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THE EUROPEAN INDOOR RADON MAP AND BEYOND

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Abstract: Started six years ago, the European map of indoor radon concentrations has evolved to include data from 25 countries, covering a fair part of Europe. As of October 2012, the map is composed of more than 18,000 non-empty grid cells with data, based on more than 800,000 individual measurements. The number of measurements per cell ranges from one up to nearly 24,000. The coverage of territory varies widely between the countries: from less than 20% for some up to more than 100% for others (due to a border effect). While the arithmetic mean for all non-empty cells in Europe (for all participating countries) is 100 Bq/m^3, the median is 65 Bq/m^3. In parallel, a European map of geogenic radon potential is under development, with a first, trial map having been published. These and other maps will eventually form parts of a planned European Atlas of Natural Radiation.

Keywords: Indoor radon, geogenic radon, mapping, Europe

1. INTRODUCTION

Under the Euratom Treaty, the European Commission (EC) is obliged to collect, validate and report data from EU Member States on radioactivity levels in the environment. This is the main task of the Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC). After the EC published the “Atlas of Caesium Deposition on Europe after the Chernobyl Accident” (De Cort et al. 1998), the JRC decided to embark on a European Atlas of Natural Radiation, intended to provide the public with a more balanced view of the annual dose that it may receive from environmental radioactivity.

We started with indoor radon, since in most cases this is the most important contributor to population dose. Its radioactive progenies are also considered by the majority of researchers to be the leading cause of lung cancer, second only to smoking (Darby et al., 2005). Given its relevance to public health, most European countries have implemented a number of regulations to identify radon-prone areas, where prevention and mitigation are considered particularly important. A survey conducted by the JRC in 2005 (Dubois 2005) showed that many European countries had attempted to display the national radon situation in the form of maps, but everywhere in a different way. The differences stemmed from the choice of mapped quantity and in the type of visualization. Weaving them together on a European scale resulted in a colourful mosaic, albeit not a very useful European radon map.

The survey also showed that indoor radon measurements are available from most European countries. After decisive discussions at the Prague radon workshop in 2006, the countries agreed to contribute indoor radon data to a European map, according to a set of technical specifications to be defined by the JRC. Also non-EU countries take part in this project.

2. THE EUROPEAN INDOOR RADON MAP

2.1. Design

The European Indoor Radon Map (EIRM) map is intended to show “means over 10 km × 10 km grid cells of (mean) annual indoor radon concentration in ground-floor rooms of dwellings.” The participants (national competent authorities, laboratories, universities etc.) aggregate original data into cells over a grid covering Europe. Defined by the JRC, this grid uses the GISCO-Lambert azimuthal equal-area projection with spherical earth as datum and centre of projection located at 9º E and 48ºN.

Specifically, participants fill the cells with the following statistics calculated from the original data: the arithmetic mean (AM), standard deviation (SD), AM and SD of the ln-transformed data, median, minimum and maximum, as well as the number of original measurements in the cell. This procedure was agreed upon to ensure data protection, because the original data and their exact location are not given away, but remain at the national level. The methods and procedures to collect and process the raw data have been further described in Dubois et al., (2010) and Tollefsen et al., (2011).

The choice of variable to be mapped can be seen as a compromise between an indoor radon map and a geogenic "radon potential" map. Moreover, restricting the data to annual mean radon concentration on ground-floor rooms means that data providers have to estimate this quantity, in the best case from long-term measurements. When measurements have been made over shorter periods, some intermediate modelling involving seasonal corrections may be necessary to estimate annual means. It is also true that most people do not actually live on ground floors. In spite of its limitations, this approach was adopted simply because most data are available for this variable.

It must therefore be stressed that statistics over the chosen quantity do not represent the ones of exposure. For that purpose, either data must result from a carefully designed survey which reflects demographic reality (samples representative for population density and house and dwelling characteristics), or model-based correction to account for demographic representativeness must be performed. Since few national radon surveys are designed that way (see below), and on the other hand the demographic data are not yet available to us, neither the "design-based" nor the "model-based" approach could be chosen for generating a European radon exposure map; it must therefore be left to future efforts.

