Modeling of a Hypothetical Major Nuclear Accident in Poland from 1096 Meteorological Situations and Analysis of Transboundary Environmental Impacts for European Countries and Their Inhabitants

Piguet Frédéric-Paul¹ⁱ, Eckert Pierreⁱⁱ, Knüsli Claudioⁱⁱⁱ, Hélder Peixoto^{iv}, Giuliani Gregory^{iv}

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ⁱ Institut Biosphère, Geneva; ⁱⁱⁱ Geneva; ⁱⁱⁱ IPPNW (Suisse), Luzern; ^{iv} Institute for environmental sciences, University of Geneva.

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¹ Corresponding author: Frédéric-Paul Piguet, Institut Biosphère, CH-1226 Geneva, fppiguet@institutbiosphere.ch

² Grünen Bundestagfraktion, Fraktionsgeschäftsführung, Dorotheenstrasse 101, DE-10117 Berlin, Deutschland

Executive Summary

The purpose of this analysis is to study the transboundary radioactivity that would be linked – in the event of a hypothetical major accident – to the nuclear power plant projected by the Polish government in the region of Zarnowiec-Kopalino, some 70 kilometers from Gdansk, close to the front of the Baltic sea. The transport of radioactive material across borders can impact the population's health, pollute soils and trigger long-lasting evacuation of populations – among other hazards. The question is whether and, if so, to which extent a major nuclear accident from the Zarnowiec-Kopalino area could trigger important transboundary damages to the inhabitants of neighboring countries.

Through meteorological simulations of the transport of radioactive materials from an hypothetical damaged nuclear reactor, the study focuses on a first circle of four regions around Poland: Germany (West), Denmark and Sweden (north), Kalinigrad-Oblast, Lithuania and Latvia (east), Czechia, Slovaguia, Ukraine and Belarus (south and southeast); It also looks at more than 30 European countries with the purpose to provide a full picture of the potential environmental damage on health. The study models a major nuclear accident using 1096 meteorological files from year 2017 to year 2020, with help of the trajectory and dispersion model Hysplit. The total release amounts to 2.72E+18 Becquerels. The 22 nuclides of the source term of the simulated accident were analyzed together with the 23 radioactive nuclides produced by the source nuclides of the source term produce all along their decay process (and during the lapse of time of the simulation). Conversion of radiation from Becquerel to Sievert was established according to the literature, from the perspective of the yearly dose limits set by Council Directive 2013/59/Euratom to protect the public and the professionals in occupational or emergency activity (1 mSv, 6 mSv, 20 mSv, 50 mSv, 100 mSv and 500 mSv). This procedure was carried out so as to clarify the scientific results through a deeper understanding of the norms in use. To assess the impact on population, demographic data were treated by a geographical information system GIS software called ArcGIS as well as with the help of C-programs. Health effects of ionizing radiation were estimated from the collective committed effective dose (CCED) impacting the population exposed to the 72h of simulation of each radioactive cloud as well as ground surface deposition during the course of one year. The global health effects were used in connection with three risk models for different issues: cancer, cardiovascular and other non-cancer diseases, genetic and other detriments.

The main results are as follows: a large part of the collective committed effective dose that increases the occurrence of severe diseases among the population could greatly adversely impact the inhabitants of Poland and beyond. On average, we found that, in case of a major nuclear accident, 3/5 of the radio-induced severe diseases (cancer, cardiovascular diseases and the related radio-induced deaths) would occur outside Poland. More specifically, in 756 out of 1096 meteorological situations (69%), at least one of the four regions around the still in project Zarnowiec-Kopalino NPP would receive a higher collective committed dose than Poland, while in 76% of the meteorological situations 30 countries together would receive a higher CCED than Poland. From the perspective of limits on public exposure, figures show that more than 7 million people located in 31 European countries (including Poland) would receive an ionizing radiation dose \geq 1 mSv. To compare with the limit that is set at 6 mSv for students or apprentices aged \geq 16 and \leq 18 years in the course of their studies if obliged to work with radiation sources, one of our results is that an ionizing dose \geq 6 mSv could impact, on average, more that 860000 Europeans (of all ages), of whom 400 000 in Poland, 112 000 in Germany, 127 000 in Kaliningrad, Lithuania and Estonia, 113 000 in Denmark and Sweden and 53 000 in Czechia, Slovaquia Ukraine and Belarus. With regard to the legal limit fixed at 20 mSv in any single year for adults in professional exposure as well as for emergency occupational whose exposure should remain, whenever possible, below 20 mSv, it is interesting to take note that 150 000 individuals (including children and teenagers) could be impacted by the radioactive cloud, on average, at the European scale, above this limit. In addition, from the perspective of the need to preserve people from the risk of radioactive ground deposition and relocate them outside contaminated areas for a period of time ranging from several months to more than one year, at the scale of the 31 countries and on average, figures were above 125 000 and 40 000 persons, for a limit set respectively at 20 mSv and 50 mSv. As a consequence, in taking into account the relocation of inhabitants living in areas where the individual dose would exceed 20 mSv per year, the number of radio-induced cancers and cardiovascular diseases would amount, on average, to 28 000, while the number of deaths would exceed 13 000.

It seems clear, from these figures and the related simulations, that if the Zarnowiec-Kopalino NPP project would finally be realized, it would constitute a potential source of radioactive transboundary pollution for many European inhabitants.

I Context

1.1 Scope of the study

The purpose of the analysis is to study the transboundary radioactivity that would be linked – in the event of a hypothetical major accident – to the nuclear power plant projected in the region of Zarnowiec-Kopalino,

Table 1.1. Transport of radioactive material within and outside the borders of Poland: geographical area of reference for this study No. Country (or region)							
No	Country (or region)	Grouping					
1	Poland	POL					
2	Germany	DEU					
3	Kaliningrad-Oblast (Russia)						
4	Lithuania	KLL					
5	Latvia	1					
6	Sweden	005					
7	Denmark	SDE					
8	Czechia						
9	Slovakia	CSUB					
10	Ukraine	6300					
11 Belarus							
Germany is on Poland's western border, KLL in the east, SDE in the northwest and CSUB in the south and southeast.							

Poland, some 70 kilometers from Gdansk. Several studies have already looked at the health impact of a nuclear accident from this region (Seibert, Hofman & Philipp 2014; Mazur 2019), but they did not specifically address the risks of contamination beyond the Polish borders. Our intention is to fill this gap. The transport of radioactive material across borders following a major nuclear accident can be considered from the perspective of different types of impacts. These include the health impact on the population, the pollution of soils, aquifers and the long-lasting displacement of populations, as well as the economic consequences on agriculture, tourism and other activities, etc. The following study will focus more particularly on the health impact on populations as well as on soil pollution.

In order to limit the number of results to be published and to issue a readable report, we have selected eleven countries whose territory is less than 400 kilo-

meters from the site of the first Polish nuclear power plant, or whose territory is adjacent to the Polish border. Table 1.1 shows the list of countries and the criteria that were followed when establishing that list. In addition to this table, 31 European countries were gathered together in order to grasp the transboundary dimension of the transport of radioactive nuclides caused by such a major accident.

1.2 Ionising radiation – health hazards – Importance of epidemiology, linear no threshold model (LNT) and beyond

Health risks (HR) of ionizing radiation (IR) have first been described in the 19th century (Edison 1896) (Doll 1995, 1339-1349). Studies on genetic effects by IR followed (Muller 1928, 714). HR in humans due to IR have been analyzed in radio-diagnostics (Giles 1956, 447; Stewart 1958, 1495-1508; Pearce 2012, 499-505; Mathews 2013, f2360), in in Japanese nuclear bomb survivors (Ozasa et al. 2012, 229-243), in nuclear workers (Richardson et al. 2015, h5359; Leuraud 2015, e276-e281; Gillies 2017, 276-290), in people exposed to radon gases (Darby 2005, 223) and in children with respect to background radiation (Kendall 2013, 3-9; Spycher 2015, 622-628).

Collective dose calculations have been proven useful in IR risk estimations for exposed populations. Extensive epidemiological studies (National Cancer Institute 2020; Linet et al. 2020; Schubauer-Berigan et al. 2020; Berrington de Gonzalez et al. 2020; Hauptmann et al. 2020; Daniels et al. 2020) on HR induced by IR have confirmed the LNT (Linear No Threshold) model (BEIR VII 2006a; BEIR VII 2006b, 1-4; Shore 2018, 1217) in the low dose range (below 100 millisieverts, mSv). According to LNT even very small doses of 1 mSv and below result in elevated HR (cancer, non-cancer diseases and detrimental effects on the reproductive process).

The internationally legally binding limit of exposure to artificial sources is 1 millisievert/year (mSv/a) per person (infra 1.5(ii), 2.6(iii)). However, NPP accidents (Chernobyl 1986, Fukushima 2011) led to individual IR exposures of mainly below 100 mSv or above this level for many millions of residents (Cardis 1996, 241-271; WHO 2013; IPPNW 2016).

1.3 Calculation from the perspective of a European directive and provisions

It is important for any study on environmental risk and ionizing radiation to adopt an interdisciplinary approach and to look at norms and regulations before structuring the data. Legal information helps to

determine what is the real issue and to shape the categories that are of interest for decision-makers and civil servants in charge of the protection of the population.

Table 1.2 shows clearly the structure of the limits on the effective dose related to ionising radiation that shall be respected and adapted to different circumstances. If the limit protecting the public is set at 1 mSv for any single year, it is established between 20 and 100 mSv in an emergency situation due to a severe nuclear accident (Art. 53.2(a)), while it could exceed 100 mSv in case of a major nuclear accident deemed to be very unlikely.

