely those from energy class H to C.
3. Results & Discussion

3.1 Distribution of emissions

The prevailing winds during the week of simulation and gridded terrain elevation of the modelled area can be seen in figure 2. The wind rose was constructed using hourly measurements of wind speed and direction from the four surface meteorological stations existing in the area: Eleusina (38.064°, 23.556° and 30 m height), Tatoi (38.109°, 23.784° and 237 m height), Elliniko (37.882°, 23.735° and 10 m height) and Eleutherios Venizelos (37.936°, 23.944° and 80m height) [48]. The basin is surrounded by high mountains on NE, NW and SE and the sea on SW and winds blow mainly from N-NE and SW. Table 5 summarizes the estimated emissions in the modeled domain for all types of sources. Emissions of CO were not modelled for the source category of residential heating due to lack of emission factors [24]. It should be noted that emissions from industrial sources are considered underestimated since only industrial facilities which exceeded E-PRTR threshold were included.

![Figure 2. Local topography and wind conditions (Feb 10-16th, 2018) for the GAA](image)

**Table 5: Summary of total emissions for all source categories (tonnes/week)**

| Species | Urban Roads | Highways | Residential Heating | Navigation | Industry |
|---------|-------------|----------|---------------------|------------|----------|
| CO      | 1.84E+02    | 0.00E+00 | 0.00E+00            | 0.00E+00   | 0.00E+00 |
| NOx     | 0.00E+00    | 0.00E+00 | 0.00E+00            | 0.00E+00   | 0.00E+00 |
| SO2     | 0.00E+00    | 0.00E+00 | 0.00E+00            | 0.00E+00   | 0.00E+00 |
| PM10    | 0.00E+00    | 0.00E+00 | 0.00E+00            | 0.00E+00   | 0.00E+00 |
| CO2     | 1.24E+04    | 1.16E+04 | 0.00E+00            | 0.00E+00   | 0.00E+00 |

It can be seen that road transport is the main source of emission for CO and NOx. Residential heating dominated PM emissions, which can be justified by the increasing use of wood as a combustion source during winter in Athens [27]. In mass terms, the pollutant emitted the most in the GAA is carbon monoxide followed by nitrogen oxides. CO is formed mainly from incomplete combustion of fuels. Road transport contributes to the majority of CO emissions and to about half of the NOx that is emitted in the air. This is also in agreement with EPA findings [49].

3.2 Comparison with monitoring receptors

To validate model’s performance, estimated concentrations at specific gridded receptors were compared with measurements from several monitoring stations situated in the GAA. We chose Patision St. in the center of Athens, monitoring CO, NO, NO2 and SO2; Nea Smyrni further south,
monitoring CO, NO, NO$_2$ and PM10 and Agia Paraskeui to the north, monitoring NO, NO$_2$, PM25 and PM10. Predictions of weekly and hourly timeseries are presented in figures 3-5.

Results show good agreement, with Patision predictions being closest to monitoring station measurements and Nea Smyrni furthest. Emissions in Nea Smyrni were mostly underestimated, and we attribute this to road transport. Syggrou avenue, which passes through Nea Smyrni, is one of the busiest roads in Attica and thus estimating its emissions based on population data and not hourly traffic flow could justify the difference. The model performed best for SO$_2$ (not shown) and CO and worst for NO$_x$, possibly because its concentration depends on chemical transformations that define the NO$_2$/NO$_x$ ratio, and are subject to a number of uncertainties. Due to lack of information of reported industrial pollutant emissions in the GAA, the model performed poorly near industrial zones which are
located mostly in the Thriassio plain. This gap of information is also evident in other reports, e.g. in the Industrial Inventory of AIRUSE Cities which didn’t include Greece due to lack of data [50].

3.3 Small Combustion

Emission rates (g/m²s) from domestic heating were allocated to each area of the grid, based on weighting factors from housing and thermal energy consumption data. Spatial distribution of averaged concentrations during the entire period of simulation are shown in figure 6. Maximum concentrations are observed in Athens urban area, which covers 35 out of the total 66 municipalities. The most polluted gridded areas in this source category include Peristeri and Aigaleo (No 54), Patisia (No 56), the municipality of the City of Athens (No 57) and finally Kalithea and Nea Smyrni (No 58), (numbering corresponds to areas in figure 1). These areas’ number of dwelling stock is among the highest in the GAA [8]. Exceedance counts occurred at receptors in all of these areas for 24 hr averaged concentrations of PM10 (figure 6c).