2.2. Sampling density

As of October 2012, 25 European countries participate to the EIRM. We have more than 18,000 non-empty cells filled with data, based on more than 800,000 individual measurements in total.

As seen from figure 1, the number of measurements per cell and coverage of territory vary widely between countries and regions of individual countries. The number of measurements per cell ranges from one up to a maximum of nearly 24,000 (for a cell in the UK). Still, there are many empty cells. The map thus reflects the status of national surveys of indoor radon monitoring in Europe.

Large areas with high sampling density are found in the Czech Republic, Austria, Switzerland, North Italy, Belgium, the UK and South Finland. The median number of measurements per cell equals 4, with a median absolute deviation (MAD) of 3. This heterogeneity of sampling density influences the statistical uncertainty of the means as estimates of the expected concentration within a cell, as it does for the standard deviation and other statistics.

Figure 2 shows the percentage of coverage over the national territories. Several countries (Denmark, the UK, Switzerland, the Czech Republic and Belgium) have covered more than 100% of their territories, because border cells of the grid have been filled with data, even when only a part of them belongs to the country. On the other hand, some countries (Serbia, Romania, Albania, Spain, Poland, Estonia, Greece and Norway) have covered (or sent data for) less than 20% of their territories. Our approach is to include all countries which have provided data and display them on the map, even if they have conducted only specific surveys in some areas or just started their national surveys. The reader should bear in mind that the figures are not necessarily representative for each country, but only present statistics drawn from the data provided to us.

The wide ranges in sampling density depend on the design of the survey from which the data originate. Since 2010, the JRC has sent a quality-assurance questionnaire to the data providers (see below), asking them *inter alia* for information about their survey designs. In most of the 20 countries that have responded so far, the datasets are a result of several studies and surveys, often carried out with different purposes and therefore different survey designs (see Fig. 3). Some countries have mainly aimed for homogeneous coverage of territory, while others (e.g. Austria) have aimed for a population-weighted estimate of the radon concentration, which results in sampling density essentially proportional to population density. Five of the countries have carried out more detailed surveys in high-radon areas in order to identify homes with high indoor radon concentrations. Some of the datasets are mainly or only based on surveys in radon-prone areas (e.g. Estonia, Greece, Romania and Poland).

As biased sampling influences the statistics, so the data are not necessarily representative for the whole countries. Some countries (Serbia, Slovenia, Hungary, Portugal and Norway) are not taken into account in figure 3, because we do not yet have detailed information about their survey design.