Table down Unior	1.2. Limits on the effective of basic safety standards for por 2013)	dose according to Council Dir rotection against the danger	rective 2013/59/EURATOM o s arising from exposure to io	f 5 December 2013 laying nising radiation (European							
(mSv)	Yearly public exposure and yearly professional exposure	Professional exposure in special circumstances	Emergency occupational exposure for the public	Emergency occupational exposure for emergency workers							
≤ 500				In order to save life in exceptional situations, the reference level for emergency workers shall not exceed 500 mSv (Art. 53.2(b))							
≤ 100			Reference levels for emergency occupational exposure shall be set, in general below an effective dose of 100 mSv (Art 53.2(a))								
≤ 50		The limit shall be 50 mSv for professionals in special circumstances if the average annual dose over any five consecutive years, including the years for which the limit has been exceeded, does not exceed 20 mSv (Art. 9.2)									
≤ 20	The limit shall be 20 mSv in any single year for adults in professional exposure (Art. 9.2)		Emergency occupational exposures shall remain, whenever possible, below 20 mSv (Art 53.1 → Art. 9.2)								
≤ 6	The limit shall be 6 mSv for Students or apprentices aged \ge 16 and \le 18 years in the course of their studies if obliged to work with radiation sources (Art 11.2)										
≤ 1	The limit shall be 1 mSv for any single year (Art. 12)										
Annex shall be approp levels s up to c	single year (Art. 12) Annex 1 of the Council Directive 2013/59/EURATOM states that, 1) for existing exposure situations, reference levels expressed in effective doses shall be set in the range of 1 to 20 mSv per year; (); 3) For the transition from an emergency exposure situation to an existing exposure situation, appropriate reference levels shall be set, in particular upon the termination of long-term countermeasures such as relocation. 4) The reference levels set shall take account of the features of prevailing situations as well as societal criteria, which may include the following: (); (b) in the range										

equal to 100 mSv per year, assessment of individual doses and specific information on radiation risks and on available actions to reduce exposures.

Similarly, as stated in Annex 1 of the Council Directive, relocation after an emergency exposure can be set from a yearly exposure of 20 mSv, or till 100 mSv with a specific accompaniment.

Despite the need for adaptation to circumstances and despite the fact that limits set between 1 and 6 mSv have no legal significance in case of a major nuclear accident, all the limits specified by Council Directive 2013/59/EURATOM show that doses above 1 mSv should not impact the public and that, more generally, thresholds in the two left columns are also of symbolic, scientific and moral significance: they are the gate keeper to protecting individual and public goods: > 6 mSv breaches students and apprentices interests (and the public good); > 20 mSv breaches professional's interest (and the public good); etc. All in all, legal provisions on emergency situations are somewhat completed by the provisions on yearly public exposure. Therefore, almost all reference thresholds of the present study come directly from the Directive on ionizing radiation, so that the public, decision maker and the media can understand the results of the simulation from the legal and moral perspectives besides the scientific one³.

³ This is interdisciplinarity in an interconnected world.

1.4 The Current Project of a Polish NPP

(i) Nuclear ambition

The Polish Government has confirmed several times his intention to plan and build several nuclear reactors, the first unit being scheduled for grid connection in 2033, and the next five, every two years till 2043 (Ministry of Energy 2018, 4). It also confirmed that the first NPP location is to be the Zarnowiec or Lubiatowo-Kopalino (Monitor Polski 2020, 15, 16).

(ii) Zarnowiec-Kopalino location of the projected plant

Historically, the first attempt to build a nuclear power plant in Poland was set up in Zarnowiec, near a small lake, 70 kilometers far from Gdansk. The decision on the location was taken in 1972 and the project was finally abandoned by the Council of Ministers (Wikipedia 2020) after the advice of the Minister of Industry, Tadeusz Syryjczyk (1999, 115). As the three possible sites of the new facility are very close, and due to the historical attempt to build a NPP in Poland, we will name the site Zarnowiec-Kopalino. In the 1096 simulations of the present study it is located near Kopalino (lat. 54.8026; long. 17.8437), which seems to be a better location than Zarnowiec to get sea water necessary for cooling the reactors.



Map 1 (PGE Group 2015), with some adaption of our own. The historical site of Zarnowiec (1) is still envisaged as a possibility to be the location of a nuclear power plant. Two other variants (2) and (3), closer to the sea, therefore easier to cool could attract the government's final choice. In this study, we ran our simulations from the Kopalino variant. Due to the historical precedent of the construction of a NPP in this area – even if never completed – we keep the name and specify the variant we study as such: Zarnowiec-Kopalino.

(iii) The Reactor model that could be built at Zarnowiec-Kopalino

It is stated by officials that the Polish nuclear reactor should amount between 1000-1600 MWe (Monitor Polski 2020, 13). October 19th 2020, the Polish government concluded a cooperation agreement on nuclear energy with the government of the United States, which stated that Westinghouse will participate in an engineering study for the planned nuclear power plants on the nuclear programme (NEI 2020). The reactor is not yet chosen, there is nonetheless ample evidence that AP1000 model, by Westinghouse, is the one most likely to be chosen by nuclear authorities at the end of the evaluation process. AP1000 has already mentioned in several documents both official and unofficial, pertaining to this nuclear ambition for many years (Sholly et al. 2014, 11; PGE Group 2015, 64; Monitor Polski 2020, 13).

The Westinghouse AP1000 2 Loops, is a PWR of third generation (III+) with a thermal power of 3400 MWth and a net capacity of 1100 MWe (U.S.NRC 2007). In the present study, it is the reference reactor in the selection process of a relevant source term to assess the possible consequences of a major nuclear accident by a NPP that would be located at Zarnowiec-Kopalino.

(iv) Source term of a major nuclear accident

This study takes into account the AP1000 source term detailed by Sholly et al. (2014, 31-32) since it matches the severity of a major nuclear accident. We explain below how the nuclides were aggregated in the simulation and how we accounted for the progeny of parent's nuclides (infra 2.2).

The list of 22 nuclides is the following: I-131⁴, Cs-134, Cs-136, Cs-137, Rb-86, Sb-127, Te-127M, Te-129M, Te-132, Ba-140, Sr-89, Sr-90, Mo-99, Ru-103, Ru-106, Ce-141, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241.

The total release amounts to 2.72E+18 Becquerels (Bq). See Table A.1 in Annex A for the amounts and half-lives of each nuclide.

II Methodology

2.1 Outline of the methodology questions

A few methodological points are discussed below: the quantities of Becquerels used in the simulations (source term study) (infra 2.2); the physical coefficients of the dispersion of rare gases and aerosols in the atmosphere (deposition velocity, in-and below-cloud removals) (2.3); the consideration of meteorological data and their influence on the results (2.4); the assessment of impacted people, soils and countries using a Geographic Information System (2.5); the calculation that allows to use Becquerels to calculate the collective committed effective dose (CCED) received by the populations and the calculation performed to compare individual CED to the legal limits in mSv (2.6); the health impact and the related number of radio-induced diseases (2.7). Only an interdisciplinary approach can carry out such a questioning.

2.2 Source term

(i) Aggregation of the source term

The total release amounts to 2.72E+18 Becquerels (Bq) (*supra* I.4(iii)). This section aims to define how nuclides released from the reactor pressure vessel into the environment have been aggregated by keeping coherent and correct figures, without any significant bias. This question is of utmost importance for determining the clouds that were simulated over 72 h (2.59E+05 s) through 1096 meteorological situations. The list of nuclides was limited to nuclides with a half-life \geq 2.04E+05 (s), which implies the shorter half-life nuclide to be included in the list is Np-239.

As the addition of two or more logarithmic curves never yields a logarithmic curve, we had to verify a first criterion: that the deviation of the decreasing curve of the total Becquerel does not deviate more than 3% from a reference logarithmic curve (whose half-life was found to be 7.35E+05 s for the present source term).

This criterion being satisfied, it became possible to approach the radioactive nuclides resulting from the decay of the elements listed in the source term. All radioactive elements decay into other nuclides (which are not always radioactive themselves). The relationship between the 'parent nuclide' and its 'progeny' is known and described (EPA 2019a). In the present case, 17 out of the 22 nuclides of the source term trigger 23 radioactive nuclides: Xe-131m, Ba-137m, Te-127, Te-127m, Te-127, Te-129, I-129, I-132, La-140, Y-90, Tc-99, Tc-99m, Rh-103m, Rh-106, Pr-144, Pr-144m, Pu-239, U-234, U-235m, U-235, U-236, Am-241, U-237 (see additional details in Table A.2 in Appendix A.

Given a simulation over 72 hours, we estimated briefly the change in the composition of the cloud during this lapse of time.

(ii) Verification of a possible bias to be eliminated

More specifically, the evolution of the radioactive cloud, modelized as a curve expressed in Bq over 72h, should be compared to the millisieverts a 'fictitious individual' would receive from the source term

⁴ Nuclide I-131 is only considered as an aerosol in our calculation.

transported by the cloud, and the decay of the source term into new radioactive elements every two hours (for control).

As it appears, the curve of the nuclides of the source term considered with the curve of the 'progeny' and summed in millisieverts decreases a bit less than the curve of the source term modelized in Becquerels. The value in millisieverts of the last two hours of the simulation represents 83% of the value in millisieverts of the first two hours, while the curve of the source term expressed in Becquerels ends at 78% of its initial value.

(iii) Accuracy or inaccuracy of the present method

On the one hand, a model lowering by 5% the amount of mSv at the end of the cloud trajectory should be avoided. On the other hand, that approach makes it possible to run the simulations with more nuclides, while the source term appears finally more accurate than it would be if limited to one or only three nuclides. Consequently, the approach described above was selected for this study.

