Part I. General framework and methodology environmental impact assessment postponement deactivation Doel 4 and Tihange 3

1 Introduction

1.1 Context of environmental impact assessment

1.1.1 Antecedents

Nuclear power has been the main source of electricity in Belgium since the commissioning of the various reactors at the Doel and Tihange sites in the years 1975-1985 (see Table 1), with an annualized production share between about 40 and 60% over the last 35 years.

The phasing out of the use of nuclear energy for industrial electricity production on the Belgian territory was regulated by the **Act of January 31, 2003** on the phasing out of nuclear energy for industrial electricity production (Act on Nuclear Exit). This stipulated that nuclear power plants would be deactivated 40 years after the date of their industrial commissioning and that all individual licenses relating to electricity production by these plants would come to an end at the same time.

The law also states that no new nuclear power plant intended for industrial electricity production by fission of nuclear fuels can be established and/or put into operation.

This Nuclear Exit Act was amended in 2013 (**Act of December 18, 2013**) to extend the operating time extension for Tihange 1 industrial electricity production by 10 years. The Nuclear Exit Act was amended again in 2015 (**Act of June 28, 2015**) in order to ensure energy supply. This authorized the restart of Doel 1 (it had already been shut down in accordance with the 2003 law) and postponed the deactivation of Doel 2 by 10 years. These new dates for deactivation are also included in Table 1.

In a judgment of March 5, 2020, the Constitutional Court ruled that this decision (the law of June 28, 2015), as well as the works necessary for the proper operation of Doel 1 and 2 during the 10 additional years, are subject to the preparation of an environmental impact assessment accompanied by a public consultation. At the same time, the Court maintained the effects of the annulled law until the adoption, by the legislature, of a new law preceded by the required environmental impact assessment and appropriate assessment, with public participation and cross-border consultation, and no later than December 31, 2022. After conducting an environmental impact assessment and public consultation, including cross-border consultation,[1] the **law of October 11, 2022** amending the law of January 31, 2003 on the gradual exit from nuclear energy for industrial electricity production was enacted.

Table 1: Deactivation calendar according to the original Core Exit Act of 2003 and its subsequent amendments (status Jan. 1, 2023).

Central	Date of industrial commissioning	Date of deactivation (original 2003 law)	Date of deactivation (amendments to 2003 law, status Jan. 1, 2023)
Doel 1	February 15, 1975	February 15, 2015	Feb. 15, 2025
Doel 2	December 1, 1975	December 1, 2015	December 1, 2025
Doel 3	October 1, 1982	October 1, 2022	Oct. 1, 2022[2]

[1] See https://economie.fgov.be/nl/themas/energie/energiebronnen/kernenergie/milieueffectbeoordeling-van

[2] In the evening of Friday, September 23, 2022, at 9:31 p.m., the operators in the Doel 3 control room shut down the reactor for the last time and disconnected it from the high-voltage grid. Because of the regulatory limitation of the duration of 1 fuel cycle to a maximum of 365 days, the reactor was shut down a few days before the deactivation deadline. At that time, the reactor had been in stretch-out mode for 2.5 months and was still producing about 60% of its power.

Central	Date of industrial commissioning	Date of deactivation (original 2003 law)	Date of deactivation (amendments to 2003 law, status Jan. 1, 2023)
Doel 4	July 1, 1985	July 1, 2025	July 1, 2025
Tihange 1	October 1, 1975	October 1, 2015	October 1, 2025
Tihange 2	February 1, 1983	Feb. 1, 2023	Feb. 1, 2023[3]
Tihange 3	September 1, 1985	September 1, 2025	September 1, 2025

In late December 2021, the government (Council of Ministers of Dec. 23, 2021) asked the Federal Agency for Nuclear Control (FANC) and FPS Economy (DG Energy) to list and analyze by Jan. 17 the actions needed to activate the so-called plan B (keeping the Doel 4 and Tihange 3 nuclear reactors open longer than planned) in connection with Belgium's energy security after 2025.

FANC's analysis showed that an extension of the operating period for the youngest nuclear reactors was possible in terms of nuclear safety, albeit subject to the necessary regulatory adjustments and safety improvements to the facilities. An extension of operation also requires an environmental impact report.

Then, **on March 18, 2022,** the federal government decided to effectively proceed with an extension of the operating period of Doel 4 and Tihange 3, thus maintaining a nuclear generation capacity of 2 gigawatts. Given the problems in terms of electricity supply from neighboring countries, the high dependence on fossil fuels, the acceleration of the energy transition, geopolitical tensions that make prices highly volatile and put pressure on natural gas supplies, the Council of Ministers decided on March 18, 2022, to take the necessary steps to extend 2 GW of nuclear capacity - specifically Doel 4 and Tihange 3 - for a period of 10 years. This decision is in line with the policy the European Commission wishes to pursue for increased independence from fossil fuels and diversified energy supply.

On April 1, 2022, at the proposal of Energy Minister Tinne Van der Straeten, the Council of Ministers approved a preliminary draft law amending the law on the gradual phasing out of nuclear energy[4]. The preliminary draft law aims to allow the activation of the Doel 4 and Tihange 3 nuclear reactors for another 10 years, and this after taking into account the results of the environmental impact assessment, the public consultation, the consultation of the authorities concerned and the cross-border consultations.

On July 22, 2022, initial talks between the Belgian State and ENGIE Electrabel led to a non-binding letter of intent. On Jan**. 9, 2023,** the Belgian government and operator ENGIE Electrabel came to an agreement to secure the keeping open of the country's two youngest nuclear reactors, Doel 4 and Tihange 3, for 10 years beyond their planned closure date in 2025.

1.1.2 Initiator and team of experts

1.1.2.1 Initiator

The initiator of the environmental impact assessment is the Belgian Federal Public Service Economy, K.M.O., Middle Classes and Energy, Vooruitgangstraat 50, 1210 Brussels.

1.1.2.2 Team of experts

The EIA was prepared by a team of independent radiological and non-radiological EIA experts. Reference to their accreditation can be found on pp. 3 and 4.

[3] At midnight on Jan. 31, 2023, Tihange 2 was also permanently shut down after 40 years of operation.

[4] https://news.belgium.be/nl/wijziging-van-de-wet-over-de-kernuitstap

Radiological EIA experts from SCK CEN (KC Doel and CN Tihange):

- Johan Camps: project coordinator and radiological EIA expert;
- Eef Weetjens: radiological EIA expert, specifically for radioactive waste and spent nuclear fuel;
- Lieve Sweeck: radiological EIA expert;
- Geert Olyslaegers: radiological EIA expert;
- Hildegarde Vandenhove: radiological EIA expert; Non-

radiological EIA experts:

- General EIA Coordination: Koen Couderé (KENTER);

For KC Purpose:

  - EIA expert on Water and Climate: Koen Couderé (KENTER); The health aspect was also addressed by Koen Couderé;
  - EIA coordinator: Katelijne Verhaegen (KENTER);
  - EIA Biodiversity expert: Annemie Pals (Mieco effect);
  - Air EIA expert: Johan Versieren (Joveco); For CN

Tihange:

  - EIE coordinator: Xavier Musschoot (SERTIUS);
  - Experte Eau de Surface et Etre humain: Maureen de Hertogh (SERTIUS);
  - Expert Biodiversité: Pierre Jacques (SERTIUS);
  - Experte Air et Climat: Amélie de Pierpont (SERTIUS).

1.1.3 Reading Guide

This EIA is composed of ten chapters divided into four sections. A first general part concerning the Project and the methodology followed, then the part concerning the environmental impact assessment for Doel 4 followed by the part concerning the environmental impact assessment for Tihange 3. Part 4 then summarizes the effects of the Project.

The original report was written in Dutch and for the non-radiological effects Tihange 3 in French. Consequently, this report contains translations of the original text.

Introductory *Chapter 1* (this chapter) describes the background of the Project that is the subject of this environmental impact assessment (EIA). Higher, the legal and policy antecedents and the objective of the assessment have already been discussed, and the team conducting this study has been introduced. Further on, Chapter 1 describes the Project and discusses some methodological aspects, such as whether or not to study alternatives and define the baseline condition, and external developments that may affect that baseline condition. It also discusses the evolution of security of supply over the 2020-2030 period, which is the motivation for the Project. Finally, Chapter 1 also briefly describes the procedure followed, focusing on the consultation and participation of the public and on the request for advice to a number of competent authorities.

Chapter 2 describes the methodology of the EIA, respectively for radiological and non-radiological aspects. As far as the non-radiological impacts are concerned, the topics that will receive special attention in this EIA are indicated here, and reasons are given as to why certain topics are not addressed in detail. A distinction is also made between the effects of the project on its environment, the avoided effects of the project, and the effects of the environment on the project. As far as radiological impacts are concerned, the basic concepts of radiation protection and of radioactive waste and its management are first discussed. It then describes the methodology used to determine the effects of routine and accidental discharges on humans and the environment and of radioactive waste.

Chapter 3 describes and assesses the non-radiological effects of the lifetime extension of Doel 4 for the themes of Water, Biodiversity, Air, Climate and Health. In each case, the assessment is based on a review of the policy objectives relevant to the theme.

Chapter 4 describes the radiological effects of the lifetime extension of Doel 4. The effects on humans and biodiversity during normal operation are discussed, as well as these effects attributable to accidental discharges, operational radioactive waste and spent fuel. Mitigation measures in the form of emergency planning are also discussed.

Chapter 5 provides a synthesis of both non-radiological and radiological effects for Doel 4. Special attention is given to transboundary effects.

Chapter 6, Chapter 7 and Chapter 8 contain successively the same information for Tihange 3 as those included in Chapters 3, 4 and 5 for Doel 4: the non-radiological effects, the radiological effects and a synthesis of both.

Chapter 9 contains an overarching synthesis of the project's impacts for Tihange 3 and Doel 4 together, for both radiological and non-radiological impacts. Finally, *Chapter 10 provides an* overall conclusion.

This EIA also includes a non-technical summary, in the form of a separate document, intended to provide a broad public understanding of the results of this EIA. Herein, for the receptor disciplines of health and biodiversity, radiological and non-radiological effects are addressed in an integrated manner.

1.2 Subject of the environmental impact assessment and alternatives to be examined

1.2.1 The Project

1.2.1.1 Introduction

This environmental impact assessment covers the strategic decision and works as known when conducting the assessment[5] for the prolongation of the Doel 4 and Tihange 3 nuclear reactors for the industrial production of electricity for a period of 10 years after the envisaged closure according to the 2003 Nuclear Exit Act, as defined in Table 2. When we refer to the prolongation of Doel 4 and Tihange 3 in this report, we always mean the prolongation as defined in the table below.

Table 2: Extension of the Doel 4 and Tihange 3 reactors for industrial electricity production as considered in this environmental impact assessment. This timing is consistent with the draft law approved at the April 1, 2022 Council of Ministers (see §1.1.1).

Reactor	Anticipated closure Core Exit Act 2003	Extension	Latest anticipated date of deactivation upon renewal
Doel 4	July 1, 2025	Ten-year period from the date of the first industrial electricity production after July 1, 2025	December 31, 2037
Tihange 3	September 1, 2025	Period of ten years from the date of first industrial electricity production after Sept. 1, 2025	December 31, 2037

[5] Information available up to the date of the end of January 2023 was included in this Environmental Impact Assessment, information that became available later was not guaranteed to be included in the assessment.

The project, as considered here, involves the extension of industrial energy production with the Doel 4 and Tihange 3 nuclear reactors/units as shown in Table 2, which are respectively part of the site of the Doel Nuclear Power Plant (KC Doel) located at Scheldemolenstraat, Haven 1800, 9130 Doel and of the site of the Tihange Nuclear Power Plant (Centrale Nucléaire de Tihange, CN Tihange), located at Avenue de l'Industrie 1, 4500 Huy, both operated by Electrabel S.A. as of February 1, 2023. The environmental impact assessment of this project will start from all applicable European Directives (2011/92/EU, 92/43/CEE and 2009/147/CE). The location of both sites in Belgium is shown in Figure 1.

Figure 1: Location of the Doel and Tihange nuclear power plants (orange). Also shown are the nuclear power plants on the borders with Belgium (green) and other Class 1 nuclear facilities in Belgium (blue).

The Doel nuclear power plant (KC Doel) and Tihange nuclear power plant (CN Tihange) comprise a total of four and three nuclear reactors respectively, the necessary auxiliary buildings and installations for the production of electricity and the storage of spent nuclear fuel. KC Doel is located in the municipality of Beveren (province of East Flanders) along the left bank of the Scheldt and at a shortest distance of 3.15 km from the Dutch border. CN Tihange is located in the municipality of Huy (province of Liège) along the right bank of the Meuse River and at shortest distances of 38 km and 58 km from the Dutch and German borders, respectively. The operation of the nuclear power plant, focusing on the operation of the Doel 4 and Tihange 3 units that are part of the project, is further described in §1.2.1.2.

The project is seen as independent from other projects ongoing and/or planned for the KC Doel and CN Tihange sites, such as the [SF2] project (the construction of a new facility for the temporary storage of spent nuclear fuel at the Doel site: the "Spent Fuel Facility" or facility for spent fuel [ni]) and the shutdown of Doel 3 and Tihange [26]. A description of the different activities running in parallel at the KC Doel and CN Tihange sites can be found in §1.2.1.3.

[6] As stipulated by the Royal Decree of January 31, 2003 on the gradual exit from nuclear energy.

This environmental impact assessment covers the strategic policy decision and necessary works for the continued opening and operation of the Doel 4 and Tihange 3 units for industrial electricity production for a period of 10 years as specified in Table 2.

Within the framework of Belgian regulations, the various establishments, which use radioactive substances or devices capable of producing ionizing radiation, are classified into *four classes of establishments*. The classification rules are based on the *potential risk of operation*. An establishment (or an installation) belongs to a certain class depending on the quantities of radioactive substances, on the power of the device or the activity of the radioactive source(s) or on the level of exposure to ionizing radiation. All Belgian nuclear installations, including KC Doel and CN Tihange, fall under *Class 1* and must therefore comply with all regulations concerning *Class 1* installations.

The project as defined here involves, as previously indicated, an additional period of operation of the Doel 4 and Tihange 3 units beyond the initial operating period of forty years. In accordance with the Royal Decree of Jan. 25, 1974 and the Royal Decree of Nov. 30, 2011 on safety regulations for nuclear installations, the operator must conduct a periodic safety review at intervals not exceeding 10 years. This is called the *Ten-Year Review or* Periodic Safety *Review*. For the period after 2025, this is the fourth review and the two units are also 40 years in operation. Consequently, this represents a longer period of operation than initially foreseen in the design of the reactors, which is also called Long Term Operations (LTO).

As far as safety is concerned, all nuclear reactors currently comply with the currently applicable safety regulations laid down in the Royal Decree of November 30, 2011. Those regulations were strengthened in 2020 with additional safety requirements applicable from 2025. Since Doel 4 and Tihange 3 are among the most modern nuclear reactors in Belgium and since they have already been subject to various improvement projects (in the framework of the previous 3 periodic safety reviews and the post-Fukushima stress tests), the potential needs/opportunities identified are not very large in number or extremely complex to implement. They largely meet the new requirements today although some safety improvements are still needed. Here a distinction can be made between the "necessary requirements" to fully meet the tightened requirements to be realized before the start of the post-2025 operation extension, and the "possible modifications" that could possibly be realized afterwards without compromising safety.

These constitute the works we consider in this environmental impact assessment and they include:

- Design improvements:

The key design improvements identified as "needs" or requirements are as follows:

  - Management of extreme temperatures: managing potential heat waves (and associated temperatures that may be higher than anticipated in the initial design) can lead to design improvements e.g. additional air coolers or humidifiers of classrooms;
  - Strengthen emergency planning centers: the habitability of existing emergency planning centers in the event of certain serious accidents cannot always be assured without the use of personal protective equipment: design improvements here may be linked, for example, to better shielding or ventilation of emergency planning centers;
  - Robustness of the cooling of the irradiated nuclear fuel docks: the existing cooling systems of the fuel docks could be improved and supplemented with additional (mobile) cooling systems that could be activated in accident situations.

- Aging management:

In terms of obsolescence management, the requirement for all safety-related systems, structures and components is to demonstrate that their qualification remains valid in the new operation period. This can either be done through a justification file (which requires the necessary study work) or by replacing these components as necessary before they exceed their qualified life span.

For the major mechanical components (reactor vessel, reactor cover, steam generators), the safety authority FANC-AFCN estimates, based on current knowledge, that they do not need to be replaced.

For other components (smaller mechanical components such as pumps or valves, electrical equipment, instrumentation, civil structures), there is currently no complete picture of possible replacement works before the operator has completed its studies. Therefore, it cannot be ruled out at this time that these replacement works may involve potential impacts, which are, however, limited in nature.

In addition to design improvements and obsolescence management, the safety authority has also identified human resources (human resources) as a factor not to be underestimated in long-term exploitation. However, this is outside the scope of the environmental impact assessment.

Based on the works as known at the time of the scoping of the potential impacts and of the assessment of these impacts,[7] it can be said that the impacts are very localized and generally limited to the site for the various non-radiological disciplines. There is no radiological impact within the period when the extension is studied and radioactive waste is assessed for the LTO including the works. A limited amount of low-level radioactive waste is expected for the works, representing only a fraction of the cumulative amount over the LTO period considered.

The latest status of the works included in the environmental impact assessment in the present report was available in a note dated March 15, 2023[8]. The description of the works and the scoping of possible impacts contained in this memorandum are not fundamentally different from those used in assessing the impacts of the works carried out in this environmental impact assessment. The actual list of works to be carried out in the framework of LTO Doel 4 and Tihange 3 may still evolve in consultation between the operator, Electrabel S.A., and the safety authorities.

1.2.1.2 Operation of the Doel 4 and Tihange 3 nuclear power plants

The finality of the extension of the Doel 4 and Tihange 3 units at the respective sites KC Doel and CN Tihange is the continued industrial production of electricity. We therefore discuss the operation of the Doel 4 and Tihange 3 nuclear power plants with also a global overview of their potential impact on humans and the environment.

Doel 4 and Tihange 3 are reactors of the so-called pressurized-water or high-pressure type (Pressurized-Water Reactor PWR) of the Westinghouse design. An overview with basic data for these two production units is shown in Table 3.

[7] Information available through January 31, 2023 was included for this purpose, information received later is not guaranteed to be included.

[8] PSR LTO KCD4 CNT 3-ELP-DESCRIPTION DES TRAVAUX DU LTO DE D4/T3" (ref CNT-KCD/4NT/0031174/000/02), Tractebel Engineering, March 15, 2023.

Table 3: Overview with basic data of the Doel nuclear power plant.

Unit	Type/design	Thermal power (MWth)	Electric Power (MWe)	Date first criticality	Containment	Fuel storage capacity
Doel 4	PWR (3 primary cooling circuits) Westinghouse	3000	1036	31/03/1985	Double with internal liner	628 positions
Tihange 3	PWR (3 primary cooling circuits) Westinghouse	2988	1038	05/09/1985	Double with internal liner	820 positions

A PWR is typically composed of 3 compartments with 3 separate circuits: the reactor building with primary circuit, the machine room with secondary circuit and the cooling circuit that forms the tertiary circuit (Figure 2).

Figure 2: Operation of nuclear power plant with reactor building, engine room and cooling circuit from left to right (Source: Electrabel nv).

The reactor building (RGB) contains the reactor vessel (or vessel) that contains the nuclear fuel or fissile material. The fuel is enriched uranium in the form of sintered uranium oxide (UO_2) with an enrichment percentage of uranium-235 (U-235) of about 4% (natural uranium contains about 0.7% U-235). Fuel tablets are stacked in zirconium alloy tubes. They provide containment of the fission products. The pins thus formed are bundled into fuel elements and are held in a network by grids. Fission (see box) produces fission products and neutrons; the latter can create new fissions so that a chain reaction is caused. To control this chain reaction and control the reactivity of the nuclear reactor, absorbing beams (control rods) and boron[9] (an element that easily captures neutrons) are used. Control rods are divided into two groups:

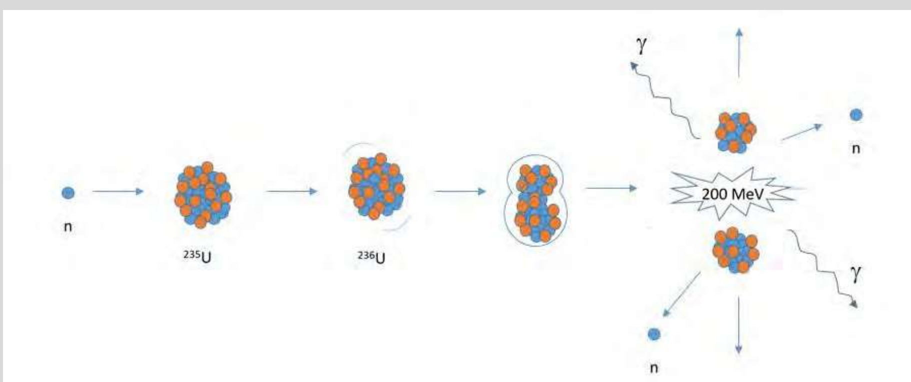
9 Present in the water of the primary circuit in the form of boric acid.

- the control rods (28 pieces) that provide rapid control of reactivity;
- the stop rods or shutdown system (also called SCRAM, 24 pieces) which, together with the control rods, allows an emergency stop to be performed.

The control rods have the property of strongly absorbing neutrons and, in the event of an automatic stop or emergency shutdown, will fall between the fuel elements by themselves due to gravity and thus stop the fission reactions (passive safety). However, because of radioactive decay of the fission products, the reactor core remains hot after shutdown and must be cooled further.

Interlude - nuclear fission

The nuclei of atoms, which consist of protons and neutrons (both called nucleons), have a very large binding energy. That is, it takes a very large amount of energy to split such a nucleus into its individual nucleons. So much energy (E), that there is even - according to Einstein's well-known formula $^{E=mc^2}$ -a non-negligible mass difference (m) between the atomic nucleus and the mass of the individual nucleons that make up the nucleus (c is the speed of light). The uranium used for fission in most nuclear reactors (uranium 235 or U-235) consists of 235 nucleons (92 protons and 143 neutrons). If you compare the mass of such a uranium 235 nucleus to the sum of the masses of the 235 individual nucleons (protons and neutrons have about the same mass, neutrons are just slightly heavier), the atomic nucleus has a significantly smaller mass. This difference (called the mass difference or mass defect) at uranium 235 corresponds to the mass of almost two individual nucleons. Atoms (electrons and the atomic nucleus) and molecules (multiple atoms) are also bound systems of particles, but the binding energy in atomic nuclei is many orders of magnitude greater than that in atoms and molecules: a factor of one hundred thousand (10^5) or more.
Nuclear fission (also called fission) can occur at heavy nuclei; the nucleus then does not split into all its individual nucleons, but rather into two smaller and (per nucleon) more strongly bound atomic nuclei. This can occur spontaneously, called spontaneous fission (which is a form of radioactive decay), or be induced by the capture of a neutron, also known as induced fission. This releases the difference in binding energy between the initial nucleus and its fragments. This is a large amount of energy since the binding energies in atomic nuclei are very large. The figure below shows an example of neutron induced fission. The uranium 235 nucleus absorbs a neutron so that the uranium nucleus now has one more neutron and has become uranium 236. This nucleus, due to the absorption of the neutron, has an energy surplus and oscillates, where the nucleus can become elongated and split into two fission products.



Sometimes (in 15 % of cases) the uranium 236 nucleus will not fission but emit its excess energy under the form of gamma radiation. In 85 % of cases, however, fission will occur, releasing a large amount of energy, an average of 200 million-electron volts (200 MeV) per fission, the electron volt being a measure of energy like the joule. For comparison, the formation of one molecule of CO_2 (when using fossil fuels, for example) releases 4.08 eV, almost a factor of 50 million ($5x10^7$) less than the fission of one uranium 235 nucleus. The energy released from fission is distributed as kinetic energy between the fission products and the neutrons released (typically 2 to 3 neutrons per fission) and under the form of prompt gamma radiation. The neutrons have an average energy of about 2 MeV. The fission products formed have a relative excess of neutrons and will decay via beta decay to eventually form stable atoms (see §2.3.2). The distribution of energy released by fission is given in the table below.

In the beta decay, the energy goes to the emitted electrons (beta radiation), gamma rays and anti-neutrinos. However, the latter particles have the property of almost not interacting with matter and thus escape completely taking their energy with them. In normal operation of a reactor like Doel 4 and Tihange 3 with a thermal power of 3000 $_{MWth}$, "approximately ^{6x1020} anti-neutrinos per second corresponding to a power of about 150 MW are sent into space, partly straight through the earth. To put this number in perspective, we can compare this with the amount of anti-neutrinos emitted during the decay of natural radioactivity present in our planet earth (also called geo-neutrinos) per second, namely ^{1025} per second. Fission can give a large number of different combinations of fission products and the average energy released in the process is 207 MeV. As discussed, an average of 12 MeV per fission there will be carried away by the anti-neutrinos and thus unavailable for energy production. However, the released neutrons that do not cause fission can be absorbed by uranium 235 and uranium 238. The newly formed nuclei will then emit gamma rays that also contribute to the recoverable energy but do not come from fission itself. Furthermore, neutron absorption by uranium 238 gives rise to the formation of transuraniums, very long-lived radioactive atoms, which are a component in radioactive waste in addition to fission products. Neutrons escaping from the nucleus will additionally be able to be absorbed into the reactor vessel, among other places, and make non-radioactive atoms (e.g., cobalt) radioactive there (cobalt-60), this is called activation or activation products. In addition to the radioactivity that is created and will emit radiation upon decay, prompt radiation (neutrons and gamma rays) is also emitted during the process of nuclear fission. This very intense radiation must be well shielded.

	Energy released from fission (MeV)	**Recoverable energy (MeV)**
Fission products	168	168
Prompt neutrons	5	5
Prompt ranges	7	7
Decay of fission products		
Beta radiation	8	8
Antineutrinos	12	-
Gamma radiation	7	7
Gamma radiation after neutron capture in U-235 and U-238	-	3-12
Total	**207**	**198-207**

Now if for each fission exactly one neutron (prompt or delayed) causes a new fission, we get a controlled fission reaction. The probability, however, that a neutron arising from fission immediately causes a new fission is small. The neutrons have a lot of energy and upon collision are mainly scattered and not absorbed by the uranium 235 nuclei. To do this, the neutrons must first be slowed down (thermalized). This can happen by colliding them with light nuclei such as hydrogen nuclei present in water, also called moderator. So the nuclear fuel must be surrounded by a moderator to slow down the neutrons before they have a sufficient chance to cause another fission. On the other hand, it must also be ensured that on average no more than one neutron per fission causes a new fission: otherwise this would mean an exponential increase in released energy. This is controlled by control rods, on the one hand, and also by adding boric acid to the water. These have the properties of absorbing neutrons, once slowed down, making them unavailable for fission. This balance must be maintained throughout the reactor cycle. At the beginning of the cycle, the fuel is fresh and there are many uranium 235 nuclei available for fission: reactivity is then high. To get a controlled nuclear reaction, boric acid is started in the cooling water, with the control rods fully lowered into the core. As the reactor cycle progresses, reactivity levels decrease. The boric acid concentrations in the primary water are gradually reduced and the control rods are increasingly removed from the core to maintain a balanced core reaction. At the end of the fuel cycle, the boric acid concentration goes to zero and the control rods are completely out of the core. At that point, the cooling water temperature is lowered to maintain reactivity at a level sufficient to keep the nuclear chain reaction going. This causes a drop in delivered power.

Radiation and radioactivity are an important safety issue in the operation of a nuclear power plant. Radiation and radioactivity come from:

- the nuclear fuel itself: it consists of uranium oxide and contains several uranium isotopes, notably U-238, U- 235 and U-236, all of which are spontaneously radioactive but have a long half-life and decay primarily via alpha decay;
- prompt gamma and neutron radiation released during the process of nuclear fission of uranium nuclei (during reactor operation);
- fission products, many of which are radioactive with half-lives from milliseconds to millions of years and decay primarily via emitting beta and gamma radiation;
- activation of various materials, primary water, ..., in this process, radioactive and non-radioactive nuclei can capture a neutron and make new radionuclides, we call these activation products (activation of the vat steel is an example, also the formation of tritium);
- successive neutron absorption and beta decay starting from the uranium in the nuclear fuel. This creates several isotopes of neptunium, plutonium, americium and curium, all of which are radioactive and including several with very long half-lives.

Thus, operation requires important safety measures, radiation protection and management of radioactive waste and spent fuel.

The energy released in fission, from the energy and radioactive decay of the fission products and from the energy of the neutrons, is transferred to water under high pressure (155 bar) in a PWR such as Doel 4 and Tihange 3. The water is also used as a "moderator" to slow down (also called thermalization) the neutrons generated during fission, to increase the likelihood of them causing another fission. Two to three neutrons are released on average per fission; in normal operation, one of these neutrons will cause another fission. The high pressure keeps the water from boiling. Doel 4 and Tihange 3 both have three circuits, which make up the primary cooling circuit (each with its own pump), and pump water around from the reactor core to the steam generators. A pressure vessel regulates the pressure in the primary circuit. These, along with the reactor, are all located in the reactor building, and the containment is double: the inside is of prestressed concrete, lined on the inside for leak tightness with a steel liner, the outside is in reinforced concrete. The space between the two containments is called the annular space. The containment is designed to withstand a LOCA (loss of cooling accident), an SLB (steam line break) and an aircraft impact on the reactor building. In summary, the design provides sequential barriers to avoid a possible dispersion of radioactive materials into the environment as shown in Figure 3.

