Global NEST Journal, Vol 12, No 1, pp 99-107, 2010

A SPATIALLY ALLOCATED EMISSIONS INVENTORY FOR CYPRUS

G. TSILINGIRIDIS[1,*]
C. SIDIROPOULOS[1]
A. PENTALIOTIS[1]
C. EVRIPIDOU[1]
C. PAPASTAVROS[2]
T. MESIMERIS[2]
M. PAPASTAVROU[2]

[1]Department of Mechanical Engineering, Aristotle University of Thessaloniki, Greece
[2]ECOGNOSIA, 46 Mekodonitissis Avenue, P.C. 240 05, Nicosia, Cyprus

Received: 07/12/09
Accepted: 11/02/10
*to whom all correspondence should be addressed:
e-mail: tsil@eng.auth.gr

ABSTRACT
In this paper, a detailed spatial allocated emissions inventory for Cyprus is presented. Top-down and bottom-up methodologies are implemented and emissions are estimated from all anthropogenic sources for the reference year 2002 with the aid of state-of-the-art algorithms. Emission factors representative for the situation in Cyprus, in the case of major industrial units, and default emission factors for the rest emission sources are adopted. Main results indicate that power generation and road transport are the major contributors to total emissions. Power generation share was 36% in total CO_2, 62% in total SO_2, 20% in total NO_x and 55% in total N_2O emissions, while the share of road transport was 29% in CO_2, 22% in SO_2, 35% in NO_x and 6% in N_2O emissions. Furthermore, comparisons to other existing emission inventories for Cyprus and official national emission data are presented and differences are partially explained.
A GIS-based approach is applied to generate, organize and spatially allocate emissions data in a 5x5 km² grid. GIS-aided spatial overlay techniques are used and maps of spatial allocation factors and gridded emissions data are produced and presented, showing that highest emission densities appear in cells, which include large industrial plants and/or cover urban areas.

KEYWORDS: Air pollutants, air quality, emission allocation, gridded data, GIS.

1. INTRODUCTION

Air pollution extends from local (urban pollution) to regional (dispersion, deposition and chemical transformation of the pollutants, acid rain, photochemical reactions) and global level (greenhouse effect and depletion of the stratospheric ozone layer). Air pollution modelling is a powerful tool capable of assisting policy makers in developing abatement strategies to reduce pollutant emissions.
One of the most crucial data sets needed to initiate chemical and photochemical reaction mechanisms included in an air quality model is the emissions inventory. An emission inventory identifies sources of air pollutants in an area and quantifies emissions from specific sources (Baldasano, 1998). Nowadays, emission inventories are under constant development and improvement worldwide. Photochemical air quality models use meteorological, topographic and emission inventory data to simulate the physical and chemical processes that influence primary or secondary pollutants, i.e. the ozone formation in an airshed. Grid-based air quality models portray the modelling region as a 3-dimensional grid matrix and pollutant concentrations are predicted for each individual grid cell in the modelling domain. To accurately represent the geographic distribution of emissions throughout a gridded modelling

domain, it is necessary to develop an emission inventory that reports emissions corresponding to each grid cell of the domain (Taghavi *et al.*, 2005). Therefore, detailed emission inventories are required as input to air quality models and must include the emission estimates reported at a grid-cell level. Modelling grids may extend over small or larger domains and may include hundreds or thousands of grid cells depending on grid resolution.

According to recent findings, concentrations of several air pollutants in the cities of Cyprus regularly exceed the limits set by the new European Union regulations for air quality (DLI, 2009). However, work on emissions inventorying in Cyprus is rather limited, i.e. a first systematic approach of emissions inventory has been compiled for 2001 (Baumbach *et al.*, 2007) and another for 2006 (Mellios and Samaras, 2009). In this paper an improved, spatially allocated emissions inventory for Cyprus is developed and presented. Activity statistics collected from various sources together with default and country-specific emission factor data sets have been used to estimate CO_2, SO_2, NO_x, NMVOC, CH_4, CO and N_2O emissions from all anthropogenic sources. For the emissions allocation, a 5x5 km² grid was created. Even though the modelling domain covers the whole of Cyprus, emissions were calculated only for the Greek Cypriot part due to the lack of access in data from the northern part of the country. Spatial overlay techniques are implemented in an integrated framework of a GIS and a database management system to provide examples of emission density maps over Cyprus. Apart from readily available emission data to be used as input data in grid-based air quality models, this paper also presents comparisons with emissions data from other inventories and official national emission data. Limitations of the inventories are discussed and suggestions are made for the improvement of inventories so as to provide more reliable emission data.

