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ORIGINAL PAPER

Variations in emission rates from solvent use in the residential sector: the case of Greece

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Abstract Solvent use is the second most significant source of anthropogenic non-methane volatile organic compound emissions in Europe, as well as in Greece, the residential solvent use being the second most important source of solvent emissions. The methodology used so far in Greece and other countries for estimating residential solvent emissions adopts literature-proposed average per person emission factors and population data. The methodology developed in this work involves the determination of solvent-containing product groups and the solvent content of products, along with the collection, evaluation and elaboration of a large amount of statistical data concerning the domestic supply of products consumed in the residential sector. The emission calculations are performed on the basis of the amount of the solvent-containing products consumed. Two hundred and sixty-six solvent-containing products used in the residential sector are classified into five groups and 24 sub-categories of similar products and an extensive field survey is carried out in order to determine the solvent content of the products. Time series of total emissions for the period 1995–2007 indicate that there is an increasing trend of total residential solvent emissions in Greece. Cosmetics, do it yourself and car care products are the most important emitting categories of residential solvent use. The resulted emission rates (expressed per capita and per year) are greater than those proposed in the literature and they approach in better way local characteristics, as well as their evolution. The methodology developed and the updated emissions rates could be useful in other counties of similar consumption behaviours, economic situation or climate conditions.

Keywords Anthropogenic emissions · Domestic solvent use · Emission factor · Non-methane volatile organic compounds · Solvent content

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Introduction

A solvent is a fluid that dissolves a solid, liquid, or gaseous solute, resulting in a solution. Solvents are usually lower or medium hydrocarbons (alcohols, ketones, esters, ethers, glycols, aromatics, aliphatics and halogenated hydrocarbons). The applications of solvents range from industrial processes to dispersion mediums for coating, cleaning agents, viscosity adjusters, surface tension adjusters, plasticizer, preservatives, etc. Solvents are usually encountered in dry cleaning, as paint thinners, as glue solvents, in detergents, perfumes, shampoos and generally in consumer products.

Solvents usually have a low boiling point and emissions from solvents are primarily the result of solvent evaporation. According to the European Commission (EC) Directive (EC 1999), volatile organic compound (VOC) can be referred to any organic compound having at 293.15 K a vapour pressure of 0.01 kPa or more, or having a corresponding volatility under the particular conditions of use.

Non-methane VOCs (NMVOCs) are the primary gases emitted from most processes employing solvents. NMVOC emissions are of great interest because certain species of them are toxic and carcinogens; exposure to even small quantities can bring about irreparable damages to human health (Clarke and Ko 1996). Indoor air quality is a factor

closely related to health issues and for that reason the air quality of residential areas or work places is studied and analysed (Assimakopoulos et al. 2008; James and Yang 2005). A serious effort is also put on abatement methods for controlling VOC emissions (Soltanali and Shams Hagani 2008; Rahbar and Kaghazchi 2005).

International bodies consider solvent use as one of the major source categories for which countries should report emissions (European Environmental Agency, EEA 2009; IPCC 2006). On European scale, solvent use contribution is roughly a quarter of total anthropogenic NMVOC emissions. On country scale, this contribution ranges from 15 to 30% of total anthropogenic NMVOC emissions (EEA 2007). The Council of the European Union has imposed a gradual implementation of measures regarding the limitation of NMVOC emissions from the use of organic solvents in certain activities and installations. This is implemented in recognition of the effects of NMVOC emissions on human health (EC 1999). In addition, the DECOPAINT Directive of the EC (2004) sets maximum VOC content limit values for certain paints, varnishes and vehicle refinishing products.

Previous work in the field of solvent emission inventorying is primarily in the context of total anthropogenic VOC emission estimations (Battye 1993; Clarke and Ko 1996; Jones et al. 2005; Klimont et al. 2002), while others deal with the speciation of NMVOC or provide spatial solvent emission patterns (Brulfert et al. 2005; Dai and Rocke 2000; Sidiropoulos and Tsilingiridis 2007; Wei et al. 2008). A number of works present national solvent mass balance inventories and tackle potential abatement issues (Fauser and Illerup 2008; Fauser 2010; Rypdal 1995; Theloke 2005).

Although emissions from solvent use in residential sector are of major importance in urban environment they are very difficult to estimate, and up to now published work in the field of emissions from solvents use in residential sector is limited.

So far, emissions from solvent use in the residential sector (excluding paint) were estimated in the context of local, regional or national emission inventories (Brulfert et al. 2005; Niedojadlo et al. 2007; Parra et al. 2006; Rahbar and Kaghazchi 2005), taking into account population statistics and adopting emission factors (EFs), expressed per capita and per year, produced in the USA, the UK and Canada (EEA 2007). The main weak point of adopting EFs from international literature is that neither cultural and local characteristics are taken into account when applied to other countries nor changes in consuming behaviours (which are largely dependent on the economic situation) through time.

Only recently a major effort is done in inventorying emissions from solvent use in the residential sector (Fauser 2010; Holmengen and Kittilsen 2009; Kittilsen 2010; Swedish Environmental Protection Agency 2011; Theloke 2005), but still emissions from solvent use in the residential sector are mainly examined, estimated and reported together with other solvent use categories.