2.3 Deposition velocity in- and below-cloud wet removal of different nuclides⁵

(i) Framework

The user of *Hysplit* has to specify the deposition velocity of rare gas, aerosols, and particles that are rejected by a source and dispersed by winds. Furthermore, *Hysplit* requires the in- and below-cloud wet removal/scavenging parameters (Draxler et al., 2018). As these parameters are partly dependent from weather condition, the numbers to be found are indicative and managed by *Hysplit* accordingly.

(ii) Review of the literature

We give below a short review of the literature on the subject in order to specify below the adequate values.

- Cesium: The dry deposition velocity of ¹³⁷cesium is given by the *Hysplit* dispersion program at 0.001 (m/s) (Stein et al. 2015). However, Guglielmelli et al. (2016) set 0.002 (m/s). Direct observation on the Fukushima accident leads to consider the figure of 0.001 (m/s) is robust for ¹³⁷Cs, ¹³⁶Cs and ¹³⁴Cs (Takeyasu & Sumiya 2014). Wet removal/scavenging in- and below-cloud is set at 8.0E-05 (1/s) by *Hysplit* for ¹³⁷Cs. For this same isotope, wet in- and below-cloud removal is estimated at 3.5E-05 (1/s) (Guglielmelli et al. 2016), or even at 3.36E-04 and 8.4E-05 respectively (Leadbetter et al. 2015).
- Iodine can be released as gas, aerosol, or both. Considering the uncertainty for the fraction of each form, the Flexrisk report subsumed all iodine under the aerosol species (Seibert et al. 2013). We adopt the same approach and look at the deposition velocity and wet removal accordingly. For the aerosol form of iodine, *Hysplit* puts deposition velocity at 0.001 (m/s) and sets wet removal/scavenging in- and below-cloud at 4.0E-05 (1/s) (Stein et al. 2015).

ENSI admits nonetheless, that the deposition velocity can be given for all aerosols (ENSI 2009, 64). For all aerosols: the deposition velocity is set at 0.0015 (m/s) (ENSI 2009, 64) and the in- and below-cloud removal/scavenging is set at 7.0E-05 (1/s) (ENSI 2009, 65). The latter figures are close to the abovementioned ones on cesium and iodine.

(iii) Parameters of deposition velocity and in- and below-cloud wet removal for aerosols

The selection of the different coefficients affecting the atmospheric dispersion and the deposition of the 32 isotopes of this study is given in Table 2.8. The selected parameters will be used to simulate a major nuclear accident. The selection is made according to the literature, mainly Sander (2015), ENSI (2009), Draxler & Rolph (2012) and Baklanov et al. (2001) (*supra*).

Table 2.8. Parameters of deposition velocity; in- and below- cloud wet removal/scavenging for aerosols								
Material Deposition velocity in- and below-cloud wet removal								
(m/s) (1/s								
Aerosols	Aerosols 0.0015 7.0E-0							
Together with the release and the duration of the release, the above figures are used by <i>Hysplit</i> .								

⁵ That section is an excerpt of the one published in EUNUPRI_2019.

(iv) Deposition velocities on different types of grounds

The different kinds of land cover have different abilities to capture radioactive particles. For instance, Sehmel quoted by Takeyasu & Sumiya (2014) give the deposition velocity for 137 Cs: 0.0003 – 0.0015 m/s for water, 0.0001 – 0.0009 m/s on 'soil', and 0.002 – 0.005 m/s on grass. These figures nonetheless cannot be generalized. Müller & Pröhl quoted by Baklanov & Sørensen (2001, 789) gave – for aerosol bound radionuclides – a deposition velocity at 0.0005 m/s in case of deposition on 'soil', at 0.0105 m/s for deposition on grass and at 0.0005 m/s on trees, knowing that such figures depend on the size of the deposited particles as well as on the size and development of the foliage of trees. Due to the high complexity and the lack of a systematic data collection on this specific issue, we do not detail the deposition process. Therefore, we publish detailed results concerning land cover in additional files for further analysis.

2.4 Meteorological aspects⁶

(i) What are atmospheric dispersion models?

Atmospheric dispersion models have been developed in the 1980s to study the effects of chemical and nuclear incidents. The aim was not only to predict the evolution of the pollutant cloud, but also to trace back the origin of a pollution in case a signal was observed at an observation point. One of the main triggers to develop this kind of models was the Chernobyl accident in 1986. Simple trajectory models existed at the time which allowed qualitative estimates, but it took a few more years until dispersion models were able to assess the event in a quantitative way (Piedelievre et al. 1990: 1205–1220).



There are many different types of dispersion models; for a review see Leelössy et al. (2014, 257-278). Generally, the dispersion models must be characterized firstly by the content (type and mass of the components) and the emission (rate, duration, height). The transport, diffusion and deposition are then driven by the meteorological fields, mainly winds and precipitation (Map 2.A.).

⁶ Section 2.4 is an excerpt of the one published in EUNUPRI_2019, as sections 2.6 and 2.7.

(ii) Considerations on the resolution of the meteorological fields

Wind fields are rather continuous over flat terrain and water surfaces but can become very complex over mountainous landscapes. On the region under consideration, the terrain is rather flat so that it is unnecessary to use a very high resolution for the wind representation.

We have chosen to use the winds provided by the NOAA at a resolution of 0.25° latitude and longitude (NOAA 2016). Wind forecasts per one hour time sequences are available up to +24 hours by a simple FTP request (NOAA 2018a). In order to reach dispersion patterns over 72 hours, we concatenated 3 consecutive 24-hour forecasts. Wind forecasts over 24 hours can be considered accurate and close enough to the observation. Although less accurate, the same can be assumed for precipitation.

(iii) The Hysplit dispersion model

Hysplit is a trajectory and dispersion model developed by the US National Oceanic and Atmospheric Administration (NOAA). *Hysplit* has been used in a variety of simulations describing the atmospheric transport, dispersion, and deposition of pollutants and hazardous materials. Some examples of the applications include tracking and forecasting the release of radioactive material, wildfire smoke, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash.

The dispersion of a pollutant is calculated by assuming either puff or particle dispersion. A collection of particles can be gathered in so called puffs, which are small clouds emitted by the pollution source. They are transported by the wind field and expand due to the atmospheric diffusion. The mean trajectory of the cloud defined by its centroid is computed and the growth is modelled by a Gaussian distribution. In this puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass (NOAA 2018b). In the particle model, a fixed number of particles are calculated in relation to the model domain "by the mean wind field and spread by a turbulent component. The model's default configuration assumes a 3-dimensional particle distribution (horizontal and vertical)" (NOAA 2018b). A full description of the model is given by Stein et al. (2015) (*infra* iv).

(iv) The Hysplit dispersion model evaluated by WMO in the case of Fukushima

The Fukushima accident in 2011 gave an opportunity to assess the various dispersion models. Unlike the Chernobyl case the models have been used in real time in order to protect or evacuate threatened populations. A comparison between dispersion models computed *a posteriori* – using deposition data and meteorological data to calculate atmospheric dispersion back to the source of the release – was carried out for the World Meteorological Organization (WMO) (Draxler et al. 2015). There was not a single ATDM-meteorology combination that provided the best results for both deposition and air concentration predictions. Generally, the *Hysplit* model driven by NOAA meteorological data performed correctly with respect to the other models. It was found that the use of high-resolution mesoscale analyses improve the dispersion model performance; however, high resolution precipitation analyses did not improve the predictions. The Fukushima study showed that the use of meteorological fields with a resolution of 20-50 km is suitable for our purpose.

(v) Production of the immission fields

Technically, we have taken the radionuclide characterization of one nuclear plant. The geographical field of analysis was defined as 50° west longitude and 50° east longitude from the NPP and as 50° south latitude and 50° north latitude from the same NPP respectively. The resolution of the result is 0.05° in longitude and latitude.

We computed the dispersion only for aerosols. As a result, we computed the amounts of radioactive particles in the bottom 100 m of the atmosphere (Bq/m^3). This layer is representative of the radioactivity to which the population is exposed by inhalation and external exposition. For solid particles (aerosols), it is also possible to compute the amount of radioactivity (in Bq/m^2) deposited on the ground and we carried it on for aerosols.

As a result of *Hysplit* these quantities are stored into so called binary 'cdump' files. The computations have been carried out for all days of 2017 and 2018 together with the period 1.12.2019 – 30.11.2020 resulting in 3 years of simulations or 1096 days. The cdump files have been stored and can be used for further analysis.

In order to assess the amount of population or the geographical areas potentially touched by the radioactivity we carried out two different methods, the isoline-kml method and the ASCII method. These are two different

methods to interpolate from the 0.05° grid onto the more detailed population grid. In both cases we first converted the amount of radioactive particles (given in Bq) into exposition doses (given in mSv) as explained below (*infra* 2.6).

First *Hysplit* allows to produce contourings out of the cdump files resulting into shapes for various dose thresholds. These are included in vector format as kml files⁷. Using a Geographic Information System (GIS), it is the possible to compute the area and population size enclosed inside the isolines. Kml files are also handy to represent the dispersion patterns superimposed on a geographical background by using for instance Google Earth.



Map 3. Example of dispersion pattern from a release on the 22nd March 2017

The second method consists to extract from the cdump files the exposition in ASCII format with the original resolution computed by *Hysplit* (0.05°). A bilinear interpolation is then applied in order to evaluate the doses on the detailed population grid. This approach is also used in order to assess the radioactivity on various towns. This is done by using the 9 *Hysplit* points surrounding the center of the town and by taking the maximum of these.