Doel 4 and Tihange 3 are organized into 3 parts: (1) the nuclear island, (2) a part with safety-related equipment and finally (3) the part with installations without nuclear safety-related systems.

In addition to the reactor building, the nuclear island also contains the nuclear auxiliary building (GNH), with the important safety systems and the buildings for the storage for the fresh nuclear fuel elements, i.e. the spent fuel pools (whose water is continuously purified and cooled), as well as the storage tanks for the liquid and gaseous effluents.

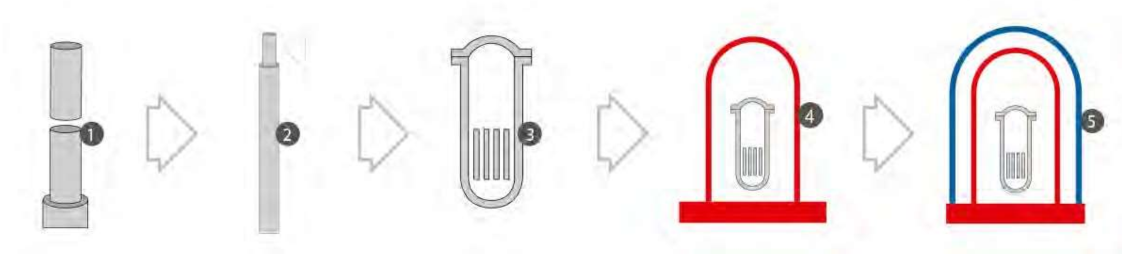


Figure 3: The successive barriers that shield the uranium and fission products from the outside world, viz. the compressed uranium oxide in tablets (1) is stacked in the fuel rods that are welded shut (2), which are located in the reactor vessel (sealed when operating, opened for loading and unloading nuclear fuel), a steel tub 25 cm thick (3) placed in the primary steel sphere of the reactor building that resists strong pressure from the inside (4) successively surrounded by the secondary wall of the reactor building in reinforced concrete that protects the facilities from external accidents (5).

The heated water under high pressure from the primary circuit goes to the steam generator where, through thousands of tubes, it releases its heat to the water on the other side (secondary circuit) where steam is formed at a pressure of 60 bar. Thus, there is never direct contact between the water from the primary and secondary circuits. The steam drives a turbine in the machine room and the attached alternator converts the rotation of the turbine into electric current. The steam in the secondary circuit continues to the condenser where the steam is converted back into liquid water that is pumped back to the steam generator. Cooling of the condenser is done with water from the tertiary circuit in the cooling circuit, again never in direct contact with the water of the secondary circuit. The tertiary circuit is fed by Scheldt water (Doel) or Maas water (Tihange). The steam from the secondary circuit transfers its heat to the Scheldt or Maas water from the tertiary circuit, which causes this Scheldt or Maas water to warm slightly. Therefore, it first goes to the forced draft cooling towers before either going to the condenser again or flowing back into the Scheldt or Meuse, respectively.

As is the case in all industrial processes, small quantities of these radioactive elements may be released into the nuclear zone during normal operation and maintenance. This creates a number of radioactive waste streams in gas, liquid and solid form in addition to the spent fuel elements. Treatment systems for the latter two also exist at the KC Doel and CN Tihange sites, for Doel it is housed in a central water and waste treatment building (WAB), for Tihange it is more dispersed over the different installations.

The operation of the KC Doel and CN Tihange nuclear power plants as a whole, and Doel 4 and Tihange 3 specifically for the production of electricity, like any industrial process, needs raw materials and will also produce a number of waste streams. The most important are summarized in the table below.

Table 4: Main raw materials and waste streams.

Main raw materials	Waste streams
Enriched uranium (nuclear fuel)	Radioactive waste streams: atmospheric and liquid discharges, radioactive waste including spent nuclear fuel
Fuel Oil	Non-radioactive hazardous waste (recycling)
Oils	Non-radioactive non-hazardous waste
Surface water for making demineralized water	Non-radioactive air emissions
Water from Scheldt (Doel) or Maas (Tihange) (cooling water)	Sanitary and industrial wastewater
City Water	Cooling water backflow
Groundwater (Tihange)	
Land use (land take).	

1.2.1.3 Periodic safety reviews and changes prior to the Project

The regulations for the construction and operation of each Belgian nuclear power plant are laid down in the safety report, the operating and environmental permits.

The main changes in the nuclear safety framework are based on Periodic *Safety* Reviews (PSRs: see 1.2.1.1)[10]. and international benchmarking with other nuclear power plants.

The PSR or decennial review has several objectives. The operator must assess the state of the installation and the organization from the point of view of international legislation, standards and good practices. In addition, strengths and possible improvements must be identified, as well as compensatory measures in case certain possible improvements cannot be implemented.

In addition to those resulting from the PSRs, other changes and improvements have been made based on insights resulting from internal and external inspections, maintenance and experience data (including those from major nuclear incidents and accidents, such as those at Three Miles Island, Chernobyl and Fukushima). External inspections are done by, among others:

- the **Federal Agency for Nuclear Control (FANC-AFCN)**. This is the nuclear safety authority, an institution of public utility under the tutelage of the Minister of the Interior and Security. The FANC-AFCN ensures that the population and the environment are efficiently protected from the danger of ionizing radiation. For permanent controls, the FANC-AFCN calls on its technical subsidiary Bel V, which, like the FANC-AFCN, has free access to the sites of KC Doel and CN Tihange.
- **The International Atomic Energy Agency (IAEA)** is an independent intergovernmental organization of the United Nations. It develops standards for nuclear safety and the protection of humans and the environment from ionizing radiation. The IAEA assembles international teams that study documents and conduct on-site reviews of how the safety of nuclear facilities is ensured in practice. This is done through OSART missions (Operational Safety Review Team)[11] and SALTO missions (Safety Aspects of Long Term Operation).

[10] An overview of the decennial reviews with the synthesis reports can be found on the FANC- AFCN website: https://fanc.fgov.be/nl/dossiers/kerncentrales-belgie/veiligheid/tienjaarlijkse-herzieningen.

[11] An OSART mission is planned for Tihange 1 and 3 from April 17 to May 5, 2023.

- **WANO (World Association of Nuclear Operators)**. This organization, created after the events at Chernobyl, aims to maximize the safety and reliability of nuclear power plants. The Doel and Tihange nuclear power plants receive a team of international experts every 4 years for a so-called WANO Peer Review, followed 2 years later by a WANO Follow Up. Each review results in suggestions to optimize the safety and performance of the nuclear power plants.

Regarding the accident experience, the European Commission took the initiative to organize resistance tests after the Fukushima accident in March 2011. This led to a series of actions: the stress tests ("Belgian Stress Tests", BEST). These actions have been carried out for Doel 4 and Tihange 3 and are not part of the Project at hand in this EIA.

The major achievements for Doel 4 and Tihange 3 before the start of the Project based on the past decennial reviews and other projects are shown below. The projects are grouped by theme:

Projects related to design improvements:

- Performance of Probabilistic Safety Assessment (PSA), to identify potential areas for improvement in facilities and implement them.
- Installation of autocatalytic recombiners to prevent hydrogen buildup in the event of a reactor building accident with fuel damage.
- Enlargement of the recirculation filters commissioned in the event of a LOCA (Loss Of Coolant Accident) - thanks to the much larger filters with smaller meshes, clogging is eliminated and all contamination is stopped in the reactor building (Barsebäck).
- Installation of one graded range global/N16 chain per steam generator for early detection of a steam generator pipe burst.
- Increasing the diameter of the siphon breakers of all fuel docks to improve the biological water barrier above the fuel elements in the event of a breakage of the docks' feed or discharge lines.
- Placement of inverse voltage relays on 6.6 kV safety boards due to incident at Byron Nuclear Power Plant.
- By establishing a connection between the low-pressure safety injection and the spray ring, the low-pressure recirculation from the spray ring is always guaranteed, even in the event of a failure of the low-pressure safety injection.
- Installation of relief valves on the primary pressure vessel qualified for both steam and water relief.
- Installation of filtered pressure valves on the reactor building (Filtered Containment Venting System).
- Connection points for supplying the primary circuit and spray systems of the reactor building from an external water source via an external pump.
- Replacement of the people monitors with a more high-performance type - these are used to monitor workers for any radioactive contamination as they leave the hot zone.
- Replacement of the door monitor at the hot zone exit - it does an additional check for any contamination of workers leaving the hot zone.
- Installation of additional fire detection systems and improvement of the physical separation of cables in the safety-bound buildings. Reinforcement of fire compartmentalization in the electrical building.

Doel 4 specifically:

- Recent investments in fire protection: modernization of fire stations, replacement of fire detection of all buildings, replacement of underground valves on fire lines, etc. The equipment meets the strictest standards.

- Replacement of the reactor building sash doors with a stronger design with a passive sealing system, this to improve the leak tightness of the reactor building.
- Conversion of cooling of 1st level safety diesels of Doel 4 from water cooling via CD circuit to aerocoolers to ensure independence between 1st and 2nd level safety systems.
- Placement of mobile door baffles at the entrances of security-bound buildings as flood protection.

Tihange 3 specifically:

- *Fire Hazard Analysis* improvements: replacement and addition of fire detectors for all buildings, improved fire compartmentation, improved physical protection of cables, etc.
- Replacement of the fire water system and installation of new pumps with larger capacity and a clean water maintenance system.
- Protection against internal and external floods, including the construction of a wall (1.8 km) to protect against ten thousand-year floods and the implementation of related measures.

Projects related to aging and availability:

- The steam generators were replaced by the Inconel 690 type with stronger pipe material. The steel used is less subject to corrosion, and has an increased exchange surface with greater cooling capacity
- Replacement of pins of control mechanisms of reactor vessel control rods
- Renovation of the concrete shell of the reactor building and the roof of the bunkered buildings
- Reactor cover replacement.
- Replacement of primary pump shafts to better withstand thermal fatigue.
- Renovation of the inside of the cooling tower.
- Retrofit of the low-pressure turbine.
- Replacement of fire dampers in ventilation systems.
- Replacement of measurement chains that monitor the atmosphere for the presence of radioactive gas, dust and iodine.
- Replacement of a range of electrical and instrumentation components such as safety-related electrical batteries, rectifiers and inverters, measuring chains and reactivity measurement electronics around the reactor vessel.
- Modifications to the switchers following the overvoltage incident at the Forsmark (Sweden) nuclear power plant.

Projects related to fuel management:

- Implementation of a continuous improvement program for the short- and long-term performance of the fuel assemblies.
- Renewal of the fuel racks in the fuel building - the use of boron steel in the new racks will ensure undercriticality in a sustainable manner.
- Provision of alternative means to ensure adequate water levels of the fuel storage docks, with an external pump and external water supplies.
- Construction of temporary spent fuel storage buildings on KC Doel and CN Tihange sites.

Projects related to knowledge, competencies, behavior and radiological dose:

- Develop and continuously improve procedures for the management of various types of accidents, taking into account international experience management.

- Renewal of the hardware and software of the control room simulator for training of the shifts- this makes the simulations even more realistic and allows installation changes to be applied to the simulator faster.
- Establishment of a permanent fire team (24/7), provision of a truck with telescopic arm to fight large-scale fires.
- Implementation of a fire protection equipment control program in technical operation specifications.
- Renovation of the control room.
- Replacement of the electronic dosimetry system that records workers' doses.

1.2.1.4 Activities at both sites - timeline

Table 5 provides an overview of recently completed, ongoing and planned activities and associated nuclear licenses at both sites, KC Doel and CN Tihange.

Table 5: Recently completed, ongoing and planned activities at KC Doel and CN Tihange sites.

Installation(s)	**Description**
LTO Doel 1 and 2 and Tihange 1 until the end of 2025	Between 2013 and 2015, the Belgian government decided to allow the long-term decommissioning of 3 nuclear reactors: Tihange 1, Doel 1 and Doel 2 until 2025. The Federal Agency for Nuclear Control (FANC-AFCN) then conducted a safety analysis for that extended operation period and then imposed work on the operator (ENGIE Electrabel SA) to bring those 3 reactors up to the latest safety standards. These works were named LTO works, which stands for Long Term Operation. ENGIE Electrabel S.A. then drew up action plans aimed at carrying out these works during each periodic shutdown of the reactors according to a defined timetable. The FANC-AFCN and Bel V closely monitored the implementation of these action plans through periodic work meetings and after each shutdown of these reactors. Since the last reactor shutdown in 2019, the last action items of the LTO works were completed.
Rollout of Doel 4 and Tihange 3 for electricity production until the end of 2025	Runs under current license
SF2 KC Doel and CN Tihange	CN Tihange: by Royal Decree of January 26, 2020, an establishment and operating permit was granted to Electrabel SA for the facility intended for the temporary storage of spent nuclear fuel on the site of Electrabel SA in Tihange. KC Doel: Royal Decree dated July 1, 2021, establishment and operating permit for Spent Fuel Storage Facility at Doel.
Restructuring permits KC Doel and CN Tihange	**KC Doel:** On March 1, 2022, the establishment and operating licenses of Electrabel S.A. for their installations at Doel nuclear power plant were amended and supplemented by Royal Decree in order to arrive at 1 overall restructured license. The decision was published by excerpt in the Belgian Official Gazette on March 15. **CN Tihange:** On May 29, 2022, by Royal Decree, the establishment and operating licenses of Electrabel S.A. for their facilities at Tihange nuclear power plant were amended and supplemented in order to arrive at 1 global restructured

Installation(s)	Description
	license. The decision was published by excerpt in the Belgian Official Gazette on June 17. These Royal Decrees constitute an administrative restructuring of the existing operating licenses of KC Doel and CN Tihange and were issued on the initiative of the Federal Agency for Nuclear Control (FANC-AFCN). This followed the procedure in accordance with Article 13 of the Royal Decree of July 20, 2001 concerning general regulations for the protection of the population, the workers and the environment against the danger of ionizing radiations (ARBIS). The FANC prepared this adaptation and presented it to the Scientific Council, which issued a favorable opinion on it. The objective of these administrative restructurings is to arrive at one completely revised and unified global license that takes into account the upcoming final shutdown of the nuclear reactors and their eventual decommissioning. In addition, harmonization of licensing conditions and several administrative and punctual improvements were also provided. In this restructuring of the licenses, no substantive relaxations were made to the existing license conditions in force.
Final shutdown of Doel 3 and Tihange 2	In accordance with the law of January 31, 2003, the date by which the Doel 3 power reactor will have to be decommissioned and will no longer be allowed to generate electricity was set at October 1, 2022. On April 1, 2022, the Federal Agency for Nuclear Control (FANC-AFCN) received the "notification of shutdown" for the Doel 3 power reactor (KCD3) from Electrabel SA. Based on its analysis, the FANC-AFCN considers it necessary to modify the conditions of the operating license of the nuclear power plant. These modifications are proposed in application of Articles 17.1 and 13 of the Royal Decree of July 20, 2001 containing general regulations on the protection of the population, the workers and the environment against the danger of ionizing radiations (ARBIS). The FANC-AFCN prepared this adaptation and presented it to the Scientific Council, which issued a favorable opinion on it. This initiative aims to: • define the Doel 3 reactor as a reactor to be permanently shut down and clarify that only operations in preparation for decommissioning and emptying the fuel docks can be carried out; • eliminate the articles related to the power operation of the Doel 3 reactor that will no longer be needed. These changes amount to administrative simplification; • create a new general chapter for permanently shutdown reactors, containing the general requirements valid during the DSZ period (after the shutdown and pending the start of decommissioning). On November 6, 2022, by Royal Decree, the establishment and operating licenses of Electrabel S.A. for their facilities at Doel Nuclear Power Plant were modified and supplemented on the initiative of the Federal Agency for Nuclear Control. The decree was published by excerpt in the Belgian Official Gazette on December 2, 2022. In this modification of the permits, no substantive relaxations were made to the existing permit conditions in force.

Installation(s)	Description
Extension Doel 4 and Tihange [312]	Subject of this environmental assessment
Decommissioning of reactors after final shutdown and possibly other facilities	Subject of new environmental impact assessment and permit

Since the final shutdown (DSZ) of Doel 3 (Sept. 23, 2022) and Tihange 2 (Jan. 31, 2023) for the industrial generation of electricity, both sites have been in a state where part of the reactors are still producing electricity (or are in temporary shutdown for maintenance or possibly other reasons) and another part that are in the phase of final shutdown or also called post-operational phase (Post-Operational phase or POP). The POP constitutes the first phase in the decommissioning of a reactor unit after shutdown, followed by the decommissioning phase and the demolition phase as shown in Figure 4, which also provides an approximate estimate of the timing for each of the phases.

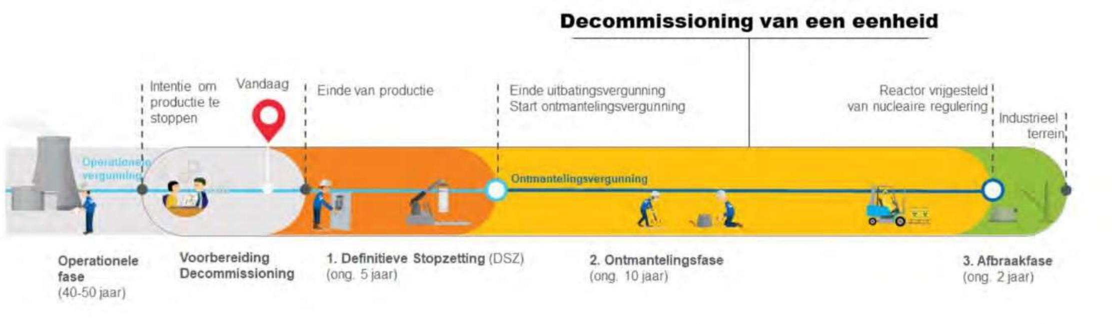


Figure 4: Decommissioning of a reactor unit as currently envisioned by Electrabel nv (Figure Electrabel nv).

The POP takes about 5 years, depending on the unit, and can be divided into four phases related to a number of defined activities. The end of a phase is linked to a specific (operational/technical) state of the unit.

Phase 1 starts after the reactor is stopped and disconnected from the power grid. The reactor is discharged and the fuel assemblies, control rods and other non-fuel high-emitting components are transferred to the fuel pool. The phase ends when the reactor is fully discharged.

Phase 2 involves the chemical decontamination of the primary circuits. The other circuits in the controlled area (except around the fuel pool) are emptied and cleaned. Chemical decontamination is done in accordance with a methodology in line with international good practices and experiences. During chemical decontamination, the insides of the main components of the systems in question are cleaned by means of chemical products, removing all or part of the layer containing the majority of the activity (precipitated activated and/or fission products). The chemical products used and the layer partially or completely removed are collected, processed and the remainder is disposed of as radioactive waste.

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[12] Includes the preparatory works necessary to make this extension possible.

Phase 3 ends when the fuel elements are removed from the fuel pool. After the residual heat is sufficiently removed, the elements are loaded into containers and transported to the fuel storage building (SCG) for the Doel site. Also during this phase, the non-fissile high-emitting components present in the fuel pool are disposed of as radioactive waste by the appropriate route. The remaining circuits will be phased out of service. For Tihange, these spent fuel elements will then be gradually transferred to the two buildings dedicated exclusively to spent fuel storage: the DE and the Spent Fuel Storage Facility (SF^2).

Phase 4 involves emptying and cleaning the fuel pool and circles around it. After completing this phase, the plant will be ready for decommissioning.

Also for Doel 4 and Tihange 3, the DSZ or POP will have to be done with or without the realization of the life extension project. The only difference is when the DSZ will happen. With project realization, it will be more than 10 years later than without project realization.

During decommissioning, which can occur in several partial phases and starts after the DSZ, the facility is dismantled. The equipment, structures and components are removed and/or decontaminated for release, reuse, recycling or for treatment as radioactive waste.

This phase is an integral part of the life cycle of the nuclear power plant. Indeed, it is the operator's job to demolish the plant after its final shutdown and restore its original environment. In practice, this means that the plants have to make way for a grass field (also called "greenfield") or for other industrial uses. To start decommissioning, a decommissioning license is required prior to a specific environmental impact assessment. Thus, based on Electrabel SA's planning, certain reactor units will be in decommissioning mode during the course of the project, the extension by another 10 years of Doel 4 and Tihange 3 after 2025.

Doel 4 and Tihange 3 will also have to be decommissioned after shutdown and POPs. We do include the impact on the quantities of radioactive waste and spent fuel in the assessment of the project.

In summary, Figure 5 shows the timeline of the project (extending Doel 4 and Tihange 3 by 10 years) in relation to the condition of the other reactors at both sites KC Doel and CN Tihange.

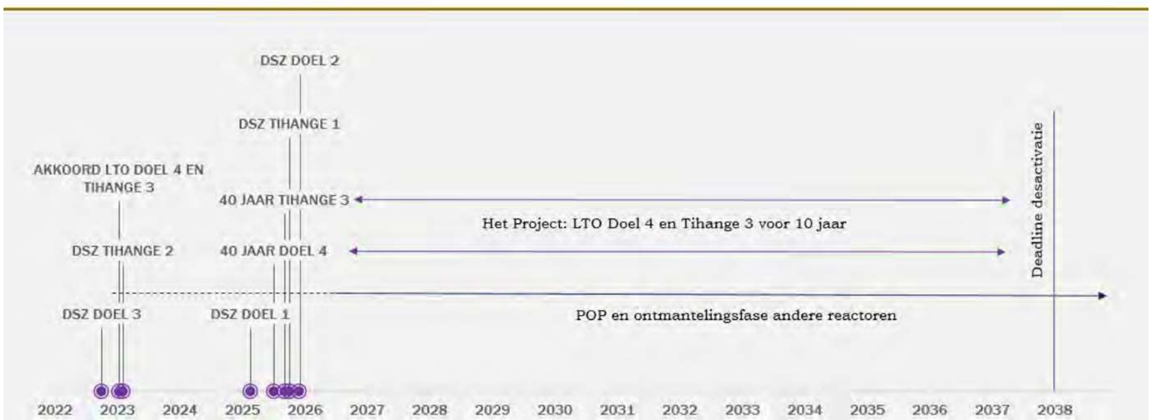

Figure 5: Timeline of activities related to the different reactors at the KC Doel and CN Tihange sites (DSZ: Definitive Shutdown, POP: Post Operational Phase, LTO: Long Term Operations). The 10-year extension period after 2025 is not precisely fixed in time and can therefore shift with the latest foreseen deactivation date upon extension being December 31, 2037 for both reactors. After the final shutdown of Doel 4 and Tihange 3, a post-operational and decommissioning phase of these reactors follows in each scenario (this is not shown in the figure for Doel 4 and Tihange 3).

1.2.2 Evolution of security of supply in the period 2023-2032

1.2.2.1 Security of supply after 2025

As mentioned earlier, the reason for the intention to extend the lifetime of Doel 4 and Tihange 3 is the concern to ensure security of electricity supply after 2025. Indeed, in that year, if the Nuclear Shutdown Act is implemented, the last 5 Belgian nuclear power plants would be shut down, which would mean a 3.9 GW reduction in generation capacity almost overnight. It is important to know what that means in terms of security of supply.

As stipulated by the Electricity Law, Elia is responsible for publishing a biennial study on Belgium's adequacy and flexibility needs for the next decade. This study analyzes policy options on the future energy mix for Belgium; both short- and long-term. The most recent version of this study was published in 2021.

In that report, Elia calculated, on the basis of an extensive simulation, that in 2025, after the proposed closure of all nuclear power plants, there would be a need for additional flexible generation capacity of some 3.6 GW to meet security of supply and flexibility standards (see Figure 6). By 2032, this need would increase to 4.6 GW, primarily due to the increasing electrification of the economy and society[13].

Imports of electricity are not a conclusive answer to that question. It is to be expected that under current market conditions, combined with the winding down of fossil plants in Germany, among others, and the partial unavailability of the French nuclear park, there will be little excess capacity on the Northwest European market at certain times. In addition, the periods of power shortages in Belgium and neighboring countries are highly correlated. Elia also points out that even if the above-mentioned capacity needs are met, there will still be an import need. In 2030-2031, this would involve imports for 200 to 500 hours per year in the EU-SAFE[14] scenario, and for 500 to 1,000 hours per year in the EU-BASE scenario.

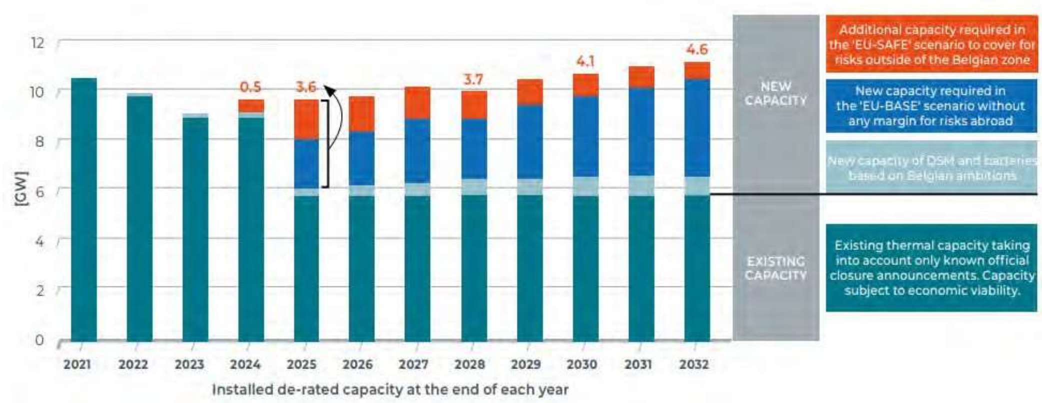

Figure 6: Evolution of existing installed capacity and newly required electricity generation capacity to meet Belgium's reliability standard (Elia, 2021).

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[13] Elia assumes (in its 'CENTRAL' scenario) an electricity demand of 95.6 TWh in 2032. Compared to demand in 2022, this represents an increase of some 11%.

[14] The EU-SAFE scenario takes into account hard-to-forecast uncertainties over which Belgium has no control. A scenario in which four nuclear sites in France are unavailable (on top of "normal" unavailabilities) is considered representative of those risks. In such a scenario, less can be imported and thus more local production capacity is needed.

The demand for additional capacity can in principle be met by any technology (on top of the capacity already included in the assumptions of the CENTRAL scenario for Belgium), such as thermal generation, renewable energy, demand-side management (DSM) or storage. Each of these choices obviously has its own limitations.

Based on economic modeling, Elia concludes that market forces will not be able to sufficiently fill the capacity shortfall from 2025 onwards; there is no sufficient incentive to invest in (expensive) new capacity. Elia therefore argues that structural intervention in the market, based on a CRM (capacity remuneration mechanism), will be necessary as of 2025. The generation system thus built must not only provide sufficient capacity, but also be able to deploy that capacity with sufficient flexibility. In practice, modern CCGT (closed cycle gas turbine) type gas plants appear to be the most suitable for this purpose.

In the slightly longer term, the shortfall could be largely and gradually filled by renewable energy, although even then the availability of readily deployable reserve capacity remains necessary - and all the more so as the share of wind energy in the energy mix increases[15].

However, Elia's analysis from the 2021 adequacy and flexibility report has since been partially overtaken by reality. The energy crisis and the war in Ukraine have changed the framework conditions. Where Elia was still assuming a gas price around €6 per Gjoule, gas prices were four times higher in the first half of 2022[16]. Moreover, (on a European scale) the security of gas supply from Russia is at risk. Added to this were the problems with French nuclear power plants, where at one point over half of France's nuclear park was inactive, due to maintenance and outages.

In this context of uncertainty, the government wishes to focus more strongly on domestic generation capacity, and reduce dependence on (foreign) fossil sources. While the auction according to the CRM mechanism has provided sufficient capacity to fill the 3.6 GW capacity deficit calculated by Elia in 2021 (see also below), in the current context the question is whether this capacity is still sufficient in all circumstances and under all scenarios, taking into account higher prices, likely lower foreign availability (both in terms of fossil energy and nuclear capacity), and general geopolitical instability. In addition, CRM capacity is currently still in its infancy.

The lifetime extension of Doel 4 and Tihange 3 is a logical decision in that context; it allows a guaranteed capacity of 2 GW to be made available to the grid again in a relatively short period of time (i.e. after the plants are first shut down in 2025 and restarted after the necessary modifications and procedures).

1.2.2.2 Supply security in the period to 2025

Even for the years leading up to the planned nuclear exit in 2025, without investment in additional capacity, there is a risk of shortages. The availability of the French nuclear park appears to play an important role in this. In the winters of 2023-2024 and 2024-2025, shortages of 1,000 and 1,400 MW[17], respectively, would occur in Belgium if 6 nuclear units were unavailable (on top of the "normal

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[15] Elia calculated that the number of hours the new efficient gas plants would run would decrease from about 7,000 hours in 2025 to 4,000 to 5,000 hours in 2032, mainly due to greater penetration of renewable energy. Elia assumes that in 2032 the share of renewable energy in Belgium's energy mix would roughly be between 35 and 55%, depending on the scenario. If the lifetime of Doel 4 and Tihange 3 are extended, it can be assumed that the operational hours of the gas plants will be lower than what is indicated here.