2. METHODOLOGY

The estimation of emissions is based on the EMEP/CORINAIR methodology of the European Environment Agency (EEA) (EMEP/CORINAIR, 2007). The Quantity (Q) of each air pollutant emitted depends on the Activity Level (AL) and the Emission Factor (EF), a factor which defines the linear relationship between Q and AL according to the general formula:

$$Q_{s,i,j,k} = 10^{-6} \times EF_{s,i,j,k} \times AL_{s,i,j}$$

where

s refers to the pollution source examined

i refers to the technology (industrial boiler, vehicle type, airplane type, solvent-related products, etc)

j refers to the activity (combustion of diesel, heavy fuel oil, vehicle km driven, airplanes landing and take off cycles operated, commodities production, etc)

k refers to the pollutant examined

$Q_{s,i,j,k}$ is the quantity of pollutant k, from source s, technology i and activity j (in t yr^{-1})

$EF_{s,i,j,k}$ is the emission factor for pollutant k, for source s, technology i and activity j (in g GJ^{-1} or in g veh km^{-1} or in g LTO^{-1} or in g t^{-1}, etc)

$AL_{s,i,j}$ is the activity level of the emission source s, the technology i and the activity j (in t yr^{-1} or in GJ yr^{-1} or in veh km yr^{-1} or in LTO yr^{-1}, etc)

Activity level data for each emission source was acquired through an extensive data collection campaign mainly from statistical handbooks (primarily from the Statistical Service of the Republic of Cyprus as well as from other public services), scientific publications, research on the Internet, personal communication with experts working in industry, etc. Table 1 summarizes the emission source activities examined, the fundamental data for the emissions calculation as well as the origin of data. The emission factors used were derived from the Atmospheric Emissions Inventory Guidebook (EMEP/CORINAIR, 2007) and, where it was available, directly from measurements in factories (e.g. in the case of emission factors of Cypriot cement factories).

Table 1. Activity data by emission source category and data sources (2002)

Emission source activity	Activity data	Data source
Power generation	Units technical characteristics Fuel consumption	EAC[1] SSRC-Sales and hold-up data of oil products
Refinery	Units technical characteristics Fuel consumption Oil balance	Cyprus Refinery
Cement factories	Cement production Fuel consumption	Cement factories in Vasiliko & Moni
Combustion in large point sources	Fuel consumption	SSRC[2]-Sales and hold-up data of oil products
Combustion in small units	Fuel consumption	
Space heating	Fuel consumption	
Production processes	Commodities production	SSRC-Industry statistics
Petrol distribution	Petrol consumption per activity (storage, distribution, carriage)	SSRC-Sales and hold-up data of oil products
Solvents use	Import, export, production of relevant chemical compounds and products	SSRC-Import and export statistics
Agriculture-Livestock	Fertilizer utilization, Number of animals	SSRC-Agricultural Statistics
Road transport	Vehicle distribution per age, category, cc and fuel	SSRC-Transport Statistics
Sea transport	Arrivals/departures of ships	CPA[3]
Air transport	LTO cycles of airplanes	DCA[4]
Off road transport	Import, export of off-road vehicle & machinery	Cyprus Customs

[1]*EAC: Electricity Authority of Cyprus*
[2]*SSRC: Statistical Service of the Republic of Cyprus*
[3]*CPA: Cyprus Port Authority*
[4]*DCA: Department of Civil Aviation*

Emissions are typically classified in three types of sources according to their spatial characteristics:

- Stationary or point source emissions originate from large point sources at fixed locations (such as power plants and industrial facilities),
- Mobile or line sources (e.g. all on-road vehicles), and
- Area sources which are stationary and/or mobile sources that are transient and widespread (for example emissions related to solvent use or to off-road machinery operation).