![Figure 6](image.png)

**Figure 6.** Contours of maximum local concentrations over the 1 week simulation period, for domestic heating pollutants only. a. CO 8h average (mg/m³), b. NOx 1 hr average (μg/m³), c. PM10 24 hr average (μg/m³) – exceedance points marked in red. d. SO₂ 1 hr average (μg/m³)

3.4 Results from EPBD implementation scenarios

Simulations were performed for the three EPBD scenarios, using different emission rates for domestic heating sources each time, depending on the expected thermal savings. The rate of implementation for each scenario, was assumed at 20%, uniformly throughout the simulation area.

a. **Insulation of walls.** Renovation of the residential building stock with available heating by applying thermal insulation to the building envelope, regardless of the fuel or boiler type used in their heating system. This measure is expected to result in a reduction of ~45% in buildings’ thermal energy requirements [46] and therefore in fuel consumption for heating. The resulting changes in pollutant emissions are shown in Table 6, with a maximum reduction in the area averaged total emission rate...
from all sources of over 8%.

b. Boiler Efficiency. The second scenario assumes an increase in boiler efficiency. The potential for savings in thermal energy demand is 15% [46]. Maximum reduction in the area averaged total emission rate from all sources is just over 1% (table 6).

c. Replacement of fuel oil with natural gas. In the third scenario, a switch from oil to natural gas was assumed and thus a 20% reduction in buildings’ thermal energy consumption [46]. Expected maximum reduction in the area averaged total emission rate from all sources is almost 4% (Table 6).

**Table 6: Area averaged emission rates from all sources before and (%) decrease after each EPDB implementation scenario**

| EPDB Scenarios                  | SO₂ Emission rate – before [g/s/m²] | NOₓ Emission rate – before [g/s/m²] | PM10 Emission rate – before [g/s/m²] | CO Emission rate – before [g/s/m²] | decrease – after [%] |
|--------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------------------|---------------------|
| a. Insulation of walls         | 1.59E-02                            | 1.33E-05                            | 3.05E-05                            | 2.82E-04                           | 0.004               |
| b. Boiler Efficiency           | 0.004                               | 5.054                               | 8.314                               | 4.316                              | 0.134               |
| c. Replacement of fuel oil with natural gas | 0.008                               | 3.830                               | 0.110                               | 0.049                              | 0.830               |

Since the emission rate (table 6) is an area average, it is then multiplied by the population density (as a fraction of the total population in the GAA) in order to define local emission rates for each grid cell area (figure 1). The variations in population density interact with topography and weather conditions to give the resulting ground level concentrations. The maximum reduction in the contribution of residential heating sources to ground level concentrations was 14.65% for PM10 24 hour average concentration for the wall insulation scenario (a), 2.13 % for the increase in boiler efficiency scenario (b) and only 0.66% for the natural gas scenario (c). Results can be explained by the fact that the largest contribution to PM10 emissions is from wood burning for residential heating and the wall insulation scenario directly reduces heat losses and therefore heating requirements. Scenarios (b) and (c) improve efficiency but only for oil type heating sources, leaving wood burning intact.

Although domestic heating is a major contributor to PM10 emissions, other sources also contribute, notably urban roads (table 5). The difference in maximum variations of PM10 24 hr average concentrations from all sources before and after the implementation of EPDB were for scenario a. 5.75%, b. 0.32% and c. 0.33%. So, overall, the largest influence is with the wall insulation scenario.

4. Conclusions
This study estimated spatial and temporal variations of emissions and concentrations of select air pollutants and GHG in the GAA during a week in February 2018. Pollutant sources included domestic heating, urban transport and highways, ports-navigation and major industrial facilities. Validation with measurements throughout the GAA was acceptable and the developed model was then used to assess the influence of EPBD implementation on the concentration levels of major pollutants. Three scenarios were taken into consideration i.e. application of insulation to building walls, increased boiler efficiency and replacement of fuel oil with natural gas. In all cases an implementation rate of 20% was assumed across the GAA. The most efficient measure to reduce PM10 concentrations was found to be the wall insulation scenario, due to its direct implications on reduced wood burning through reduced heat losses and therefore energy consumption.

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