[16] Since then, the price of gas did fall significantly, but it is illustrative of the volatility of the market.

[17] The increase in deficits over the three winters (in the absence of the build-out of additional capacity) is related to the closure or capacity reduction of some conventional Belgian power plants (Rodenhuize, Vilvoorde) and to the likelihood of lower available capacity in neighboring countries.

unavailabilities) in France. Elia assumes a slightly better availability in its EU-SAFE scenario, in which "only" 4 or fewer additional units would be unavailable[18]. Under this assumption, the (relatively limited) shortage indicated above could turn into a capacity surplus, at least for the winter of 2023-2024.

Given the vulnerability of French nuclear generation, as it has been demonstrated in recent months, it is clear that as much as possible should be deployed on indigenous capacity to fill the potential shortfalls created by the nuclear exit. This is particularly important in the period up to about 2028; indeed, after that, an additional capacity of some 2.2 GW of wind power should normally become available from the new Princess Elisabeth zone to be developed in the North Sea[19].

In terms of security of supply, there are two crucial periods:

- **winters of 2023-2024 and 2024-2025**, when nuclear capacity will be systematically reduced. Doel 3 was already shut down on Sept. 23, 2022. So was Tihange 2 on Jan. 31, 2023. Then, in 2025, Doel 1 (15/2), Tihange 1 (1/10) and Doel 2 (1/12) will be permanently shut down successively. Added to this will be the closure of the conventional power plants at Rodenhuize and Vilvoorde. Moreover, around 26 GW of thermal capacity would disappear across Europe over the period 2022-2025. On the other hand, Elia assumes that the new Flamanville EPR plant would be at least partially operational from 2024. An increase in renewable energy over this period also helps fill part of the shortfall. This explains why over the period 2021- 2025, during which nuclear capacity is being systematically reduced, there appears to be little or no need for new capacity (on top of that already planned). As mentioned, the availability of French nuclear capacity does play an important role here. It is also conditional on no currently available capacity leaving the market during this period.
- **Winters 2025-2026 and 2026-2027**. Indeed, in 2025 the nuclear reactors Doel 4 (1/7) and Tihange 3 (1/9) would also be shut down, in accordance with the Nuclear Shutdown Act. This shutdown will not be permanent, since according to current plans, the intention would be to restart both reactors in the fall of 2027. During the period 2025-2027, the preparations necessary to make a restart possible are taking place. However, no nuclear capacity is available in the two intervening winters. Compared to the situation before September 23, 2022, a total of 5.9 GW less of nuclear generating capacity will then be available; of this, 3.9 GW will be closed in the year 2025. As shown in Figure 6, there would be a capacity need of about 3.6 GW in the period 2025-2027.

As mentioned, the present project has no contribution to filling this shortfall, which occurs before the life extension will be a reality. However, it is true that the government will have to make every effort anyway to avoid shortages in the winters of 2025-2026 and 2026-2027. The CRM mechanism will in principle be operational (and able to provide the necessary power) by then, but given the uncertainty associated with the current context, it cannot be ruled out that additional measures will be necessary. The measures taken in that context will hopefully be sufficiently sustainable and cost-effective to further contribute to safeguarding security of supply even after the restart of Doel 4 and Tihange 3.

[18] The additional unavailability of 6 and 4 French units, respectively, represents a loss of available capacity of about 5.4 and 3.6 GW, respectively, out of a total French nuclear park capacity of about 60 GW. Of this, just under 10 GW are unavailable in "normal" winters, but in recent years the figure has been higher.

[19] The federal government assumes that with the increased capacity of (future) wind turbines in the same area, a capacity of up to 3.5 GW could possibly be expanded.

1.2.3 Alternatives

An alternative to a plan or project can be defined as "*another way to achieve the objectives of the plan or project*. So the question is whether there are alternative ways to achieve the intended policy objective.

The policy objective pursued by the lifetime extension of Doel 4 and Tihange 3 is to *ensure security of* electricity *supply*. A complete nuclear phase-out as foreseen in the Act would eliminate some 5.9 GW of production capacity by the end of 2025. Keeping both reactors open longer, combined with the capacity already in place and to be further developed (gas plants, renewables, etc.) will indeed anchor the achievement of this goal more firmly.

The decision to extend the lifetime of the Doel 4 and Tihange 3 nuclear reactors by 10 years is pre-eminently a policy decision, driven by unexpected and undesirable developments in the energy market and in the geopolitical situation in Europe. It can be assumed that in preparation for making that decision, the government checked whether equivalent alternative options were available, and if so, weighed up the pros and cons of those options.

Nevertheless, it is useful to briefly consider the potential alternatives that, at least in theory, are (or could be) available for securing electricity supplies. In theory, any combination of energy forms that can guarantee sufficient capacity and a high degree of operational security qualifies. However, it is not enough to come up with theoretical replacement alternatives in the form of alternative energy mixes. These alternatives must also pass the test of reasonableness. This means, among other things, that they must be realistic and promising, i.e. that realizing these alternatives in the short term is a plausible option. We therefore briefly review the various options available below.

The **CRM mechanism** was until recently seen as the solution par excellence to bridge the period between the definitive closure of all nuclear power plants (in 2025) and the moment when sufficient renewable energy capacity would be available. As seen above, Elia calculated in 2021 that in 2025, after the proposed closure of all nuclear power plants, there would be a need for additional flexible generation capacity of some 3.6 GW to meet security of supply and flexibility standards. Incidentally, in the 2019 Adequacy and flexibility study', Elia already indicated that even with a lifetime extension of two reactors with a combined capacity of 2 GW (= Doel 4 and Tihange 3), there would remain a structural need for additional capacity. So the gas power plants (and other CRM forms) whose construction and operation are planned by the government will remain necessary in any case.

Although the CRM mechanism is in principle open to any type of existing or future capacity (generation, storage, demand-side management), in practice it appears that the candidates are mainly betting on gas power plants (CCGTs). As mentioned, in the current economic climate, with high gas prices and a reduction (at European level) in the supply of gas from Russia, this is not necessarily the most obvious option. The CO_2 emissions associated with gas power plants are also a concern. Through the ETS system, those emissions also affect the cost price of production.

The first auction in 2021 selected a total capacity of 4447.7 MW based on the bids; 80.6% of this was in the form of combined cycle gas turbines (CCGT). Of this, a capacity of 1607.6 MW consisted of new units. In April 2022, based on the 2021 auction, a new allocation of 805.3 MW occurred, replacing CCGT units with a combined cycle capacity of 796 MW, for which no environmental permit was obtained in Flanders. The 2022 auction again offered 807 MW of new CCGT capacity, along with some other, smaller offers. However, none of these offers was selected because the required volume was fully covered by the volume carried over to the second auction. The additional capacity available in 2025 (though much of it still needs to be built) thus remains at about 4.48 GW. In principle, this is sufficient to close the capacity gap that will arise from 2025, but as mentioned above, the government does not wish to rely completely and solely on CRM capacity in the current context.

The **strategic reserve system** involves paying producers to provide additional production, on demand, when (temporary) shortages threaten. In addition to additional production, this may also involve a reduction in off-take on the demand side. Each year, Elia uses forecasts and model calculations to determine whether there may be a need to use the strategic reserve during the following winter, and how much additional capacity should be provided. However, the strategic reserve system is not suitable as a structural solution to a systemic capacity shortage.

Belgium is one of the best interconnected countries in northwestern Europe. The interconnection capacity allows about half of the peak demand to be imported. However, this implies that sufficient reserves must also be available abroad. As seen, however, **import possibilities** from abroad have been under pressure for some time, due in part to Germany's nuclear exit and fossil fuel phase-out. Recently, problems with the French nuclear power plants have been added (cf. supra). While Belgium has been a net exporter of electricity since 2019 (with exports of 7.88 TWh in 2021, equivalent to over 8% of Belgium's net electricity production), this trend will not continue as the nuclear exit becomes more concrete and its own available capacity is further reduced.

For example, Elia has calculated that in 2025 (if the nuclear exit envisaged by the law were complete) Belgium would need to rely on an import capacity of at least 3 GW for more than 2,000 hours a year, and that an import capacity of at least 5 GW would be needed for more than 200 hours a year - assuming that no new capacity would be built to compensate for the nuclear power lost in Belgium. This figure also obviously does not take into account the extension of Doel 4 and Tihange 3.

The expansion of **renewable energy** production is in full swing; the capacity created acts (especially at the European level) primarily to compensate for the loss of fossil-fueled production units. At the end of 2021, the total installed capacity of renewable energy in Belgium was 13.06 GW, or about 47% of the total installed capacity for electricity generation. However, due to the relatively low load factor[20] of these generation assets, renewable energy production only amounted to about 18% of total Belgian production, where nuclear energy (with a capacity share of only 21.3%) was responsible for 49.7% of production. This shows that renewable energy production still has a significant amount of catching up to do if it is to eventually replace the completely lost nuclear capacity. Again, licensing issues, among others, may cause problems. For example, the connection by 2028 of about 3.5 GW of new wind energy from the so-called "Princess Elisabeth Zone" in the North Sea depends on the permit and realization of the Ventilus project.

Elia assumes an available capacity in 2032 of (in the "CENTRAL" scenario) 12.2 GW of solar power, 5.4 GW of onshore wind, 4.4 GW of offshore wind, 157 MW of hydropower and 904 MW of biomass; together, a capacity of about 23 GW, or an increase of more than 76% over the situation in 2021.

In summary, several of the possible alternative energy sources are not a real alternative: renewable energy capacity is not yet sufficiently developed, import possibilities are under pressure, and the strategic reserve is not intended to be used structurally. The CRM mechanism is the most obvious alternative, and is therefore being further developed. In this sense, it is not a real alternative but an additional guarantee, in conjunction with the lifetime extension of Doel 4 and Tihange 3, to ensure security of electricity supply. As mentioned, Elia also assumes that even with a lifetime extension of both plants, the capacity provided by the CRM mechanism will continue to be needed. This is obvious, given that the shortfall in 2025 was estimated at 3.6 GW, of which only 2 GW will be filled by keeping the plants open longer.

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[20] Ratio of actual production to theoretical production under continuous availability at rated capacity.

In the present analysis, we limit ourselves to depicting the environmental effects of keeping the Doel 4 and Tihange 3 nuclear reactors open longer, over a period of 10 years. Thus, we do not compare this with the effects of alternative (hypothetical) solutions[21] which, as seen, are otherwise lacking in the short term. What we do compare is the situation where the project would not have been carried out and the lifetime extension would therefore not have been realized.

1.2.4 Reference state and reference scenario

In an environmental assessment, depicting the impact of the plan or project requires a clear definition of the baseline condition. By definition, the baseline condition is the state of the environment that would result if a plan or project were not implemented; it forms the basis of comparison for the impacts of the plan or project. Thus, in this case, the baseline condition is the condition that would arise if the lifetime of Doel 4 and Tihange 3 were not extended, if, in other words, Doel 4 and Tihange 3 were to be permanently shut down in 2025 according to the calendar of the Nuclear Shutdown Act. The condition that would result if the project did go ahead (lifetime extension) is compared to that reference condition (no lifetime extension). The difference between the two indicates the impact of the plan or project (in this case, the lifetime extension) (Figure 7).

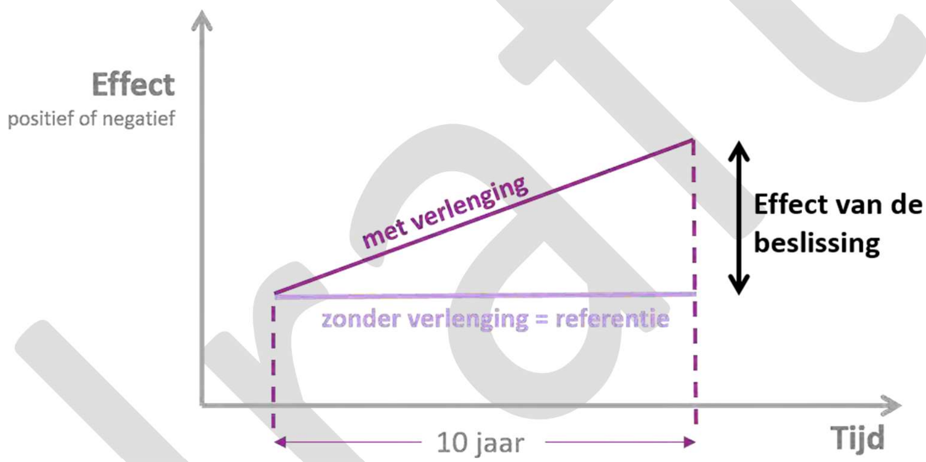

Figure 7: Schematic representation of the reference state.

The reference state in this case is basically the state of the environment in the year 2025.

The basic assumption is that this reference state does not fundamentally change (under the influence of evolutions not related to the operation of Doel 4 or Tihange 3) over the period of the lifetime extension, or at least not in such a way that the assessment of the effects on the environment would be altered. Should this be the case, the (changed) reference state at the end of this period must be taken into account.

In addition to the reference condition, we also use the terms "reference period" and "reference scenario" in this EIA. These terms follow from the particularity of the Project which is that the effects are confined to a time-limited period, the beginning and end of which are fixed. We call this time-limited period the *reference period*. For impacts that have a clear time dimension (e.g. amount of pollutants emitted per year, amount of waste produced per year, ...), the environmental impact assessment also considers the impact cumulated over the reference period, by summing up the quantities per year to a total for the

[21] Except with respect to so-called "avoided emissions," see below.

period or by making a comparable estimate of the cumulative effects over the life extension period.

Finally, we also talk about the *reference scenario* in this environmental impact assessment. This describes the project-related developments during the reference period if the project is not implemented. For the Doel and Tihange sites, this scenario implies that no nuclear reactor is still operating at the site. For the Doel 3 and Tihange 2 plants, by 2027 the post-operational phase will be fully or largely over, and decommissioning will have begun. For the Doel 1, Doel 2 and Tihange 1 reactors, the post-operational phase will run until around 2030, after which decommissioning will also have begun for these reactors.

The form that decommissioning will take and the environmental impacts associated with it are not available at this time; therefore, they cannot be taken into account in the present environmental impact assessment. However, comprehensive environmental impact assessments at the project level will be carried out for the decommissioning of the various reactors in the future.

1.2.5 Potentially relevant autonomous and controlled developments

In order to know the reference situation in terms of environmental quality, we need to see if there are evolutions between today and 2025 that could give rise to a difference with the situation today. Furthermore, we must also see if and how these evolutions continue over the period of life extension.

In the first place, there are a series of **autonomous evolutions**, which may possibly result from human actions, but which are not controllable within the time and space frame of the project. One example is climate change. It can be assumed that the state of the climate in 2037 will be different from the state in 2023. Whether this is relevant and what the possible consequences of this are is addressed in the discipline Climate.

Next, we need to consider **policy-driven evolutions** that have the effect of improving environmental quality. This is the case, for example, for water and air quality, and is further explained under those respective disciplines. As a result of these evolutions, the state of the environment in 2025 is not expected to be fundamentally different from the state in 2023. Over the life extension period, the improvement initiated will of course (in all likelihood) continue.

Finally, there are the **other driven evolutions**, which follow directly from human actions but are not policy-related. These include, for example, new projects that may be realized in the vicinity of the project sites, or other (spatial) developments with potential effects on the environmental state. If these developments have implications for the vulnerability of the environment, or if they could give rise to meaningful cumulative effects with the effects of Doel 4 and Tihange 3 discussed in this EIA, this will be indicated. The impact assessment will therefore take these elements into account (if appropriate).

For the **KC Doel** site, the main potentially relevant developments are briefly described below.

- Complex project extra container capacity Antwerp (CP ECA): this project involves the realization of a new tidal dock in the port of Antwerp, east of the village of Doel, connecting to the existing Deurganck dock. Large container ships (up to 400 m in length) will dock in this dock. On the container quays, containers will be supplied and removed, unloaded and loaded and/or temporarily stored. Adjacent to the container dock, a new logistics area will also be constructed where, for example, activities in the field of value added logistics can take place.
  Currently, this project is still in the development phase (=study phase). The project decision for this project is expected during 2023. Following the project decision, construction of the dock will begin. Construction of the dock will take more than three years. So by the time Doel 4 restarts, the new dock may already be operational, although probably not yet at full capacity. That capacity will likely be filled over the 10-year period that

corresponds to the life extension of Doel 4; in parallel, atmospheric emissions will also increase, especially those coming from marine vessels.

Given that conventional atmospheric emissions attributable to Doel 4 are (very) small compared to ECA emissions (and a fortiori compared to emissions in the entire port area), cumulative atmospheric emissions within the study area are hardly affected by whether or not Doel 4 remains open. This reasoning applies, mutatis mutandis, to mobility and noise effects as well. Also for these aspects, the environmental quality is primarily determined by developments independent of the lifetime extension of Doel 4 impacts on the reference situation, and the additional impact of Doel 4 on this reference situation is limited.

- For the village of Doel, which is not to disappear for ECA, a separate project is underway to draw out a sustainable future perspective, within the context of the preferred ECA decision. Currently, Doel is residential (according to the zoning plan) and there is habitation in the facts. This situation (planning and factual) is not expected to fundamentally change. Over the period of the lifetime extension of Doel 4, no significant increase or decrease in the number of residents in Doel is assumed. Therefore, it does not significantly change the vulnerability of the environment in terms of human receptors. Again, exposure to conventional environmental effects in the village is dominated by the effects of the port.
- Across the Scheldt, between Scheldelaan and Kanaaldok B2, INEOS is planning 'Project ONE' a propane dehydrogenation plant (PDH) in which propane gas will be converted to propylene and an ethane cracker in which ethane gas will be converted to ethylene. Due to its size and complexity, the project will be realized in several phases over a four- to five-year period. It is likely that the facilities will already be largely operational by the time the Doel 4 life extension begins. During the first years of Doel 4's period of additional operation, Ineos Project One will gradually reach full capacity. Again, we can say that the effects of Doel 4 will be small compared to the effects of Project One.
- Nature development: as part of the development of the Port of Antwerp and the Sigmaplan, nature development projects are being planned and implemented in the immediate vicinity of KC Doel. These projects give rise to an increase in the natural values and thus the potential vulnerability of the area. Since these compensation projects must be completed before the implementation of ECA can start, it can be assumed that they will be fully part of the reference situation as of 2027.
- Realization of the different steps in the law on the nuclear phase-out: the present EIA studies the consequences of keeping the Doel 4 reactor open longer. However, this in itself does not affect the other steps foreseen in the law on the nuclear phase-out. During the reference period, the three other reactors at the site will be idle, and will be at different stages of DSZ (post-operational phase or decommissioning), as described above. Cumulative impacts with these activities are not explicitly considered in this EIA, as too little is known about the nature of these activities and their associated emissions. However, project EIAs will also have to be drawn up for the decommissioning activities, which could possibly include the operation of Doel 4 in the reference situation, whereby the cumulative effects are also included. To the extent that the decommissioning of Doel 1, 2 and 3 would have an impact on the reference situation against which the effects of keeping Doel 4 open longer would be compared (e.g. because emissions decrease), this is taken into account in the present EIA. However, unless otherwise stated in the discussion of the various environmental themes, we assume that the reference situation does not fundamentally change during the period of lifetime extension of Doel 4, compared to the situation today.

In summary, several projects are in the pipeline in the vicinity of the site, which can be assumed to be (at least partially) operational at the time when the lifetime extension of Doel 4 begins. To take into account the fact that the impact of those projects will be may evolve over the reference period, we propose the assumption that those projects (ECA, Project One) will be operational at full capacity starting in 2027.

Compared to the situation today, the future *reference situation* over the period of the lifetime extension for Doel will thus be characterized, as a result of the developments described above, by more nature development on the one hand, but also more atmospheric emissions and a deteriorated noise climate on the other hand, combined with a strong increase in traffic generation. To the extent that cumulative effects occur, the contribution of Doel 4 to these effects is very limited.

With respect to the **CN Tihange** site, a number of autonomous and controlled developments that may be relevant to the assessment of the environmental impacts of postponing the deactivation of Tihange 3 are listed below:

- Capacity expansion of the Ampsin lock, about 1 km downstream on the Meuse. This expansion will allow large-gauge inland navigation (4,500 tons in the case of Ampsin) from Namur to the Netherlands and Antwerp, via the Albert Canal. Work has already begun and navigation has been open since January 2022. Work is continuing and should be completed during 2024 or 2025. This project will be carried out during the extension.
- Although this is a major infrastructure project, it is not assumed that it will interfere with the project covered by this EIR. To the extent that the construction phase with associated environmental impacts (noise, emissions, traffic generation, etc.) will be completed, the impacts of this project are part of the baseline environmental assessment for Tihange 3. Since the effects in the operational phase are related to the increase in river traffic, it is assumed that no cumulative effects are to be expected with the expansion of Tihange 3.
- Several major industrial projects are planned within a ten-kilometer radius of the Tihange power plant :
  a. Project for a new waste sorting center by the company Vanheede in Hermalle-sous-Huy (> 6 km east of CN Tihange);
  b. Project for a new plant for the production of compressor blades for aircraft engines by the Safran company in Marchin (± 4.5 km southwest of CN Tihange);
  c. The CO2ncREAT project, stemming from the carbonation technology developed by Orbix, offers a sustainable way to recover certain steel industry by-products by reacting these materials with CO_2 for the manufacture of building elements. The project is being carried out by the consortium Prefer (producer of building materials), Fluxys Belgium (expert in pipe transport), Lhoist (lime producer, supplier of the CO_2) and Orbix. The exact location is not currently known, but it is expected to be more than 6 km from CN Tihange (between the existing Lhoist site 6 km away and the Prefer site which is even further east).

  For now, these projects are still in the development phase (= study phase). This phase, depending on the project, will normally last until the end of 2023 or during 2024, ending with a decision on each project. Once the decision on a project is made, its construction begins, which would take 1 to 3 years. Thus, these projects could become operational between 2024 and 2027.

  Given the distances involved (> 4 km), only the following potential impacts are of concern:

  a. Mobility: traffic generated by these projects during the construction and operation phases would mainly use the N90 and/or the N684. As mentioned in § 2.2.1, traffic on these national roads is not saturated and is only affected by up to 8% of the traffic related to CN Tihange. Therefore, no significant cumulative effects are to be expected with these projects;
  b. Atmospheric emissions: the potential cumulative effects are mainly related to emissions from combustion plants (e.g. NOx) and greenhouse gas emissions (CO_2). In terms of emissions, the nature of the projects implies low emissions (no large combustion plants - more than 50 MW_{th}) and the potential impacts have a limited radius of action (about 3 km), which means that

the potential cumulative effects are negligible. It should be noted that the CO2ncREAT project would even have a beneficial effect on reducing CO_2 emissions within the affected radius;

c. Thermal effects on the Meuse, with effects on the aquatic biosphere, due to the discharge of cooling water: the very nature of the projects means that there is no large combustion plant (more than 50 MWth) and no large amounts of cooling water are produced. Therefore, there is no significant cumulative effect to fear.

In summary, given the distance between these projects and CN Tihange and the nature of the projects themselves, no significant cumulative effects are to be expected with the major industrial projects currently planned near the plant.

- Combined Cycle Gas Turbine (CCGT) projects in Awirs and Seraing: these two projects are intended to partially compensate for the closure of Belgium's nuclear reactors between 2022 and 2025 (other measures were recommended, such as the consideration of foreign reserves). These projects have been designated through the Capacity Remuneration Mechanism (CRM) set up in response to the planned nuclear phase-out. These projects have already received environmental permits and the respective sites started in 2022 to be operational in 2025. Both projects have a capacity of 805 MW. These plants are located downstream of CN Tihange, along the Meuse River, ± 12 km in the case of Awirs and ± 17 km in the case of Seraing.
- As with the other projects mentioned above, the distance between the project and these thermal power plants means that no cumulative impact is expected for any environmental aspect, with the exception of thermal discharges into the Meuse, which may affect aquatic fauna. Indeed, CN Tihange and these two thermal power plants discharge very large amounts of cooling water into the Meuse, the dilution and thermal loss of which in the Meuse require long distances. Interactions in this regard have been identified in the environmental impact assessment of the two plants and are the subject of specific operating conditions in their permits. This issue will be addressed in more detail in the water component of the non-radiological impact assessment for the Tihange power plant (see § 6.2) ;
- Realization of the different steps of the nuclear exit law: this EIA examines the consequences of keeping the Tihange 3 reactor in operation longer. However, this has no impact on the other steps of the Nuclear Shutdown Act. On October 1, 2025 and February 1, 2023, respectively, electricity production at Tihange 1 and Tihange 2 will cease. During the reference period, the other two reactors at the site will thus be shut down and in various stages of decommissioning, as described above. The cumulative effects of these activities are not explicitly mapped in this EIR because there is too little information available at this stage about the nature of these activities and their associated emissions. However, Project EIAs will also be required for the decommissioning activities, where the operation of Tihange 3 will be part of the reference situation

  , so that cumulative effects are taken into account. To the extent that the shutdown of Tihange 1 and 2 would have a significant effect on the effects of the operation of Tihange 3 (because the baseline situation changes, e.g., by reducing discharges), this is taken into account in this EIR. However, unless otherwise stated when discussing the different disciplines, it is assumed that the non-radiological background quality of the environment will not change significantly during the extended operation of Tihange 3.

1.3 Procedure

As indicated above, this environmental assessment is carried out within the framework of the European EIA Directive, the Habitats Directive and the Birds Directive. However, these directives contain little or no procedural provisions on how the EIA process should proceed.

In summary, the main provisions with procedural scope from the EIA Directive relate to:

1. Consulting with those agencies that "by virtue of their specific environmental responsibilities may be affected by the project" (Article 6.1);
2. Informing the public, at an early stage of the environmental decision-making process, of, among other things, the procedure, opportunities for public participation and the subject matter of the permit application (Article 6.2);
3. Making available to the public the results of the environmental impact assessment and opinions issued (Article 6.3);
4. Consulting competent authorities in other member states (Article 7);
5. Informing the public of, among other things, the content of the decision regarding the permit and the considerations on which the decision is based (Article 9);
6. Appeals (Article 11).

These provisions will obviously be followed. It may also be noted that for the environmental impact assessment of the present Project, the detailed procedures (in terms of e.g. deadlines) prescribed under federal or regional regulations do not apply.

The required notifications under the Espoo Convention, the Aarhus Convention and the EIA Directive (cross-border and within Belgium) are carried out by the Belgian government, Federal Public Service Economy and the Minister of Energy.

On Thursday, July 14, 2022, a pre-notification was sent by the Federal Public Service Economy through the ESPO contact regarding the proposed project, namely the postponement of the deactivation of Doel 4 and Tihange 3 to the authorities of the countries located in a 1,000 km radius around Doel 4 and Tihange 3. Figure 8 gives an overview of the nuclear power plants in Belgium (Doel and Tihange) and its surroundings and shows the countries and their nuclear power plants within a 1,000 km radius of Doel and Tihange, respectively. This notification and consultation was carried out by the Federal Public Service Economy in accordance with Article 7.1 EIA Directive. The countries expressing an interest in participating in the cross-border consultation will have the opportunity to provide the opinions of their public and relevant authorities on the environmental impact assessment summarized to the General Directorate of Energy of the Federal Public Service Economy, K.M.O., Middle Classes and Energy.

After the completion of the environmental impact assessments, the Federal Public Service Economy will organize a consultation with the three Belgian regions, the Belgian provinces, interested municipalities, the Federal Council for Sustainable Development, the National Agency for Radioactive Waste and Enriched Fissile Materials (NIRAS) and the Federal Agency for Nuclear Control (FANC-AFCN).

In addition, an online public consultation will also be organized for 60 calendar days through a website dedicated to the publication of the complete environmental assessment file regarding the deferral of the deactivation of Doel 4 and Tihange 3 (strategic level environmental impact assessment and works). The notification regarding consultation and public participation is carried out by the Federal Public Service Economy.

Figure 8: Sites with nuclear power plants in Belgium (Doel and Tihange) and surrounding areas. Sites in green are sites with operational units, in white are sites indicated in full decommissioning and in blue sites where new reactors are under construction. Map based on the "Power Reactor Information System" (PRIS) database IAEA (https://www.iaea.org/pris). The circles represent the area with a radius of 1,000 km around the Doel and Tihange nuclear power plants, respectively.

2 General methodology

2.1 Evaluation of available information

For assessing the environmental impacts of the Project, a list of required information was compiled based on a scoping of the potential impacts. This information is partly publicly available; on the other hand, additional information from the operator is necessary to evaluate the impacts. This concerns, on the one hand, an overview of the planned works entailed by the Project and, on the other hand, a number of technical data, analyses and documents concerning the operation of the Doel 4 and Tihange 3 nuclear reactors and their post-operational phase. A list of necessary information was requested from the operator of the nuclear power plants KC Doel and CN Tihange in September 2022 at the start of the environmental impact assessment. Information from the operator was made available following the January 9, 2023 agreement between the Belgian government and the operator ENGIE Electrabel S.A. to extend the ten-year operating life of our country's two youngest nuclear reactors, Doel 4 and Tihange 3. Most information was received between January 19 and 30, 2023, additional information or clarifications were obtained during February 2023. These were still included to the extent possible. The information available was sufficient to perform an adequate environmental impact assessment. Where certain details were missing, conservative assumptions were made to estimate potential impacts. In addition, the description of gaps in knowledge are part of the assessment.