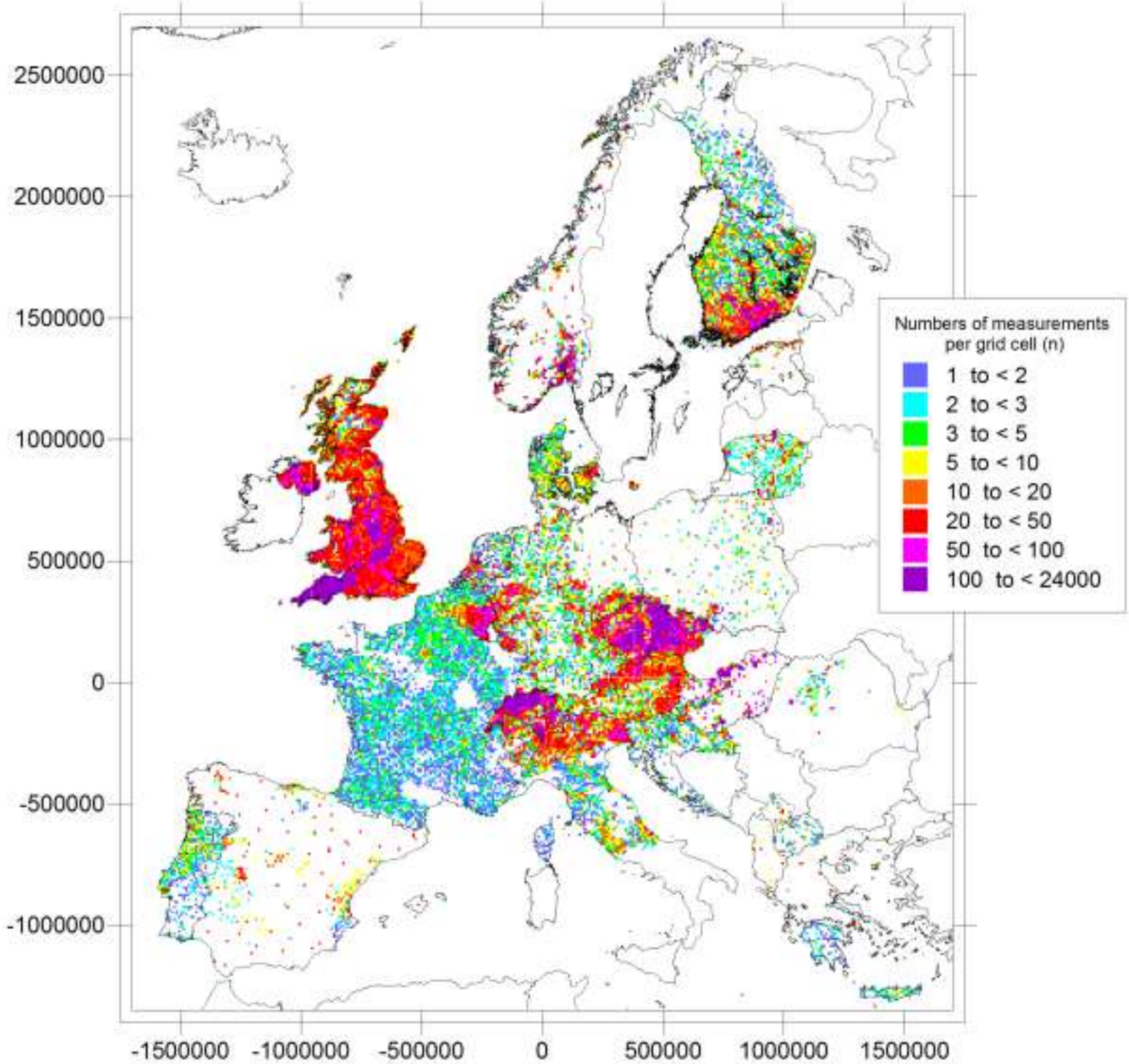

Figure 1. Number of measurements per 10 km × 10 km cell. Data available until October 2012 included.

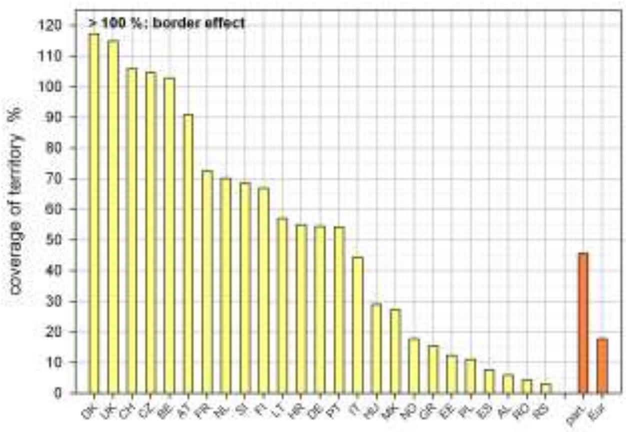

Figure 2. Percentage of coverage of territory for each country, all participating countries and Europe. The ISO country codes are: AL – Albania; AT – Austria; BE – Belgium; CH – Switzerland; CZ – Czech Republic; DE – Germany; DK – Denmark; EE – Estonia; ES – Spain; FI – Finland; FR – France; GR – Greece; HR – Croatia; HU – Hungary; IT – Italy; LT – Lithuania; MK – F.Y.R. of Macedonia; NL – the Netherlands; NO – Norway; PL – Poland; PT – Portugal; RO – Romania; RS – Republic of Serbia; SI – Slovenia; UK – the United Kingdom.

A discussion of selected quality-assurance topics can be found in Bossew et al., (2012).