A GIS-based approach was applied to generate, organize and display gridded emissions data. The geographic locations of large point sources, such as power plants and factories are known, providing a method to assign emissions from these sources directly to their specific locations. In contrast, line and area sources are usually smaller, transient and widely distributed throughout a region. Due to the fact that the exact locations of line and area sources are often unknown, the geographic distribution of these sources must be approximated using emissions surrogates. This surrogate data (e.g. road traffic counts, population density, housing statistics, etc.) is used as indicators of emissions activity because their spatial distributions are assumed to be representative of the geographic distribution of emissions sources.

In Figure 1 the spatial allocation of the major emission sources, e.g. urban and other built up areas, highways, industrial areas and large industrial plants, is presented.

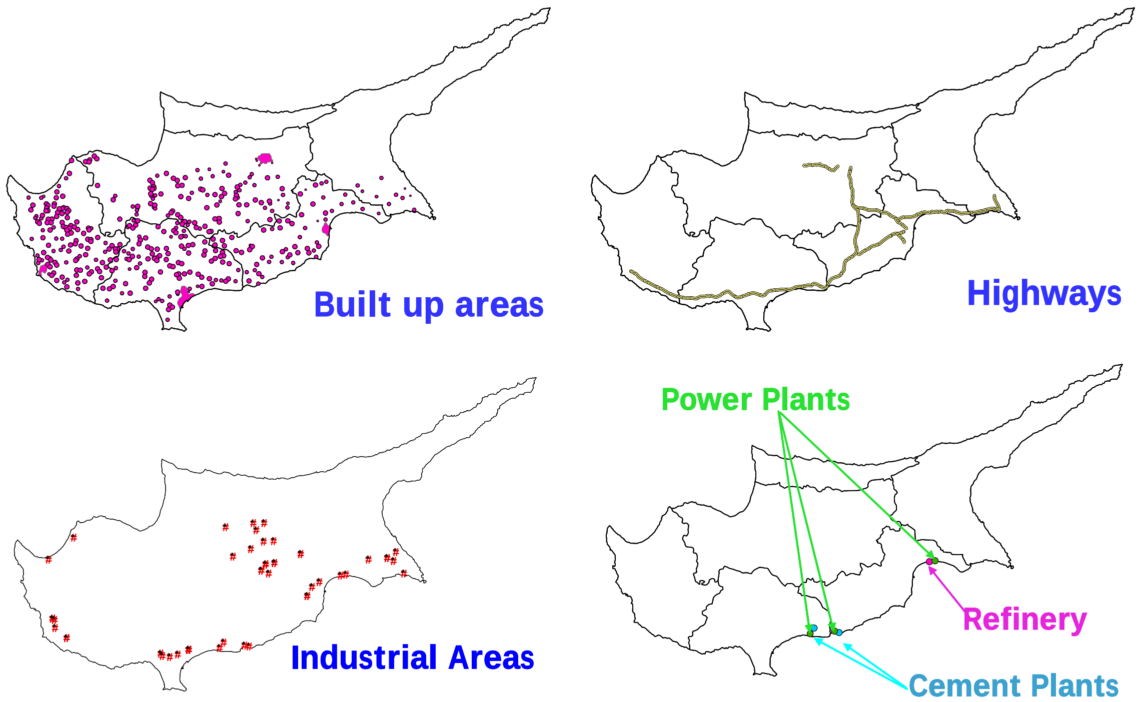


Figure 1. Spatial allocation of major emission sources

A thorough review was performed to identify sources of various spatial data sets appropriate for use in the development of emissions surrogates and spatial allocation factors in the case of Cyprus. The development of emissions surrogates was a labour-intensive process that involved acquiring, formatting, and processing spatial data sets in several different formats and from many different sources. Spatially resolved surrogate data associated with point, line, or polygon geographic features were obtained from local transportation and/or planning organizations, state agencies and commercially available data sources. The spatial data sets created were then imposed onto the defined modelling grid and the geographic features were disaggregated into the grid cells. This was made possible using GIS-aided spatial overlay techniques analyzed elsewhere in detail (Dai and Rocke, 2000; Sidiropoulos and Tsilingiridis, 2006). Finally, maps of spatial allocation factors and gridded emissions data were produced.

More details on data, estimation procedures, results and spatial allocation can be found elsewhere (Tsilingiridis and Fessas, 2008).

3. RESULTS AND DISCUSSION