2.2 General methodology for evaluating non-nuclear impacts

2.2.1 Scoping

2.2.1.1 Concept

Scoping (selection of potentially significant impacts) aims to identify from the beginning of the EIA the (presumably) most important environmental themes and impacts and to distinguish them from other, less relevant themes. In this way, the EIA process focuses on the essentials.

Scoping consists of two clearly distinguishable steps:

- identifying possible effects (can the effect occur?);
- verifying significance (is the effect likely to be significant?).

The first step attempts to get as complete an overview of the possible effects as possible. In the second step, the rough list of possible effects is narrowed down by considering which of these effects may be (potentially) significant. In determining whether effects are potentially significant, consideration is usually given to such factors as:

- The nature, scale, duration and reversibility of the effects;
- the importance, rarity, sensitivity or vulnerability of the environmental factors affected by the impact;
- the location of the proposed initiative, in relation to the policy objectives and legal provisions applicable to the receiving environment (environmental priorities);
- The extent to which studying a particular effect substantially contributes to the decision supported by the EIA.

2.2.1.2 Approach

The scoping was conducted as part of the present environmental impact assessment with the support of the following actions:

- Analysis of the main characteristics of the Doel and Tihange sites, and more specifically of the Doel 4 and Tihange 3 reactors (and associated facilities), in light of the environmental impact that may be associated with them;
- Analysis of environmental vulnerability;
- Consultation on previously conducted environmental impact assessments for both sites, and the scoping done therein;
- Organization of a scoping workshop in the presence of the various (radiological and non-radiological) EIA experts. The interaction that ensued led to additional insight into the operation of the plants and the effects that may result.

The selection of potentially significant impacts thus captured is discussed in more detail when discussing the various themes. The results of the scoping are outlined below.

The conclusion of this exercise was that discussion of impacts should focus on the final receptors of those impacts, namely human health on the one hand and biodiversity on the other. This applies to both radiological and non-radiological impacts.

2.2.1.3 Outline scoping

Step 1: analysis of potentially impact-generating elements

The first step of the scoping process is to define the nature of the impacts that may occur. This analysis starts from a list of the main components and installations of the plants and then assesses whether the operation or presence of these components and installations could give rise to environmental impacts. This analysis draws on expert knowledge of cause-effect relationships, and also draws on information available in previous environmental impact studies or impact statements (Doel: EIA 2010, Screening Note 2015, EIA relating to works 2021; Tihange: EIA project SF^2 2018, EIA project SF^2 2019 and environmental statements 2012 to 2022).

The result of this analysis is shown in Table 6. The symbols in this table have the following meanings:

XEffect can occur and is potentially significant; the focus of the assessment is on these effects.

(x) Effect may occur but is probably negligible

The table distinguishes between the receptor disciplines (climate, biodiversity, people and landscape) and the other disciplines, which we refer to here as auxiliary disciplines. Effects of power plants on the receptor disciplines often do not occur directly, but through the auxiliary disciplines. For example, pumps and generators do not directly impact biodiversity, but they do through the noise and air emissions they generate.

Table 6: Overview of the main Doel 4 and Tihange 3 facilities and activities and their relationship to potential environmental impacts.

	Auxiliary disciplines					Recipe disciplines			
Component	**Water**	**Soil/groundwater**	**Air**	**Mobility**	**Sound**	**Climate**	**Biodiversity**	**Health**	**Landscape**
1. Treatment and discharge of wastewater	X		(x)				X	(x)	
2. Cooling water discharge	X						X		
3. Stormwater Management	X	(x)							
4. Cooling water capture	X						X		
Cooling towers and cooling circuits.	X		X		X	(x)		(x)	X
6. Steam boilers, generators and heating plant			X		(x)	X	(x)	(x)	
7. Reactor, steam turbines and alternator					(x)				
Transformers and high voltage infrastructure		(x)			(x)		(x)	(x)	
9. Compressors and pumps/pumping stations					(x)		(x)		
10. Storage of non-nuclear hazardous materials		(x)	(x)						
11. Storage of non-nuclear waste (oil, residual waste, etc.)		(x)	(x)						
12. Outdoor lighting							(x)		
13. Traffic			(x)		(x)		(x)		

The present EIA does not intend to describe the full impacts of the Doel and Tihange nuclear power plants, but only to indicate the difference between the impacts in case of, on the one hand, deactivation of Doel 4 and Tihange 3 in 2025 and, on the other hand, extending their lifetime by 10 years after the restart. This means that not all impacts generated by the nuclear power plant are relevant to this EIA.

Effects that are *not* exclusively attributable to the operation or presence of Doel 4 and Tihange 3, respectively, are part of the reference situation of this EIA; they occur in both cases and thus do not determine the difference between the situations with or without lifetime extension of both reactors. An example is the decommissioning activities of the previously deactivated reactors at both sites. These activities (and their associated impacts) take place in any case, regardless of whether or not the lifetime of Doel 4 and Tihange 3 is extended. They do of course determine the overall impact of the Doel and Tihange sites, but not the specific differences between the situation where Doel 4 and Tihange 3 are still in operation and the situation where they are not.

Step 2: selection of themes (disciplines) within which potentially relevant effects may occur

In this step, based on Table 6, it is determined which themes will require further attention in this strategic environmental assessment. In practice, these are the themes within which potentially significant impacts may occur that can be attributed, at least in part, to the operation or presence of Doel 4 or Tihange 3.

Furthermore, in this step we also extend the focus to some so-called "avoided" impacts of the Project; these are impacts that do not occur with lifetime extension, but do occur if Doel 4 and Tihange 3 are deactivated. This is discussed in more detail later.

The outline scoping at the theme level is shown schematically in Figure 9.

As shown in this diagram, three groups of potentially significant impacts emerge from the scoping: - effects of the Project, avoided effects of the Project and effects on the Project.

Impacts of the Project

These are effects directly attributable to the Project, i.e. to the strategic policy decision (and associated works) leading to the extension of the lifetime, by a period of 10 years, of the Doel 4 and Tihange 3 units, and to the effects of the works necessary to enable this lifetime extension. As mentioned above, the discussion of the topics will specify the exact impacts involved. Here we follow a receptor-oriented approach, primarily identifying impacts on biodiversity and on human health[22]. To do that, however, it is important to also have an understanding of the effects of the power plants on air quality on the one hand and on the water system on the other. Greenhouse gas emissions are also addressed in this EIA, as a direct effect but also as an "avoided" effect.

Thus, Air, Surface Water, Biodiversity, Health and Climate are the five themes (disciplines) for which the direct impacts of the Project are determined in this EIA. The expected impacts and associated assessment criteria for each of these themes are discussed in more detail later in this EIA.

[22] Health effects are primarily (potentially) relevant to radiological effects.

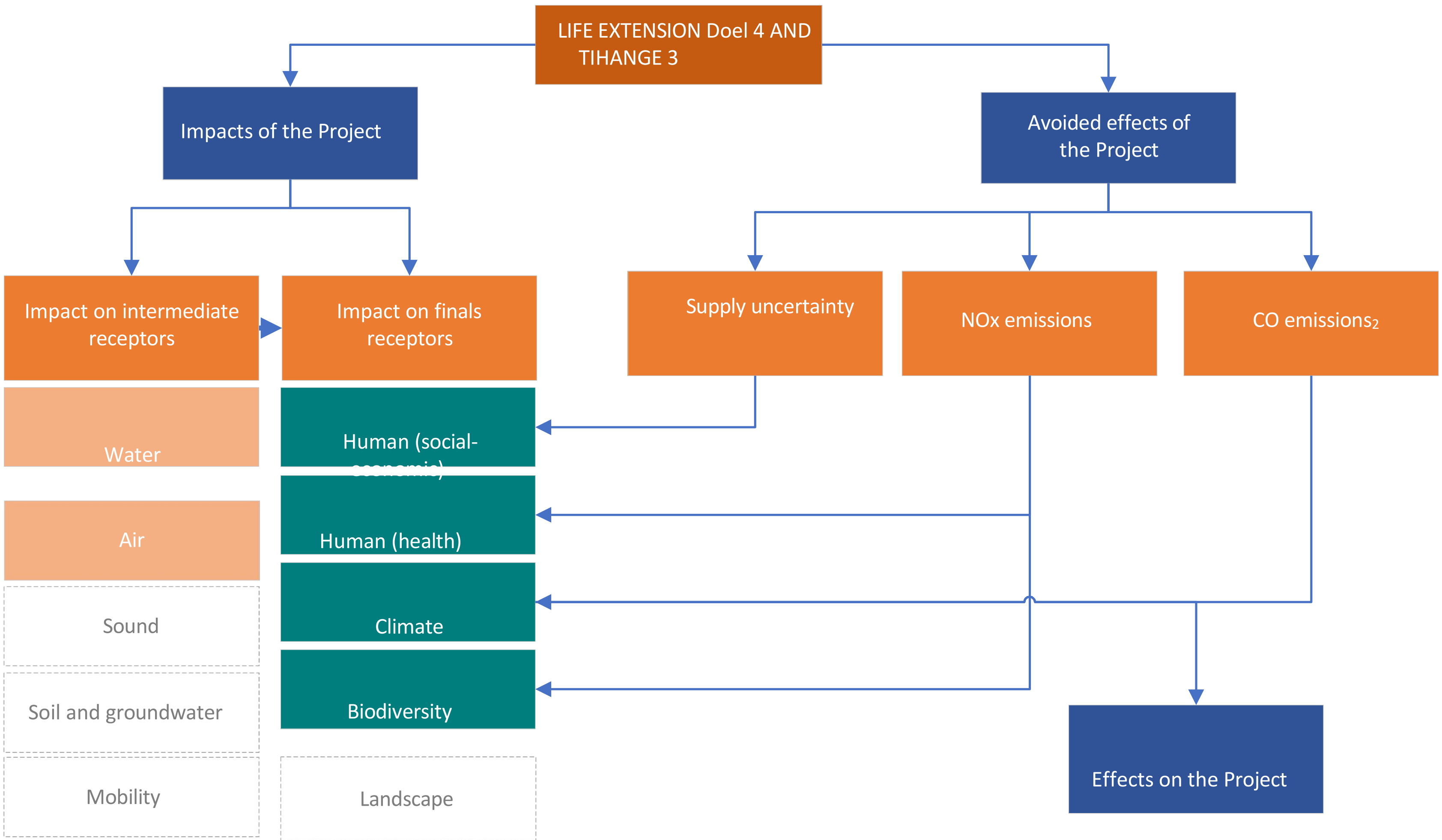

Figure 9: Schematic representation of the outline scoping for the environmental impact assessment of the policy decision to extend the life of Doel 4 and Tihange 3.

Thus, a number of other non-radiological themes are not addressed in this Strategic Environmental Assessment. Table 7 provides brief justification for each of these themes.

Table 7: Overview of themes not studied in the Strategic Environmental Assessment, and corresponding rationale.

Theme	Motivation for not studying this topic in strategic-level environmental impact assessment
Bottom	The facility is legally bound to a periodic exploratory soil survey because of the risks of storage of hazardous substances in the facility. That storage is done according to the conditions of Vlarem II for Doel and of the environmental permit in force for Tihange. Based on previous investigations, several plots of land at the Doel site were included in OVAM's register of contaminated land, but none of the contamination posed a serious threat to humans or the environment, or required soil remediation. At the Tihange site, certain plots of land were included in the Walloon soil database (Banque de Données de l'Etat des Sols). Some plots were examined, and some contaminants were found. However, most contaminants were found not to pose a serious threat, and a few others were remediated. The storage and handling of hazardous substances in large quantities (diesel, neutralization products, ...) potentially poses certain risks of soil and groundwater contamination. Part of that storage is also directly related to Doel 4 and Tihange 3 (e.g., part of the diesel storage needed to run pumps in case of loss of electricity supply). Thus, keeping Doel 4 and Tihange 3 open longer theoretically increases the likelihood of additional soil contamination due to diffuse leaks or accidents. However, since a number of measures have been taken at both sites in accordance with the respective environmental permit regulations (e.g. containment, leak detection, etc.), it can be stated that the likelihood that significant new soil contamination would occur during the additional 10-year operating period is very low. The operation of Doel 4 and Tihange 3 includes the surfacing of the part of the site occupied by the installations. Life extension involves perpetuating this ground cover for at least 10 years. However, it can be assumed that even if the plants were to be permanently shut down in 2025, the pavement would not be removed during the following 10 years, given the long time required for decommissioning. For their part, the work required to enable the extension does not involve a significant increase in ground pavement.
Landscape	The landscape impact of the Doel and Tihange nuclear power plants is determined primarily by the tall cooling towers and their characteristic water vapor plumes, and to a lesser extent by the reactor buildings. The high-voltage power lines also contribute to the visual impact. Taking into account the duration of decommissioning activities, it can be said that the landscape impact of both sites will be significant at least until 2037, regardless of whether Doel 4 and Tihange 3 are shut down or not. The landscape impact of any additional installations that would be required to enable the extension can be considered negligible compared to the other installations on the site.
Groundwater	The Doel power plant does not use groundwater. Therefore, whether or not the lifetime of Doel 4 is extended has no effect in this area. The Tihange plant pumps groundwater to guarantee the water supply for the cooling circuits should other water sources fail. However, whether or not the deactivation of Tihange 3 is delayed makes little or no difference, as groundwater supplies are only drawn upon in very exceptional circumstances. The presence of several pre-existing buildings whose foundations and foundation piles extend to the depths of the Tertiary sediments at Doel and the Maas alluvium at Tihange, and of diaphragm walls around various parts of the power plant, may reduce the natural groundwater flow does disturb groundwater flow. However, this situation is not fundamentally different in a situation

	with or without life extension, since activities at the site will continue for many years even if electricity production ceases. In terms of potential groundwater contamination, reference can first be made to the considerations on the topic of Soil (cf. supra), which show that the likelihood of additional soil (and thus groundwater) contamination as a result of the storage of pollutants is very small, given the measures taken in accordance with current regulations. An effect on the groundwater balance should not be expected either, since within the reference period no significant differences in paved area are expected between the situation with and without deferred desactivation.
Mobility	Traffic movements resulting from the operation of the Doel and Tihange sites are mainly caused by staff and subcontractor vehicles to and from the site. There are also vehicle movements of personnel within the sites. In addition, there are the transports in function of the supply and maintenance of the installations (chemicals, fuel, spare parts, waste removal, etc.). Transport associated with the daily operation of the plants is by road. In Doel, (heavy) traffic to and from the nuclear power plant goes via the Waaslandhaven, more specifically around the Deurganck dock and from there to the junction with the R2 (and from there either to the A12, the E34, the E17 or the R1). No residential areas are crossed in the process. There are obviously a number of variants on this main route, with traffic finding its way through the polders, possibly via Kieldrecht and via the N451 directly to the junction with the E34. On average, some 1,700 people are present on the site (during the day) and this presence can be linked to some 1,300 vehicles, approximately broken down into 900 passenger cars, 300 vans and 100 trucks. Major works/revisions increase the number of vehicle movements. Saturation of the local road network to the Doel site does not occur. However, heavy traffic in morning and evening rush hours is possible. The construction of the planned Western Waaslandhaven access road, which will take place during the Doel 4 life extension period, will significantly improve access to the site. Thus, even with an increase in vehicle movements to and from the site (which is not expected), there would likely be no effect on the smooth flow of traffic. (Heavy) traffic to and from the Tihange site is via the N90, which has direct access to the site, and the N684, which crosses the Meuse and connects to the E42 (exit 15). These are wide roads (3 to 4 lanes) adapted to the traffic of the nuclear power plant. On average (during the day), some 1,200 people are present on the site: 1,000 employees and 200 suppliers, subcontractors or visitors. It is estimated that an average of 900 vehicles visit the site daily, including about 650 passenger cars, 200 vans and 50 trucks. This corresponds to about 950 passenger car equivalents per day in each direction. During major works/revisions, the number of vehicle movements increases. Since traffic is in the order of 15,000 passenger car equivalents per direction on the N90 and 12,500 passenger car equivalents per direction on the N684, it follows that traffic attributable to the Tihange power plant represents between 6 and 8% of traffic on these national roads. Saturation of the local road network to the Tihange site does not occur, although heavy traffic during the morning and evening rush hours is possible. The lifetime extension of Doel 4 and Tihange 3 does not significantly increase or decrease the number of vehicle movements to and from the site compared to the period before 2025. Decommissioning of Doel 1, 2 and 3 and of Tihange 1 and 2, respectively, will continue throughout the life extension period.
Sound	Several noise sources can be distinguished at the sites of both nuclear power plants, which collectively represent the total noise emission from open-air operation. Here a distinction should be made between sources that are in continuous operation, and sources that are only actually in operation for a limited part of the time (< 1%), such as emergency groups and emergency cooling banks. Temporary sources are operated only in emergency situations, but are also tested monthly for safety and maintenance reasons. The 2010 EIA showed that in Doel the two cooling towers were responsible for 55% of the noise power (mainly the noise from falling water). The auxiliary cooling towers (fans) represent

	a 20 % and the openings and walls of machine rooms and reactor buildings another 15 %. Cumulatively (i.e. for the entire site, with all installations in operation), this leads to an exceeding of the Vlarem guideline values, especially east of the site. During the lifetime extension period, the noise sources linked to Doel 4 will remain in operation, but the noise impact of the site as a whole will decrease, presumably to a level where exceedances of standards will no longer be an issue. The EIA for Tihange conducted in 2019 showed that the site complies with Walloon noise regulations. So here the lifetime extension has no effect anyway. If the life extension would require the construction or operation of some new facilities or buildings, it is assumed that in operational phase it would not cause a significant increase in noise and associated nuisance to local residents. This assumption is confirmed by the example of the recent SF² project at Tihange, which had no significant impact on noise levels. However, the decommissioning of the other reactors present at the sites will create new noise sources.

Avoided impacts of the Project.

These are effects that do not occur if the Project is implemented, but do occur if the Project is not implemented. They are therefore effects that occur in the reference situation. Since the magnitude of an effect is determined by making the difference between the project situation and the reference situation, these are negative or "avoided" effects.

In order to make a statement about the magnitude of these avoided effects, it is necessary to define the reference situation in more detail in terms of how the lost production capacity would have been filled over the lifetime extension period. This is obviously a theoretical exercise, with no intention of comparing the effects of different (unrealized) energy mixes[23].

To simplify this exercise, it was decided in this environmental assessment that, for the purpose of determining the avoided effects, the filling in of the capacity that may or may not be lost will be done according to the same proportions as those within the current share of non-nuclear capacity. Given the great uncertainty about the way in which the capacity of Doel 4 and Tihange 3 that may be lost could be filled (renewable energy, CCGT or other forms of capacity compensation, energy savings, imports from abroad, etc.), this is the most obvious fallback option. Given the uncertainty about the actual filling of the dropped capacity, we do not study a number of effects that may be associated with it (but which depend heavily on the nature and location of the replacement plants). These include, for example, effects on landscape, air quality, or water quality.

Specifically, we limit the study of avoided impacts to:

- Avoided greenhouse gas emissions (with knock-on effects in the Climate discipline);
- The avoided emissions of NOx (with knock-on effects in the Human and Health discipline).

In addition, we also consider the avoided supply uncertainty. Avoiding this uncertainty is the very objective of the plan, and in that sense not a side effect of it. Nevertheless, it is good to get an idea of the effects on this aspect if the lifetime of Doel 4 and Tihange 3 were not extended. We look at the effects of supply uncertainty primarily in the context of the "People" theme.

Effects on the Project

The "effects on the Project" relate specifically to the effects of climate change on the plan. The obligation to include this aspect in the environmental impact assessment follows from the amendments made

[23] Such an exercise did occur in the Federal Public Service Economy's "Study on Electricity Supply Prospects by 2030 (2015)" and its accompanying plan EIA.

to the 2011/92/EU EIA Directive by Directive 2014/52/EU. Indeed, Annex IV of that Directive states that an environmental impact assessment must include, among other things, a description of *the project's impact on climate* (e.g., the nature and extent of greenhouse gas emissions) and the project's *vulnerability to climate change*.

This may involve both the integrity or operation of the Project. The rationale itself of a Project may also change as a result of climate change, and the impacts of a Project described in an EIA may become more or less important with a changing climate.[24]

2.2.2 General assessment framework

The assessment is done relative to the various policy objectives within a given discipline/policy area. For each policy objective, we make one of the following statements:

1. The Project contributes noticeably to achieving the objective -> score "positive.
2. The Project does not noticeably contribute to achieving the objective, but neither does it noticeably counteract it -> score "neutral.
3. The Project noticeably works against achieving the objective -> score "negative.

To determine whether or not the Project contributes to the achievement of a particular objective, certain effects must be examined. These may or may not correspond to the "classic" effects from, for example, the guidelines books.

For example: if a nature policy objective could be formulated as "species conservation," then the various effects that could affect this must be discussed: land take, fragmentation, disturbance, ... These effects are only discussed and not assessed; the assessment is done only at the level of the objectives.

2.2.3 Specific assessment frameworks

In each of the disciplines dealt with later in this EIA, the effects that will be studied and the assessment criteria that will be used are discussed in more detail. Where relevant, it will also be indicated what the results of the impact assessment will be tested against (assessment framework).

2.2.4 Depth of assessment

As indicated earlier, the environmental impact assessment related to the policy decision to extend the lifetime of Doel 4 and Tihange 3 by 10 years is situated at a strategic level[25]. The approach taken here is different from that of an environmental impact assessment for an implementation project.

In practice, there are not really sharp boundaries between what we consider a strategic-level assessment or a project-level assessment. Rather, there is a gradual transition from strategic to operational thinking. The key elements and polarities of this strategic-operational continuum are presented graphically in Figure 10.

[24] A classic example is the extent to which the effect of a discharge on a watercourse would become more significant if climate-related drought changed the average discharge of that watercourse.

[25] The impact of the works does occur at project level, but since this impact does not go beyond the contours of the site and can be compared to the impact of previous maintenance works, they do not play a meaningful role in determining the overall impact of the project

Clearly, the present EIA is on the left rather than the right side of this continuum. This means, among other things, that this EIA primarily uses existing data, that the impact description and assessment will be predominantly non-quantitative. Moreover, the focus of the present (strategic) EIA is on impacts whose impact may be significant. Impacts with expected only limited impacts are not addressed in this environmental impact assessment. Given the strategic nature of the decision underpinned by this EIA, this is also acceptable.

	Project: postponing the deactivation of Doel 4 and Tihange 3	
	Environmental impact assessment of policy decision to defer	**Environmental impact assessment of associated works**
Nature of action	Strategic, conceptual	Direct, operational
Scale of effects	Large-scale	Local
Timescale	Long to medium term	Medium to short-term
Key data sources	Existing data from e.g. environmental reports	Data based on fieldwork and project data
Type data	Rather qualitative	Rather quantitative
Options	Area-wide, technological, intermodal	Specific location, design
Uncertainty and substantiation	More uncertain	More substantiated

Figure 10: Key elements of the strategic-operational continuum of environmental impact assessment[iv], applied to the environmental assessment of the project.

2.3 General methodology for nuclear impact assessment, including radioactive waste and spent fuel

2.3.1 Introduction

This chapter describes the nuclear or radiological environmental aspects considered in relation to the Project. In the first instance, this is the exposure to ionizing radiation, both during normal operation and during accident situations (nuclear incident or accident), and this both for the most exposed person (critical individual) and for the environment (fauna and flora). Furthermore, (potential) transboundary effects are also considered. Secondly, the impact of the Project on the quantities of radioactive waste and spent nuclear fuel is considered, more specifically the quantities of radioactive waste produced during the extended period of industrial energy production (the Project), as well as the quantities of waste expected during decommissioning after final shutdown. Since the methodology to describe these impacts is identical for Doel and Tihange, we discuss them together. The current situation, the effects in the case of extension of the Doel 4 and Tihange 3 units for 10 years beyond 2025 (the Project) and in the case of non-extension (deactivation or final shutdown) of Doel 4 and Tihange 3 in 2025 (the zero alternative) will be discussed in the specific sections for Doel 4 and Tihange 3.

To make sense of the effects and methodology, we first provide an overview of the basic concepts of radioactivity and radiation, the effects of radiation on humans and the environment, radioactive waste, and radiation exposure pathways.

2.3.2 Basic concepts of radiation protection used in assessment, including relevant legislation

Radioactivity is a property of certain atoms in which they spontaneously emit energy in the form of radiation, changing - we call this **radioactive decay** - to a more stable form, until they eventually become stable atoms. The radiation emitted can take the form of particles such as electrons, helium nuclei, neutrons, ...or electromagnetic radiation (photons). This radiation has a lot of energy and can interact with the matter through which it moves to ionize atoms directly or indirectly and is therefore also called ***ionizing radiation***.

Different forms of radioactive decay exist in which specific radiation is also emitted. For example, the most important are ***alpha, beta and gamma decay***, in which alpha, beta and gamma radiation are emitted, respectively. A less common form of radioactive decay is spontaneous fission, in which the nucleus splits into two fission products with release of a number of neutrons, also a form of ionizing radiation. The latter process also takes place in a nuclear reactor, but is induced by the neutrons present and we then speak of induced fission (see §1.2.1.2). In the decay of certain atoms, a combination of these different forms of radioactive decay may occur, in which case a combination of the different types of radiation is also emitted, in other words, a radioactive source consisting of only a single type of radioactive atoms may emit different types of radiation with different energies.

Interlude - atomic construction and notation of radionuclides

All matter is composed of atoms, which in turn consist of an atomic nucleus and electrons. The atomic nucleus itself contains a number of protons and neutrons. Protons are positively charged, electrons are negatively charged and neutrons are not electrically charged. A neutral atom has an equal number of protons and electrons. The number of protons (atomic number Z) in the nucleus determines the type of atom, **the chemical element**. However, elements with a certain number of protons in the nucleus can have a different number of neutrons (N): these are called **isotopes** of a particular element. Nuclides is the collective name of the different possible combinations of protons and neutrons in the nucleus, and we name them with the chemical element (or the abbreviation used for it) followed by the mass number which is equal to the number of nuclear particles (nucleons: protons and neutrons). Nuclides can be stable or radioactive, in the latter case we refer to them as ***radionuclides***. Some examples:

- caesium-137 (or Cs-137, often also ^{137Cs}) is a caesium atom with 137 nuclear particles (nucleons). Since cesium always has 55 protons in its nucleus (atomic number), Cs-137 will therefore contain 137-55=82 neutrons. Cs-137 is radioactive and decays. Cs-134 is another **isotope** of the element cesium and is also radioactive. Cs-133, on the other hand, is a stable form of caesium, even the only stable form of the element caesium;
- Hydrogen-1 (or H-1, often also ^{1H}) is the most common stable form of hydrogen, its nucleus consists of only one proton. Deuterium (hydrogen-2, H-2 or ^{2H}) is also stable, and about 0.01% of all hydrogen is deuterium, it contains 1 proton and 1 neutron in the nucleus. Tritium (hydrogen-3, H-3 or ^{3H}) is still a form of hydrogen but now with 2 neutrons in the nucleus and is radioactive. Specific to hydrogen, the different isotopes have names: hydrogen, deuterium and tritium;
- technetium-99m (Tc-99m or ^{99mTc}) is a technetium atom with 99 nuclear particles, it is radioactive. The "m" refers to the fact that the technetium-99 nucleus is in a higher energetic state (we call this an excited nuclear state). Tc-99m decays to the ground state of Tc-99 which is itself radioactive, so Tc-99m and Tc-99 refer to two different nuclear states of the same isotope that both decay differently.

A ***radioactive source*** is a collection of radioactive atoms, these can all be the same radionuclides (e.g., Cs-137) or a mixture of different radionuclides (e.g., Cs-137 and Cs-134).

The ***activity*** of a radioactive source is the number of radioactive atoms decaying per second. The unit is the becquerel (Bq). 1 becquerel corresponds to 1 radioactive atom decaying per second. The becquerel is a small unit. Weak radioactive sources, e.g. for testing a device that measures radiation, usually already have an activity of several thousand becquerels (several kBq). An overview of the activity of some radioactive sources can be found in Table 8.

Table 8: Examples of the activity of a number of radioactive sources, in increasing strength. The prefixes used (k, M, G, T, P) can be found further in the text.

Radioactivity in seawater	12 Bq/liter
Radioactivity in potatoes	160 Bq/kg
K-40 present in human body	3 kBq
Total activity in the human body (K-40, H-3, C-14, Ra-226, ...)	8.5 kBq
Discharge of radioactive I-131 to air from KC Doel and CN Tihange combined per year- average in period [2016-2020].	30 MBq
Tc-99m used in bone scintigraphy for diagnosis/patient	740 MBq
I-131 used to treat thyroid cancer/patient	2 GBq
1 million tons of uranium ore	720 TBq
Cs-137 released to atmosphere in Fukushima accident (2011)	6 to 20 PBq
Cs-137 released to atmosphere at Chernobyl accident (1986)	85 PBq
Total amount of Cs-137 released in above-ground atomic bomb tests (mostly in period 1950-1965)	948 PBq

Radioactive atoms can also be mixed with non-radioactive material, e.g. when radioactivity is discharged into water, that water will thus contain a certain activity per liter of water (Bq/l). Analogously, radioactivity can be present in e.g. food (Bq/kg), in air ($^{Bq/m3}$) or deposited on the ground ($^{Bq/m2}$).