In Greece, solvent use is the second most important source of anthropogenic NMVOC emissions accounting for about 16% of total NMVOC emissions in 2004, according to the National Observatory of Athens (NOA 2006). In the greater urban area of Thessaloniki, the second largest city in Greece, solvent NMVOC emissions accounted for 29.3% (6.74 kt) and 23.2% (6.46 kt) of total anthropogenic emissions (23.03 and 27.89 kt) in 1995 and 2002, respectively, while road transport was responsible for 44.9% (10.34 kt) in 1995 and 52.8% (14.72 kt) in 2002 (Moussiopoulos et al. 2009; Tsilingiridis et al. 2002). According to recent findings, the categories, which contribute significantly to total solvent NMVOC are paint applications (~45%) and solvent use in the residential sector excluding paint (~39%) (Sidiropoulos and Tsilingiridis 2009).

The aims of this research are to overcome the weaknesses of the methodology used so far, providing a detailed transparent and consistent methodology for NMVOC emissions inventorying from residential solvent use, to improve the residential solvent emission estimation procedures by attributing NMVOC emissions to certain categories of use, as well as to produce detailed NNVOC EFs representative of the solvents use in Greek households. This is significant in many cases where there is need for reliable input data, i.e. in conducting exposure assessment studies, in developing emission scenarios or in air quality modelling efforts, where input data (emissions, meteorology, elevation, and land cover) must be characterized by high spatial and temporal resolution. Due to the direct contact of humans with indoor NMVOCs, a compilation of an emissions inventory, which will quantify the NMVOC emissions from residential solvent use is of vital importance. Such an inventory can be an additional support tool for decision makers to identify priority sectors for measures to control emissions and to achieve compliance with the solvent emission directives.

To accomplish the aforementioned goals, a large amount of activity data is collected concerning the consumption of solvent-containing products for the period 1995–2007. The diffuse structure of solvent use as a pollution source (Reis 2005), the difficulties in obtaining and handling the activity data (e.g. complexity, scarcity, overlapping, and diversity), along with the determination of the solvent content of the products used, are the major difficulties in residential solvent emission inventorying. To overcome them, an extensive market research is carried out, combined with literature review and judgment of experts.

Materials and methods

The methodology followed so far in Greece (NOA 2006; Sidiropoulos and Tsilingiridis 2009) was the simple one proposed by the EEA (2007) and based on a single average EF expressed on a per person basis (2.6 kg/cap/year) to derive emission estimates by multiplying the EF by population. The recent EEA emission inventory guidebook (EEA 2009) proposes, for the simple methodology, a default EF of 1 kg/cap/year (lower–upper value: 0.5–3.0 kg/cap/year), which has been derived from an assessment of the EFs presented in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model of the International Institute for Applied Systems Analysis (IIASA 2008). It represents a weighted average of the EF from this model for all the countries considered in 2000. It should be noted that per person EF is likely to vary considerably among countries, particularly Western from Eastern European countries, or Northern from Southern countries.

In a more detailed approach, residential solvent use is classified into the following categories: (1) household products, (2) cosmetics and toiletries, (3) do it yourself (DIY) products/buildings, (4) car care products (EEA 2007). According to the detailed approach, EFs are proposed for each source category. These EFs are derived from studies in the USA, the UK and Canada (EEA 2007) and are presented in Table 1.

The above EFs are from the early 1990s, therefore they reflect people's behaviour 15–20 years ago and this raises concerns as to whether consuming behaviours (and especially those of other countries) can be equally matched. To overcome this 'mismatch' of the above-mentioned EFs to local characteristics and culture and because of general consuming behaviour differences, an analytical method is developed, which involves the collection of data on the solvent content of each type of consumer product. This is combined with consumption statistics in order to obtain estimates of quantities of NMVOCs used in each category of products. The solvent contained in some consumer products may not all be emitted into the atmosphere; therefore, the solvent content and the consumption statistics are combined with suitable factors to derive emission estimates.

In the present work, solvent-containing products used in the residential sector are classified into five major categories. An extensive field survey is carried out in order to attribute all the solvent-containing products available in the market to the following categories:

- Washing and cleaning products (W/C).
- Personal healthcare products (H/C).
- Cosmetics.
- Homeware and DIY products.
- Car care products.

The separation into five major categories is made for reasons of compliance with data derived from the Statistical Authority of Greece (ELSTAT) and European statistics (EUROSTAT). Personal communication and interviews were conducted with representatives of the aforementioned institutions during the separation process in order to assure the validity of the activity data.