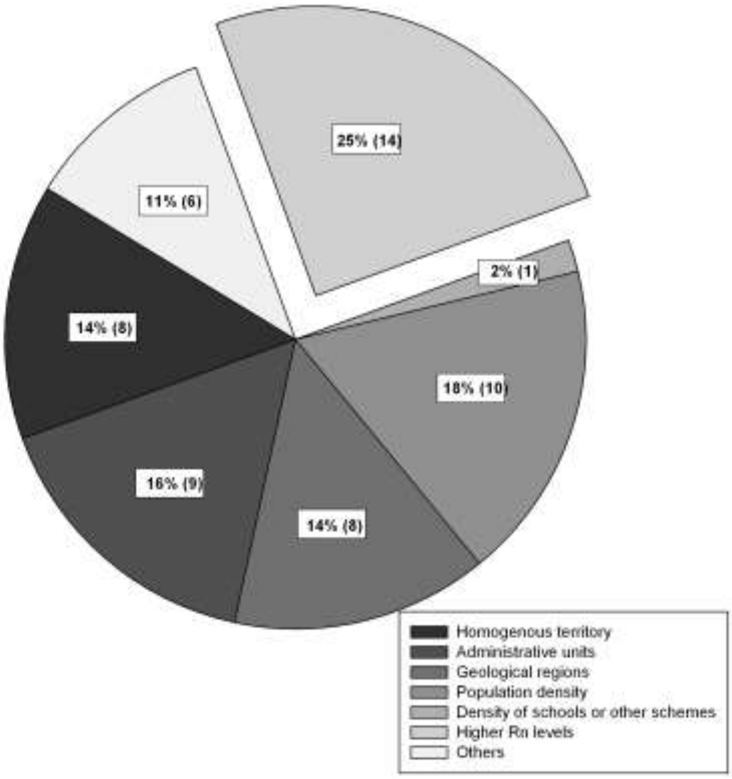

Figure 3. Designs of radon surveys in the countries which have responded to the data-quality questionnaire (20 out of 25). The sectors represent (from dark to light shade): Homogeneous territory; administrative units; geological regions; population density; density of schools or other schemes; higher radon levels; others.

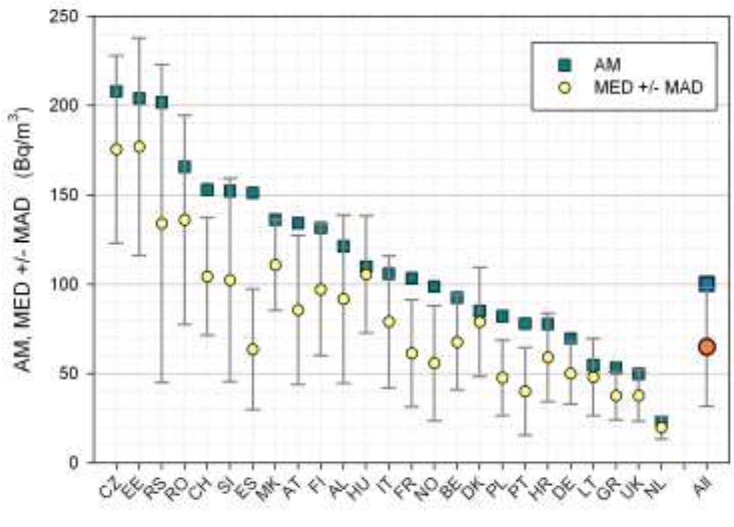

Figure 5. Estimated spatial mean Rn concentrations per country. AM – arithmetic mean over AMs within cells; MED – medians over AMs within cells; MAD – median absolute deviation = MED{|AM_i – MED(AM_i)|}, where AM_i = AM in cell *i*. See Figure 2 for country codes.

2.3. Cell means

Figure 4 shows the geographical distribution of cell means. The map reveals a spatial trend in indoor radon concentrations across Europe, essentially reflecting the underlying geology. Regions of high radon concentrations are found in granitic areas of the Bohemian Massif, the Iberian Peninsula, the Massif Central, the Fennoscandian Shield, Corsica, Cornwall and the Vosges Mountains, in the crystalline rocks of the Central Alps and karst rocks of the Swiss Jura and the Dinarides, the black shales in North Estonia and in certain volcanic structures in central Italy.

Physical reasons for the dependence of the geogenic radon potential (see section 3) on geology are the different, typical uranium and radium contents of rocks and soils and different permeability. Rocks with often high uranium content are typically acidic silica-rich magmatites such as certain granites (notably, e.g., young Variscan in Central Europe and the Iberian Peninsula) or sedimentites, which in their genesis include organic matter which under anoxic conditions tends to precipitate and accumulate uranium, such as black or alum shale, common in e.g. Scandinavia and Estonia.