Interlude - use of prefixes

For specific quantities in radiological effects assessment such as activity and dose, standard prefixes are used to represent very large and very small values in the standard units used.

Prefix		Base 10	Decimal
Name	Symbol		
beta	P	10^{15}	1.000.000.000.000.000
tera	T	10^{12}	1.000.000.000.000
giga	G	10^{9}	1.000.000.000
mega	M	10^{6}	1.000.000
kilo	k	10^{3}	1.000
		10^{0}	1
milli	m	10^{-3}	0,001
micro	µ	10^{-6}	0,000001
nano	n	10^{-9}	0,000000001
pico	p	10^{-12}	0,000000000001
femto	f	10^{-15}	0,000000000000001

Examples are: GBq (gigabecquerel), PBq (pètabecquerel), ▪ Sv (microsievert), nSv/h (nanosievert per hour), ... but of course also used in other fields, think MW (megawatt) , kWh (kilowatt hour), ...

The activity of a source of a specific radionuclide is proportional to the number of radioactive atoms it contains; the proportionality constant is specific to each radionuclide. This implies that the activity of a source of a specific radionuclide decreases exponentially as a function of time. The time at which the activity is halved is called the ***half-life*** and it is thus radionuclide-specific and can range from less than a millisecond to billions of years. For example, Tc-99m has a half-life ($T_{1/2}$) of 6.0072 hours, I-131 (iodine 131) 8.0252 days, tritium 12.312 years and Cs-137 30.05 years. Half-lives are radionuclide-specific and to a very large extent constant, it is not however that factors such as e.g. pressure, chemical environment have no effect on half-lives of radionuclides, but these effects are extremely small. So a radioactive source will only decrease in strength with time as shown in the figure below. After one half-life the activity will have decreased to half (1/2) the original activity. After 2 half-lives to a quarter (1/4), etc.... After 10 half-lives, the activity will be less than 1/1,000 of the original activity. In addition to radioactive decay, in principle, there is also the possibility of converting a radionuclide into another (usually also radioactive) nuclide via nuclear reactions. We call this transmutation.

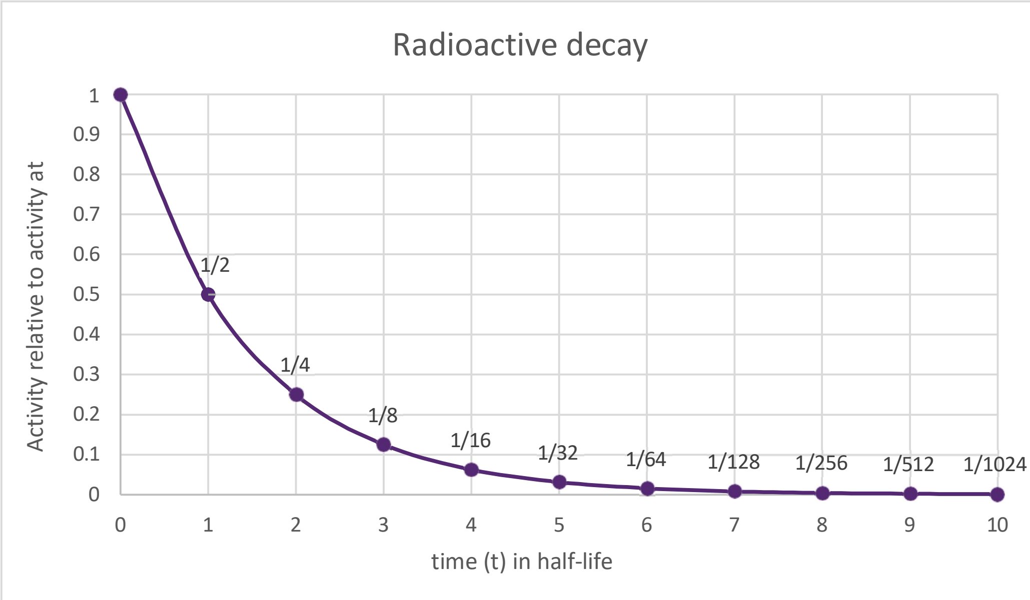

Figure 11: Exponential decrease in activity of a radioactive source with time (time is shown in half-life or the time required for the activity of a radioactive source to decrease by half).

Radioactivity is a natural phenomenon and everything around us is radioactive to a greater or lesser extent, we therefore distinguish ***natural radioactivity*** and ***artificial or artificial radioactivity***.

Natural radioactivity is caused by a series of naturally occurring radionuclides. The main part of these have been present since the creation of the earth, we call them primordial radionuclides. These are *long-lived radionuclides*, the most important being potassium-40 (K-40), uranium-238 (U-238) and thorium-232 (Th- 232). Potassium-40 decays immediately to stable atoms, but U-238 and Th-232 decay through a whole series of successive radionuclides until they form stable lead: these are the natural decay series (uranium and thorium series) and they contain radioactive elements such as radium-226 (Ra-226) and radon (Rn-222 and Rn-220, the latter is also called thoron because it occurs in the thorium series). These radionuclides are therefore present worldwide, with significant natural variations. Other natural radionuclides are constantly produced by cosmic radiation (cosmogenic radionuclides) that reaches us from space and gives rise to natural radionuclides such as tritium (H-3) and carbon-14 (C-14) via nuclear reactions. The latter two radionuclides are also created artificially during the operation of a nuclear reactor.

Artificial or artificial radioactivity results from radionuclides made by humans. Several sources of artificial radionuclides exist, ranging from atomic bomb tests, the operation of nuclear reactors and particle accelerators, the medical use of radionuclides, ... Some artificial radionuclides do not occur (almost) naturally and are thus almost exclusively derived from human activity (e.g. iodine-131); other radionuclides, such as tritium and C-14, occur both naturally and artificially.

Exposure to ionizing radiation from radioactive sources can occur in several ways:

- one can be irradiated by a radioactive source located at a distance; we call this ***external irradiation or exposure***. Gamma radiation and neutron radiation are the main sources of external radiation;
- one may be ***contaminated or contaminated*** with radioactive particles, this can:
  - external: only (part of) the skin is infected;

- internally by e.g. inhalation of radioactive particles, ingestion of contaminated food or ingestion through wounds in case of external contamination or in medical context when administering a radioactive source for diagnosis or treatment.

An infected person (internal or external or both) will automatically be irradiated as well. These different exposure pathways give rise to a different radiological impact and are always taken into account in a radiological impact analysis.

In general, one is not contaminated by external irradiation: only external irradiation with neutrons (and very high-energy gamma or X-radiation which is not applicable in this context) can give rise to activation, here radioactive atoms are formed via nuclear reactions of stable atoms with neutrons. One example is the formation of radioactive tritium through neutron absorption when interacting with stable deuterium. Another example is that limited amounts of the stable cobalt-59 (Co-59) present in the reactor vessel absorb neutrons, giving rise to radioactive Co-60.

Alpha radiation (α radiation) emitted in alpha decay consists of He-4 nuclei, these emit all their energy over a very short distance (centimeters in air, micrometers in tissue) so that they pose no or very limited danger of external radiation, but can be very dangerous (tissue damage) if internally contaminated.

Beta radiation (β radiation) emitted in beta decay consists of electrons or positrons and these give off their energy over a limited distance (meters in air, millimeters in water or tissue) and thus can be an external radiation problem, but also a problem in external or internal contamination. Because these particles give off their energy over a greater distance/volume, they are less dangerous than alpha emitters in internal contamination.

Gamma radiation (γ radiation) is a form of electromagnetic radiation (like light but with a much smaller wavelength or higher frequency) emitted in gamma decay. Gamma radiation often occurs after alpha decay or beta decay and has a long gestation (hundreds of meters in air, tens of centimeters in tissue) and thus is important both in external radiation and infection.

Neutrons emitted in spontaneous or induced nuclear fission or other nuclear reactions, have a long carrier, specific materials are required for shielding and they are primarily important in external irradiation

The effect or impact of ionizing radiation is described by the concept of ***dose.*** However, there are several dosimetric quantities: the physical quantities, the quantities used in radiation protection, and the operational quantities (used in practical monitoring, e.g. through measurements). Often these are used interchangeably, yet it is important to distinguish them, see Figure 12. Here we discuss the most important dosimetric quantities in the context of assessing radiological effects on humans.

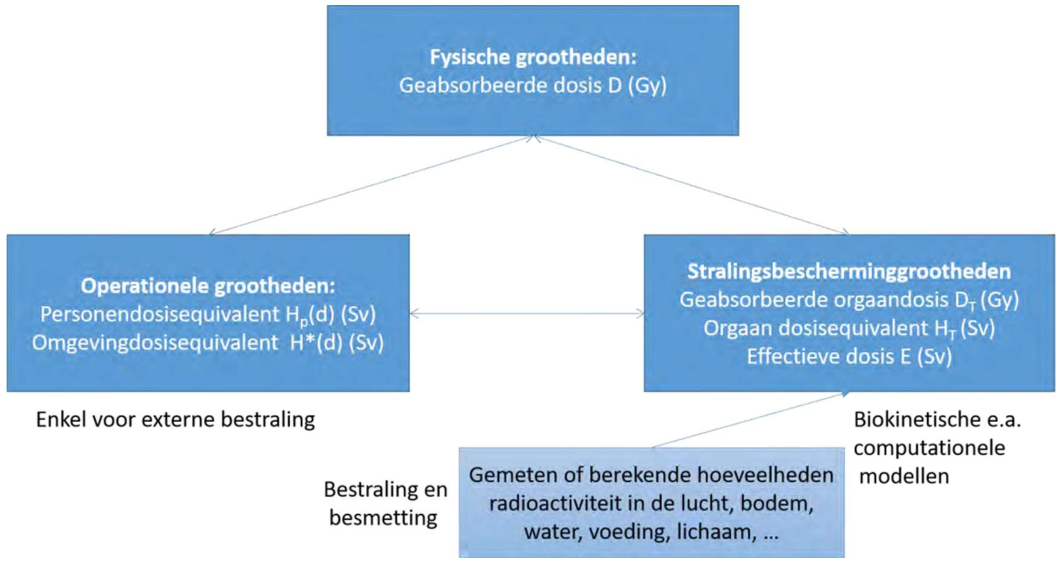

Figure 12: Overview of the different dose magnitudes with their symbol and unit (see text for further discussion).

Absorbed dose is the amount of energy absorbed per amount of mass: $D = \frac{dE}{dm}$ and is expressed in gray, which corresponds to 1 joule (unit of energy) per kilogram, or $1\ Gy = \frac{1J}{1\ kg}$. The gray is a large unit: for a full external body irradiation with gamma radiation in a short time with 4 to 5 Gy (i.e., 4 to 5 joules per kilogram), the irradiated person has only a 50% chance of survival (lethal dose) without medical treatment. The person will thus exhibit radiation symptoms at this dose, also called deterministic effects, or according to the most recent terminology referred to as tissue reactions. Absorbed dose is therefore used to describe these tissue reactions. These effects occur from a certain threshold dose, examples being reddening of the skin and damage to intestinal cells. Absorbed dose can be used both for a particular part of the body (tissue or particular organ), this is then often referred to as D_T (with T from the English tissue), as well as for the irradiation of objects, plants and animals. Deterministic effects or tissue reactions are to be avoided at all times.

Equivalent dose is the absorbed dose weighted for the type of radiation to account for the biological effect of the type of radiation. For the same absorbed dose, alpha radiation will do much more damage than beta or gamma radiation. Neutrons also generally produce a greater biological effect. The equivalent dose is then defined, for a given organ or tissue, as:

$$H_T = \sum_R w_R D_T$$

with w_R a weighting factor for the type of radiation (the R here stands for English 'Radiation') that describes the biological effect of the type of radiation: $w_R = 20$ for alpha radiation, $w_R = 1$ for beta and gamma radiation and w_R for neutrons depends on their energy[v]. The equivalent dose is expressed in sievert (Sv) and is again a large unit.

Effective dose is the equivalent dose weighted for the sensitivity of the different organs.

$$E = \sum_T w_T H_i$$

This weighting factor is tissue/organ dependent. The most recent weighting factors can be found in the Royal Decree of August 19, 2020 amending the Royal Decree of July 20, 2001 containing general regulations on the protection of the population, workers and the environment against the danger of ionizing radiations. The weighting factors are important for determining the risk of stochastic effects and consequently effective dose is always related to an estimate of the probability of stochastic radiation effects, *especially* the induction of (lethal) cancer and genetic effects. This is the most important quantity in radiation protection and allows comparison of different exposures/exposure situations. Also, dose limits or reference levels are often defined as effective dose (see below).

Tissue reactions (or deterministic effects) occur only when a certain threshold dose is exceeded. Below this threshold dose, the effect does not occur. The threshold dose is different for different radiation effects but for the occurrence of clinical effects is typically above 1 Gy, doses that are to be avoided in any case and exceeded only in very serious radiation accidents. In addition, there are ***stochastic effects***, especially the risk of cancer and genetic effects, which can already occur at lower doses. We know from epidemiological studies that the occurrence of these increases linearly with the effective dose. Consequently, at low doses, the occurrence of stochastic effects is small and is indistinguishable from spontaneous occurrence (without radiation exposure). In radiation protection, we assume a linear relationship to very low doses without considering a threshold dose as a precaution (Linear non-threshold or LNT approach). In the radiological environmental assessment as performed here for the normal operation of nuclear reactors such as Doel 4 and Tihange 3 and even in a significant number of possible accident scenarios, we are in this range of effective doses (often very far) below 50-100 mSv, where radiation effects have never been epidemiologically established.

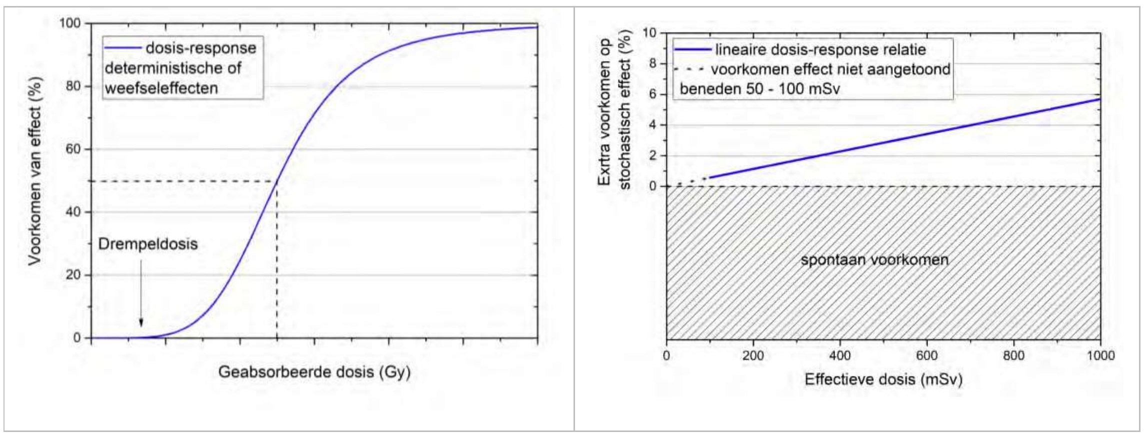

Figure 13: Schematic dose-response relationships for tissue responses (left) and for stochastic effects (right). Tissue reactions occur starting at a certain threshold dose. After that, the occurrence increases rapidly until it will occur in everyone. The occurrence of stochastic effects shows a linear relationship with the dose to which one is exposed. At low doses (below 50-100 mSv effective dose), however, this has never been demonstrated and a linear extrapolation is assumed from the precautionary principle. Here the total occurrence of stochastic effects (cancer and genetic effects) for a person in the public at low dose rate is shown, where at 1 Sv effective dose an additional 5.7% occurrence (on top of spontaneous occurrence which is much more likely) of stochastic effects is expected.

Table 9: Probability of stochastic effects due to radiation exposure above natural background in percent when exposed to an effective dose of 1 Sv at low dose rate (Based on precautionary principle, following the 'linear non-threshold' approach, an exposure of 1 mSv above natural exposure thus gives 1/1,000 of the values below).

	Cancer	Hereditary disorders	Total
Employees	4.1 %/Sv	0.1 %/Sv	4.2 %/Sv
Population	5.5 %/Sv	0.2 %/Sv	5.7 %/Sv

The effective dose allows comparing different exposures and thus their risk. Table 10 gives the effective dose for an average Belgian per year (for 2015), where the contribution for different types of exposure is given.

Table 10: Effective dose load average Belgian in 2015[vi].

Dose load per caput in 2015	mSv/year
Cosmos (cosmic radiation, cosmogenic radionuclides, air travel, higher altitude stays)	0,35
Earth radiation (external radiation natural radioactivity in soil)	0,40
Inhalation of natural radionuclides (radon, thoron and decay products)	1,40
Ingestion of natural radionuclides (all natural radioactivity in food and drinking water)	0,29
Industrial applications (discharges, ...)	<0,01
Medical applications (X-ray, CT, SPECT, PET, etc.)	1,53
Total (average)	**3,98**

It should be noted that there are geographical differences in terrestrial radiation due to radon/thoron, with higher radiation loads in the south of the country, mainly in the Ardennes, due to a higher concentration of primordial radionuclides in the soil and associated higher radon and thoron concentrations. Thus, the combination of cosmic and terrestrial radiation in the vicinity of Doel amounts to 0.70-0.75 mSv/year, and in the vicinity of Tihange to 0.90-0.95 mSv/year. On the other hand, there are of course also individual differences, mainly due to different medical exposure, and further due to differences in frequency of air travel, diet, ... We can further make a division between natural exposure (cosmic and terrestrial radiation, inhalation and ingestion of natural nuclides) and artificial exposure (industrial applications and medical exposure) and these amount respectively to 2.44 mSv/year and 1.54 mSv/year for an average Belgian. For comparison with other European countries, the lowest exposure to natural radiation is found in the Netherlands (1.48 mSv/year) and the highest exposure to natural radiation is found in Finland (6.16 mSv/year). The European average of natural exposure is 3.20 mSv/year. There are also important differences in artificial exposure between different European countries, especially those due to medical procedures. For this, Belgian exposure values are at the high end of the spectrum compared to medical exposures in the various other European countries, but do follow a slight downward trend.

In addition to absorbed, equivalent and effective dose, there are a number of operational dosimetric quantities such as ***person dose equivalent*** $H_p(d)$, a quantity used in person dosimetry, and ***ambient dose equivalent*** $H^*(d)$, used in ambient measurements of radiation dose and where the *d* refers to the depth at which it is evaluated and is equal to 10 mm by default.

For dosimetric quantities, in addition to the total dose, we can also look at the dose per unit time, i.e., the dose rate (e.g., the ambient dose equivalent rate as measured by an active radiation detector, called dose rate for short).

Radiation Protection ([ICRP103vii]) distinguishes between 3 possible exposure situations, which were also introduced in Directive 2013/59/EURATOM and Belgian legislation:

- planned exposures, such as the operation of a nuclear power plant, and in particular Doel 4 and Tihange 3 with all the activities involved belongs to this category;
- existing exposure situations, an exposure situation that already exists at the time a decision on its control is to be made and for which the application of urgent measures is not or no longer required; e.g., historical contamination due to past activities where, e.g., different discharge limits were in effect;
- exposure in emergency situations (see specifically also Nuclear Emergency Planning).

The ***radiation protection system*** rests on the following 3 main pillars:

- justification (justification);
- dose optimization;
- dose constraint

for all situations in which exposure may occur.

Justification, planned exposures are justified when they can ensure that the benefits they bring to the individual or the community outweigh the health harm they may cause. The authorization is proof of justification (RD 19/08/2020).

Dose optimization, requires that the exposure of individuals be optimized to keep individual doses, the probability of exposure and the number of individuals exposed as low as reasonably possible. This pillar is practically achieved by limiting the time at the radiation source, maximizing the distance from the radiation source, and avoiding or limiting shielding of the radiation source/diffusion.

Dose limitation - Dose ***limits***[26] are defined for planned exposures and are established through RD. The most recent dose limits can be found in the RD of August 19, [2020viii] and are given in Table 11. A distinction is made between persons of the public and occupationally exposed persons (e.g., persons working in the nuclear section of a nuclear power plant).

[26] Dose limits refer to the combined exposure resulting from all actions that may cause an increase in the received dose, while dose constraints refer to the exposure resulting from one particular action.

Table 11: Dose limit [mix].

Dose limits		Public	Occupationally exposed persons (*)	Pupils and students (16 -18 years old)
Effective dose (E)		1 mSv per year 1 mSv during pregnancy	20 mSv per 12 consecutive sliding months	6 mSv per year
Equivalent doses (H)	Eye Lens	15 mSv per year	20 mSv per 12 consecutive sliding months	15 mSv per year
	Skin (average dose over an area of 1 cm^2)	50 mSv per year	500 mSv per 12 consecutive sliding months	150 mSv per year
	Hands, forearms, feet and ankles	Not applicable	500 mSv per 12 consecutive sliding months	150 mSv per year

(*) A worker is considered occupationally exposed when there is a risk that any of the dose limits established for the public may be exceeded.

The dose limit of 1 mSv/year effective dose to the public, as well as the other dose limits, must be understood as the additional dose due to human activities in addition to the dose from natural exposure and doses received in the context of a medical diagnosis or treatment. However, the average Belgian receives less than 1% of this dose limit (<0.01 mSv/year) as a result of industrial nuclear and radiological applications, including nuclear power plants for energy production.

To evaluate radiological effects on humans, the radiation protection magnitudes are used as described above. In normal operation, the doses are so small that only stochastic effects have to be considered. Effective doses are thus calculated and compared with the limit of 1 mSv/year for the public. For accident situations, the intent is to avoid tissue reactions at all times (see accident methodology) and the effective dose as well as the equivalent thyroid dose are the quantities generally evaluated.

An important note here is that the calculations of the effective dose and also organ doses, such as thyroid dose, depend on age and that the evaluation is always performed for a critical individual, i.e., the most sensitive age group[27] and for the most exposed person from that category. Regarding the most exposed individual, the assumptions are that (i) the individual is permanently in the same location with the highest concentration of radioactivity; (ii) feeds significantly on products from the garden with the highest deposition and (iii) feeds on products from local agriculture, hunting and fishing. Regarding the age category, exposure depends on diet, respiratory volume per unit time, biokinetic processes and sensitivity to ionizing radiation in addition to the radioactivity present. Following age categories are considered:

[27] This is not the same in every irradiation situation, it is quite possible that for one exposure young children are most sensitive and for another exposure teenagers or adults, because the dose impact depends not only on tissue sensitivity to radiation but also on factors such as diet, respiratory volume per time, etc ...

- Infants: age <1 year;
- Children with ages between 1-2 years;
- Children with ages between 2-7;
- Children with ages between 7-12;
- Children with ages between 12-17;
- Adults: age > 17 years.

Radioactivity that enters the body through breathing or food can, depending on physical and biological properties, expose the individual to radiation for an extended period of time. Some radioactive elements will quickly disappear from the body due to radioactive decay and/or biokinetic factors; others may remain in the body for decades. When calculating equivalent organ doses (such as the thyroid dose) and the effective dose, this is taken into account as follows for a single internal contamination via inhalation or ingestion the total dose that the person incurs as a result of this internal contamination is considered over a period of 50 years from the contamination for adults and up to age 70 for the other age categories (children and infants). This is called the **follow-up dose** (Committed equivalent dose and Comitted effective dose). In calculating the total dose incurred by an individual, the combination of the dose incurred from external irradiation (during direct or immediate exposure) and the follow-up dose (from inhalation, ingestion) is always made and this estimate is always made very conservatively, cf. the critical individual described in the paragraph above.

The criterion for evaluating the **Radiological impact on the environment, especially the effects on fauna and flora** resulting from exposure to radioactive radiation is the absorbed dose rate. The unit for this is joules per kilogram or gray per unit time. The radionuclide concentrations in the environment are converted to the effective dose rate taking into account the possible exposure pathways of the species considered. To account for the variation in biological impact associated with the different radiation forms (gamma, beta, alpha), a weighting factor is often introduced for the absorbed dose. This assumes that the absorbed energy is uniformly distributed throughout the organism. The absorbed dose rate is the energy absorbed per unit time, for fauna and flora usually expressed in microgray per hour (µGy $^{h-1}$).

The radiological impact of a facility on the environment is characterized by fluxes and/or concentrations of radionuclides that may enter the environment. Radiological safety studies consider
(1) whether these quantities are comparable to fluxes and concentrations that occur naturally in the environment and (2) whether the calculated impact may involve environmental degradation. For radiological impacts, the risk to the environment is calculated using a specific safety indicator, a screening value, expressed in microgray per hour (µGy $^{h-1}$).

2.3.3 General methodology exposure in normal operation

This section describes the methodology used to determine the radiological effects on humans and the environment during normal operation of a nuclear power plant. For this purpose, the total dose incurred by the most critical individual and by reference organisms, respectively, is determined and, consequently, it is important to know the radiation exposure pathways during operation of a nuclear power plant. The different exposure pathways when operating a nuclear power plant are summarized in the table below. How they are further evaluated is discussed in the following sections.

Table 12: Summary of potential exposure pathways during operation of a nuclear power plant.

Origin exposure	Method of exposure		Comments
Radioactivity and radiation on site	Direct exposure to radiation		Radioactivity and ionizing radiation occurs in several places in a nuclear power plant (reactor, treatment and storage of radioactive waste, etc.) and is very well shielded to the outside world. Thus, it is only radiation with high penetrating power such as gamma and neutron radiation that can potentially contribute to this exposure pathway.
Gaseous discharges			A system of barriers, lapse tanks and filtration systems ensures that gaseous discharges are limited.
	Internal exposure	Inhalation	Inhalation of radioactivity in the overlying cloud, in principle, inhalation after deposition of radioactivity on the ground and other surfaces after re-suspension is also possible, but generally of little importance.
		Consumption	In addition to deposition and ingestion, of course, strongly linked to diet (what type of food, quantities and from what location).
	External exposure	Exposure to the passing cloud containing the gaseous discharges.	Mainly due to gamma radiation emitted by decay in the radioactive cloud during traversal.
		Exposure to deposition on the ground surface.	Deposition can occur under both dry conditions (dry deposition) and precipitation (wet deposition). Just all radionuclides will deposit in the same way: e.g., noble gases do not deposit.
Liquid discharges			Wastewater with radioactivity is first treated and monitored/measured before discharge.
	Internal exposure	Direct use of water into which discharges enter.	-
		Irrigation of crops with water into which discharges enter for direct human consumption and for animal consumption (animal feed)	Because of its salinity, the Scheldt water near KC Doel is not used for irrigation.
	External exposure	Swimming and nautical sports	-
		Shipping	-
		Stay at banks and dredging silt	-

2.3.3.1 Direct exposure to radiation

This is evaluated on the basis of measurements at the edge of the site. These measurements are carried out, on the one hand, within the framework of radiological surveillance on the Belgian territory (FANC-AFCN, see §2.3.5) and, on the other hand, by the operator.

2.3.3.2 Gaseous and liquid discharges

During normal operation of KC Doel and CN Tihange, limited amounts of radioactivity are discharged in a controlled manner:

- into the atmosphere, in the form of gaseous discharges;
- into surface waters, in the form of liquid discharges.

The gaseous discharges to the atmosphere contain radioactive substances in gaseous form (gas and steam), or in the form of aerosols when they are solid or liquid particles in suspension in the discharged air. These effluents originate, among other things, from processes to ensure the degassing of primary cooling water and may first be collected in storage tanks where the short-lived radionuclides decay and thus their activity is greatly reduced before being discharged. The gaseous effluents also come from the general ventilation of the nuclear buildings. In all nuclear facilities, safety regulations require that the air present inside the buildings be permanently refreshed by forced ventilation. The volumes of air emitted to the outside, which depend on the volume of the buildings and on the flow rates of ventilation, are peculiar to each installation.

The liquid effluents contain radioactive substances in the form of a solution, when they are dissolved ionic salts, or in the form of a suspension, when they are solid particles mixed with the effluents. These effluents come mainly from the process circuits, such as those used to treat primary cooling water in nuclear power plants. They are also formed by the sanitary wastewater (showers, lavabos, etc.) and the cleaning water from the floors in the nuclear zones that are managed as potentially radioactive effluents, although they do not normally contain radioactivity.

Based on the radiological impact of these discharges on humans and the environment, discharge limits are determined which are part of the operating license of the nuclear power plants. The steps involved are shown in Figure 14.