In Table 2 the shares of each emission source category to total emissions are presented. Power generation and road transport are the major contributors to total emissions in Cyprus. Power generation share was 36% in total CO_2, 62% in total SO_2, 20% in total NO_x and 55% in total N_2O emissions, while the share of road transport was 29% in total CO_2, 22% in total SO_2, 35% in total NO_x, 48% in total NMVOC and 78% in total CO emissions.

In order to validate the inventory, emissions results from existing emissions inventories for Cyprus are presented as well. Table 3 summarizes the emission results from inventories compiled by the Ministry of Labour and Social Insurance of Cyprus, Department of Labour Inspection for the years 2001 and 2002 (DLI, 2009). Table 4 shows the first systematic approach of emissions inventory compiled for the year 2001 (Baumbach *et al.*, 2007). Significant differences are observed between the three inventories for CO emissions (especially in the transport sector), while for SO_2 emissions, a fuel-dependent pollutant, the deviations are non-significant. As far as NO_x emissions are concerned, the *DLI* results are in good agreement with the results of the work conducted by *Baumbach et al.*, but about half of the present work results. In the present work NMVOC emissions are about 30% higher than *DLI* results, while total VOC emissions are higher than *Baumbach et al. work* by a factor of 3.

Table 2. Air pollutant emissions by emissions source category in Cyprus

Emission Source Category	CO_2	SO_2	NO_x	NMVOC	CH_4	CO	N_2O
Power generation	36.0%	61.6%	19.6%	1.8%	0.2%	1.4%	55.1%
Refinery	1.2%	1.6%	0.8%	0.1%	0.1%	0.5%	0.5%
Cement factories	7.4%	6.9%	4.3%	0.2%	0.3%	0.6%	1.5%
Combustion in the rest large point sources	7.6%	0.3%	0.4%	0.0%	0.0%	0.2%	0.0%
Combustion in small units	6.8%	0.7%	0.3%	0.0%	0.0%	0.1%	0.6%
Space heating	6.7%	5.5%	0.9%	0.5%	0.2%	0.9%	1.9%
Production processes				12.7%			
Petrol distribution				4.6%			
Solvents use				12.5%			
Agriculture-Livestock			1.9%		96.0%		23.2%
Road transport	28.7%	21.9%	35.2%	47.8%	2.7%	78.8%	5.6%
Sea transport	0.2%	0.1%	1.0%	0.1%	0.0%	0.1%	0.0%
Air transport	0.2%	0.1%	1.0%	0.9%	0.1%	1.0%	0.1%
Off road transport	5.2%	1.4%	34.4%	18.8%	0.3%	16.4%	11.5%
Total [kt yr^{-1}]	8277	50	41	21	15	55	3

Table 3. National air pollutant emissions by emissions source category (DLI, 2009)