Household products have been separated in washing and cleaning products and personal healthcare products because they comprise different fractions of solvent emitted and they can be included in different abatement measures. Washing and cleaning products include cleaning preparations, air-fresheners and toilet blocks. It is noted that cleaning preparations include both dish-washing and clothes-cleaning products, as well as all-purpose cleaners. Personal health care products include dentifrices, shampoos, hair softeners, bath and shower preparations, soap and shaving preparations. Cosmetics include manicure or pedicure preparations, make-up, skin care, suntan preparations, lip and eye make-up preparations, hair lacquers, hair-gel preparations, deodorants and antiperspirants, perfumes and lotions for personal use. Homeware and DIY products include glues and adhesives available in retail

Table 1 Emissions factors (kg/cap/year) for residential solvent source categories (EEA 2007)

Product category	UK[a]	Canada[b]	USA[c]
Household products	0.238	0.578	0.431
Cosmetics and toiletries	0.773	0.785	1.061
Do it yourself/buildings	0.292	0.270	0.499
Car care products	0.428	0.980	0.649
Aerosol propellant	0.786	Included in the above categories	Included in the above categories
Total	2.517	2.612	2.641

According to EEA, sources of these data are: [a] Atlantic Consulting (1995): emissions of volatile organic compounds from non-aerosol consumer products in the UK. Unpublished report commissioned by AEA Technology on behalf of the UK Department of the Environment. [b] UN ECE (1990): emissions of volatile organic compounds (VOC) from stationary sources and possibilities for their control, University of Karlsruhe.[c] US EPA (1995): EPA consumer products survey (draft only)

sale, anti-rust and anti-corrosion preparations, leather waxes and polishes, furniture waxes and polishes and turpentine. Car care products include car polishes, anti-freezing preparations and hydraulic break fluids. In Table 2, all 5 categories and 24 sub-categories used are presented in more detail.

For ease of access and management of products, a database is developed in which 266 household products are recorded in order to securely assess solvent composition. It should be noted that the majority of the solvent-containing products of each sub-category use the same solvent or solvents having similar properties. In Table 3, a distinct separation of all the chemical compounds recorded as solvents in the aforementioned products is presented, which is the main outcome of the survey and personal communication and interviews.

Emission calculations are performed for all sub-categories on the basis of the amount of the solvent-containing products consumed. Generally, the total amount of solvent used, either as pure solvent-product or as content of other products, is released into the atmosphere. However, in some products the NMVOC will be 'lost' mainly in waste water. The following formula is used to estimate NMVOC emissions from all sub-categories:

Table 2 Solvent-containing products for residential use

Product category	Sub-category
Washing and cleaning	Surface-active preparations, washing preparations, auxiliary washing preparations and cleaning preparations put up for retail sale (excluding organic surface-active agents, soap and organic surface-active preparations in the form of bars, cakes, moulded pieces or shapes, and products and preparations for washing the skin in the form of liquid or cream)
	Preparations for perfuming or deodorizing rooms, including odoriferous preparations used during religious rites (excluding agarbatti and other odoriferous preparations which operate by burning)
Personal healthcare	Dentifrices (including toothpaste and denture cleaners)
	Shampoos
	Preparations for use on the hair (excluding shampoos, preparations for permanent waving or straightening and hair lacquers)
	Perfumed bath salts and other bath and shower preparations
	Soap in the form of flakes, granules, powder, paste or in aqueous solution
	Shaving preparations, including pre-shave and after-shave products
Cosmetics	Manicure or pedicure preparations
	Beauty or make-up preparations and preparations for skin care (other than medicaments), including sunscreen or suntan preparations (excluding medicaments, lip and eye make-up preparations, manicure or pedicure preparations and make-up or skin care powders, including baby powders)
	Lip make-up preparations
	Eye make-up preparations
	Hair lacquers
	Preparations for permanent waving or straightening
	Personal deodorants and antiperspirants
	Perfumes and toilet waters (excluding aftershave lotions, personal deodorants and hair lotions)
Homeware and do it yourself	Products suitable for use as glues or adhesives put up for retail sale as glues or adhesives, with a net weight of $\leq$1 kg
	Lubricant preparations, including cutting-oil preparations, bolt or nut release preparations, anti-rust or anti-corrosion preparations and mould-release preparations, based on lubricants and containing petroleum oil or bituminous mineral oil (excluding preparations containing, as basic constituents, $\geq$70% of petroleum oil or bituminous mineral oil by weight and preparations for treating textiles, leather, furskins and other materials)
	Polishes, creams and similar preparations, for the maintenance of wooden furniture, floors or other woodwork
	Polishes, creams and similar preparations, for footwear or leather
	Turpentine
Car care	Polishes and similar preparations for coachwork, whether or not in the form of paper, wadding, felt, non-wovens, cellular plastics or cellular rubber, impregnated, coated or covered with such preparations (excluding artificial and prepared waxes of heading 3,404 and metal polishes)
	Anti-freezing preparations and prepared de-icing fluids (excluding prepared additives for mineral oils or other liquids used for the same purposes as mineral oils)
	Hydraulic brake fluids and other prepared liquids for hydraulic transmission not containing petroleum oil or bituminous mineral oil, or containing <70% petroleum oil or bituminous mineral oil by weight

Table 3 Chemical compound categories and respective solvents used in products used in residential sector