2.5 Analysis of the impact through the Geographic Information System (GIS)

The impact of radioactivity on the population and soil cover was calculated using GIS tools of ArcGIS Pro software, by Environmental Systems Research Institute (ESRI). The kml files generated by HYSPLIT software were converted to ESRI-shapefiles with the "KMLToLayer_conversion" tool, so that they could be used in statistical analysis. The shapefiles contain several polygons with different radiation concentration levels. Each shapefile was overlaid with a raster layer using the "ZonalStatisticsAsTable" tool which yielded a table with the affected number of population and land cover types.

The raster layers containing the population counts, for individual countries and for the year 2020, were obtained from the worldPop website, which includes datasets with a resolution of 30 arc (approximately 1km at the equator) created with the "top-down unconstrained" method. The land cover raster was obtained from

⁷ KML means Keyhole Markup Language and the related files are employed for geographic mapping.

the Copernicus website which makes the Corine Land Cover products available for download. The raster used is the CLC2018 dataset produced within the frame of the Copernicus Land Monitoring Service referring to land cover / land use status of the year 2018. The dataset includes the classification of satellite images produced by teams from all the 39 countries members of the European Environmental Agency (EEA39). The land cover is represented in 44 different classes with a 100m resolution, which have been grouped in 4 classes for the present study. The projection used for the analysis is the Geographic Coordinate System, WGS84. The analysis were performed using ArcGIS integrated Python Window, which made possible the geoprocessing of large amounts of data.

In the present study, the 4 selected classes of land cover are: vineyards, herbaceous, cultivated, others. For the original classes of CLC2018, see the Appendix (Table A.3.)

2.6 From Becquerels to the collective committed effective dose received by the impacted population

(i) From Becquerels to mSv

The different sources of radioactivity are calculated by *Hysplit* in Becquerels (Bq). To evaluate the health impact of all persons affected implies to estimate the population dose in millisieverts (mSv). The calculation from Bq to mSv is carried out through well-known dose factors for inhalation (ICRP 2012), ground surface (EPA 2019b) and air submersion (or external exposition) (EPA 2019c). The related equations have to consider the specific unit account of each dose factors, the time integrated concentration expressed in (Bq·s/m³) or (Bq·s/m²).

(ii) First part of the calculation of the health impact

Radioactivity impacting people has been calculated through three clouds (rare gas, aerosols and refractories). The calculation is completed by the integration of the deposition of aerosols and refractories. As a result, it gives the five sources of radioactivity below:

When calculating committed effective doses from deposition we only considered external exposition. Inhalation of radioactive aerosols from resuspension in the atmosphere is far from negligible. However, we did not calculate it.

Hysplit ran the five sources of radioactivity in Becquerels (Bq). Besides this, we estimated the committed effective doses (CED) in millisieverts (mSv) through well-known equation. The purpose is to prepare the evaluation of the health damages to all affected persons.

As a next step, the individual committed effective doses (CED) can be used to estimate the collective committed effective dose (CCED) received by the population:

CCED = CED ⋅ number of affected persons

The CCED is expressed in person-Sieverts (persSv) and it is determined together by the radioactivity level as well by the number of persons exposed to radioactivity. For high doses \geq 1000 mSv, we calculated the dose by multiplying the value of the isoline by the number of affected persons (isoline approach), while for doses <1000 mSv, we used data having the specific dose of each pixel (pixel-dose approach).

(iii) Indoor factor for radioactive deposition.

We took into accounts the indoor factor at 0.4 when calculating radioactive deposition and we ignored low doses below 1 mSv. Additionally, it is assumed that persons in areas with doses above 20 mSv during the first year would be evacuated (according to EU directive), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition.

2.7 Methodology of the health question

(i) Context

lonizing radiation (IR) is ubiquitary. IR from natural sources leads to an annual world population collective committed effective dose (CCED) of 18000000 person-Sievert (2.4 mSv/1000 \cdot 7.5E+09 persons) (Bennet 1995, 3-12). IR acts either internally by incorporation of radionuclides (ingestion or inhalation), or externally by skin penetration of beta-, gamma-rays and neutrons (by immersion from cloudshine and groundshine) or direct skin contact with radionuclides. The energy of IR provokes mutations of the genome and other critical cellular processes such as bystander effect leading to genomic instability (Sipyagina et al. 2015, 18-22). In this

way radiation induces cancer, congenital malformations, and genetic diseases which are passed from generation to generation.

(ii) Estimating the numbers of victims in a major NPP-Accident – retrospectively and prospectively

The estimated number of human victims due to the Chernobyl disaster varies between 4,000 cancer deaths (IAEA 2006, 118-120), and more than 1,000,000 victims due to cancer and non-cancer pathologies (Yablokov et al. 2009, 58-160). This discrepancy of more than two orders of magnitude is attributable to some degree, to the stochastic nature of health detriments by IR, as well as to long latency periods between exposure and manifestation of radio-induced pathologies. More important, however, are diverging estimates of the source term, populations studied, varying exposure periods and different risk-factors chosen by published scientific studies with diverging commitments (Fairlie & Sumner 2006, Claussen & Rosen 2016, Lenoir 2016). Considering the abovementioned divergence in determining *retrospectively* the number of victims due to the Chernobyl NPP accident, we use the following three calculation models (A, B, C) to estimate *prospectively* the number of victims of a future potential major European NPP accident. The calculation is based on the Collective committed effective dose expressed in person-Sievert (persSv) (supra i).

(iii) Model A

Model A: Cancer-based model - estimations according to UNSCEAR / WHO

This model places emphasis on victims with radio-induced cancer and is originally based on the ICRP-Document 103 (ICRP 2007). The latter uses an EAR (Excess Absolute Risk) factor of 5.5%/Sv (0.055/Sv) for cancer mortality which is applied to collective committed effective dose (CCED) of IR. However, calculations by ICRP also include a "reduction factor" ("dose and dose rate effectiveness factor", DDREF) of 2 which is outdated nowadays according to UNSCEAR/WHO (WHO 2013, 31-32) and also to the German SSK (2014, 5-16).

Summary Methodology Model A

Model A contains numeric estimates of radio-induced cancer using a risk factor of 0.2/Sv for incidence and 0.1/Sv for mortality. Results are presented with confidence intervals according to BEIR VII (2006a).

(iv) Model B

Model B: Updated cancer and cardiovascular risk estimates

Model B refers to more recent studies on radio-induced cancer risks. Additionally, cardiovascular risks due to a major nuclear accident are included in Model B.

B1. Cancer risks

With respect to radio-induced cancer risk, there is new epidemiological evidence in favor of higher risk factors (Cardis et al. 2005, 77-80; Körblein & Hoffmann 2006, 109-114; IPPNW 2014, 3; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8) than used in Model A (Appendix, Table A.4). These EAR-factors are about 4.5 times higher than the EAR of 0.055 for radio-induced cancer mortality used by ICRP 103 (2007). In Model B this would translate into a doubling of the estimated cancer cases in comparison to Model A (which has already allowed for a DDREF of 1).

B2. Cardiovascular risks

According to ICRP elevated risks for nonmalignant diseases are known after IR exposure (Ozasa et al. 2012, 229-243). However, the suggestion of the ICRP (ICRP 2012, 1-2) for a threshold of 500 mSv for radio-induced diseases other than cancer is outdated (Appendix, Table A.5. *Methodology Model B2*). Cardio-vascular excess risks have been described in children and adults due to IR exposure after Chernobyl (Nyagu 1994, Prysyazhnyuk et al. 2002, 188-287, Lazyuk et al. 2005, 24-25). Studies on low level exposure to IR found an elevated risk for arterial hypertension in nuclear workers (Azizova et al. 2019) as well as a significant excess mortality from cardiovascular diseases Gillies 2017) at a similar level as excess cancer mortality after IR exposure (Little et al. 2012, 1503-1511). Generally – as for cancer – incidence rates are higher than mortality

rates also for cardiovascular diseases. In Europe the ratio of mortality to incidence for cardio-vascular diseases is about 1 to 3 (European Heart Network 2017).

Summary Methodology Model B

Model B contains numeric estimates of cancer incidence using a risk factor of 0.4/Sv (and 0.2/Sv for cancer mortality) and using a risk factor of 0.15/Sv for cardiovascular disease (CVD) incidence (and 0.05/Sv for mortality).

Severe diseases (cancer and CVD combined) therefore make 0.55/Sv for incidence and 0.25/Sv for mortality. Results are presented both for average and variable meteorological situations without confidence intervals (*infra 3.2*).

(v) Model C

Model C: Broadened Radiation Health Risk Assessment

Acknowledging that cancer and cardiovascular diseases reflect only the "tip of the iceberg" of radio-induced health effects observed after the Chernobyl NPP accident (Tereshchenko et al. 2003, 283-287), estimates of both Model A and Model B seriously underestimate the true burden of radio-induced pathologies. Model C therefore includes cancer and cardiovascular cases as mentioned in Model B and, in addition, covers the risks for other radio-induced diseases as well as reproductive and developmental hazards by ionizing radiation. For these conditions no EAR-risk factors are systematically established, although for some conditions ERRs (excess relative risks) > 1/Sv are documented (Appendix, Table A.6.).

C1. Non-cancer diseases other than cardiovascular diseases

Apart from cardio-vascular diseases, many other nonmalignant diseases (of the respiratory, gastrointestinal, neurological, central nervous, endocrine, immune- and musculo-skeletal system, infections, skin diseases, non-neoplastic hematological disorders and diseases of the lymphatic system) are associated with exposure to IR (Appendix, Table A.6.). Many of these diseases, especially of the endocrine, neurologic, and musculo-skeleton system, cause chronic debilitation and eventual death. They are huge burden for individuals, families and society.