Local anomalies of high uranium content which usually give rise to an elevated radon hazard can be found in almost all rocks. They result from primary processes of ore formation (magmatic differentiation), to geochemical transformations in zones of contact of magmatite and surrounding rock, and to secondary processes of erosion of uranium-rich soil and accumulation in sediments or relocation (solution and precipitation) by groundwater.

High permeability allows generated radon to migrate in the ground and eventually infiltrate into buildings. Certain fractured and weathered granites are permeable, as is unconsolidated or coarse rubble-type material, typical for post-glacial structures (Alpine, Northern Europe). Similarly, karst in itself (Slovenia, Swiss Jura), as limestone, usually has low uranium content, but is strongly fractured and therefore permeable up to macroscopic channels and caves. Very permeable ground does not require high radium content still to have high radon potential. On the other hand, material with sometimes relatively high uranium content, such as clay, usually has low radon potential due to its very low permeability.

Figure 5 illustrates the AM and median (± MAD) of the AMs of the cells for each country. The radon concentrations vary strongly within most countries (see also Fig. 4) due to geology. For instance, the AM of Spain is more than twice the median, as some very high radon concentrations in granitic regions influence the AM more than the median; similarly also for Portugal. The figure shows that countries are affected by the radon problem to a very different extent: the median of the AMs of all the non-empty cells in the Czech Republic approaches 180 Bq/m^3, nearly 10 times that of the Netherlands. The high median of the AMs in Estonia must beinterpreted relative to a sampling scheme targetted towards the high-radon areas in the north.

The AM of all non-empty cells in all of Europe (for participating countries) is 100 Bq/m^3, while the median is 65 Bq/m^3. See table 1 for more statistical parameters of the dataset which underlies the map.

Again we emphasize that the cell mean (AM or median over cell means) is an estimate of the spatial mean of the "long-term mean radon concentration in dwellings in ground-floor rooms", but neither (a) the mean over radon in ground-floor dwellings, nor (b) the mean over all dwellings, i.e. an estimate of exposure. For (a) we would have to calculate a weighted mean with population density by cells as weights; for (b) the distribution of dwellings over floors would have to be included as weight, together with a model which accounts for floor level. Since (a) population centres are preferentially located in valleys and flatlands, often over quaternary geology which in most cases has lower radon potential, and (b) radon