Compound category	Main solvents
Alkanes	Propane, butane, and isobutane
Aliphatics	White spirit and naphtha
Aromatics	Toluene, ethyl benzene, and xylene (mixed isomers)
Alcohols	Ethanol, isopropanol, C12–C13 alcohol, alcohol ethoxylates, hexanol, butoxypropanol, 2-aminoethanol, benzyl alcohol, methanol, *n*-butyl or isobutyl alcohol, polyvinyl alcohol, and glycerine
Esters	Benzyl acetate, butyl acetate, ethyl acetate, and 1-methoxy-2-propanol acetate
Glycols and ethers	Dipropylene glycol *n*-propyl ether, 2-butoxyethanol, phenoxyethanol, dipropylene glycol methyl ether, ethoxydiglycol, polyethylene glycol, ethylene glycol *n*-hexyl ether, glycol ether, ethylene glycol *n*-butyl ether, 1,3-butylene glycol, propylene glycol, diethylene glycol monoethyl ether, di-propylene glycol, butylene glycol, hexylene glycol, diethylene glycol, triethylene glycol, diethylene glycol monobutyl ether, diethylene glycol monopropyl ether, tetraethylene glycol, tetraethylene glycol diethyl ether, ethylene glycol monopropyl ether, dimethyl ether, ethoxytriglycol, butoxytriglycol, an octylene glycol
Ketones	Acetone and methyl-ethyl-ketone
Others	Limonene, kerosene, and turpentine

$$\text{NMVOC emissions} = \text{DC} \times \text{SC} \times \text{FE}, \quad (1)$$

where DC is the domestic consumption (t/year), SC the solvent content (%), and FE is the fraction emitted (%).

Domestic consumption (DC)

DC data concern the domestic supply of products consumed in the residential sector. The fundamental statistical activity data collected for each category are sales of domestic production, imports and exports of solvent-containing products, which are derived from national (ELSTAT 2010) and European statistics (EUROSTAT 2010), in quantities (kg/year or 100 kg/year) and in monetary values (€/year). The data management and the attribution to categories are made possible through communication and collaboration with ELSTAT and EUROSTAT officials.

The DC of solvent-containing products is calculated by elaborating raw statistical data using the formula:

$$\text{DC} = \text{S} + \text{I} - \text{E}, \quad (2)$$

where *S* is the sales of the domestic production (t/year), *I* the import (t/year), and *E* is the export (t/year)

At this point it has to be noted that 7% of total raw data was considered inaccurate/unreliable, e.g. 10–25 times higher than previous and next year value, and was replaced with the average value of the previous and the next year, or in very few cases was excluded. Disqualified values mainly concerns data for the years 2001, 2002 and 2005, accounting for about 20, 11 and 11%, respectively, of total disqualified values. The excluded data come mainly from the sub-categories: nail polish, face make-up, car polishes and waxes and anti-rust/anti-corrosion products. However, only nail polish share in total emissions is worth noticing (up to 6%).

Solvent content (SC)

The SC represents the amount, in percentage, of the chemical compound that is used as solvent in the products corresponding to the sub-categories mentioned above. This percentage has an upper and a lower value and is obtained after an extensive market research and personal communication with manufacturing companies, which provided the material safety data sheets (MSDS) for their products. Personal communication with Greek stakeholders validated that the compositions correspond to Greek reality. Table 4 presents the range of solvent content in each sub-category in the form of an upper and a lower limit. Although washing and cleaning category comprises different activities, an average lower and upper limit was set due to insufficient details on the activity data.

Fraction emitted (FE)

The FE is the proportion of the solvent contained in a product, which is actually emitted into the atmosphere. The FE will vary depending on the way the product is used. According to EEA (2009) for products, which are used diluted in water (i.e. dishwasher detergents, fabric-detergents, etc.) 1% is assigned; for products, which are removed with water after performing their function (i.e. shampoos, soaps, toothpaste, household cleaners, etc.)

Table 4 Solvent content of end-products (%)

Product category/sub-category	SC_{min}	SC_{max}
Washing and cleaning		
Washing/cleaning[a]	1.1	11
Room deodorants	1	7
Personal healthcare		
Toothpaste	0	70
Shampoo	0	0.5
Hair softeners/conditioners/colours	0.6	24.5
Bath and shower gels	0	10
Crème soaps/soaps	0	5.5
Pre-shave and after-shave	0	60
Cosmetics		
Nail polish	18	97
Make-up/skin care	1.75	11.75
Lipstick	0.1	60
Eye make-up	3	30
Hair spray	25	91
Hair gel	2.1	13
Deodorants and antiperspirants	10	95
Perfumes	45	95
Homeware and do it yourself		
Glues/adhesives	0	75
Furniture waxes and polishes	39	90
Leather waxes and polishes	7	75
Anti-rust/anti-corrosion	1	50
Turpentine	100	
Car care		
Polishes and waxes	7	75
Antifreeze	90	96
Brake fluids	48	100

[a] Washing/cleaning category comprises liquid fabric-detergents for washing machine (WM), liquid fabric-detergents for low temperatures (WM), liquid fabric-detergents for hand-wash (HW), dishwasher detergent products WM and HW, floor detergents, all-purpose glass cleaners

minimum and maximum values of 5 and 50% are assigned; for all other activities the FE is set to 100%, considering that the total amount of solvent contained in the product is released into the atmosphere.

Results and discussion

The resulting total and category emissions for the period 1995–2007 are presented in Fig. 1.