These non-malignant diseases far exceeded the number of malignant diseases and frequently evolved rapidly during the first decade after the Chernobyl NPP accident (Yablokov 2016, 294). This is clearly different from radio-induced cancer cases which are typically diagnosed in later decades. Thus, increased risks for radio-induced non-cancer diseases were observed shortly after just a few single yearly doses, which correspond to total doses from the low-dose range.

Of particular concern is the significant excess of many of these conditions in children living in contaminated regions. In the Ukraine this has been observed especially concerning the respiratory, cardiovascular and digestive system, thyroid and other endocrine diseases, and immunodeficiency disorders, with more than 70% of children being chronically ill 10 years after the Chernobyl NPP accident (Prysyazhnyuk et al. 2002, 188-276). According to data from the Belarussian Ministry of Public Health, in 1985 – just before the 1986 catastrophe – 90% of children were considered "practically healthy". By 2000, fewer than 20% were considered healthy, and in the most contaminated Gomel Province, fewer than 10% of children were well (Yablokov et al. 2009, 58-160).

Significant excess mortality to respiratory, digestive diseases and nonmalignant diseases of the blood is also documented from Japanese atomic bomb survivors (Ozasa et al. 2012, 229-243). A recent study on nuclear workers' external exposure to low dose of IR demonstrated an elevated mortality associated with mental disorders (significant) and respiratory and digestive diseases (not significant) (Gillies et al. 2017, 276-290) (Appendix, Table A.7.).

C2. Reproductive and developmental hazards by ionizing radiation

All along the complex human reproductive process, elevated risks by ionizing radiation at many levels are well known. Their medical and societal relevance is evident considering the extensive radiobiological and epidemiological research over decades on the consequences of the Chernobyl disaster. IR health effects encompass pre-conceptual aspects such as female endocrine dysfunction leading to infertility as well as preexisting parental irradiation associated with consecutive severe development detriments and diseases in

the offspring (Hoffmann et al. 2017, 12). Exposure to IR during pregnancy causes chromosomal aberrations leading – among others – to elevated incidence of Down's syndrome (Sperling 1987, 1991, 1994a, 1994b) and changes of the sex odds ratio (Scherb et al. 2016, 104-111). In utero irradiation furthermore leads to adverse effects on the embryo or fetus inducing spontaneous abortions and congenital malformations, radio-induced excess risks for low birth weight, perinatal and infant mortality as well as elevated risks for childhood malignancies (Hoffmann et al. 2017) (Appendix, Table A.7). In-depth details about non-cancer health effects are given elsewhere (Claussen & Rosen 2016; Hoffmann et al. 2017, 10-3).

Summary Methodology Model C

To conclude on Model C, quantitative estimates for cancer and cardiovascular diseases are performed according to Model B. In addition, Model C developed semi quantitative estimates of other non-malignant radio-induced health effects according to Yablokov who suggests that these cases outnumber cancer cases by a significant margin (Yablokov et al. 2009, 58-160).

III Results

3.1 Distribution of the collective committed effective doses (CCED)

(i) Reminder of the main hypothesis

As already stated (supra 2.2(ii)), we tempered the pixel-dose approach by the 'isoline' approach. We took into account the indoor factor at 0.4 when calculating radioactive deposition and we ignored low doses below 1 mSv. Additionally, it is assumed that persons in areas with doses above 20 mSv during the first year would be evacuated (according to EU directive), which makes only people living in areas where doses from deposition are below 20 mSv would receive a committed effective dose from deposition (supra). The meteorological situations proceed from a simulation of radioactive releases on 1096 meteorological situations (from 1096 days strictly representative of the four seasons – including a bissextile year of 366 days.

(ii) Distribution of the average CCED

Table 3.1 shows that the CCED of deposition amounts to only 20911 persSv (i.e. 2/5 of the cloud CCED (520142 persSv). The latter would be somewhat higher if evacuation was finally set up over 50 mSv/(1st year) or 100 mSv/(1st year). In the present configuration (evacuation with persons located in area above 20 mSv/(first year), Poland would receive 20995 persSv, less than the half CCED of EUR31, while DEU, KLL, SDE and CSUB would receive, respectively 1/7 (6323 persSv), 1/8 (5140 persSv), 1/10 (4274) and 1/7 (6303 persSv) of the average EUR11 CCED (52142 persSv). In other terms, on average and for 1096 meteorological simulations, Poland despite being the most impacted country would receive 2/5 of the total CCED in case of a major nuclear accident. The other 3/5 would radio-contaminate, on average, the surrounding countries. However, the average amount of CCED does not tell the whole picture.

 with three population evacuation threshold 	olds for deposit	ion, duriı	ng the fir	st year,	over 20,	50 and	100 mSv			
respectively (over 1096 simulations equally representative of the seasons)										
NPP: Zarnowiec-Kopal.	Impacted area	EUR31	POL	DEU	KLL	SDE	CSUB			
		(persSv)	(persSv)	(persSv)	(persSv)	(persSv)	(persSv)			
Deposition [1, 20[average	20 911	7 030	2 845	2 298	1 933	2 802			
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 20[average	52 142	20 995	6 323	5 140	4 274	6 303			
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 50[average	53 927	22 698	6 326	5 198	4 290	6 303			
c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 100[average	55 612	24 372	6 326	5 204	4 295	6 303			
NPP: Zarnowiec-Kopal. Deposition [1, 20[c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 20[c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 50[c (dose[1, 500[+ isoline[1000, 2000]) + d dose[1, 100[Impacted area average average average average	EUR31 (persSv) 20 911 52 142 53 927 55 612	POL (persSv) 7 030 20 995 22 698 24 372	DEU (persSv) 2 845 6 323 6 326 6 326	KLL (persSv) 2 298 5 140 5 198 5 204	SDE (persSv) 1 933 4 274 4 290 4 295	CSUB (persSv) 2 802 6 303 6 303 6 303			

Table 3.1. Collective committed effective dose – through the 'pixel-dose' approach tempered by the 'isoline' approach

Notation: c = cloud; d = deposition

POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus). EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

(iii) Transboundary distribution of the radioactive load

The severity of the radioactive load expressed through the person-Sievert approach varies depending on meteorological situations. As the Zarnowiec-Kopal. NPP is projected beside the sea front, meteorological circumstances could spread the radioactive load into sea water. If we look at table 3.2 and refer at the 31

countries together (EUR31), the median (30316 persSv) represents 1/10 of the highest centile (Q99: 308796 persSv), while the lowest centile (Q1: 456 persSv) represents 1/66 of the median⁸. The contrast between the highest and lowest parts of the distribution is considerable.

Poland is the country that would receive the highest CCED of the five regions we considered in this study. For different reasons, Kaliningrad-Oblast and Latvia together with Lithuania as well as Czechia, Slovakia and Ukraine together with Belarus would be hurt by a CCED in a bit less than 3/5 of the simulations; Sweden and Denmark would receive such a radioactive load in 2/5 of the meteorological configurations, while Germany would be impacted in 1/5 of the 1096 situations simulated in this study. However, in disadvantageous meteorological situation, Germany could be affected by a very high CCED, despite having its border more than 250 km from Zarnowiec-Kopal.. In a hundredth of the cases, the CCED received by Germany (149342 persSv) would be as high as 6/7 of the corresponding CCED received by Poland (176257 persSv), while it would exceed by three times the corresponding CCED that would hurt KKL (47755 persSv) and by roughly two times the CCED that could impact SDE (60481 persSv) and CSUB (57792 persSv). In a twentieth of the meteorological situations, the CCED incurred by Germany (41241 persSv), KKL (24685 persSv), SDE (26532 persSv) and CSUB (33222 persSv) would represent, respectively, 2/5, 1/4, 1/4 and 1/3 of the corresponding CCED for Poland (104186 persSv).

Table 3.2. CCED from the cloud and deposition < 20 mSv during the											
first year dist	first year distributed by quantiles (and average)										
Cloud + deposition < 20 mSv (1st year)											
Collective committed effective doses											
NPP: Zarnowiec-Kopal.											
Impac. area	mpac. area EUR31 POL		DEU	KLL	SDE	CSUB					
	(persSv)	(persSv)	(persSv)	(persSv)	(persSv)	(persSv)					
Average	52 142	20 995	6 323	5 140	4 274	6 303					
Max	430 368	364 289	318 682	91 933	145 083	166 223					
Q99	308 796	176 257	149 342	47 755	60 481	57 792					
Q95	177 646	104 186	41 241	24 685	26 532	33 222					
Q85	102 369	53 277	482	12 100	7 546	15 203					
Q75	70 113	23 963	0	6 396	1 0 2 3	6 988					
Q50	30 316	1 730	0	79	0	16					
Q25	11 089	186	0	0	0	0					
Q15	6 044	94	0	0	0	0					
Q5	2 060	52	0	0	0	0					
Q1	456	3	0	0	0	0					
Min	137	0	0	0	0	0					
Results over 109 POL (Poland), DE	6 meteorolo U (Germany	gical simula 1). KLL (Kalin	tions (2017- ingrObl. &	-20) without Latvia & Lit	low dose <: huania). SD	L mSv. E (Sweden					

POL (Poland), DEU (Germany), KLL (Kaliningr.-Obl. & Latvia & Lithuania), SDE (Sweden & Denmark), CSUB (Czechia & Slovakia & Ukraine & Belarus). EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN)

Furthermore, we organized the data so as to evaluate them through temporal synchronicity (which is not the case in Table 3.2). Table 3.3 shows that the four regions together - DEU & KLL & SDE & CSUB could be impacted by a higher collective committed effective dose than Poland on 756 out of 1096 simulations (69%). Moreover, Germany, KLL, SDE and CSUB could also get impaired by a higher CCED than Poland in, respectively, 96, 374, 265, 184 meteorological configurations. 732 meteorological situations out of 1096 simulations (67%) have been identified whereupon one, two and even three countries/regions - considered individually - could be simultaneously hampered by a CCED higher than the one received by Poland during the same meteorological situation. From the latter figure, one can deduce Poland would be

affected by the highest CCED among the four countries/regions in 'only' 364 weather situations (33%), while it would weigh down under a highest CCED than EUR31 in 'only' 24% of the meteorological situations.