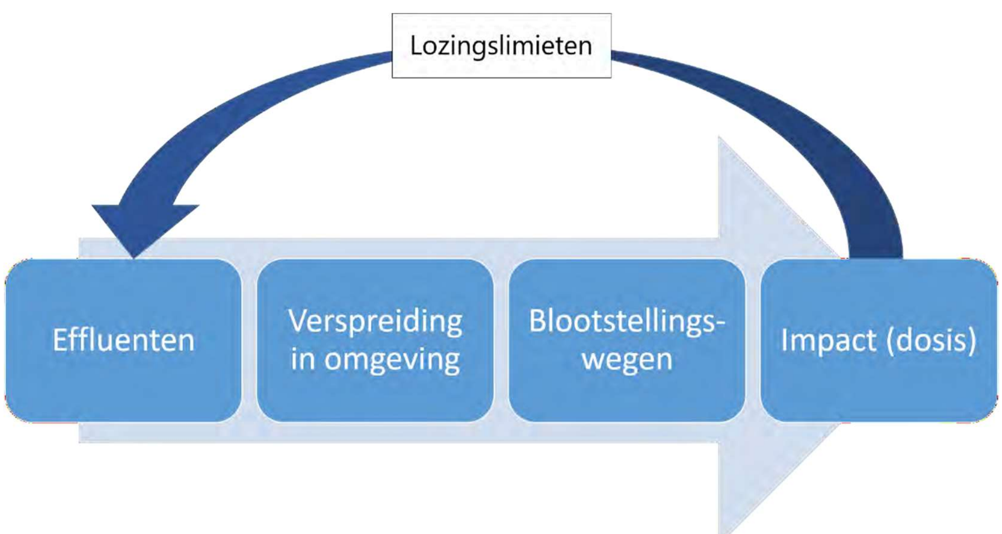

Figure 14: Steps in methodology for radiological impact of discharges in normal operation.

In all cases, allowable discharge limits must be lower than the regulatory limit for exposure of persons of the public to ionizing radiation. The effective dose limit is set at 1 mSv (millisievert) per year (see basic concepts). This value applies exclusively to the additional exposure caused by human activities, including, among others, the operation of the entire Doel and Tihange nuclear power plants, which include Doel 4 and Tihange 3 respectively, and this independently of natural exposure (cosmic radiation, radon, etc.), or medical exposure (radiographs, scanners, etc.). Furthermore, in accordance with the optimization principle used in radiation protection, discharge limits should be set at as low a level as reasonably achievable, taking into account technical, economic and social factors. A wide spread in exposure is possible from members of the population, depending on lifestyle habits. Permissible discharge limits should be sufficiently low and for the most exposed part of the local population (critical individual).

Since the principle of dose optimization is followed, there is an optimization of the real discharges (see below) compared to the licensed ones, with the limits of the license set sufficiently below the limit of 1 mSv/year. This follows the principles as e.g. internationally recommended by the ICRP and is presented in Figure 15, along with the average total dose of radiation received by the Belgian per year.

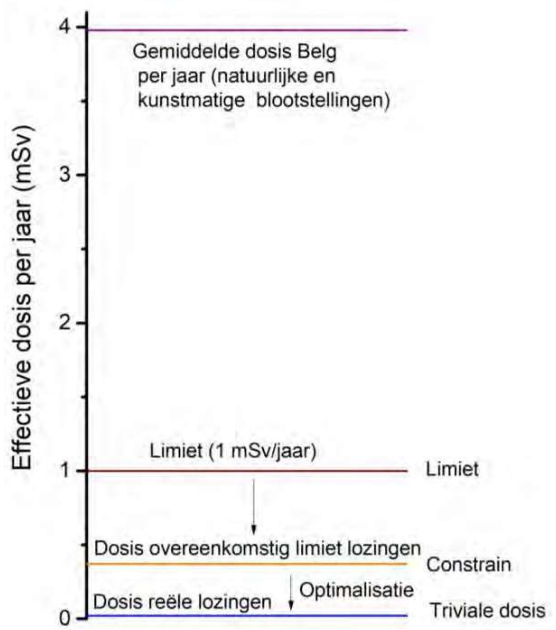

Figure 15: Principle of dose limits and optimization: the dose limit of 1 mSv/year relative to the average dose per year received by a Belgian from all exposures (natural, medical and industrial) and relative to the typical values of doses from radioactive discharges (both dose from discharge limits and dose from real discharges are shown) for Doel and Tihange nuclear power plants.

Gaseous discharges

As described above, during normal operation of a nuclear power plant, limited amounts of volatile radioactive compounds may be released to the atmosphere. These volatile radioactive compounds are divided into the following groups according to their chemical and physical properties:

- noble gases
    - with the main ones being xenon-133 (Xe-133), xenon-135 (Xe-135), krypton-85 (Kr-85), krypton-88 (Kr- 88) as fission products and argon-41 (Ar-41) as activation product resulting from neutron absorption by the stable argon-40 (Ar-40);
- iodine
    - whose main isotopes are: iodine-131 (I-131) and iodine-133 (I-133) which are fission products, iodine can be in different forms: as I_2, as aerosol or in organic form;
- aerosols, sometimes further broken down according to radioactive decay
    - beta-gamma aerosols
        - with the main ones being strontium-90 (Sr-90), cobalt-60 (Co-60), cesium-134 and -137 (Cs-134, Cs- 137) being a combination of fission products as activation products;
    - alpha aerosols
        - including americium-241 (Am-241);
- tritium (H-3) in the form of condensate tritiated water;
- carbon-14 (C-14) that results from various nuclear reactions of the neutrons generated by fission during reactor operation with stable isotopes of elements such as oxygen, nitrogen and carbon and can be released in various chemical forms. For PWRs, this is primarily in the form of carbon monoxide, methane and other hydrocarbons.

Discharges are continuously monitored and checks are made to ensure that discharge limits are not exceeded. The exceptions are the gaseous discharges of carbon-14 (C-14) and tritium (H-3), due to difficulty in measurement. Carbon-14 is therefore determined based on reactor power. Detailed international studies for this were conducted that give a range of possible values for carbon 14 for PWRs as a function of installed electrical or thermal powerx[, xi]. A conservative value of 185 GBq/year for an installed power of 1,000 MWe is assumed. For Doel and Tihange with a total of 3 GW installed electrical power each (situation before final shutdown of Doel 3 and Tihange 2), this amounts to 15 Ci (= 5.55 10^{11} Bq = 555 GBq). Since 2019, C-14 discharges have been measured at the chimney at Tihange 2. These measured values are significantly lower than the conservatively assumed ones and have therefore recently been used in the dose calculations for CN Tihange.

The impact of these radioactive discharges on humans and the environment can be evaluated in 2 complementary ways:

- for the *potential discharges* from the Project, these discharges can be compared to the discharge limits for the sites. The discharge limits are set so that for discharges from the entire KC Doel and CN Tihange sites the 1 mSv/year will certainly not be exceeded and are kept as low as reasonably achievable. Monitoring the discharges with tests against the discharge limits is then a guarantee that the impact remains limited;
- specific radiological impact calculations can then be made for *real discharges*, and these can be supplemented by measurements in the environment that quantify any traces of these discharges. Determination of Impact based on measurement results is then possible.

Models for theoretical reference groups have been established for determining the radiological impact of radioactive discharges into the environment. The effective full dose due to radioactive discharges is calculated based on FANC-AFCN accredited guidelines [NRC, 1977] from the United States Nuclear Regulatory Commission (US-NRC) and the calculation methodology prepared by FANC-AFCN [FANC, 2013a].

To calculate the impact of the discharges to the atmosphere, atmospheric dispersion models are used to calculate the activity concentration of the various discharged radionuclides in the air (in Bq/m^3) and by determining deposition (deposition) on the ground (in Bq/m^2). These calculations require meteorological data representative of the site over an extended period, typically a year or more. Radioactivity is carried with the wind and the concentration will dilute greatly with distance. Figure 16 shows the relative frequency of occurrence of a given wind direction at Doel on the one hand and at Tihange on the other based on hourly data over a 5-year period (Jan 1, 2018 to Jan 1, 2023, source RMI - ECMWF). Wind direction is defined as the wind direction from which the wind blows (in degrees clockwise from north). Consequently, if we consider discharges over a long period, the impact will be greatest in the direction to which the wind blows most frequently. For KC Doel and CN Tihange, the dominant wind direction is southwest, so the expected impact is greatest in the northeast direction of the sites. This information is also used, for example, to set up a monitoring program around both sites, specifically taking samples at the site with the highest potential impact and reference samples at a greater distance in the least dominant wind direction.

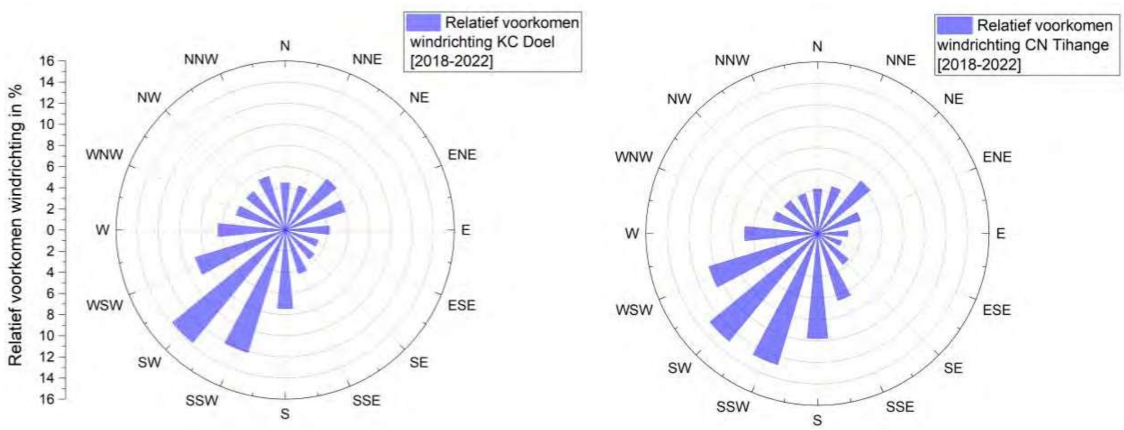

Figure 16: Relative occurrence of wind direction (left Doel - right Tihange) based on hourly data for a 5-year period [2018-2022] (Source: KMI - ECMWF[28]).

In addition to wind direction, wind speed, amount of precipitation and atmospheric stability are necessary parameters. The atmospheric dispersion calculation will also take into account the height of the discharge (chimney height with any correction for precipitation effects of the plume and any plume rise due to amount of movement and heat content of discharged plume). Bi-Gaussian models are used where the concentration distribution in the plume is assumed to be Gaussian distributed in both directions perpendicular to the wind direction. The width of the Gauss distribution in horizontal and vertical directions, increasing as a function of distance from the point of discharge, is described by specific parameters adapted to the terrain and specific to atmospheric stability at the time of discharge. Deposition on the ground is described by deposition parameters. For dry deposition this is the dry deposition rate, for precipitation a "washout" coefficient. These parameters depend on the physical and chemical properties of the discharged radioactive substances; for example, noble gases will not deposit and elemental iodine is assumed to deposit in dry conditions 10 times more than aerosols at the same concentration at ground level.

The result of these atmospheric dispersion models are average concentrations and depositions for a unit discharge (discharge of 1 Bq); also called dilution coefficients, for the most exposed person off-site.

[28] Data provided by the Royal Meteorological Institute (RMI), data based on numerical weather data based on the "European Centre for Medium-Range Weather Forecasts" ECMWF.

Liquid discharges

In addition to the maximum quantities that may be discharged annually, the discharge permit also contains the nature of the radioactive substances discharged. The nuclear power plant discharges mainly tritium into the Scheldt and Meuse rivers. The other radionuclides (e.g. ^{110m}Ag, ^{58}Co, ^{60}Co, ^{51}Cr, ^{140}La, ^{106}Ru, ^{124}Sb, ^{125}Sb, ^{95}Zr, ^{241}Am,...) are discharged in much lower quantities.

The radionuclides in liquid discharges into the Scheldt or Meuse can be divided according to their physical and chemical characteristics into the following groups;

Tritium in the form of tritiated water. Tritium is mainly produced in the primary cooling water of nuclear reactors as it circulates in the core. It exists in the form of tritiated water (HTO) or tritium gas (HT) and thus can be found simultaneously in the liquid and gaseous effluents.

- Beta, gamma emitters: ^{60}Co, ^{89}Sr, ^{90}Sr, ^{95}Nb, ^{134}Cs,^{137}Cs,^{110m}Ag.Most of these radionuclides are produced by the fission of the nuclear fuel in the core of the reactors and can be found in both liquid and gaseous effluents.
- Alpha emitters: Am-241 is radiologically the most important alpha-emitter and is produced in nuclear reactors from plutonium 241 by beta decay and can also be found in the liquid and gaseous effluents.

To calculate the concentrations of discharged radionuclides in the Scheldt and Meuse water, a simple river model is used that takes into account the dilution of the discharged volumes by the flow rate of the river water.

The Scheldt is a tidal river. Near Doel, the tidal flows are very large, averaging 5,000 m3/s with a resulting discharge flow to the sea of 70 $^{m3/s}$. This discharge flow ensures that the discharged activities are strongly diluted in the Scheldt water.

The dilution factor in the Meuse is higher due to the higher discharge rate. The normal average flow of the Meuse is 300 m^3/s in winter and 50 m^3/s in summer (FANC, 2011[29]).

The river model does not take into account the adsorption of radionuclides on the sediment, which would further lower the concentrations of radionuclides in the water (and thus also the dose impact), nor the fact that the tides of the river will increase the residence time of radionuclides in the Scheldt (and thus possibly also the dose impact). The calculations of the dose impact for the population take into account an average flow rate of 101 $^{m3/s}$ for the Scheldt. For the Meuse, an average flow rate of 239 $^{\text{m3/s is taken into account}}$.

2.3.3.3 Impact on humans

Persons of the public living near, or regularly attending, nuclear sites may be exposed to some degree to radioactive substances from atmospheric discharges from the facilities. The modes of exposure are well known and are classified into two distinct categories:

- external radiation from the ionizing radiation emitted during radioactive decay of radionuclides:
  - present in the air (and therefore proportional to the concentration in the air);
  - deposited on soil and other surfaces by deposition (and thus proportional to deposition);
- internal exposure through absorption of radioactivity into the body:
  - by inhaling radioactive substances in the air;

[29] FANC, 2011. Belgian resistance tests. National report for nuclear power plants.

- o through ingestion of plant foods (fruits, vegetables, cereals, etc.) that have absorbed radioactivity through deposition on the soil and/or through ingestion of meat and animal products (milk, cheese, etc.) derived from animals of local animal husbandry and that have themselves eaten such crops.

Radiological impact calculations for the current situation and planned activity are done for the most exposed person. Thus, calculations are done for the 6 age categories: infants, children from 1 to 2 years, from 2 to 7 years, from 7 to 12 years, adolescents from 12 to 17 years and adults. For them, specific parameters are assumed in the calculations, such as inhaled volume per unit time, diet and specific dose coefficients used to determine the effective dose. Furthermore, the results are calculated based on conservative lifestyle habits to obtain envelope values for the dose load.

The nuclear power plant operator is required to calculate the impact of routine discharges on humans and demonstrate that the dose is below the legal limit of 1 mSv/year. To calculate the dose, all possible exposure pathways are taken into account. The population can be exposed to radioactivity by consuming river water, by spending time on the water or river banks, and by consuming fish from the river. The dose incurred can vary greatly depending on the lifestyle habits of the population. The dose due to liquid discharges into the river is calculated in accordance with the FANC-AFCN guideline for the calculation of radiological consequences of Class I nuclear facilities, where, by analogy with atmospheric discharges, the determination of the dose assumes a "worst-case" scenario using in particular conservative input values for consumption, dwell times, etc. which do not underestimate the exposure of the population.

For calculating the dose to the representative person from discharges to river water, the following exposure pathways are considered;

- Internal radiation by:
  - o consumption of river water as drinking water;
  - o consumption of fish.
- External exposure by staying on banks, by shipping, by staying on soil contaminated with dredged bed sediment.

The dose for the representative person was also calculated for the 6 age classes, taking into account the consumption values mentioned in the directive of FANC-AFCN. As for the calculation of the dose due to atmospheric discharges, a critical person is assumed to be permanently present at the site of maximum dose exposure

2.3.3.4 Impact on biodiversity (fauna and flora)

Until the 1990s, it was assumed that if humans were protected from ionizing radiation, the environment was automatically protected as well. A paradigm shift took place in recent decades, partly because of increasing global interest in environmental sustainability and partly because of the fact that there may be situations where the environment is more exposed to radiation than humans. Several international organizations, such as the IAEA, ICRP, UNSCEAR as well as various national organizations (e.g. US DOE, UK Environment Agency) have since issued advice and guidelines for the protection of the environment from ionizing radiation.

In Belgium, guidelines describing the methodology to be followed are not yet available. However, data on the effects of radiation or exposure to radionuclides on fauna and flora have been collected and evaluated by several (inter)national organizations and expert groups with the aim of deriving threshold values. As a result, how threshold values are derived, their interpretation, and the level of protection (individuals, populations, ecosystems) may differ. In a regulatory context, environmental protection aims to protect populations of species, which also protects biodiversity. Therefore, most numeric threshold values are intended to protect populations. To derive threshold values that are relevant at the population level, only impacts that have direct relevance to population dynamics should be included in the analysis. By the [IAEA xii] and [UNSCEAR xiii], the threshold values of 40 μGy h^{-1} for terrestrial animals and 400 μGy h^{-1} for terrestrial plants and aquatic organisms were proposed, derived from available studies on effect data. UNSCEAR[xiv] reviewed the effect data obtained since 1996 and concluded "*Overall, the Committee concluded that chronic dose rates of less than 100 μGy h^{-1} to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities and that maximum dose rates of 400 μGy h^{-1} to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level*."

ICRP [4] recommends the use of Derived Consideration Reference Levels (DCRL) for a number of reference animals and plants (RAP: Reference animals and plants). These reference levels are intended as reference points to evaluate a possible effect of ionizing radiation on fauna and flora. The DCRL define dose rate intervals within which there is some probability of a possible adverse effect of ionizing radiation for the reference biota categories (RAP) in question. These reference levels were derived based on available studies on effect data for the different RAPs. DCRLs can vary widely depending on the RAP considered, ranging from 4-40 μGy h^{-1} for e.g. mammals to 400-4,000 μGy h^{-1} for e.g. invertebrates. The ICRP [4] does not provide an interpretation of how effects observed at the individual level may manifest at the population level. Thus, the threshold values of the ICRP[xv] are also associated with the individual rather than the population.

The thresholds proposed in the EC-ERICA projectxvi[,xvii] and the EC-PROTECT projectxviii were derived using methods used for chemical contaminants[xix]. A generic threshold PNEDR (Predicted No Effect Dose Rate) of 10 μGy h^{-1} was derived under the ERICA project. This PNEDR is considered the threshold below which the structure and functions of generic ecosystems (including all populations) are protected. Thus, situations for which the estimated dose rates (PEDR - Predicted Environmental Dose Rate) are lower than the PNEDR (PEDR/PNEDR<1) may be considered as not resulting in an adverse effect at the population or ecosystem level. The PNEDR is applicable as a threshold for additional exposure, i.e. in surplus to background radiation. The ERICA reference value is certainly not intended as a limit or action level. EC-PROTECT also proposes a generic threshold value of 10 μGy h^{-1}, but additionally gives threshold values for certain organism groups: 2 μGy h^{-1} for vertebrates, 200 μGy h^{-1} for invertebrates and 70 μGy h^{-1} for plants.

The above shows that the threshold values recommended by the various (inter)national organizations vary widely: from 4 to 4,000 μGy h^{-1}. The natural background dose rates for fauna and flora vary considerably less, between 0.07 and 6 μGy h^{-1} [xx,xxi].

The risk of radiological exposure to fauna and flora would best be determined quantitatively by comparing the estimated dose rate with a threshold, e.g., the PNEDR thresholds. However, for most of the scenarios to be evaluated, we do not have sufficient information to allow a quantitative estimate of radiological exposure. Furthermore, most of the impact data were obtained and the impact models were developed for equilibrium situations and not for accidental situations. Therefore, where necessary, the different scenarios will be compared based on the probability of absence of significant exposure. Based on the literature cited above, we have developed a significance framework, which is shown in Table 13.

Table 13: Significance framework for radiological effects on fauna and flora.

Dose rate	**Probability of absence of significant exposure**
<10 μGy h^{-1}	Very high
10-100 μGy h^{-1}	High
100-400 μGy h^{-1}	Fairly high
400-4,000 μGy h^{-1}	Moderate
>4,000 μGy h^{-1}	Low

Because the impact on an ecosystem is difficult to evaluate because of its complexity, different categories of reference organisms are used to determine the radiological impact on the environment. These reference organisms are assumed to be representative of the habitats where they reside, the uptake of radionuclides, their dimensions (with an effect on the dose calculation). The set of reference organisms refers to a well-defined ecosystem (terrestrial, aquatic). Reference organisms should be chosen to cover the different trophic levels and to provide a simplified representation of the structure and functioning of an ecosystem. Thus, one must establish a conceptual model of the study area, have an understanding of the source term and exposure pathways, and select representative reference organisms for the impact analysis. Because the organisms considered as indicator species in a specific environmental risk analysis must be representative of a specific site, therefore, the indicator species will also vary from assessment to assessment. When selecting indicator species or specific reference organisms, additional consideration is given to the "value" of an organism within the ecosystem under study.

As additional information, we hereby provide the differences between the methodology for determining environmental and population impacts (see Table 14).

Table 14: Main differences between methodology for determining radiological impact on humans and the environment.

Man	Environment (fauna and flora)
Protection at the level of the individual	Protection at the level of populations/ ecosystems.
Tissue reactions and stochastic effects of radioactivity are taken into account.	Generally, only effects at the level of organism or population are considered .
Internal doses are calculated with biokinetic models that simulate the uptake of radionuclides in the human body.	Internal doses are calculated using transfer factors based on the activity in the environment.
Reference person (biokinetic model)	Reference organisms (represented as simple ellipsoids)
Different age classes	No age classes
Accumulation of radionuclides in the organs is considered.	Radionuclides are uniformly distributed throughout the organism .
Effective dose (Sv)	Absorbed dose rate (Gy $^{s-1}$) (μGy $^{h-1}$)

2.3.4 General methodology accidents

Throughout the life of a nuclear installation, the installation must be able to withstand accident conditions and the necessary measures must be taken for this purpose. A nuclear installation is preventively designed with a number of barriers, based on the principle of "layered protection," this to avoid exposing the population and the environment to an unacceptable dose of ionizing radiation. The principle of layered protection aims to: i) minimize the impact of external hazards, whether extreme hazards and hazards caused by nature or by unintentional human action, ii) prevent abnormal operation or malfunctions, iii) control abnormal operation or detect malfunctions, iv) control design accidents, v) control the modalities of design expansion and, in particular, prevent the development of accidents into serious accidents and limit the consequences of serious accidents, and vi) enable emergency management (see §9.4.1)[xxii]. In order to apply the principle of layered protection, a detailed analysis of possible occurrences, both occurrences within the design (design basis occurrences) and occurrences that may occur in the extension of the design (design extension occurrences), against which the plant must be able to withstand or the must take necessary action. These occurrences can lead to accidents, namely Design Basis Accidents (Design Basis Accidents) and Beyond Design Basis Accidents (Beyond Design Basis Accidents).

The relevant international and European guidelines related to accident scenarios, as well as a summary of their (most relevant) contents, are listed in Table 15.

Table 15: Relevant international and European guidelines regarding the identification of accident scenarios.

International and European directive	Relevant content regarding accident situations
IAEA Safety Standard Series SSR-2/1, 2012 [xxiii]	This IAEA guideline provides the safety requirements for the design of a nuclear power plant.
IAEA Safety Standard Series SSR-2/1 (Rev. 1), 20 17 [xxiv]	This IAEA guideline is a revision, initiated after the Fukushima accident, of the previous guideline. The revision of this guideline resulted in some limited changes.
IAEA Safety Standards Series SSG-2, 2010 [xxv]	This IAEA guideline provides guidance on the deterministic safety analysis of nuclear power plants. Safety analysis is used to identify occurrences, classify them and identify accident scenarios.
IAEA Safety Standards Series SSG-2 (Rev. 1), 2019 [xxvi]	This IAEA directive is a revision, based on lessons learned from the Fukushima accident, of the previous directive.
Euratom treaty, 2012 [xxvii]	The Euratom Treaty relating to the establishment of a European Atomic Energy Community. One of its main objectives is to establish uniform safety standards for the protection of the population and workers.
Directive 2014/87/EURATOM, 2014xxviii	This EU directive is a revision of Directive 2009/71/Euratom, initiated after the Fukushima accident. The directive provides a Community framework for the nuclear safety of nuclear installations in the European Union.

The condition in which a nuclear power plant may find itself was identified by the IAEA as schematized in Figure 17. Two categories of accident conditions are considered: a) Design Basis Accidents and b) Design Extension Conditions. In addition, the latter category considers two types of occurrences: a) occurrences without significant fuel degradation and b) occurrences with core meltdown. In design extension occurrences, the radiological consequences are worse than in design basis accidents or involve additional disturbances [xxiv].

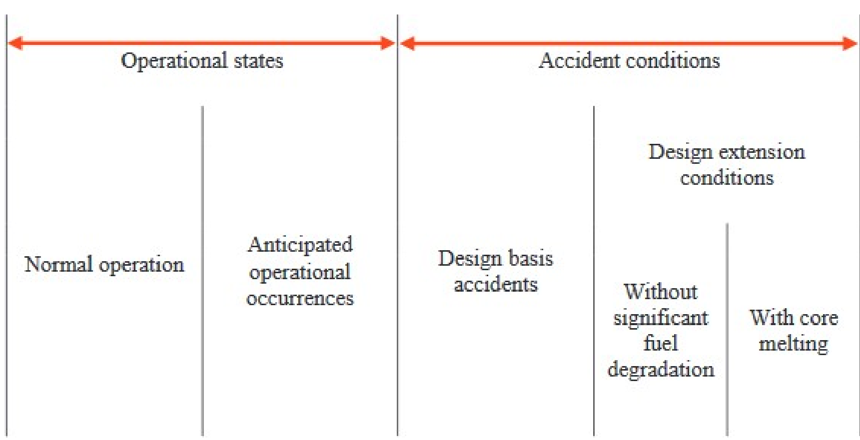

Figure 17: Operational and accidental condition of a nuclear power plant [xxiv].

In addition to IAEA and EU guidelines, the WENRA ("Western European Nuclear Regulators' Association"), in which Belgium participates, published harmonized safety levels and requirements for design basis and design expansion for existing reactors in 2014 [xxix].

Terminology used accidents

Design basis: the set of circumstances and events taken into account initially including upgrades, of a nuclear installation, in accordance with established criteria, in such a way that the installation can resist those events without exceeding the licensed limits in the planned operation of the safety systems.

Design basis accident: an accident considered in the design basis.

Design extension: the set of circumstances and events that are more complex or severe than those included in the design basis. These conditions may be caused by multiple initiating events, multiple failures, highly improbable events, or may be postulated conditions.

Design expansion accident: an accident considered in the design expansion. Two categories of accidents are considered:

- Design expansion accidents within domain "A" (DEC-A) for which it is possible to avoid premature or massive radioactive discharges, as well as fuel damage where appropriate.
- Design expansion accidents within domain "B" (DEC-B or Severe Accidents) for which it is not possible to avoid premature or massive radioactive discharges as well as, where appropriate, fuel damage.

At the Belgian level, design and off-design accidents were defined in the Royal Decree of November 30, 2011 on safety regulations for nuclear installations and the necessary requirements were established xxx. The RD has been adapted over the years both in terms of content and terminology. The aforementioned RD of November 30, 2011 is the transposition into Belgian law of the EU directive and the WENRA safety levels. The latest version of the RD considers design basis and design expansion accidents in line with the most recent IAEA and EU directives and are discussed further.

2.3.4.1 Draft base accident

The objective of the design basis in the aforementioned RD is to take measures "to ensure that potential radiological effects on the population, workers and the environment do not exceed prescribed limits and are kept as low as reasonably practicable." More specifically toward accidents, "the design basis must be to prevent anticipated operating incidents and accidents and, if unsuccessful, to mitigate their consequences."

During the preparation of the design basis, "a list of all presupposed initiator events is prepared that includes all events that may compromise the nuclear safety of the facility. From this list, a number of design basis events are selected, based on a combination of deterministic methods, probabilistic methods and expert judgment, to determine the boundary conditions under which the structures, systems and components important to nuclear safety should be designed to demonstrate that the required safety functions are ensured and that the design basis objectives are achieved. "[xxx]

Further requirements for preparing the list of initiator events in the draft are given in Article 20 of the [RDxxx].

> *"In compiling the list of initiator events, experience feedback and analysis regarding similar installations and sites are taken into account.*

Credible combinations of individual events are identified and accounted for.
The selected occurrences of internal origin include at least

- *equipment failure;*
- *the accidents involving loss of primary cooling (LOCA);*
- *human errors;*
- *other risks such as fire, explosion, flooding with internal cause.*

The selected occurrences of external origin include occurrences resulting from human activities, including at least:

- *the crash of a representative commercial airliner and a representative military aircraft;*
- *accidents caused by nearby transportation and industrial activities, including fires, explosions and other plausible threats to the safety of nuclear facilities.*"

For events of external origin, specifically the crash of a representative commercial or military aircraft, an alternative event can also be considered, but an adequate level of protection must be demonstrated by ensuring reasonable margins and using conservative methods, assumptions and arguments.

2.3.4.2 Draft expansion accident

The design extension in the RD aims to improve safety "by strengthening the capability to cope with events or conditions more severe than those of the design basis; by minimizing, to the extent reasonably possible, radioactive discharges harmful to the public and the environment during such events or conditions." The RD distinguishes between DEC-A ("Design Extension Conditions" - A) and DEC-B analysis as follows:

"*The DEC-A analysis aims to identify reasonably practicable measures to prevent significant fuel damage and conditions that could lead to premature or massive radioactive releases.*

Substantial damage from the spent fuel in the deactivation basin must be made, with a high degree of confidence, extremely unlikely unless its effects can be sufficiently mitigated by containment.