Emissions show an increasing trend up to 2004–2005 and a decreasing trend afterwards. The increasing trend resulted from the increased product mass balance of cosmetics, car care and personal healthcare categories, which contribute significantly to the total NMVOC emission. This can be attributed to both increased touristic activity during years 2003–2005 because of Athens 2004 Olympic Games and the promotion of Greece as a tourist destination and to the significant financial incentives in the automotive sector the same period. Washing and cleaning products, which show a relatively stable emissions level, contribute the least of all categories, largely because of the very low FE factor assigned. On the other hand, emissions from personal healthcare products show an increasing trend until 2004. This can be attributed to the emergence of many 'discount-markets', not only in major urban centres but also in the province, offering products at lower prices. Relatively low total emission values in 2002 are the result of the decreased consumption of that year (low values of product mass balance) due to financial irregularity caused by the introduction of Euro, which replaced national currency.

Cosmetics appear to be the major NMVOC-emitting source in residential solvent emissions mainly because of the frequent use of the products included in this category. This agrees to recent findings in other countries, too (Kittilsen 2010). Perfumes and deodorants/antiperspirants are the most important products of cosmetics category and turpentine and glues contribute the most, in order of importance, in homeware and DIY category. For car care

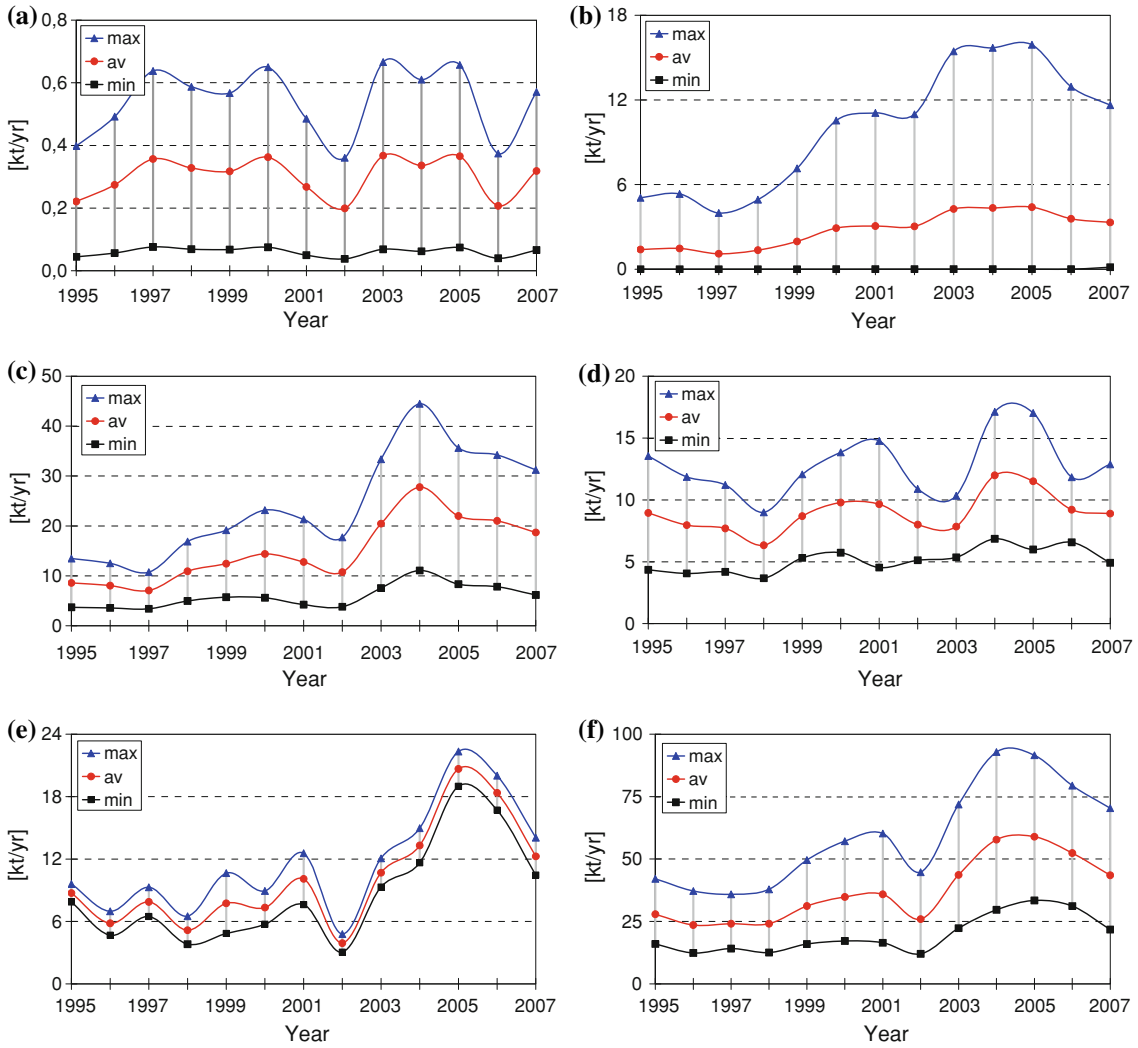

Fig. 1 NMVOC emissions from residential solvent use in Greece. **a** Washing and cleaning, **b** personal healthcare, **c** cosmetics, **d** homeware and do it yourself, **e** car care, **f** total emissions

category, the main contributor is anti-freezing sub-category.