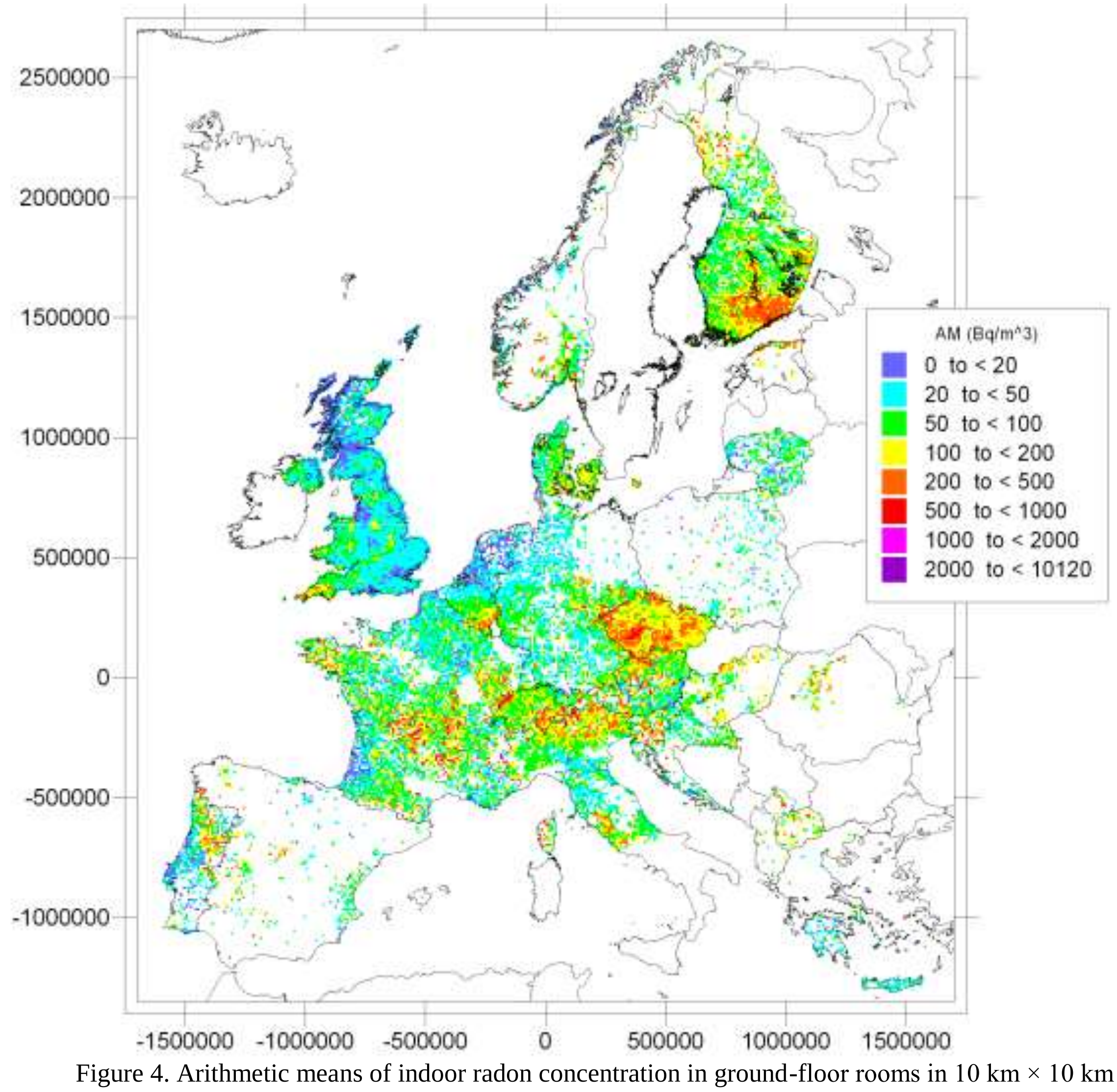

Figure 4. Arithmetic means of indoor radon concentration in ground-floor rooms in 10 km × 10 km cells.

concentration generally decreases with floor level, demographically weighted mean radon concentrations and mean exposure are generally lower than the spatial mean of the quantity discussed here.

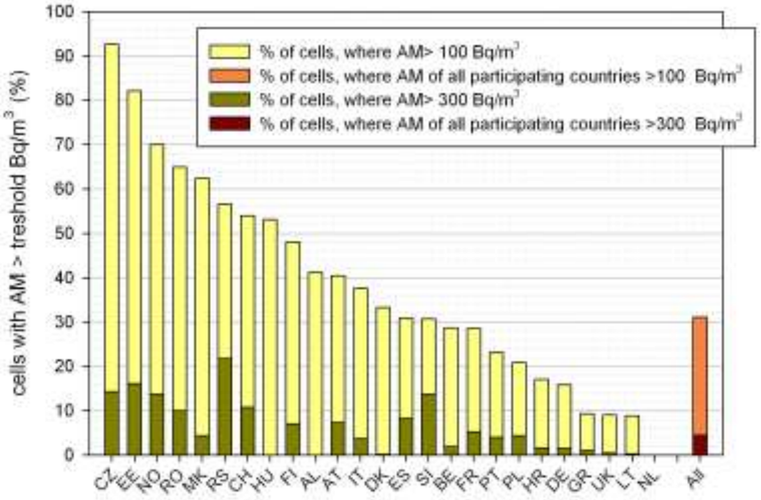

Figure 6. Percentage of cells with AM radon concentration above reference levels of 100 and 300 Bq/m^3 per country and for all participating countries. See figure 2 for country codes.