Table 3.3. Occurrence of meteorological situations where the health impact would be higher beyond Poland's borders (over 1096 simulations equally representative of the seasons)

NPP: Zarnowiec-Kopal.						
Impacted regions:	(EUR31 - Pol) > Pol	(4 regions) > POL	DEU > POL	KLL > POL	SDE > POL	CSUB > POL
Situations (No)	835	756	96	374	265	184
Situations/(1096 simulat.) (%)	76%	69%	9%	34%	24%	17%

Poland (POL); four regions: (Germany (DEU), Kaliningr.-Obl.+ Latvia + Lithuania (KLL), Sweden + Denmark (SDE), Czechia, Slovakia, Ukraine, Belarus (CSUB))EUR31: POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN, ITA, LIE, LUX, MDA, NLD, NOR, ROU, SMR, SRB, SVN

All in all, we found 732 meteorological situations where one, two and even three countries would be simultaneously hampered by a CCED higher than the CCED Poland would receive as a consequence of the same simulation of a major nuclear accident in Zarnowiec-Kopalino.

⁸ In Table 3.2, the dates of the events are not coordinated from one column to the other; to this extent, each column is independent of the other ones.

In other terms, a higher CCED outside Poland's borders is more probable than the opposite.

3.2 Distribution of the health impact

CCED is an important step in the accounting of the health impact of a major nuclear accident. As stated earlier, this study is based on the no-threshold approach (supra 1.2) that estimates the health impact from the CCED and EAR factors expressed as a fraction of a Sievert (x/Sv). In other words, the distribution of quantiles in below Tables 3.4 & 3.5 is calculated using different EARs and CCEDs as displayed in the first column of Table 3.2 (supra).

(i) Table 3.4. Model A, radio-induced cancer cases

The first three columns of Table 3.4-3.5 display model A being dispatched through the confidence interval (low, medium, high). They give the estimate of radio-induced cancer cases according to Model A issued by WHO/UNSCEAR. Based on the CCEDs (the first column of Table 3.2) and a medium risk factor (EAR) of 0.2/Sv for cancer incidence and (according to UNSCEAR 2013), we have estimated radio-induced cancer cases for EUR31, on average and by quantiles (and confidence intervals according to BEIR VII (2006a).

Table 3.4 shows that the figure of Model A(medium), on average, with 10428 cases, represents a bit more than 1/3 of the result given by Model B (28678 cases). It is worth highlighting that Model B includes radio-induced cardio-vascular diseases while Model A does not (*supra and infra*).

(ii) Table 3.4. Model B, radio-induced cancer cases and radio-induced severe cardiovascular diseases

The fourth column of Table 3.4 estimates the number of radio-induced cancer cases as well as radio-induced cardiovascular diseases according to Model B. Model B is more recent and seems preferable to Model A due to new epidemiological data (Cardis 2005, 77-80; Körblein & Küchenhoff 2006, 109-114; IPPNW 2014; Richardson et al. 2015, h5359; Hoffmann et al. 2017, 6-8). With respect to cancer cases and cardio-vascular diseases, Model B implies a risk factor (EAR) set at 0.55/Sv (*supra* 2.4(iv)). The low level of cases for the first part of the distribution is due to the location of the plant near the sea front. The highest part of the distribution shows that, for Model B, the number of cases is above 16 600, while it exceeds 97 700 cases above Q95) and could even hit 236 702 cases of radio-induced severe diseases.

Table 3.4.	able 3.4. Radio-induced severe diseases (cancer case					Table 3.5. F	Radio-induc	ed deaths (i	from cancer	for Model
for Model A	A, and, cardi	o & cancer c	ases for Mo	del B)		A, and from	n cancer & c	ardiovasc. d	iseases for N	Vodel B)
Cloud + (depos	sition < 20 mSv	/ (1st year))				Cloud + (depos	sition < 20 mSv	/ (1st year))		
NPP: Zarnowie	ec(Kopal.)					NPP: Zarnowie	ec(Kopal.)			
Impac. area	EUR31	EUR31	EUR31	EUR31		Impac. area	EUR31	EUR31	EUR31	EUR31
	Model A(lo)	Model A(me)	Model A(hi)	Model B			Model A(lo)	Model A(me)	Model A(hi)	Model B
	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)			Deaths (No)	Deaths (No)	Deaths (No)	Deaths (No)
Average	4 693	10 428	18 250	28 678		Average	2 607	5 214	9 907	13 035
Max	38 733	86 074	150 629	236 702		Max	21 518	43 037	81 770	107 592
Q99	27 792	61 759	108 079	169 838		Q99	15 440	30 880	58 671	77 199
Q95	15 988	35 529	62 176	97 705		Q95	8 882	17 765	33 753	44 412
Q90	11 392	25 317	44 304	69 621		Q90	6 329	12 658	24 051	31 646
Q85	9 213	20 474	35 829	56 303		Q85	5 118	10 237	19 450	25 592
Q75	6 310	14 023	24 539	38 562		Q75	3 506	7 011	13 321	17 528
Q50	2 728	6 063	10 611	16 674		Q50	1 516	3 032	5 760	7 579
Q25	998	2 218	3 881	6 099		Q25	554	1 109	2 107	2 772
Q15	544	1 209	2 115	3 324		Q15	302	604	1 148	1 511
Q10	339	754	1 319	2 072		Q10	188	377	716	942
Q5	185	412	721	1 133		Q5	103	206	391	515
Q1	41	91	160	251		Q1	23	46	87	114
Min	12	27	48	75		Min	7	14	26	34
Results over 10	096 meteo. sin	nulat. (2017-20)) without low do	ose <1 mSv.		Results over mSv.	1096 meteo.	simulat. (201	7-20) without	low dose <1
EUR31 (POL	EUR31 (POL, DEU, DNK, SWE, FIN, RU1, EST, LVA, LTU, BLR,					EUR31 (POL	, DEU, DNK,	SWE, FIN, R	U1, EST, LVA	, LTU, BLR,
UKR, SVK, C	UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN,					UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV, HUN,				
11A, LIE, LUX	K, MDA, NLD,	NOR, ROU, S	SMR, SRB, SV	/N)		TTA, LIE, LUX	K, MDA, NLD	, NOR, ROU, S	SMR, SRB, S	VN)

(iii) Table 3.5. Model A, radio-induced deaths from cancer

The first three columns of Table 3.5 estimates (mean and confidence interval) the number of radio-induced deaths from cancer cases according to Model A issued by WHO/UNSCEAR (for the number of estimated radio-induced cancer deaths divide cancer cases by 2).

(iv) Table 3.5. Model B, radio-induced deaths from cancer cases and severe cardiovascular diseases

The fourth column of Table 3.5 shows the number of deaths from added cancer cases *and* added severe cardiovascular diseases as a consequence of a major nuclear accident. For the estimates of the number of deaths, the number of cases of the preceding table has to be divided by 2.2. The average number of deaths would reach around 13 035, while the median numbers 7 579 deaths and the highest hundredth could exceed 77 100 deaths. The 'low' number of cases below the median is explained elsewhere (*supra* ii).