The DEC-B analysis seeks to identify reasonably practicable measures to mitigate the effects of significant fuel damage and conditions that could lead to premature or massive radioactive releases, to the extent that such damage or conditions have not been made, with a high degree of confidence, extremely unlikely."

A representative list of design expansion conditions should be prepared as [followsxxx]

"*A representative list of design expansion conditions is prepared and justified based on a combination of deterministic methods, probabilistic methods and expert judgments.*

Consideration is given to occurrences that may simultaneously affect different facilities at a site, as well as the various possible interactions between facilities at the site or at other nearby sites.

The selection process of DEC-A conditions assumes occurrences or combinations of occurrences that cannot be considered extremely unlikely with a high degree of confidence and that could result in significant fuel damage or premature or massive radioactive releases.

The selection process of DEC-A conditions is based on:

- *occurrences that occur in the various operating states;*
- *occurrences arising from internal or external risks;*
- *failures with a common cause.*

The list of DEC-B conditions includes those situations for which the ability to prevent either significant fuel damage or premature or massive radioactive releases is not adequate, or those situations for which preventive measures are not working as desired.

The list of DEC-B conditions includes the presupposed accidents with significant fuel damage, including for the fuel used in the deactivation basin, to the extent that such accidents have not been made extremely unlikely with a high degree of confidence."

The RD further describes design expansion occurrences in Article 21.

"*Occurrences more severe than the design basis occurrences should be identified as part of the design extension analysis.*

If a high confidence natural phenomenon included in the design basis is extremely unlikely, then no design expansion event should be considered for this phenomenon.

The selection of occurrences for design extension analysis is based on an exceedance frequency of severity or other parameters concerning the occurrence when possible.

The analysis of design expansion events:

1. *shows that there is sufficient margin relative to the "cliff effects" that could lead to the loss of a fundamental safety function;*
2. *Identifies and evaluates the most robust means of ensuring fundamental safety functions;*
3. *takes into account that:*
    a) *different redundant or diversified groups of a security system;*
    b) *different structures, systems and components;*
    c) *various site installations as well as site infrastructure;*
    d) *surrounding infrastructure, external supplies and other countermeasures; may be affected by the occurrences;*
4. *demonstrates that adequate resources remain available at sites with multiple reactor units that provide to share equipment or services;*
5. *includes field controls to the extent possible.*"

Finally, we can take a look here at historical accidents (frequency and severity) with reactors of a similar type to Doel 4 and Tihange 3. Doel 4 and Tihange 3 are 'Pressurized Light- Water Moderated and Cooled Water Reactor' (PWR) type nuclear power plants. Since the first large-scale PWR nuclear power plant, 'Shippingport Atomic Power Station' in the US, in [1957xxxi], a whole fleet of PWR nuclear power plants have been built worldwide. By the end of 2021, there were 372 existing PWR nuclear power plants worldwide (both operating and non-operating), based on data available from the [IAEAxxxii]. This global fleet of PWRs, since the commissioning of the first PWR, has been in operation for a total of 8,295 years based on data available in the IAEA [PRISxxxiii]. During this number of operating years, there has been one accident involving a PWR, specifically reactor 2 at the Three Mile Island nuclear power plant, in the US, in 1979. Based on the INES scale (International Nuclear and Radiological Event Scale), which was not developed until 1990, this accident would have been categorized as INES 5.

The INES scale was developed in 1990 by the IAEA and the OECD/NEA after the Chernobyl accident and is a tool to convey to the public the importance of the safety of nuclear and radiological events communicate. INES 1 through 3 refer to incidents, while INES 4 through 7 refer to accidents[xxxiv].

The March 28, 1979 accident at the Three Miles Island Nuclear Power Plant (TMI), was the most serious nuclear accident in a PWR. This accident resulted in a meltdown, there were no fatalities or injuries, and radioactive contamination was limited. The causes that led to the meltdown of Unit 2 of the nuclear power plant (TMI-2) were a sequence of design errors, human error and hardware failures. Finally, no explosion or fire occurred and reactor containment was maintained. The radioactive discharges had negligible effects on human health and the environment (see, for example, [xxxv], [xxxvi] and [xxxvii]). After studying this narrowly averted disaster, requirements for design, control systems, personnel training and emergency procedures have been greatly strengthened and improved.

2.3.4.3 Analysis of impact

To calculate the impact of accidents, we start from the source term discharged to the atmosphere. This is the amount and composition of radioactivity released and released to the outside air through the chimney or leaks in the containment. Furthermore, discharge parameters such as height of discharge, etc. are included. Based on atmospheric dispersion and deposition models that use meteorological information in addition to source term and discharge parameters, analogous to discharges during normal operation, the concentration and deposition of radionuclides are calculated for the local scale (first kilometers around the site) in order to determine the exposure (e.g., effective dose, thyroid dose) of the critical individual. The exposure pathways in an accident situation with discharge of radioactivity to the atmosphere are shown in Figure 18.

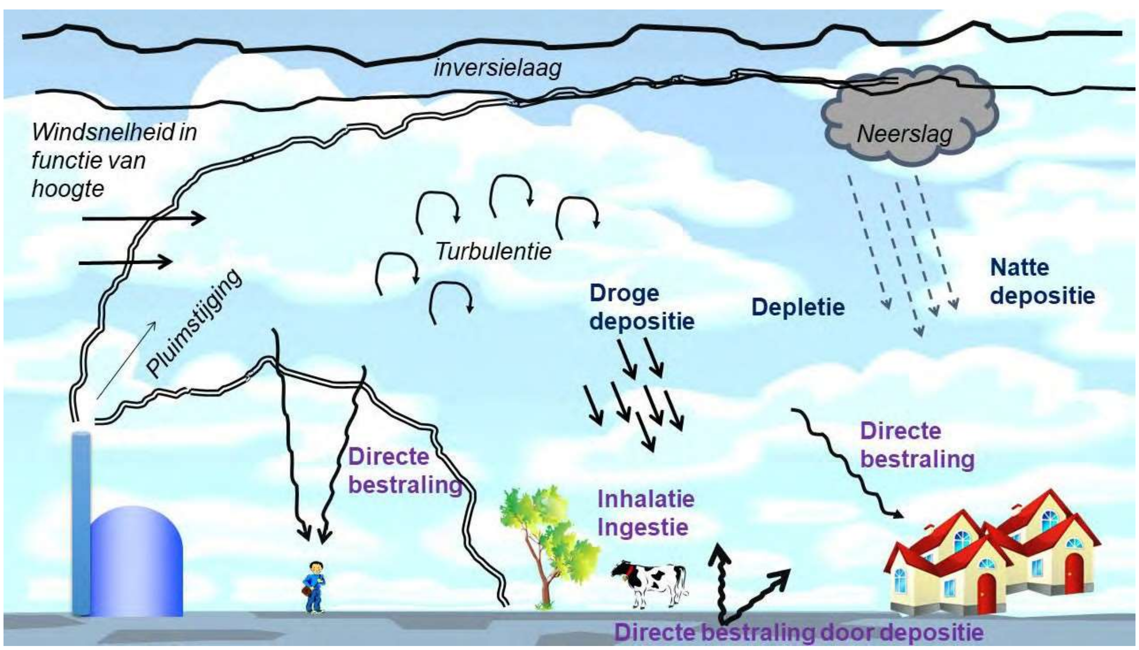

Figure 18: The spread of radioactivity and exposure pathways for persons in the vicinity in an accident scenario with discharge of radioactivity to the atmosphere.

For design basis accidents are defined under Article 37 of the Euratom Treaty.

General data under Article 37 of the Euratom Treaty for the Doel 3 and Doel 4 units were prepared in 1981. Two design accidents were identified for this purpose: i) primary pipeline main break and ii) fall of an irradiated fuel element[xxxviii]. The authorization limits for the radiological consequences of design basis accidents at the edge of the site and at the nearest boundary (Netherlands at 3.15 km), are based on the most pessimistic scenario (primary pipeline main rupture) for thyroid dose and total effective dose.

General data under Article 37 of the Euratom Treaty for the Tihange 2 and Tihange 3 units were also prepared in 1981. Two design accidents were also identified for this purpose: i) primary pipeline main break and ii) fall of an irradiated fuel element[xxxix]. The license limits for the radiological consequences of design basis accidents at the edge of the site and at the nearest boundary are based on the most pessimistic scenario (primary pipeline main rupture) for thyroid dose and total effective dose.

These permit limits must be respected for the critical individual. The most exposed individual is considered at a location where the person is exposed to the highest (time-integrated) concentration of radioactive discharges[xli]. This person belongs to the age group most affected by exposure to the radioactive discharges.

A brief description of these accidents is given below:

A **primary line main rupture (Loss of coolant or LOCA)** is the result of a suspected rupture in the primary circuit or a line connected to the primary circuit before the first isolation valve where the fuel cladding is damaged under the influence of high temperatures. Due to the loss of coolant, the core heats up until the fuel cladding is damaged. Gaseous fission products are released in the primary circuit, and further upon breakthrough into the interior of the reactor building. Some of the gaseous fission products then leak through the reactor containment into the interstitial space, among others, and also immediately into the atmosphere. It is further assumed that, among other things, the safety injection systems are in service and recirculation to cool the core is started, the water is contaminated and some of this contamination leaks to the environment The discharge to the environment is assumed to last for 30 days with intensity decreasing as a function of time.

When an **irradiated fuel element (Fuel handling Accident or FHA) falls** during a spent fuel operation, it is assumed that all the fuel rods are damaged. In this situation, gaseous fission products are in the space between the cladding and the fuel and are released into the water in which the fuel elements are located. Some of the fission products are absorbed by the pool water. The rest diffuses into the environment and is eventually released through the vent to the chimney and atmosphere (chimney discharge).

For Doel and Tihange, based on a probabilistic safety analysis and in accordance with the WENRA 2014 guidelines, which take into account lessons learned from the 2011 TEPCO Fukushima Dai accident, an enveloping design expansion accident was identified. For this scenario, a **Complete Station Black-Out (CSBO)** is **assumed with core meltdown** (corresponding to DEC-B), given successful accident management measures. As a result of a core melt in this accident, radioactivity is released to the environment on the one hand through a containment design spot and on the other hand through controlled vents if the pressure rises too much over the Containment Filtered Venting System, (CFVS), a filtration system that captures iodine and aerosols with high efficiency for discharge through the chimney of the CFVS to the atmosphere. Several vents and a continuous design spot are assumed over a 10-day period. The Tractebel calculations are specific to Doel 4 and Tihange 3 and the MELCOR and ASTEC codes were used to calculate the source term of this severe accident. The CSBO design expansion accident also includes events of external origin, including the crash of an airplane into the nuclear power plant.

The general data for KC Doel and CN Tihange under Article 37 of the Euratom Treaty include license limits for the nearest border with the Netherlands. There are no legal limits for transboundary radiological effects of accidents at longer distances. As an indication, the dose limit value of 1 mSv/year, as indicated for normal operation in Article 12 of Directive 2013/59/Euratom, can be used.

In order to assess the impact of the design accidents on the most critical individual, the dispersion of radioactivity and the effective committed dose resulting from it were calculated on the basis of a methodology approved by the FANC-AFCN and prepared by the United States Nuclear Regulatory Commission (NRC, 1977). The results must comply with the Royal Decree concerning the authorizations of establishment of the Doel and Tihange nuclear power plants and the corresponding general data in the framework of Article 37 of the Euratom Treaty (see above). The required safety studies are documented in the safety reports and are periodically updated, based on updated insights and standards.

On the other hand, additionally for the assessment of these accidents and also for the design expansion accident, studies of Tractebel based on the new guidelines of the FANC-AFCN and Bel-V are used.

In 2017, the FANC-AFCN published a guideline for achieving the safety demonstration of new Class [lxl] nuclear facilities. The recommendations in this guideline provide detailed information on the FANC-AFCN's requirements regarding "layered protection" and quantitative radiological objectives in the context of the safety demonstration of new Class I nuclear facilities. Since Doel 4 and Tihange 3 are existing Class I facilities, this guideline is not directly applicable, but the recommendations can nevertheless be used to evaluate the safety demonstration based on current standards.

The FANC Directive was supplemented by a Bel V Directive, which provides recommendations in the application of conservative and less conservative approaches for the analysis of radiological consequences [nxli listed] in the FANC Directive. Like the FANC Directive, the Bel V Directive is aimed at new Class I nuclear facilities. V

Differences in results are broadly due to a somewhat different methodology for calculating dispersion and the use of more recent dose coefficients. It should be noted that both methodologies are conservative, but the difference in results reflects primarily the difference in conservatism of approach.

In addition to the limits for design basis accidents as defined in context of Euratom Article 37 and the criteria defined for accidents in the context of new Class 1 facilities, the results of the analyses can also be compared with the guidelines regarding countermeasures as defined in the Federal Nuclear and Radiological Emergency Plan (RD March 18, 2018)[cvii]. This contains specific reference levels in the form of dose criteria for immediate, urgent protective measures: sheltering, evacuation and the intake of stable iodine to protect the thyroid gland (see Table 16), derived levels of soil contamination for various radionuclides where food chain measures may be necessary (Table 17) and the maximum permissible levels for the free movement of food and feed within the EU (Table 18).

Table 16: Specific reference levels for immediate, urgent protective measures. (*) outside ingestion.

Protective measure	**Dose criteria and integration période**	**Target**	**Guideline**
Hide	Effective dose in 24h (*)		5 mSv
Intake stable iodine	Equivalent dose to the thyroid gland (*)	Children, pregnant and breastfeeding women	10 mSv
		Adults	50 mSv
Evacuation	Effective dose in 7d (*)		50 mSv

Table 17: Derived levels of soil contamination (Bq/m2).

	Milk	Vegetables	Meat
90Sr	10.000	4.000	300.000
131I	4.000	10.000	40.000
134Cs	10.000	6.000	10.000
137Cs	10.000	6.000	10.000

Table 18: Maximum permitted levels for the free movement of food and feed (Bq/kg) within the EU.

	Food (Bq/kg)					Animal Feed
	Baby food	**Milk products**	**other life resources, except minor life resources**	**Minor life resources**	**Liquid life resources**	
Total strontium isotopes, particularly 90Sr	75	125	750	7.500	125	
Total iodine isotopes, particularly 131I	150	500	2.000	20.000	500	
Total alpha-emitting isotopes of plutonium and transplutonium elements, particularly 239Pu et 241Am	1	20	80	800	20	
Total all other nuclides with half-lives greater than 10 days, especially 134Cs and 137Cs	400	1 000	1 250	12 500	1 000	pigs: 1 250 poultry, lambs, calves: 2 500 other: 5 000

To estimate the potential impact of an atmospheric radioactive discharge in the event of an accident from the Doel and Tihange nuclear power plants on neighboring countries, a series of calculations were made with the Lagrangian stochastic particle model Flexpart. Flexpart calculates the transport and dispersion of radioactive particles through the atmosphere following an atmospheric discharge. The model also considers dry and wet depletion and calculates the associated dry and wet deposition, if applicable. The focus here is on distances greater than 10 kilometers: the potential impact of Doel on the Netherlands is thus not examined with this method, but it was evaluated with the local impact method given the distance from Doel to the Dutch border (3.15 km).

Flexpart calculations were performed for the full year 2020 to account for different weather conditions. The calculations were performed using historical numerical weather data from the European Centre for Medium-Range Weather Forecasts (ECMWF). This data was obtained through the Royal Meteorological Institute of Belgium (RMI). In the calculations, a discharge time of 1 hour was assumed. By aggregating the results of the calculations, other discharges can also be taken into account (e.g., a 6-hour discharge). Calculations were done for noble gases (no dry or wet depletion), elemental iodine I_2 and aerosols. During the discharge, a constant emission was assumed totaling 1 TBq. Since the concentration and deposition scale linearly with the discharge, the results can also be used for discharges according to the accident scenarios. The calculations stopped 48 hours after the end of the discharge. The calculations for elemental iodine 131 considered radioactive decay, while the calculations for noble gases and aerosols did not consider radioactive decay. The latter is conservative, since in reality concentrations decrease with time due to radioactive decay.

The results of the calculations were written hourly into two different calculation grids with dimensions as shown in Figure 19. The small grid has a resolution of 0.01° (+/- 0.9 km), while the large grid has a resolution of 0.1° (+/- 9 km). The air concentration for each simulation was then summed over time to obtain the time-integrated concentration (TIC). Accumulated dry and wet deposition was also summed for each simulation. Two examples of such calculations are shown in Figure 20 and Figure 21. Then the highest value of the TIC and total deposition was determined for both grids shown in Figure 19 for different areas: The Netherlands, Germany, France, Luxembourg and the United Kingdom. For completeness, the maximum over sea and land was also determined.

For a given nuclear power plant (Doel or Tihange), a given radionuclide (noble gas, iodine or aerosol), a given discharge duration and a given area (the Netherlands, Germany, France, Luxembourg and the United Kingdom, land or sea), there are 8,784 values for the maximum TIC and total deposition. This is because Flexpart calculations were started for every hour of the full year 2020 (24 x 366 = 8,784). This allows for statistical interpretation of the results. We give two examples here. Figure 22 shows the distribution of the maximum time-integrated concentration of radioactive noble gases in France after a notional 6-hour discharge from the Doel nuclear power plant. Figure 23 shows the distribution of the maximum deposition in Germany after a notional 6-hour discharge of radioactive aerosol from Tihange. To finally calculate the impact, we use the highest value obtained for the year 2020, for a given scenario. This is a very conservative estimate: as it concerns the only possible meteorological situation in a year (2020), at all other times of the year the meteorological conditions are more favorable, in the sense that there will be a lower impact for the same accident scenario. We can also see from these figures that in 99% of meteorological situations the impact will be only half to one-third of the maximum impact.

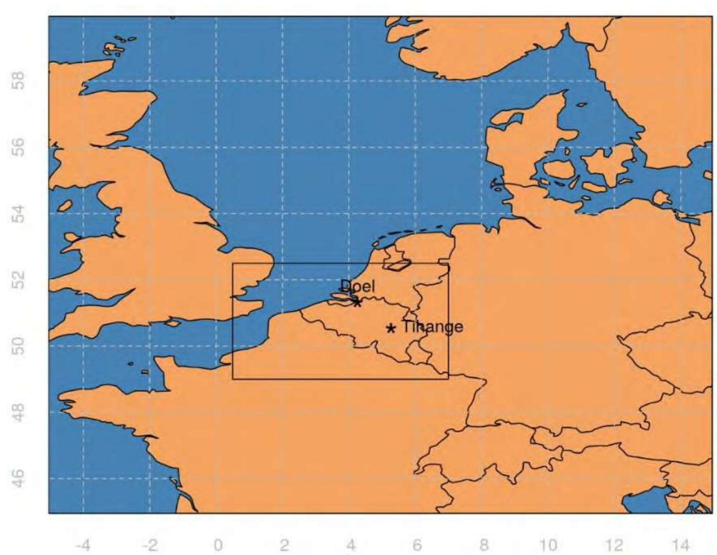

Figure 19: Calculation domain for the transboundary effects of the accident scenarios. The numbers at the bottom of the figure represent longitude [°], the numbers to the left of the figure represent latitude [°]. (See text for further explanation).

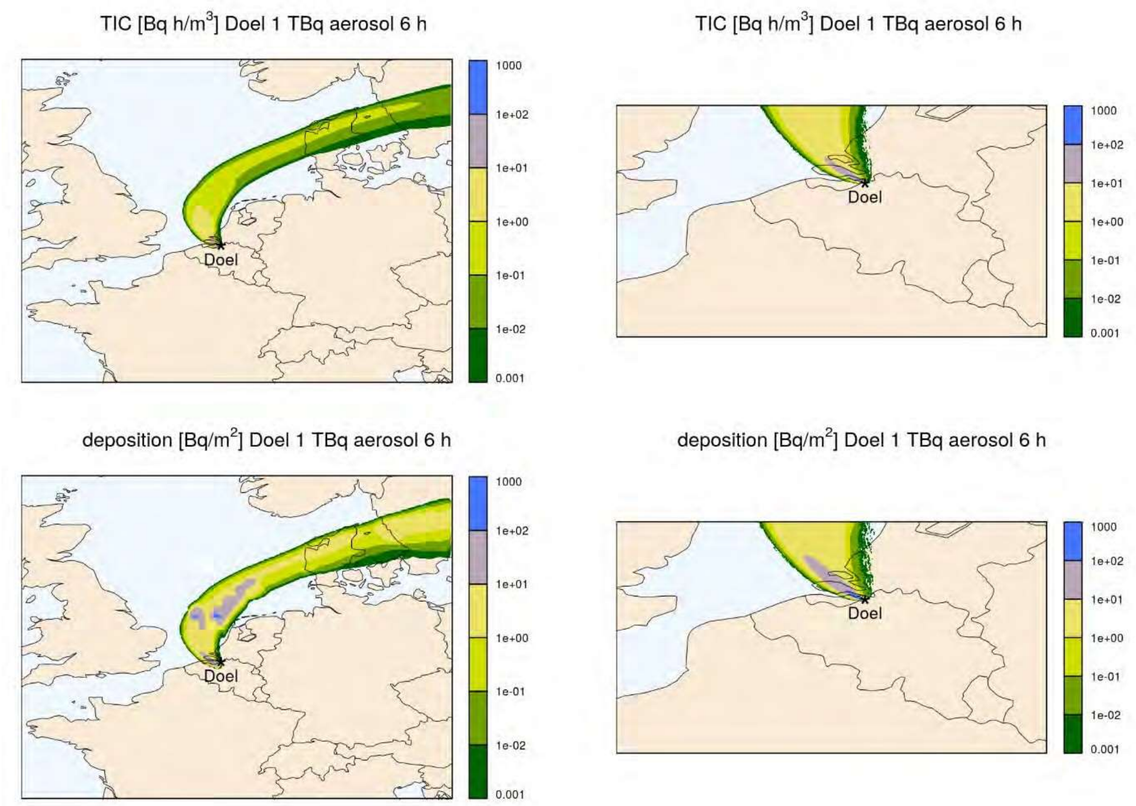

Figure 20: Example Flexpart calculation for a notional discharge on January 1, 2020 between 00:00 UTC and 06:00 UTC of 1 TBq of radioactive aerosols from the Doel nuclear power plant. The top row shows the time-integrated concentration; the bottom row shows the total deposition. The results of the calculations are shown for the large grid (left column) and the small grid (right column).

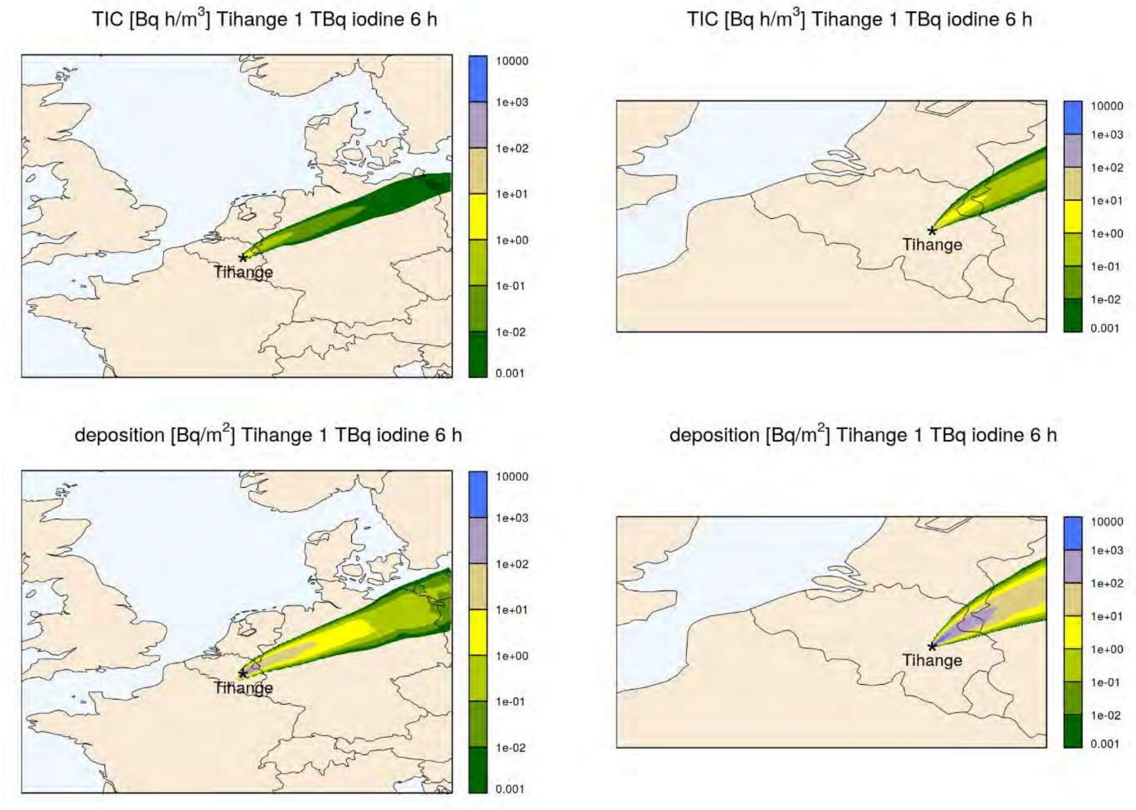

Figure 21: Example Flexpart calculation for a notional discharge on July 1, 2020 between 00:00 UTC and 06:00 UTC of 1 TBq elemental iodine 131 from the Tihange nuclear power plant. The top row shows the time-integrated concentration; the bottom row shows the total deposition. The results of the calculations are shown for the large grid (left column) and the small grid (right column).

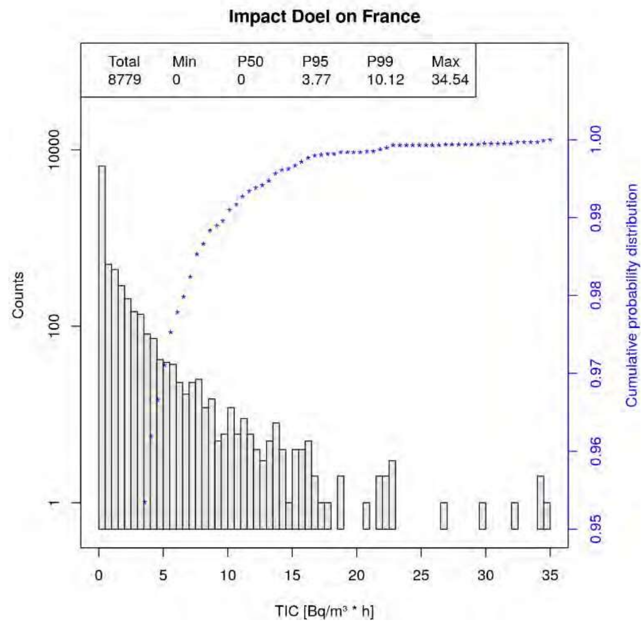

Figure 22: Distribution of the maximum time-integrated concentration (TIC) in France after a hypothetical 6-hour discharge of radioactive noble gases from the Doel nuclear power plant. The total number of TIC values shown in the distribution is 8,779[30].

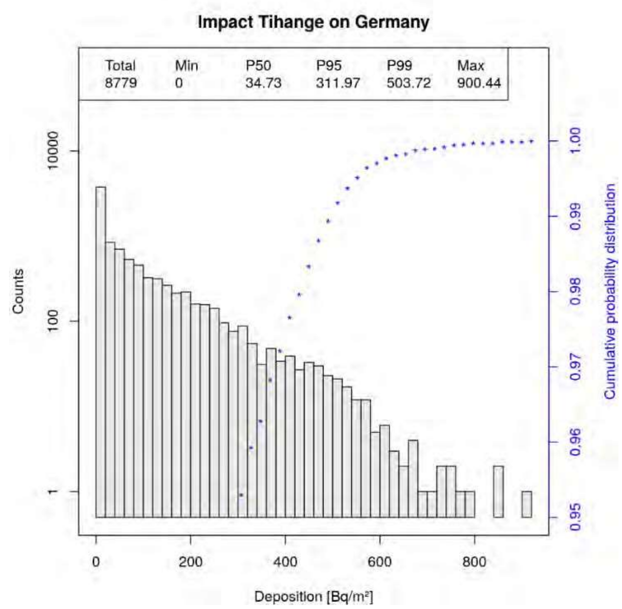

Figure 23: Distribution of the maximum total deposition in Germany after a hypothetical 6-hour discharge of radioactive aerosols from the Tihange nuclear power plant. The total number of TIC values shown in the distribution is 8,779.

[30] That is slightly lower than 24*366 = 8,784, since 8,784 hourly discharge calculations were aggregated to 8,779 6-hourly discharges in the year 2020.

Based on the atmospheric dispersion and deposition calculations, the total effective dose and equivalent thyroid dose are then determined for the different accidents considered.

2.3.5 Monitoring radiological conditions in the living environment.

Belgium, like all European Union member states, is required to comply with the European Commission's (EC) requirements under the Euratom Treaty. Article 35 of the Euratom Treaty requires each member state to establish the facilities necessary to continuously monitor levels of radioactivity in air, water and soil and to ensure compliance with the Basic Safety Standards (BSS). The wording "air, water and soil" is assumed to be all-encompassing and include all compartments of the biosphere. The environment is not limited to the vicinity of a nuclear facility, but applies to the entire territory.