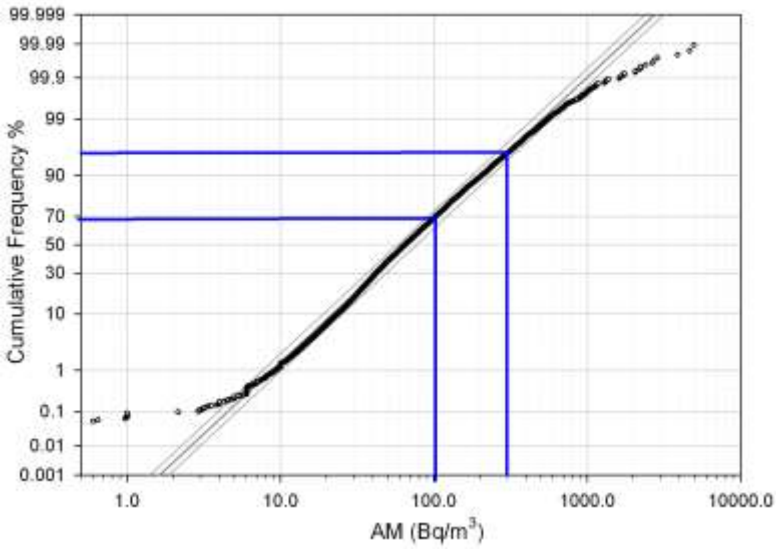

Figure 7. Cumulative frequency distribution of the AMs for non-empty cells.

Table 1. Descriptive statistics of the dataset on which the European indoor radon map is based, as of October 2012.

Number of non-empty cells	18,734
Total number of measurements	818,704
Measurements per cell, MED ± MAD	4 ± 3
Min/Max number of measurements per cell	1 / 23,993
Cell mean, AM ± CV %	100.2 Bq/m^3 ± 152%
Cell median, MED ± MAD	64.9 ± 33.1 Bq/m^3
Percentage Cell AM > 300 Bq/m3	4.51 %
Percentage Cell AM > 100 Bq/m3	31.0 %
CV within cells, MED ± MAD	(55.4 ± 27.6) %
GSD within cells, MED ± MAD	1.87 ± 0.40

CV – coefficient of variation, CV = SD/AM

2.4. Exceedance probability

According to the proposed, new Euratom Basic Safety Standards (European Commission 2011), Member States should establish a radon action plan. They are asked to impose national reference levels for indoor radon concentrations not exceeding (as an annual average) 200 Bq/m^3 for new dwellings and new buildings with public access, 300 Bq/m^3 for existing dwellings, and 300 Bq/m^3 for existing buildings with public access, allowing for low occupancy time a maximum of 1000 Bq/m^3. They shall identify dwellings above reference level and encourage remedial actions, ensure measurements in buildings with public access in radon-prone areas, establish building codes to prevent radon ingress from soil and building materials and provide information (local and national) on the radon situation, risks and means for reducing concentrations.

Figure 6 shows the percentage of cells in which reference values of 100 and 300 Bq/m^3 are exceeded. For all participating countries, more than 30% of the non-empty cells have an arithmetic mean above 100 Bq/m^3 and 4.5% above 300 Bq/m^3 (see Table 1). In the Czech Republic, more than 90% of the AMs of all-non empty cells exceed 100 Bq/m^3. At the other end, none of the cells in the Netherlands have an AM above this level. This highlights the different impact of the radon problem on the various countries. But, as already pointed out, the figure also includes countries with low coverage of their territory or with surveys only in radon-prone areas. In general, the caveat raised above for the spatial mean also applies here.

The cumulative frequency distribution of the arithmetic means of the non-empty cells shows an approximately log-normal behaviour with some extremes (see figure 7), (For further discussion of the log-normality of the data, see Bossew, 2010). Half of the non-empty cells of Europe have an AM below 60 Bq/m^3. For 99.8% of the cells an AM below 1000 Bq/m^3 can be expected; for 95% below 300 Bq/m^3 and for 69% below 100 Bq/m^3 (see blue lines in figure 7).