u

3.3 Distribution of the health impact among countries according to Model B

-				/ 1.	• ·										
Table 3.6.	Radio-ind	uced seve	re disease	es (cardio	& cancer)	Model B									
among dif	ferent cou	ntries and	regions												
Cloud + depo	sition < 20 m	Sv (1st year)													
NPP: Zarnow	iec-Kopal.														
Impac. area	EUR31	POL	DEU	KLL	SDE	CSUB									
	Model B	Model B	Model B	Model B	Model B	Model B									
	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)	Pers. (No)									
Average	28 678	11 547	3 478	2 827	2 351	3 467									
Max	236 702	200 359	175 275	50 563	79 796	91 423									
Q99 169 838 96 941 82 138 26 265 33 264 31 786															
Q95 97 705 57 302 22 683 13 577 14 593 18 27															
Q85 69 621 29 303 265 6 655 4 150 8 362															
Q75	56 303	13 180	0	3 518	563	3 844									
Q50	38 562	952	0	44	0	9									
Q25	16 674	103	0	0	0	0									
Q15	6 099	52	0	0	0	0									
Q5	1 133	28	0	0	0	0									
Q1	251	2	0	0	0	0									
Min	75	0	0	0	0	0									
Results over	1096 meteo.	simulation (2	2017-20) wit	hout low dos	e <1 mSv.										
POL (Poland)	, DEU (Germ	any), KLL (Ka	liningrObl.	& Latvia & L	ithuania), SI	DE (Sweden									
& Denmark)	CSUB (Czech	ia & Slovaki	a & Elkraine	& Belarus)											
Q Definiark),						CDD UDV									
SVVE, FIIN, KU	I, ESI, LVA,	LIU, BLR, UN	K. SVK. UZE.		& Denmark), CSUB (CZECNIA & SIOVAKIA & UKRAINE & BEIARUS). EUKSI (POL, DEU, DNK, SWE EIN RITEST IVA ITH RIP IKR SVK CZE ANT DEI DIE CHE EDA CAD HOV										
				SWE, FIN, RU1, EST, LVA, LTU, BLR, UKR, SVK, CZE, AUT, BEL, BIH, CHE, FRA, GBR, HRV,											
HUN, ITA, LIE	, LUX, MDA,	NLD, NOR, R	OU, SMR, SR	B, SVN)		, obk, mkv,									
HUN, ITA, LIE	, LUX, MDA,	NLD, NOR, RO	OU, SMR, SR	B, SVN)		, OBN, HINV,									
HUN, ITA, LIE Table 3.7	, LUX, MDA, I	duced de	ou, smr, sr	ording to	Model E	3 among									
HUN, ITA, LIE Table 3.7 different c	, LUX, MDA, I . Radio-in ountries a	duced de	eaths acco	prding to	Model E	3 among									
Table 3.7 different c	, LUX, MDA, I . Radio-in ountries a sition < 20 m	duced de nd regions Sv (1st year)	eaths acco	prding to	Model E	3 among									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow	, LUX, MDA, I . Radio-in ountries a sition < 20 m iec-Kopal.	duced de nd regions Sv (1st year)	ou, smr, sr eaths acco	prding to	Model E	3 among									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area	, LUX, MDA, I . Radio-in ountries a sition < 20 m iec-Kopal. EUR31	duced de nd regions Sv (1st year) POL	ou, smr, sri eaths acco	ording to	Model E	3 among CSUB									
Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area	, LUX, MDA, I . Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B	ULD, NOR, Ro duced de nd regions Sv (1st year) POL Model B	DU, SMR, SR eaths acco	brding to KLL Model B	Model E SDE Model B	3 among CSUB Model B									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area	, LUX, MDA, Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths	DU, SMR, SR eaths acco DEU Model B Deaths	B, SVN) prding to KLL Model B Deaths	Model E SDE Model B Deaths	3 among CSUB Model B Deaths									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area	, LUX, MDA, Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No)	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No)	DU, SMR, SR eaths acco DEU Model B Deaths (No)	KUL, DEC, DEC, DEC, DEC, DEC, DEC, DEC, DEC	SDE Model B Deaths (No)	3 among CSUB Model B Deaths (No)									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area	, LUX, MDA, I . Radio-in ountries a isition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249	DU, SMR, SR eaths acco b DEU Model B Deaths (No) 1 581	KILL Model B Deaths (No) 1 285	SDE Model E Model B Deaths (No) 1 069	CSUB Model B Deaths (No) 1 576									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max	, LUX, MDA, I , Radio-in ountries a isition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072	DU, SMR, SR eaths acco be DEU Model B Deaths (No) 1 581 79 671	KLL Model B Deaths (No) 1 285 22 983	SDE Model E Model B Deaths (No) 1 069 36 271	CSUB Model B Deaths (No) 1 576 41 556									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max Q99	, LUX, MDA, I , Radio-in ountries a isition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199	NLD, NOR, RO duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064	DU, SMR, SR eaths acco be DEU Model B Deaths (No) 1 581 79 671 37 335	KLL Model B Deaths (No) 1 285 22 983 11 939	SDE Model E Model B Deaths (No) 1 069 36 271 15 120	CSUB Model B Deaths (No) 1 576 41 556 14 448									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046	DU, SMR, SR DEU aths acco b DEU Model B Deaths (No) 1 581 79 671 37 335 10 310	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171	SDE Model E Model B Deaths (No) 1 069 36 271 15 120 6 633	CSUB Model B Deaths (No) 1 576 41 556 14 448 8 306									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area Average Max Q99 Q95 Q85	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319	DU, SMR, SR DEU aths acco be Model B Deaths (No) 1581 79 671 37 335 10 310 120	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025	SDE Model B Deaths (No) 1069 36 271 15 120 6 633 1 887	CSUB Model B Deaths (No) 1576 41556 14448 8 306 3 801									
HUN, ITA, LIE Table 3.7 different o Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991	DEU saths acco be Model B Deaths (No) 1581 79 671 37 335 10 310 120 0	KIL B, SVN) brding to KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599	SDE Model B Deaths (No) 1069 36 271 15 120 6 633 1 887 256	CSUB Model B Deaths (No) 1576 41556 14448 8 306 3 801 1 747									
HUN, ITA, LIE Table 3.7 different of Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433	DEU saths acco be Model B Deaths (No) 1581 79 671 37 335 10 310 120 0 0	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0	CSUB Model B Deaths (No) 1576 41556 14448 8 306 3 801 1 747 4									
HUN, ITA, LIE Table 3.7 different c Cloud + depc NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25	, LUX, MDA, , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47	DU, SMR, SR DEU Model B Deaths (No) 1581 79 671 37 335 10 310 120 0 0	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0	CSUB Model B Deaths (No) 1576 41556 14 448 8 306 3 801 1 747 4 0									
HUN, ITA, LIE Table 3.7 different of Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15	, LUX, MDA, , LUX, MDA, , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23	DU, SMR, SR DEU Model B Deaths (No) 1581 79 671 37 335 10 310 120 0 0 0	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0	CSUB Model B Deaths (No) 1576 41556 14 448 8 306 3 801 1 747 4 0 0									
HUN, ITA, LIE Table 3.7 different of Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15 O5	, LUX, MDA, , LUX, MDA, , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511 515	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23 12	DU, SMR, SR DEU Model B Deaths (No) 1581 79 671 37 335 10 310 120 0 0 0 0	KLL Model B Deaths (No) 1285 22983 11939 6171 3025 1599 20 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0 0	CSUB Model B Deaths (No) 1576 41556 14 448 8 306 3 801 1 747 4 0 0									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15 Q5 Q15 Q5	, LUX, MDA, , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511 515	NLD, NOR, R duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23 13	DU, SMR, SR DEU saths acco b Model B Deaths (No) 1 581 79 671 37 335 10 310 120 0 0 0 0 0	KLL Model B Deaths (No) 1285 22983 11939 6171 3025 1599 20 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0 0 0	CSUB Model B Deaths (No) 1576 41556 14 448 8 306 3 801 1 747 4 0 0 0									
HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15 Q15 Q1 Q1	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511 515 114	NLD, NOR, RC duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23 13 13	DU, SMR, SR DEU saths acco b DEU Model B Deaths (No) 1 581 79 671 37 335 10 310 120 0 0 0 0 0 0 0 0	KUL B, SVN) brding to KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20 0 0 0 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0 0 0	CSUB Model B Deaths (No) 1576 41556 14 448 8 306 3 801 1 747 4 0 0 0 0									
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HUN, ITA, LIE Table 3.7 different c Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15 Q15 Q1 Min Results over	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511 515 114 34 1096 meteo.	NLD, NOR, RC duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23 13 1 1 0 simulat. (202	DU, SMR, SR DEU eaths acco b DEU Model B Deaths (No) 1 581 79 671 37 335 10 310 120 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0 0 0 0	CSUB Model B Deaths (No) 1576 41556 14448 8306 3801 1747 4 0 0 0 0 0 0 0									
HUN, ITA, LIE Table 3.7 different C Cloud + depo NPP: Zarnow Impac. area Average Max Q99 Q95 Q85 Q75 Q50 Q25 Q15 Q15 Q15 Q1 Min Results over EUR11: POL	, LUX, MDA, I , Radio-in ountries a sition < 20 m iec-Kopal. EUR31 Model B Deaths (No) 13 035 107 592 77 199 44 412 25 592 17 528 7 579 2 772 1 511 515 114 34 1096 meteo. (Poland), DEU	NLD, NOR, RG duced de nd regions Sv (1st year) POL Model B Deaths (No) 5 249 91 072 44 064 26 046 13 319 5 991 433 47 23 13 1 1 0 simulat. (202 J (Germany)	DU, SMR, SR DEU saths acco b b beaths (No) 1 581 79 671 37 335 10 310 120 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	KUL B, SVN) brding to KLL Model B Deaths (No) 1 285 22 983 11 939 6 171 3 025 1 599 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	SDE Model B Deaths (No) 1 069 36 271 15 120 6 633 1 887 256 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	CSUB Model B Deaths (No) 1576 41556 14448 8306 3801 1747 4 0 0 0 0 0 0 0									

3.4 Distribution of individual doses to persons

According to European Directive (supra), some legal threshold for individual doses are set up – over one year – at 1 mSv, 6 mSv, 20 mSv, 50 mSv, 100 mSv.