Emission Source Category	SO_2		NO_x		NMVOC		CO	
	2001	*2002*	*2001*	*2002*	*2001*	*2002*	*2001*	*2002*
Energy production	29.83	30.2	5.64	6.49	1.78	2.06	0.45	0.52
Refinery	0.98	1.1	0.20	0.17	0.73	0.68		
Manufacturing Industry & Construction	4.77	5.7	0.48	0.53	0.05	0.06	0.81	0.98
Transportation	7.29	10.08	10.05	10.08	9.39	9.09	84.36	80.93
Central Heating	2.74	2.63	0.57	0.55	0.09	0.08	0.11	0.10
Agriculture (pumps-tractors)	0.82	0.84	0.69	0.67	0.14	0.15	0.53	0.52
Oil storage					0.25	0.24		
Oil distribution					0.52	0.53		
Cement production	3.38	3.34	3.78	3.73	0.01	0.01	0.48	0.47
Lime production	0.04	0.04	0.01	0.01				
Paints					2.40	2.66		
Dry cleaning					0.20	0.20		
Solvents (rest)					0.28	0.23		
Total emissions [kt yr^{-1}]	49.85	50.72	21.42	22.23	15.84	15.99	86.74	83.52

Table 4. Air pollutant emissions in the Greek Cyprus Community area for the year 2001 (Baumbach *et al.*, 2009)

Emission Source Category	SO_2	NO_x	VOC	CO	PM
Boilers	39.93	11.75	0.52	0.22	1.66
Dry cleaners	0.33	0.03	0.21	0.01	0.01
Hotels	0.09	0.02	0.00	0.01	0.00
Domestic Heating	1.67	0.07	0.00	0.10	0.04
Agriculture	0.50	0.02	0.00	0.03	0.01
Petrol stations	-	-	0.74	-	-
Aircrafts	0.02	0.26	2.61	0.06	0.09
Road Traffic	7.08	13.26	8.27	39.55	0.67
Total emissions [kt yr^{-1}]	49.62	25.40	12.35	39.98	2.47

In Table 5 the comparison of the emission sources' contribution of the present work (PW) to the inventory compiled for the year 2006 by the Laboratory of Applied Thermodynamics (LAT) of Aristotle University of Thessaloniki, Greece (Mellios and Samaras, 2009) is presented. LAT inventory, which is based on the EMEP/CORINAIR methodology, too, includes some additional emission categories, the most important being the "Waste management", but misses some others, the most important being the "Off road vehicles and machinery". Moreover, contribution of most categories in total emissions shows deviations, which in most cases are important and cannot be attributed to the four years difference in the reference time of the inventories. Finally, LAT inventory reports particulates but misses CO_2, SO_2 and N_2O emissions.

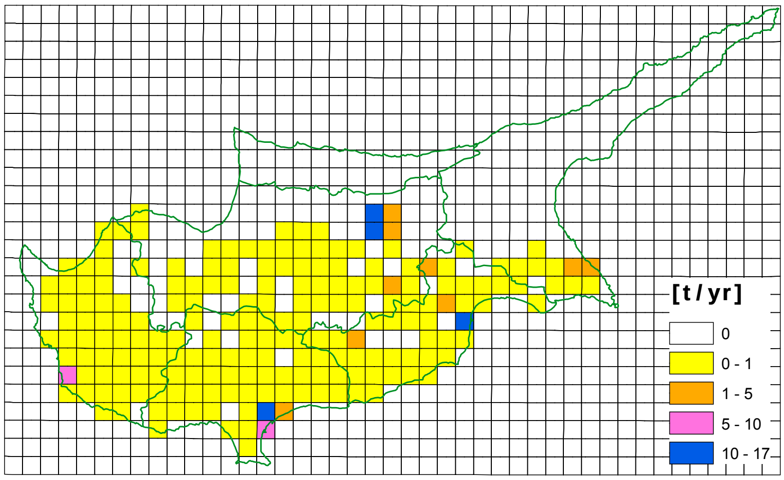
Table 5. Comparison of emission sources' contribution in total emissions