Due to the fact that not all solvent-containing products are actually consumed during a calendar year as statistical data imply, 3-year average emission values (years $i-1$, i, $i+1$) have been calculated for all sub-categories and attributed to each year (i). The total sum of 3-year average emission values is presented in Fig. 2, together with the yearly estimated values. In this way, emission trends are more clear and reliable. Three-year average total NMVOC emissions show similar increase up to 2005, resulting in a doubling of total emissions, and decrease afterwards.

In Fig. 3, the contribution of each main category to total 3-year average emissions for the years 1996–2006 is presented. Cosmetics category is the most important source accounting for 42, 46 and 44% of the total residential solvent emissions in 1999, 2003 and 2004, respectively. Car care and homeware and DIY products are the next two most important contributing categories. Car care category accounts for about 30% in 1996, 31% in 2005 and 33% in 2006. Homeware and DIY category accounts for about 33,

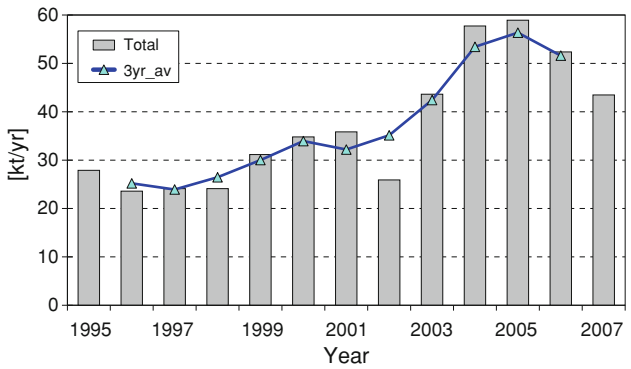

Fig. 2 Evolution of NMVOC emissions (yearly and 3-year average values) from residential solvent use in Greece

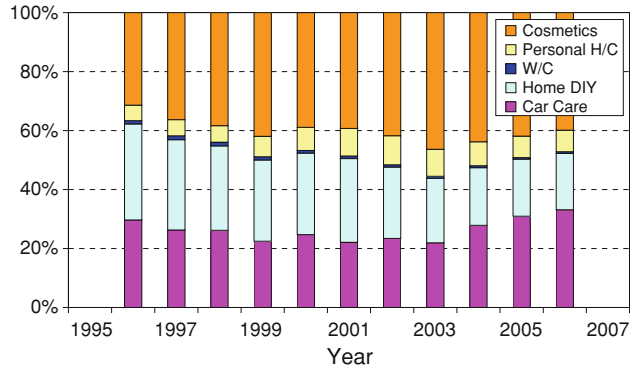

Fig. 3 Contribution of solvent-containing product categories to total NMVOC emissions from 1996 to 2006

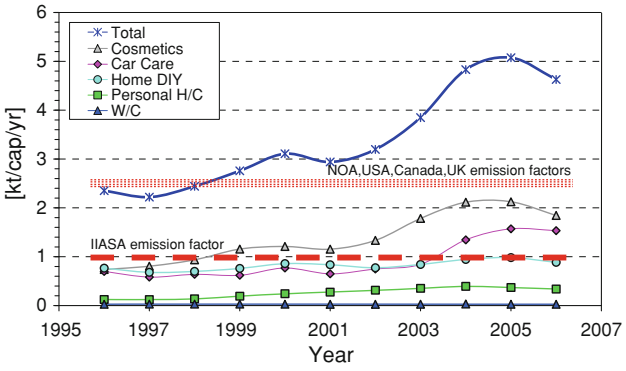

Fig. 4 Comparison of estimated EFs with EFs from literature

31 and 29 for the years 1996, 1997 and 1998, respectively. Personal healthcare and washing and cleaning categories contribute the least to total emissions (10% in 2002 and 1.3% in 1997 peak emissions, respectively).

In Table 5, min–max values of EFs of the main categories calculated by the present work are presented, together with the EFs used by the NOA (2006) and the EFs from the USA, the UK, Canada and IIASA proposed by literature (EEA 2009). In Fig. 4, the average values of the calculated EFs of main categories are presented. It is evident that NMVOC estimated EFs are in relative compliance with the EFs from NOA, the USA, the UK and Canada, with deviations less than 10%, only for the years 1996–1999, i.e. close to the years the literature EFs were determined. The comparison shows that deviations in the following years increase steadily and in 2005 the estimated EFs are twice as high as the proposed values. The increased deviations reflect the dynamic behaviour of solvent-containing products use in the residential sector reflecting social and economic changes in Greece, a country with different cultural customs and climate conditions from the USA, the UK and Canada.