3. THE EUROPEAN GEOGENIC RADON MAP

Even in countries with a completed indoor radon survey, areas remain uncovered (because they are uninhabited, lack of measurements etc.). Moreover, indoor radon concentrations are subject to human activity, natural (geological) and anthropogenic factors such as construction types, building materials, living habits and meteorology, and are temporally variable and characteristic for each particular house (these factors may still show regional trends caused by regionally predominant climate and cultural preferences). For instance, two differently built houses on the same geological ground will have different average indoor radon concentrations, as will two identically built houses on the same ground, but with different living habits of the inhabitants. As another case, improving the insulation of a house can influence its indoor radon concentration. Therefore, one is interested in mapping a quantity which is closer to hazard, and which measures "what earth delivers" in terms of radon, irrespective of anthropogenic factors and temporally constant over a geologic timescale. This quantity, or spatial variable, is called geogenic radon potential, and the idea of the European Geogenic Radon Map (EGRM) is to map such a variable.

While mapping indoor radon is far from straightforward, mapping geogenic radon is even more complex (some of the problems are discussed in Gruber et al., 2012a). In order to discuss methods and possible strategies and define the variable called "geogenic radon potential", a group of experts, mainly geologists and physicists, was established. As a first step, a report is in preparation which collects knowledge from the relevant scientific fields; it should serve as a basis for further discussions and decisions how to proceed with the EGRM. After several meetings the experts decided that the EGRM should be closely linked to the OneGeology project (OneGeology), which provides geological maps and definitions of 20 European countries in a harmonized way. To define the target variable, a multivariate classification of several relevant and available parameters seems to be the most stable and effective method to start with. For this purpose the JRC created a geogenic radon database and asked the participating countries to fill it with all relevant and available data, based on geological units linked to OneGeology. Not all countries will have enough data for all variables and geological units to classify their radon risk. Therefore transfer models, which are not a trivial issue, will be necessary. As a major goal the database should also help to identify geologically similar units in other regions or countries where no measurement data exist, so that they can be used there as default values. Out of this we aim to construct a harmonized European map of geogenic radon, which will evolve step-by-step as more data or transfer models become available for the geological units. More details about the idea, methods and problems faced for the EGRM can be found in Gruber et al., (2012a).

Since this work will take quite some time, a simplified, trial geogenic map was presented at the Prague radon workshop in 2012 (Gruber et al., 2012b). The idea was to classify geological units calibrated with soil gas radon measurement data from Germany and apply this scheme to similar geological units in other countries (Bossew, 2012). Discussions at the workshop revealed that this approach might be too simplified, as geology is too complex and diverse and the radon potential also is influenced by local (natural and artificial) special features. So all these parameters should be collected and taken into account in the above EGRM database.

4. CONCLUSIONS

After six years in the making, the EIRM (as of October 2012) displays data from 25 countries on a 10 km × 10 km grid across Europe. More than 18,000 cells have been filled with data, stemming from more than 800,000 individual measurements. Still, between the participating countries and between regions within those countries, large variations occur in sampling density and coverage of territory. The number of measurements per cell ranges from one up to a maximum of nearly 24,000. Overall, the median number of measurements per cell equals 4, with a median absolute deviation of 3. Several countries have covered more than 100% of their territory with data, due to a border effect. At the other end of the scale, a few countries have sampled less than 20% of their territory.

Within most countries, the indoor radon concentrations vary strongly, essentially reflecting the underlying geology. The AM of all non-empty cells in Europe (for all participating countries) is 100 Bq/m^3, with a median of 65 Bq/m^3.

The EIRM is far from complete. Some countries (e.g. Ireland) had survey strategies which produced datasets incompatible with the European grid, and others (e.g. Sweden) do not have a national database. The JRC will continue to collect data from new participants and from established ones as they complement or improve their data, and will publish updated versions of the map from time to time. At the radon workshop in Ispra in 2011, a number of Balkan countries agreed to participate, or continue to participate, to this mapping effort (Tollefsen 2011).

Complementary to this effort, the EGRM aims to map "what earth delivers" in terms of radon, independent of anthropogenic factors. A first, trial map has been published and a database established to collect all available data relevant to the radon potential Using this database, different approaches (multivariate classification, continuous) can be followed to create a harmonized European map.

In the longer term, a European Atlas of Natural Radiation will include maps other than radon, such as cosmic rays, terrestrial gamma radiation, radiation from building materials and water. The plan is to combine these maps and calculate total exposure and dose caused by natural sources and their respective contributions in spatial resolution (De Cort et al., 2011).

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