Emission Source Category	**NO_x**		**CO**		**VOC**	
	LAT	*PW*	*LAT*	*PW*	*LAT*	*PW*
Road Transport	40.7%	35.2%	81.2%	78.8%	3.5%	29.2%
Off road vehicles and machinery	-	34.4%	-	16.4%	-	11.2%
Air & Sea transport	8.9%	2.0%	2.7%	1.1%	0.2%	0.7%
Power plants	42.7%	19.6%	2.4%	1.4%	0.0%	1.1%
Cement Industries	3.3%	4.3%	6.1%	0.6%	0.2%	0.2%
Small Industries	4.1%	1.6%	1.4%	1.2%	0.1%	0.4%
Mining and Quarrying	0.0%	-	0.0%	-	0.2%	-
Storage and distribution of liquid fuels	0.0%	0.0%	0.0%	0.0%	0.7%	2.7%
Solvent use	0.0%	0.0%	0.0%	0.0%	2.1%	7.3%
Waste management	0.0%	-	0.0%	-	78.6%	-
Agriculture - Livestock	0.0%	1.9%	0.0%	0.0%	14.3%	39.6%
Forest fires	0.3%	-	6.2%	-	0.3%	-
Production processes	-	0.0%	-	0.0%	-	7.5%
Refinery	-	0.8%	-	0.5%	-	0.1%

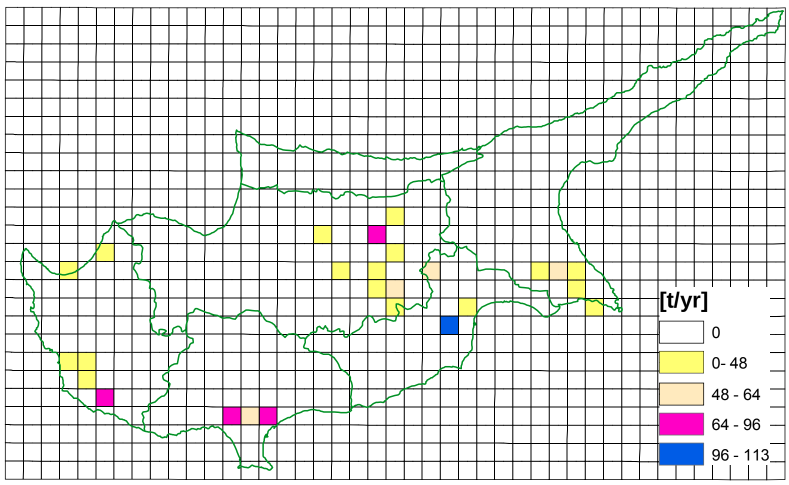
The issues that arise comparing these works are:

1. Emission sources categorization: each emission inventory classifies differently the emission sources it examines and possibly overlapping errors occur. In DLI inventories, no data is given about the methodology implemented, let alone the definition of emission source categories. In the present work the standard procedure of the internationally approved EMEP/CORINAIR methodology system is followed to overcome inconsistencies, examine effectively as many air pollution sources as possible and avoid double counting of emissions or other relevant problems.
2. Activity data: there is not a thorough description (if any at all) of the activity data and especially the activity data sources and manipulation in the other inventories. Therefore, from this point of view the comparisons concerning the emissions data estimates are somewhat problematic.
3. Emission factors: an important source of uncertainty in the emission estimates is attributed to the emission factor data set applied. It is certain that part of the deviation in the emission results originates from the use of different emission factors data sets: in the present work, country-specific emission factors are used (e.g. cement factory) and EMEP/CORINAIR default emission factors are adopted in the rest cases. In the work of *Baumbach et al.* EPA emission factors (for boilers for example) are applied. However, their appropriateness in Cypriot installations is questionable.
4. Methodology: in *Baumbach et al*. work, for example, the aircraft emissions estimation is a fuel-based procedure, while in the work presented a more detailed analysis (airplane-specific approach) is considered.
5. Weaknesses: the main weakness of the present work is that estimates of the Turkish Cypriot Community domain are not considered (due to the fact of no access to the necessary data).
6. Spatial allocation: although gridded maps are presented in *Baumbach et al.*, yet no methodological guidelines are indicated to provide a meaningful spatial disaggregation of emissions. The spatial allocation of emission in the present work was described in detail