Although in the present work a serious effort is made to better model and estimate solvent NMVOC estimates in the residential sector, uncertainty issues exist. A main uncertainty of the present methodology lies in the fact that the solvent content of products has a broad range and it is assumed to remain constant during the whole period the methodology was applied. Considering the impacts of recent directives on lowering the solvent content in concern of human health implications it is deemed that the

Table 5 Estimated minimum and maximum EFs (kg/cap/year) compared with EFs from literature

Year	W/C Min–max	H/C Min–max	Cosmetics Min–max	Homeware and DIY Min–max	Car care Min–max	Aerosol propellants	Total Min–max
1996	0.006–0.048	0.000–0.448	0.333–1.143	0.392–1.140	0.592–0.805		1.322–3.584
1997	0.006–0.053	0.000–0.441	0.370–1.242	0.368–0.992	0.463–0.704		1.207–3.431
1998	0.007–0.055	0.000–0.494	0.434–1.439	0.405–0.993	0.466–0.813		1.311–3.794
1999	0.006–0.055	0.000–0.693	0.500–1.814	0.450–1.069	0.441–0.799		1.398–4.430
2000	0.006–0.052	0.000–0.878	0.476–1.943	0.475–1.242	0.556–0.981		1.513–5.097
2001	0.005–0.046	0.001–0.993	0.416–1.894	0.468–1.202	0.499–0.800		1.389–4.934
2002	0.005–0.046	0.001–1.138	0.473–2.196	0.455–1.092	0.606–0.892		1.540–5.363
2003	0.005–0.050	0.001–1.274	0.679–2.889	0.524–1.159	0.725–0.962		1.934–6.333
2004	0.006–0.058	0.001–1.418	0.813–3.419	0.549–1.340	1.204–1.487		2.572–7.722
2005	0.005–0.049	0.001–1.337	0.818–3.432	0.583–1.380	1.421–1.720		2.828–7.919
2006	0.005–0.048	0.005–1.210	0.668–3.022	0.522–1.248	1.380–1.687		2.581–7.215
11-year average	0.006–0.051	0.001–0.938	0.543–2.221	0.472–1.169	0.759–1.059		1.781–5.438
NOA							2.60
IIASA							0.50–3.00
UK	0.13–0.40		0.30–1.10	0.04–0.10	0.25–0.70	0.40–2.00	1.12–4.30
USA	0.20–0.60		0.50–1.50	0.20–0.90	0.30–1.00		1.20–4.00
Canada	0.30–0.80		0.40–1.20	0.03–0.10	0.60–1.50		1.33–3.60

calculated emissions of the early years are underestimated. Furthermore, a weak point of the emission estimates presented in this work is the assignment of an averaged fraction emitted for the activities in which the product is diluted to water and of a relative broad range fraction emitted for the activities in which the product is removed with water. Future work should be focused on more detailed determination of the solvent content and the fraction emitted of the products used in the residential sector. This could reduce the uncertainties involved and improve the accuracy of emission estimations.

Conclusion

A detailed NMVOC emission estimation from residential solvent use (excluding paints) in Greece is performed for the years 1995–2007. The analytical methodology developed and proposed in this work involves the determination of solvent-containing product groups and the solvent content of products, along with the collection, evaluation and elaboration of a large amount of statistical data concerning the domestic supply of products consumed in the residential sector. It helps to better understand and estimate solvent emissions from the residential solvent use, specify main contributors, improves existing methodology and proposes EFs expressing local characteristics, as well as their evolution. In addition, by introducing the share of activities, which are included in the main categories points out major emission sources for the application of abatement measures. This work could be an additional support for decision makers to identify priority sectors for measures to control emissions and to achieve compliance with the solvent emission directives.

Time series of total emissions for the period 1995–2007 indicate that there is an increasing trend of total residential NMVOC in Greece. Cosmetics, homeware and DIY, and car care categories are the main contributors in total NMVOC emissions.

The resulted EFs (expressed as emission rates per capita and per year) are greater than those proposed in the literature and they approach local characteristics as well as their evolution in a better way.

The methodology developed and the analytical estimation procedure in the present work can be followed in other countries of similar consumption behaviours, economic situation or climate conditions, since in international level the majority of the solvent-containing products used in residential sector are the same or have similar properties. The updated emissions rates/factors can be easily used in the case there is no possibility for detailed work or there is a need for instant results or for comparison purposes.

The present work also indicates the need towards regular and extensive campaigns for a better determination and breakdown of the data provided by international and national statistical authorities, as well as the determination of the solvent content and the fraction emitted of the product used in the residential sector. This could lead to a more improved and detailed estimation by reducing the uncertainties involved.

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References

Assimakopoulos VD, Saraga D, Helmis CG, Stathopoulou OI, Halios CH (2008) An experimental study of the indoor air quality in areas of different use. Global NEST J 10:192–200

Battye W (1993) Trends and uncertainties in volatile organic compound emissions from anthropogenic sources. Water Air Soil Pollut 67:47–56

Brulfert G, Chollet JP, Jouve B, Villard H (2005) Atmospheric emission inventory of the Maurienne valley for an atmospheric numerical model. Sci Total Environ 349:232–248

Clarke AG, Ko YH (1996) The relative significance of vehicular emissions and other emissions of volatile organic compounds in the urban area of Leeds, UK. Sci. Total Environ 189–190: 401–407

Dai J, Rocke DM (2000) A GIS-based approach to spatial allocation of area source solvent emissions. Environ Model Softw 15:293–302

EC (1999) Council Directive 1999/13/EC on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and installations

EC (2004) DECOPAINT Directive 2004/42/CE on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products and amending Directive 1999/13/EC