Table 3.8 Number of meteorological situations where a region is impacted by the cloud and number of persons affected by different levels of individual doses											
NPP: Zarr	NPP: Zarnowiec-Kopal.										
Region	Levels of contamination by the cloud \rightarrow \geq 1 mSv \geq 6 mSv \geq 20 mSv \geq 50 mSv \geq 10										
POL	Number of situations with impact (No)	1 096	1 096	1 095	1 0 9 1	1 082					
POL	No of situations with impact/1096 situati. (%)	100%	100%	100%	100%	99%					
POL	Average No of pers. in these specific situati. (No)	1 605 797	398 144	114 928	46 904	18 875					
DEU	Number of situations with impact (No)	218	143	38	2	0					
DEU	No of situations with impact/1096 situati. (%)	20%	13%	3%	0.2%	0%					
DEU	Average No of pers. in these specific situati. (No)	5 479 163	862 357	284 942	48 165	()					
KLL	Number of situations with impact (No)	648	507	240	57	8					
KLL	No of situations with impact/1096 situati. (%)	59%	46%	22%	5%	1%					
KLL	Average No of pers. in these specific situati. (No)	916 562	276 280	95 539	37 505	14 561					
SDE	Number of situations with impact (No)	444	310	173	58	7					
SDE	No of situations with impact/1096 situati. (%)	41%	28%	16%	5%	1%					
SDE	Average No of pers. in these specific situati. (No)	1 255 801	400 524	64 352	8 958	10 388					
CSUB	Number of situations with impact (No)	631	329	35	2	0					
CSUB	No of situations with impact/1096 situati. (%)	58%	30%	3%	0.2%	0%					
CSUB	Average No of pers. in these specific situati. (No)	2 600 644	184 297	50 285	6 978	()					
Poland (F Slovakia,	OL); four regions: (Germany (DEU), KaliningrObl.+ Ukraine, Belarus (CSUB))	Latvia + Lithu	iania (KLL),	Sweden + D	enmark (SD	E), Czechia,					

Table 3.9. Number of meteorological situations where a region would be impacted by the deposition and number of persons affected by different levels of individual doses

NPP: Zarno	owiec-Kopal.									
Region	Levels of contamination by deposition (1st year)	≥1 mSv	≥6 mSv	≥20 mSv	≥50 mSv	≥ 100 mSv				
POL	Number of situations with impact (No)	1 096	1 096	1 095	1 091	1 078				
POL	No of situations with impact/1096 situati. (%)	100%	100%	100%	100%	98%				
POL	Average No of pers. in these specific situati. (No)	1 464 349	332 220	96 553	38 810	14 483				
DEU	Number of situations with impact (No)	221	139	30	1	0				
DEU	No of situations with impact/1096 situati. (%)	20%	13%	3%	0.1%	0%				
DEU	Average No of pers. in these specific situati. (No)	4 721 104	672 427	194 643	56 077	()				
KLL	Number of situations with impact (No)	652	492	215	48	7				
KLL	No of situations with impact/1096 situati. (%)	59%	45%	20%	4%	1%				
KLL	Average No of pers. in these specific situati. (No)	837 606	233 322	75 088	22 994	8 100				
SDE	Number of situations with impact (No)	447	308	157	39	6				
SDE	No of situations with impact/1096 situati. (%)	41%	28%	14%	4%	1%				
SDE	Average No of pers. in these specific situati. (No)	1 142 218	319 424	46 877	8 160	8 155				
CSUB	Number of situations with impact (No)	635	324	33	3	0				
CSUB	No of situations with impact/1096 situati. (%)	58%	30%	3%	0.3%	0%				
CSUB	Average No of pers. in these specific situati. (No)	2 189 922	125 367	37 320	431	()				
Poland (PC Slovakia, L	Poland (POL); four regions: (Germany (DEU), KaliningrObl.+ Latvia + Lithuania (KLL), Sweden + Denmark (SDE), Czechia, Slovakia, Ukraine, Belarus (CSUB))									

3.5 Impacts on cities and towns

The question of the impact measured in millisiverts on the inhabitants of towns and cities of different sizes continues the exploration of the concept of transboundary radioactive pollution in a preventive perspective. The examination of the results nevertheless begins with the cities of Poland.

The following table shows that the Polish city most likely to be affected is Gdynia, which is affected 224 times for 1,096 simulations (1/5) and would also record the highest level of contamination. Next come the cities of Gdansk and Olsztyn, the latter with lower levels of contamination.

Table 3.10. Possible impacts on cities from the cloud: number of occurrences over 1096 simulations, average mSv for these occurrences, and higher mSv impacts											
NPP: Zarnowiec-Kopalino	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland	Poland
	Bialystok	Bydgosz.	Gdansk	Gdynia	GorzW.	Koszalin	Lodz	Olsztyn	Poznan	Szczecin	Warsaw
No of impacts with a dose such as (mSv > 0) (No)	199	125	199	224	96	122	116	199	109	92	149
Average mSv of the above 92 to 224 impacts (mSv)	3.5	3.8	23.1	43.3	3.0	12.1	3.0	5.9	3.3	3.3	2.8
Higher impact identified (mSv)	47.7	33.2	227.5	339.6	19.4	99.5	35.5	58.2	21.1	20.0	27.6
Third higher impact identified (mSv)	23.2	19.0	193.4	295.8	15.8	75.8	12.5	46.4	14.0	16.3	15.7

If we look at the next table, it appears that several cities outside Poland's East border (Kaliningrad, Kaunas and Klaipeda) would have a higher probability to be hit than Polish cities mentioned in the above table. Danish and Swedish cities like Kalmar seem also to be exposed.

Table 3.11. Possible impacts on cities or towns from the cloud: number of occurrences over 1096 simulations, average mSv for these occurrences, and higher mSv impacts										
NPP: Zarnowiec-Kopalino	DNK	DNK	SWE	SWE	SWE	SWE	SWE	Kali. Ob.	LTU	LTU
	Copenha	Bornhol.	Kalmar	Malmö	Växsjö	Gotland	Stockho.	Kaliningr.	Kaunas	Klaipeda
No of impacts with a dose such as (mSv > 0) (No)	102	117	117	107	111	147	104	294	251	239
Avera. mSv of the above 102 to 294 impacts (mSv)	4.5	10.0	7.0	5.1	4.2	5.2	2.9	8.9	2.9	6.2
Higher impact identified (mSv)	38.7	75.9	73.3	37.7	40.3	39.8	26.0	90.4	26.0	60.4
Third higher impact identified (mSv)	18.0	66.4	40.7	24.0	29.5	27.7	15.2	66.4	16.0	42.0

Outside the Western border, the probability to be impacted seems a bit lower than outside the northern and eastern border. It is nonetheless comparable to several Polish cities. The weight of the potential impact can be rather high in some meteorological conditions (93.1 mSv in Neubrandenburg, an amount whose addition to the figure of deposition would exceed 100 mSv and exceed the highest limit considered in emergency situations that the Council Directive aims at protecting as a public good and whose breach leads to totally insufferable consequences (European Commission 2017, Art. 53.2(a)).

Table 3.12. Possible impacts on cities or towns from the cloud: number of occurrences over 1096 simulations, average mSy for these occurrences, and higher mSy impacts									
NPP: Zarnowiec-Kopalino	DEU	DEU	DEU	DEU	DEU	DEU	DEU	DEU	DEU
	Anklam	Berg. Rü.	Berlin	Francf O.	Greifswld	Hambur.	Neubran.	Rostock	Schwedt
No of impacts with a dose such as (mSv > 0) (No)	96	100	80	88	100	75	79	97	88
Avera. mSv of the above 75 to 100 impacts (mSv)	4.0	4.9	3.1	3.0	4.7	3.7	3.8	3.7	3.0
Higher impact identified (mSv)	38.3	43.9	32.1	25.3	45.8	32.1	93.1	24.9	19.3
Third higher impact identified (mSv)	26.5	27.0	15.6	13.9	21.3	20.3	9.7	21.1	12.8

To conclude this point, on the one hand, the probability of impacting this or that city (or town) mentioned in the above tables ranges between 7% and 27% and it would even be lower if we considered only substantial impacts; this is not surprising since the surface in square kilometers of cities is much smaller than that of countries.

On the other hands, it is clear that, all in all, the probability that no city will be affected in the event of a major nuclear accident is not very high. Locating a nuclear power plant in the area of Zarnowiec-Kopalino, on the shores of the Baltic Sea, does not extinguish the risk of a massive radioactive pollution, which would occurred at the expense of one, or two, Polish or foreign cities.

Table 3.13. Correspondence between millisieverts and Becquerels in calculation on radioactive deposition									
NPP: ZA2 3415 MWth									
Parents' Becquerels(t1) (Bq m-2)	2.50E+06	1.66E+07	4.16E+07	8.32E+07	2.08E+08	4.16E+08	8.32E+08	1.25E+09	1.66E+09
ALL nuclides (mSv (1st yr)-1)	3	20	50	100	250	500	1 000	1 500	2 000
Cs-137(t1) (Bq m-2)	1.04E+05	6.95E+05	1.74E+06	3.47E+06	8.69E+06	1.74E+07	3.47E+07	5.21E+07	6.95E+07
Cs-137 + Ba-137 (mSv (1st yr)-1)	0.5	3.3	8.1	16.3	40.7	81.5	162.9	244.4	325.9
Note: From Bq to mSv> through specific half-lives & dose factors; and through indoor factor at 0.4									

Table 3.14. Average number of radioactive square kilometers, for different levels of individual dose, over 1096 meteorological simulations

NPP: ZA2 3415 MWth

Area: EUR39									
ALL nuclides (mSv (1st yr)-1)	≥3	≥20	≥50	≥100	≥250	≥500	≥1000	≥1500	≥2000
All surfaces (km2)	17 949	763	212	106	41	14	3	1	1
Excerpt: Cultivated + herbaceous (km2)	2 862	122	35	17	6	2	0	0	0

Note: From Bq to mSv -> through specific half-lives & dose factors; and through indoor factor at 0.4

EUR39: ALB, AUT, BEL, BIH, BGR, HRV, CYP, CZE, DNK, EST, FIN, FRA, DEU, GRC, HUN, ISL, IRL, ITA, (kos), LVA, LIE, LTU, LUX, MLT, MNE, NLD, MKD, NOR, POL, PRT, ROU, SRB, SVK, SVN, ESP, SWE, CHE, TUR, GBR

IV Conclusion

This study modelling a major nuclear accident of the planned nuclear power plant Zarnowiec-Kopalino from the data of 1096 realistic meteorological situations reveals a highly significant potential for transboundary radio-contamination both of the 11 surrounding countries but also a in wider circle of 31 European states. Victims outside Poland – mainly hit by radioinduced cancer and non-cancer diseases – would exceed the number of cases in Poland itself. Meteorological extremes could carry the radionuclides thousands of kilometers away from the original source.

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