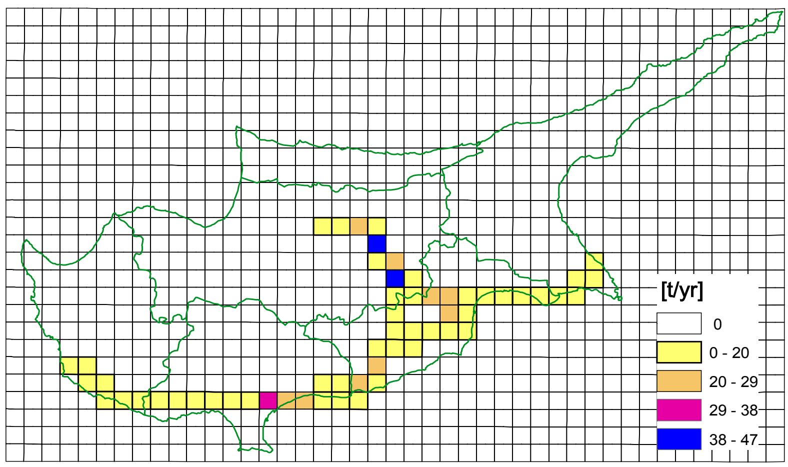
in the methodology paragraph and examples are given in Figure 2. More specifically, in Figures 2(a), 2(b) and 2(c) the spatial allocation of NMVOC emissions from space heating, industry and highway traffic are presented respectively, highlighting the areas with higher emission densities (mainly urban areas and large industries locations). In Figure 3 gridded total NMVOC emissions are shown and emphasis is placed on peak emission values.



(a) Space heating



(b) Industry



(c) Highway traffic

Figure 2. Spatial allocation of major sectors' NMVOC emissions in a 5x5 km² grid

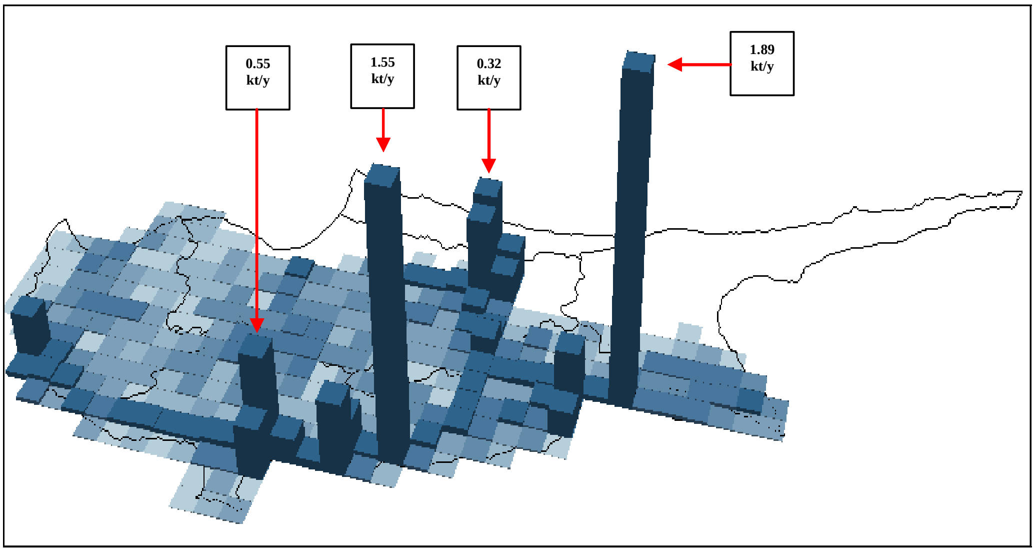


Figure 3. Spatial allocation and peak values of total NMVOC emissions

4. CONCLUSIONS

According to the emissions inventory, which covers the Greek-Cypriot community area presented in this paper, power generation and road transport are the main contributors to total emissions in Cyprus. Power generation share was 36% in total CO_2, 62% in total SO_2, 20% in total NO_x and 55% in total N_2O emissions, while the share of road transport was 29% in total CO_2, 22% in total SO_2, 35% in total NO_x, 48% in total NMVOC and 78% in total CO emissions. The emission results are based on the acquisition and processing of a large amount of activity data and have been calculated with the aid of state-of-the-art algorithms. Cypriot-specific emission factors were used (where available) in the framework of an internationally approved emissions estimation method (EMEP/CORINAIR methodology).