EEA (2007) EMEP/CORINAIR emission inventory guidebook-2007. Group 6. Solvent and other product use. Technical report No 16/2007. http://www.eea.europa.eu/publications/EMEPCORINAIR5/B600vs2.2.pdf (accessed August 2010)

EEA (2009) EMEP/EEA air pollutant emission inventory guidebook-2009. 3.D.2 Domestic solvent use including fungicides. Technical report No 9/2009. http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/3-product-use/3-d/3-d-2-domestic-solvent-use.pdf (accessed August 2010)

ELSTAT (2010) Data on solvent-containing products: imports, exports and domestic production. http://www.statistics.gr (accessed in June 2010)

EUROSTAT (2010) Data on solvent-containing products: imports, exports, domestic production and sales. http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database (accessed July 2010)

Fauser P (2010) Danish Emission Inventory for solvent use in industries and households. National Environmental Research Institute, Aarhus University, Denmark. NERI Technical Report no. 768. http://www.dmu.dk/Pub/FR768.pdf (accessed July 2011)

Fauser P, Illerup JB (2008) Danish emission inventory for solvents used in industries and households. Atmos Environ 42:7947–7953

Holmengen N, Kittilsen MO (2009) Estimating emissions of NMVOC from solvent and other product use. Revised model, Report 2009/14, Statistics Norway. http://www.ssb.no/english/subjects/01/04/10/rapp_200914_en (accessed July 2011)

IIASA (2008) Greenhouse gas and air pollution interactions and synergies (GAINS) model. http://www.iiasa.ac.at/rains/gains-online.html

IPCC (2006) In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan

James JP, Yang X (2005) Emissions of volatile organic compounds from several green and non-green building materials. A comparison. Indoor Built Environ 14:69–74

Jones DL, Fudge S, Battye B (2005) Solvent mass balance approach for estimating VOC emissions from eleven nonpoint solvent source categories. 14th Annual US Emission Inventory conference, Las Vegas

Kittilsen MO (2010) Norwegian NMVOC emissions from sector 3: solvent and other products use. Providing a basis for discussing the inclusion of new emission sources in the guidebook. Statistics Norway, June 2010. http://www.ssb.no/emner/01/04/10/notat_201020/notat_201020.pdf (accessed July 2011)

Klimont Z, Streets D, Gupta S, Cofalaa J, Lixin F, Ichikawa Y (2002) Anthropogenic emissions of non-methane volatile organic compounds in China. Atmos Environ 36:1309–1322

Moussiopoulos N, Vlachokostas Ch, Tsilingiridis G, Douros I, Hourdakis E, Naneris C, Sidiropoulos C (2009) Air quality status in Greater Thessaloniki Area and the emission reductions needed for attaining the EU air quality legislation. Sci Total Environ 407:1268–1285

Niedojadlo A, Becker KH, Kurtenbach R, Wiesen P (2007) The contribution of traffic and solvent use to the total NMVOC emission in a German city derived from measurements and CMB modelling. Atmos Environ 41:7108–7126

NOA (2006) National Inventory Report. Report to the Hellenic Ministry for the Environment, Physical Planning and Public Works of Greece (in Greek)

Parra R, Jiménez P, Baldasano JM (2006) Development of the high spatial resolution EMICAT2000 emission model for air pollutants from the north-eastern Iberian Peninsula (Catalonia, Spain). Environ Pollut 140:200–219

Rahbar SM, Kaghazchi T (2005) Modeling of packed absorption tower for volatile organic compounds emission control. Int J Environ Sci Technol 2(3):207–215

Reis S (2005) Costs of air pollution control-analyses of emission control options for ozone abatement strategies. Springer, Berlin

Rypdal K (1995) Løsemiddelbalance for Norge-Uttslip, Forbruk og Metode (A solvent balance for Norway-emissions, consumption and methodology). Statens Forurensningstilsyn, Report 95:02. Oslo, Norway (in Norwegian)

Sidiropoulos C, Tsilingiridis G (2007) Composition changes in NMVOC emissions from solvent use in Greece for the period 1990–2005. Fresen Environ Bull 16:1108–1112

Sidiropoulos C, Tsilingiridis G (2009) Improved sectoral allocation of NMVOC emissions from solvent use in Greece. Sci Total Environ 407:4075–4083

Soltanali S, Shams Hagani Z (2008) Modeling of air stripping from volatile organic compounds in biological treatment processes. Int J Environ Sci Technol 5(3):353–360

Swedish Environmental Protection Agency (2011) National Inventory Report 2011. Sweden. http://www.naturvardsverket.se/upload/05_klimat_i_forandring/statistik/2010/NIR-submission-2011.pdf

Theloke J (2005) NMVOC-emissionen aus der Lösemittelanwendung und Möglichkeiten zu ihrer Minderung (NMVOC emissions from solvent use and abatement potentials). Doctoral thesis, Fakultät Maschinenbau, Universität Stuttgart (in German)

Tsilingiridis G, Zachariadis T, Samaras Z (2002) Spatial and temporal characteristics of air pollutant emissions in Thessaloniki, Greece: investigation of emission abatement measures. Sci Total Environ 300:99–113

Wei W, Wang S, Chatani S, Klimont Z, Cofalaa J, Hao J (2008) Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China. Atmos Environ 42:4976–4988