Despite some weaknesses (e.g. coverage of emissions of Greek-Cypriot part only), this work contributes to the efforts for a more systematic approach of emission inventorying procedures in Cyprus, which are rather at a premature stage. The application, on which the emission inventory was based, is 'open', i.e. the activity and emission factor data can be easily revised/updated so that yearly emission inventories can be compiled. At the same time, emissions can be spatially allocated through an easy to use and functional tool. More specifically, the spatial allocation can be made possible with a GIS-aided approach and the generation of reliable data with high spatial resolution data can feed air quality models. The findings of this work can be used for preparing improved national emission estimates, producing maps of emission densities and as a basic source of information for air quality modelling.

Comparisons to other existing emission inventories for Cyprus and official national emission data show differences in the air pollutants set that each inventory reports and deviations in sector contributions to total emissions. Moreover, there are significant deviations in NO_x, NMVOC and CO emissions, but non-significant deviations for SO_2 emissions, a fuel-dependent pollutant. To overcome these discrepancies, Cypriot authorities have to compare and evaluate all available emission inventories and totally or partially adopt methodologies used, calculation procedures, data sets, etc, so as to provide the most reliable emission results. Moreover, in future works the influence of natural emissions (e.g. resuspended dust, sea salt, VOCs) and their contribution in relation to the anthropogenic emissions has to be examined.

ACKNOWLEDGEMENTS

The authors wish to acknowledge financial support from the General Secretariat for Research and Technology (Greece) and the Research Promotion Foundation (Cyprus) made available for the bilateral programme 'Mapping of air pollutant emissions in Cyprus'.

REFERENCES

Baldasano J.M. (1998), Guidelines and formulation of an upgrade source emission model for atmospheric pollutants, Air Pollution Emissions Inventory, H. Power and J.M. Baldasano (Eds.), Computational Mechanics Publications, Southampton, UK and Boston, USA.

Baumbach G., Bari A., Pfeiffer H., Sarachaga-Ruiz L., Kleanthous S., Poulida O. and Beyaz E. (2007), Assessment of air quality in Cyprus, *Newsletter of WHO Collaborating Centre for Air Quality Management and Air Pollution Control*, **39**, 2-9.

Dai J. and Rocke D. (2000), A GIS-based approach to spatial allocation of area source solvent emissions, *Environ Model & Softwr*, **15**, 293-302.

Department of Labour Inspection (DLI), *Annual reports on air quality in Cyprus*, Internet site: http://www.airquality.dli.mlsi.gov.cy (accessed 02/2009).

EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (2007), 3rd edition, European Environment Agency, Copenhagen, Internet site: http://reports.eea.europa.eu/EMEPCORINAIR4/en (accessed 02/2009).

Mellios G. and Samaras Z. (2009), Emissions Inventory, Presentation in the Workshop Development of an emissions inventory and simulation of air quality in Cyprus, Nicosia, 30 January, 2009.

Sidiropoulos C. and Tsilingiridis G. (2006), Development of a spatial database for handling atmospheric emissions data in Greece: the case of road transport, E-Proc. of Int. Conf. Protection and Restoration of the Environment VIII, P-291, Chania, Greece, July 3-7, 2006.

Taghavi M., Cautenet S. and Arteta J. (2005), Impact of a highly detailed emission inventory on modeling accuracy, *Atmos Res*, **74**, 65-88.

Tsilingiridis G. and Fessas J. (2008), Final Report of Greece – Cyprus Bilateral Project: Mapping of air pollutant emissions in Cyprus. (in Greek)