Furthermore, Article 36 on the communication of monitoring data on radioactivity in the environment (airborne radioactivity, airborne particulate matter, surface water and drinking water, milk and food) must be complied with. This also includes the new rules on food chain monitoring following the protection measures after the Chernobyl and Fukushima disasters as well as Recommendation 2000/473/EURATOM2 on Article 36 of the Euratom Treaty, which provides in point 4 that Member States should communicate to the Commission all necessary data for monitoring radioactivity in the "mixed regime" in order to obtain global information on the uptake of radioactivity by humans, through the food chain.

The OSPAR Convention (OSlo-PARis) on the Protection of the Marine Environment of the North Sea and North-East Atlantic obliges member countries to develop monitoring and research programs on the impact of radioactive discharges on the marine environment. The program is organized into six strategies: (1) Protection and conservation of marine biodiversity and ecosystems; (2) Eutrophication; (3) Hazardous substances; (4) Offshore oil and gas industry; (5) Radioactive substances; (6) Monitoring and assessment. The Convention provides for the drastic reduction of radioactive discharges into the marine environment to near zero concentrations for artificial radioactivity. Also, under the OSPAR strategy, the European Commission encourages member states to invest in fundamental research programs regarding the impact of radioactive discharges in the marine environment (flora, fauna and people).

Finally, there are international guidelines, such as those of the International Atomic Energy Agency (IAEA Safety Guide N° RS-G-1.8 "Environmental and source monitoring for purposes of radiation protection"). According to these guidelines, an off-site monitoring program should include the following measurements: measurement of the external dose or dose rate and radionuclide activity in environmental samples relevant to human exposure in particular in air, drinking water, soil, sediments, agricultural products and natural foods as well as bioindicators (lichens that concentrate radioactivity and can provide a trend as a function of time).

The FANC-AFCN is in charge of monitoring the radioactivity of the entire territory and of monitoring the dose of ionizing radiation received by the population and has been carrying out this radiological surveillance program on the Belgian territory since 2001. The surveillance program concerns both natural and artificial radioactivity and is carried out in two ways:

*In a **continuous manner***: through the automatic TELERAD network for measuring local environmental radioactivity, a network of 250 measuring stations spread over the entire Belgian territory that continuously measure radioactivity (more specifically gamma radiation) in the air and river water. This makes it possible to have near real-time (real-time) radiation readings 24 hours a day and to react quickly if the radiation level exceeds a predetermined threshold. The network has densifications around nuclear facilities such as KC Doel and CN Tihange, consisting of a large number (about 20 per site) of ring stations installed on the perimeter of the site and agglomeration stations in the vicinity of the site.

The TELERAD network is one of the densest networks for measuring radiation levels in Europe and the world with 5.3 stations per 1000 ^{km2}. It includes:

- *162 ambient dose equivalent stations* (Geiger Müller type detector, H*[10]), for the measurement of gamma radio activity in the environment;
- *64 spectroscopic measuring stations*: 1.5 "x1.5" sodium iodide (NaI) scintillation detectors + Geiger Müller (GM) counters for dosistempi > 400 ・Sv/h) for the measurement of gamma radioactivity in the environment and the measurement of a number of radionuclides (10 pre-defined radionuclides). These are distributed along the fence around the SCK CEN nuclear sites, the Doel and Tihange nuclear power plants, as well as around the IRE;
- *11 monitoring stations along rivers* ($_{LaBr3}$) that continuously measure gamma radiation in river water;
- *13 meteorological stations (30-meter high mast)*.

All stations measure dose rate (ambient dose equivalent rate H*[10] which in almost all cases gives a conservative estimate of the effective dose absorbed by a person from external radiation) and are able to accurately measure both background levels, where the variation in natural background radiation can be observed as a function of time, as well as make accurate measurements at highly elevated dose rates (accident situations). The data are available online at the website http://telerad.fgov.be. In addition, data from all European countries are collected and made available via EURDEP: "The Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC)" of the European Commission: https://eurdep.jrc.ec.europa.eu/Entry/Default.aspx . There, in addition to Belgian data, data from the other European measurement networks can also be consulted, such as, for example, the results of the Dutch National Radioactivity managed by the RIVM, which has stations just across the border in the vicinity of KC Doel (see also: https://www.rivm.nl/nationaal-meetnet-radioactiviteit/resultaten).

Based on the continuous TELERAD data, the dose due to external radiation on an annual basis can also be determined. This is shown in *Figure 24*.

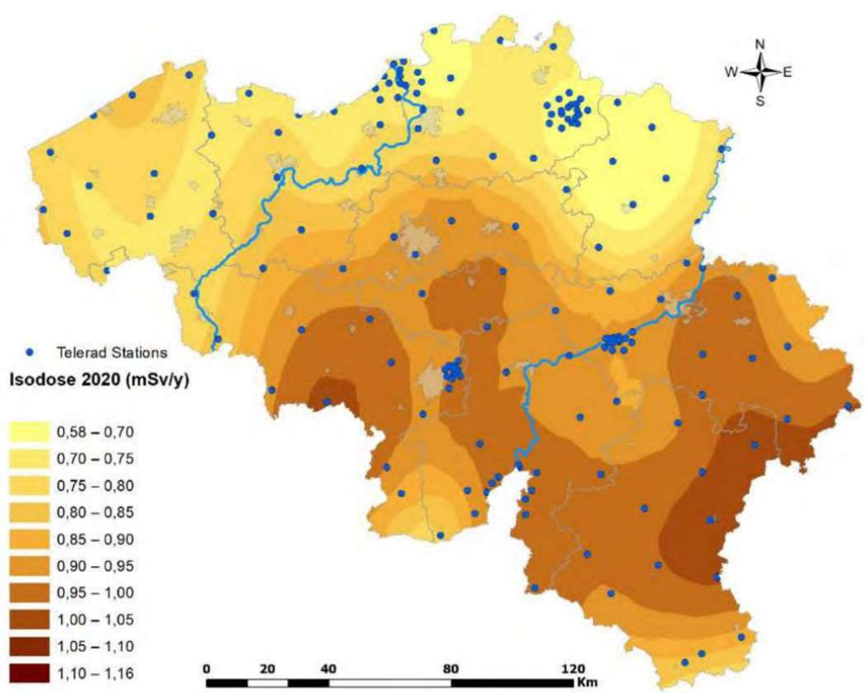

Figure 24: The dose in mSv per year due to external radiation (cosmic and terrestrial radiation) as determined on the basis of TELERAD measurements (year 2020). Mainly due to the composition of the subsurface, the external dose over Belgium varies considerably on an annual basis between 0.58 and 1.16 mSv/year. This figure also nicely shows the different layers of the TELERAD network: a densified network around the nuclear installations with ring stations and agglomeration stations and, in addition, the national network covering the entire territory with typically 1 detector every 20 km x 20 km (Figure: FANC-AFCN).

*In a **discontinuous manner**: through* periodic measurements in situ (sampling), which are then analyzed in specialized laboratories. This makes it possible to measure very small amounts of radioactivity.

The whole provides a control of radioactivity in air, rainwater, surface waters and drinking water, soil and river deposits (sediment), the coastal zone and products from the food chain, among others.

Moreover, the surveillance program has two components: (1) global surveillance over the entire territory, outside the areas where nuclear activities take place and (2) close surveillance around nuclear facilities. In addition, a specific reference area is also defined, namely Brussels. The results of both are publicly available with reports for the years from 1996 to [2021xlii].

In addition to the FANC-AFCN surveillance program, Electrabel SA also has its own radiological surveillance program around the KC Doel and CN Tihange sites, the design and results of which are discussed in the respective environmental impact assessment sections of Doel 4 and Tihange 3.

During the normal operation of nuclear power plants, monitoring of radioactivity in the environment provides a complementary picture to that of monitoring gaseous and liquid discharges in terms of estimating the radiological impact on humans and the environment, as shown in Figure 25.

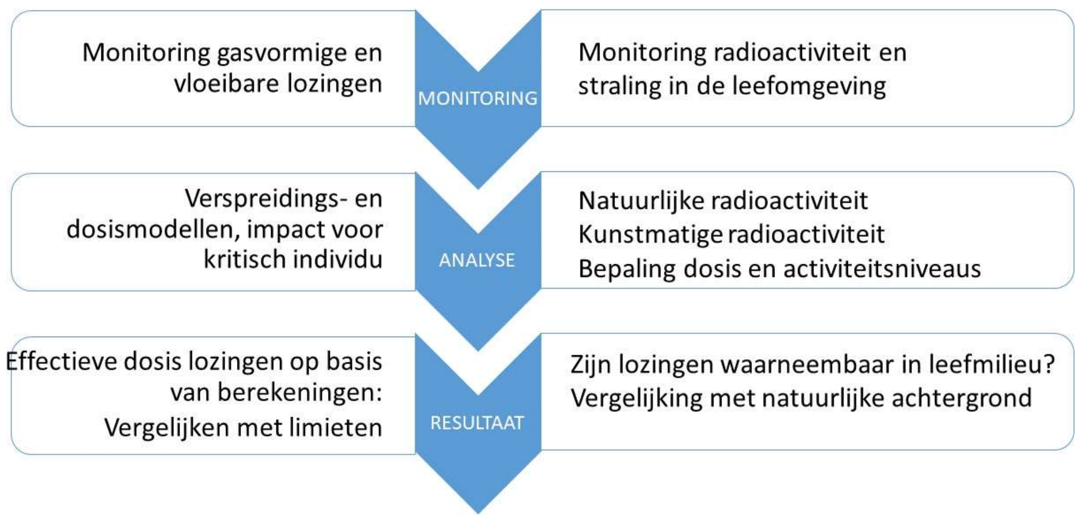

Figure 25: The impact on humans and the environment of the operation of KC Doel and CN Tihange is monitored through two complementary avenues: the monitoring of discharges and the monitoring of the environment.

For potential incidents and accident situations, the monitoring program is also an important link; the continuous network provides instantaneous information about elevated levels of radiation and/or radioactivity in the environment. If preset levels are exceeded, response actions are triggered automatically. The discontinuous program, given its greater sensitivity to detect very small amounts of radioactivity in air, water, soil, food, can detect very small potential anomalies related to the operation of the nuclear power plants. For emergency situations, this monitoring program is complemented by the provisions of the Nuclear and Radiological Emergency Plan for the Belgian territory (Royal Decree of March 1, 2018).

2.3.6 Classification of radioactive waste and management of such waste and spent fuel

According to the June 3, 2014 law transposing European Directive 2011/70/Euratom, radioactive waste is defined as follows[31]:

"Radioactive waste means a radioactive substance in a gaseous, liquid or solid state for which the State or a natural or legal person whose decision has been accepted by the adoption of a National Policy regarding this substance as referred to in §6 and §7 of this Article, no longer envisages or contemplates further use and which is considered as radioactive waste by the competent regulatory authority, or if this substance is to be considered as radioactive waste by virtue of a legal or regulatory provision."

Proper classification of radioactive waste is necessary to ensure that the collection, transportation, storage and treatment of waste is carried out in a manner that protects the environment and human health and is in accordance with legal requirements.

Radioactive waste, with respect to operational radiation protection at nuclear power plant sites, is classified into three categories based on dose rate on contact:

- Low-level waste (dose rate < 5 mSv/h);
- Medium active waste (dose rate ≥ 5 mSv/h and ≤ 2 Sv/h);
- High-level waste (dose rate > 2 Sv/h).

Regarding long-term management, radioactive waste is classified according to the amount (activity) and type of radiation and the time period during which it remains radioactive (related to the half-life). Based on these properties, waste can be classified according to the degree of containment and isolation of a disposal system required to ensure long-term safety, taking into account the potential hazard of different types of waste. This reflects a graduated approach to ensure safety.

In Belgium, NIRAS (the National Agency for Radioactive Waste and Enriched Fissile Materials) classifies radioactive waste into three categories: A, B and C.

- **Category A**: refers to low- and intermediate-level short-lived waste. Low-level waste contains small amounts of radioactivity. It arises mainly from the operation of nuclear power plants, but also from reprocessing, research and production of radioisotopes and their use in nuclear medicine and industry. Examples of Category A waste include contaminated shoe covers and clothing, fibers, mops, filters, medical tubing, cotton swabs, hypodermic needles, syringes, waste from dead animals (cadavers) and other tissues. It can also include fire-resistant fabrics and protective plastic coverings used in maintenance operations, as well as parts of equipment removed from a plant.
- **Category B**: groups low- and intermediate-level long-lived waste. Medium-level waste contains higher levels of radioactivity than low-level waste and requires shielding when treated. It comes mainly from nuclear fuel fabrication, nuclear research and spent fuel reprocessing. When a reactor is decommissioned, some parts of the reactor are also classified as intermediate-level waste.
- **Category C**: contains highly radioactive long-lived waste. It comes mainly from spent fuels that were declared as waste and from spent fuel processing. Category C waste has "such a high level of radiation that it generates heat and requires heavy shielding.

[31] Note that this definition differs slightly from the one used in art. 3 of the ARBIS (RD of July 20, 2001) : " radioactive waste: all radioactive substances originating from an authorized operation or from an occupational activity considered in whole or in part as a non-exempt operation in application of article 9.3, and for which no further use is foreseen within the establishment, as well as the radioactive substances originating from an intervention carried out in application of article 72bis or from a protective measure applied in the event of a radiological emergency ".

2.3.7 General management of radioactive waste and spent fuel

2.3.7.1 Objective

The overarching goal of radioactive waste management is to protect both people and the environment, now and in the future. The best way to do this is to concentrate, contain and isolate the waste from the environment. This allows any release into the environment to be limited and subject to regulation. The generation of radioactive waste must be prevented or, if not reasonably practicable, limited in terms of quantity and activity.

Actors

Synatom

Synatom SA is a private company whose capital is wholly owned by Electrabel SA, but in which the Belgian State holds a golden share that gives the Federal Minister of Energy a veto right on decisions by the Board of Directors that could run counter to our country's energy policy. The purpose of Synatom, after an expansion in 2003, is to manage activities related to the nuclear fuel cycle as well as the facilities built for the decommissioning of nuclear power plants and the management of fissile materials irradiated in these plants.

Operators

The operators (Electrabel SA, EDF Luminus, Belgoprocess, IRE, hospitals, isotope producers, research centers such as SCK CEN, etc.) are the primary responsible parties for the radioactive waste generated in their facilities. They are responsible for drawing up and implementing the overall waste management strategy for their facility, and for financing the management of radioactive waste, in accordance with the "polluter pays" principle. Electrabel S.A. operates the Doel and Tihange nuclear power plants.

Waste management organization: ONDRAF/NIRAS

NIRAS, the National Agency for Radioactive Waste and Enriched Fissile Materials was established by Article 179, §2, 1°, of the Law of August 8, [1980xliii]. As a national waste management organization, it is [responsiblexliv] for the safe management of radioactive waste (regardless of its origin and provenance) in the short and long term. Belgoprocess nv is a subsidiary of ONDRAF/NIRAS that operates a series of radioactive waste storage buildings, and also provides processing and storage of radioactive waste for producers who request it.

Safety authority and regulator: FANC

FANC, the Federal Agency for Nuclear Control, is the competent authority in the field of safety and security of nuclear applications and was established by Article 2 of the law of April 15, [1994xlv]. Bel V, established in 2007, as a subsidiary of FANC, provides the necessary technical support in this regard. The supervisory missions that FANC can delegate to Bel V and their practical modalities were included in the amendment to the ARBIS of December 6, 2018. A management agreement was signed in 2019 to concretize this RD [xlvi].

Federal Public Service Economy, SMEs, Self-Employed and Energy

The Nuclear Applications Service within the General Directorate of Energy of the Federal Public Service Economy, SMEs, Self-Employed and Energy, oversees nuclear research activities and also supervises the activities of (among others) Synatom and ONDRAF/NIRAS, under the tutelage of the ministers of energy and economy.

2.3.7.2 Waste reduction, treatment and conditioning

Limiting radioactive waste generation is an important initial step in waste management. Therefore, operators should attempt to design, construct, operate and decommission a facility in such a way as to reduce both waste volume and radioactivity to an absolute minimum. The key elements of waste minimization include:

- source reduction, both volume reduction and pollution prevention/activation;
- the reuse and recycling of valuable materials from the waste cycle; and

- the optimization of waste treatment.

The goal of waste treatment and conditioning is to convert radioactive waste into a solid and stable end product that meets specifications for storage and final disposal.

The processes for processing and conditioning radioactive waste are applied at the nuclear power plants themselves (for part of their own waste) or are centralized at the Belgoprocess site at Dessel.

Depending on the nature of the waste stream, waste treatment at Belgoprocess is [appliedxlvii] as follows:

- liquid radioactive waste is collected in tanks and reduced to a small volume of sludge by chemical or thermal treatment;
- solid combustible radioactive waste is incinerated at a temperature of 900°C;
- solid noncombustible radioactive waste is collected in steel drums which, if possible, are pressed under very high pressure (2,000 tons) into a disc about 25 centimeters high;
- noncombustible and nonpressible waste is cut up and collected in standard drums.

The residue remaining after processing is encapsulated in cement so that the radioactive particles are retained. After this, everything is packed into steel drums. Once the radioactive waste is processed and enclosed in a vessel, it is called "conditioned.

2.3.7.3 Storage

Storage facilities are designed to take waste colli into an appropriate nuclear facility, with the possibility of removing them back from that facility. Since storage relies on active elements of maintenance, control and monitoring, it does not constitute a long-term management solution. However, there are several reasons for the *temporary* storage of radioactive waste, including:

- to allow decay of short-lived radionuclides to occur to a level where radioactive waste is exempt from regulatory control;
- to collect and retrieve a sufficient quantity of radioactive waste prior to transfer to another facility for processing/conditioning or disposal;
- To reduce heat production from high-level waste.

In Belgium, conditioned radioactive waste is temporarily stored in suitable shielded storage buildings at the Belgoprocess site. Belgoprocess has eight suitable bunker buildings for low-activity conditioned waste, intermediate-activity conditioned waste, high-activity vitrified waste and waste emitting alpha particles.

High-level waste is the smallest in volume (1.4% of all waste), but represents 98% of the radioactivity in all stored waste. High-level waste consists mainly of vitrified waste transported to Belgium after reprocessing in France of spent fuel elements from Belgian nuclear power plants.

Spent nuclear fuel is currently not (yet) classified as waste. The current owner of the nuclear fuel, Synatom, has not yet made a decision regarding the possible (partial) recycling of possible raw materials from the spent fuel. Until several years ago, Synatom considered in its reference program a scenario in which about 1,200 tHM (corresponding to about a quarter of the projected inventory of spent fuel at the end of the reactors' lifetimes) would be reprocessed [txlviii]. Synatom believed that partial reprocessing could initially be a solution to the lack of storage capacity. However, as the valorization potential of the recovered fissile material was too [limited32] and as permits have recently been obtained (2021) for the creation and operation of new nuclear power plants, Synatom did not consider partial reprocessing to be a solution.

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[32] The production of fuel elements based on reprocessed irradiated fuel is possible only after a cooling period of several years. According to Areva, the complete reprocessing procedure takes about 10 years. Consequently, the time remaining until the closure of the last reactor is (much) too short to reuse the fuel from reprocessing the entire stock of Belgian nuclear fuel in our plants. On top of that time aspect, obtaining a new

storage facilities both at Doel and Tihange through the "Spent Fuel Storage Facility" or ^{SF2} project xlixl, a scenario without reprocessing now seems more likely. Pending the final decision, the spent fuel bundles are being temporarily stored today at the sites of the Doel and Tihange nuclear power plants.

At Doel, storage is of the dry type. Used fuel elements are placed in "dual purpose" casks (DPC) (Figure 26) that are stored in a special building at the Doel site. DPC are containers that can be used both for interim storage and for transport on and off site. The current spent fuel storage building at Doel, the Fuel Container Building or SCG, has a maximum storage capacity of 165 DPC-type fuel containers and will become saturated after 2024.

The SF^2 project provides additional interim storage capacity for spent fuel at the KC Doel production site. The SF^2 project makes it possible to empty the nuclear units' fuel docks after the final shutdown of the nuclear units. Emptying the docks is necessary before decommissioning of the nuclear units can begin. The SF^2 project includes three buildings: the main building (SFB) where DPC type fuel containers will be stored, the auxiliary building (AUX) and the equipment storage building (ASB). The maximum capacity of the SFB includes 108 containers. In reality, a maximum of 97 containers will be stored because 2 positions will be kept free for container handling and 9 positions for mitigation measures in an accident situation. Electrabel SA anticipates that the new storage building can be commissioned in 2025. [li]

Storage at Tihange is currently of the wet type. Fuel elements are stored in purpose-built pools located in the DE storage building at the Tihange site. Even there, storage capacity would reach saturation after 2022. The ^{SF2} project at Tihan [gelii] provides for the construction of a new storage facility in a very similar manner to Doel: i.e. using dry storage of DPC-type fuel containers. At its maximum capacity, the new storage building will be able to accommodate 117 DPC containers. The new storage building at the Tihange site is currently under construction, with plans to bring it into service during 2023.

operating license for the possible MOX fuel. Indeed, no Belgian nuclear reactor currently has such a license.[xlviii]

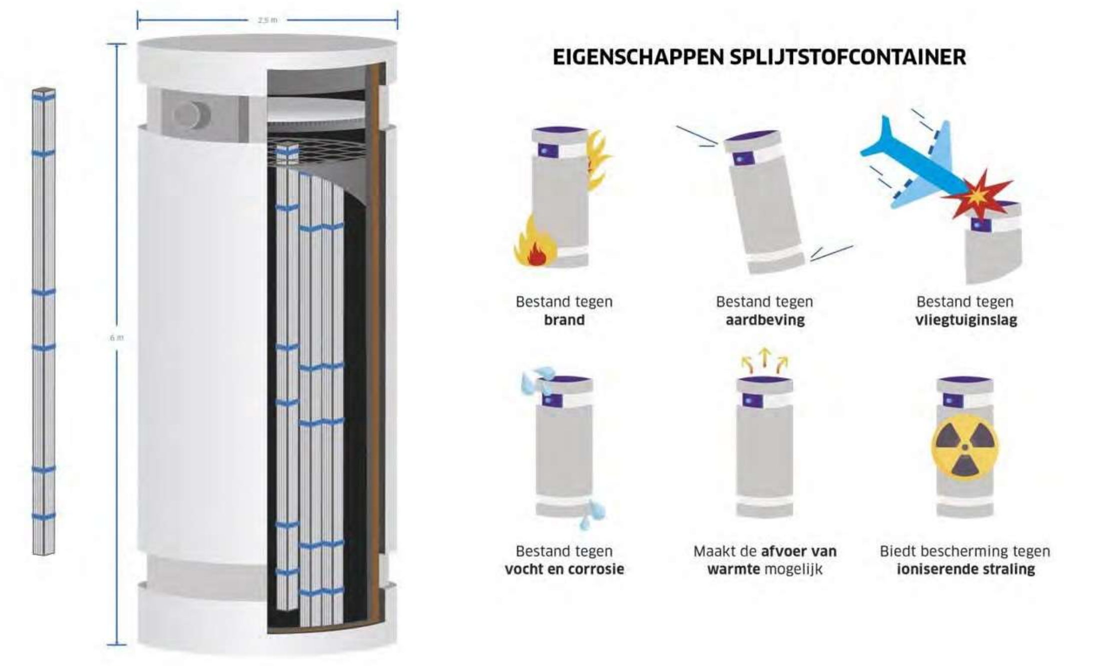

Figure 26: Principle of dry storage of spent fuel elements in Dual Purpose Casks (DPC) as provided in the SF2 storage facilities[liii]. The packaging consists of a metal structure designed to allow the residual heat of the spent fuel to be passively dissipated by internal conduction, radiation and natural convection. The package is made of metal and other materials that provide protection from ionizing radiation.

Both new storage facilities are designed to operate for 80 years such that they can become fully independent after the decommissioning of the other nuclear facilities.

2.3.7.4 Storage

The disposal of radioactive waste, as defined in Belgian legislation, refers to its placement in an installation without the intention of recovering the waste, but without prejudice to the possibility of proceeding to the recovery of the waste, where appropriate.

The term "surface disposal" refers to the disposal of low- and intermediate-level short-lived radioactive waste (Category A waste) in a suitable facility on the earth's surface.

The term "deep disposal" refers to the disposal of radioactive waste in an underground repository in a stable geological formation to contain and isolate the waste from the accessible biosphere on a long-term basis. Deep disposal is internationally regarded as a suitable management solution to sustainably protect humans and the environment from the risks associated with highly radioactive and/or long-lived waste (category B and C waste).

Surface disposal

The permit application for the Category A waste surface disposal facility at Dessel is pending. By federal government decisions of January 16, 1998[liv] and June 23, 2006[lv], Category A waste is destined for disposal in a surface disposal facility on the territory of the Dessel municipality. The purpose of the surface repository at Dessel is to safely dispose of all current and planned Category A waste in Belgium in a surface repository consisting of 34 disposal units (concrete modules). The total volumetric capacity of the repository is 163200 m^3 (4800 m^3 per module) of waste disposal volume. This disposal volume, corresponding to the external dimensions of the caissons (concrete boxes) which, once filled with waste and filler mortar, are called monoliths, allows for a storage volume of 70500 m^3 of category A waste.

There are 3 types of caissons in which the waste will be placed and immobilized (Figure 27):

- Type I caissons can hold 4 400L drums or 5 220L drums of conditioned waste;
- Type II caissons (limited number) are used for non-standard packaging with typically larger volume; and
- Type III caissons are provided for the direct introduction of raw and/or processed radioactive waste (bulk waste). The waste is placed in an inner basket to protect the inside of the caisson from shock during loading and to promote the presence of filler mortar between the inner walls of the caisson and the waste.

Figure 27: Illustrations of the three types of caissons[lvi] containing waste: type I (left), type II (center) and type III (right). After placing the lid and filling the space between waste and caisson with filler mortar, these disposal colli are called "monoliths."

The monoliths are transported to the modules by a trolley. In the modules, monoliths are positioned and stacked by means of a rolling bridge with a gripper designed for this purpose. The filling of the modules is done layer by layer, in layers of 12 × 13 monoliths (Figure 28). A module can contain 936 type I monoliths in 6 layers, or 780 type II or III monoliths in 5 layers.

Figure 28: Sketch of the repository for category A waste during backfilling with monoliths[lvii].

The exact amount of waste that will be salvaged depends, among other things, on the future production of operating and decommissioning waste, and will also be limited by the radiological capacity of the repository[33].

Deep storage

Deep disposal should be understood as the placement of radioactive waste in a repository at an appropriate depth in a suitable geological formation in order to protect the population and the environment from the radiological and physicochemical risks posed by this waste. Deep disposal is proposed as the reference solution for B&C waste, i.e. high-level radioactive waste and long-lived low- and intermediate-level waste, including spent nuclear fuel classified as waste.

In September 2020, ONDRAF/NIRAS submitted a draft Royal Decree establishing the first part of the National Policy on the long-term management of highly radioactive and/or long-lived waste[34], and clarifying the step-by-step process for establishing the other parts of this National Policy, to its guardian ministers [lviii]. In summary, the proposal amounts to the following:

1. Deep disposal on Belgian territory at one or more site(s) is conceptually the recommended scientific-technological and societal choice as final destination for these waste categories. The choice of deep disposal is in line with international standards and recommendations, with the 2011/70/Euratom Directive, with the worldwide scientific consensus, and with the recommendations of the FANC.
2. The following parts of the National Policy are being prepared, developed and, if necessary, adapted as part of an incremental, participatory, gradual and reversible decision-making process

[33] The long-term impact due to disposal, and its acceptability, depend strongly on the considered radiological source term. Restrictions are imposed on the radionuclides that most strongly determine the impact, from the basic principle of limiting the activity content of long-lived radionuclides.

[34] Note that a specific policy measure will be developed for the most radioactive fraction of radium-containing waste derived from historical radium production activities at Olen.

that is intended to prepare future decisions; these parts include at least the decision-making process, the modalities of reversibility, retrievability and monitoring for a period to be determined and location(s) where the deep disposal will be carried out.

3. In order to evaluate the variants, alternatives and optimization of geological disposal, a continuous follow-up of scientific, technical, financial and social developments at international and national level[35] and, on the other hand, an evaluation of the possibility of developing a joint repository in Belgium or in another country will be carried out.

Recently, on Nov. 22, 2022, a Royal Decree was published that establishes the first part of the National Policy on the long-term management of highly radioactive and/or long-lived waste in Belgium. It thus ratifies the decision in principle for deep disposal on Belgian territory, and lays the groundwork to specify the implementation modalities at a later stage and within a clear framework. This will be done gradually through a participatory, transparent and step-by-step decision-making process (part 2), leading to the choice of one or more implementation sites (part 3).

Worldwide, geological disposal sites in stable geological formations are worked out as the most suitable final destination for this type of waste. The most studied formations in this regard are granite formations (e.g. Scandinavian countries), salt (e.g. USA, Germany, Netherlands), and clay (e.g. France, Switzerland, Canada, Netherlands). Little hardened clay layers[36] are also being investigated by ONDRAF/NIRAS in Belgium as a host formation for deep disposal. For example, the Boom Clay[37] has been studied in this context since the 1970s. In the early 1980s, an underground laboratory (HADES) was built in the Boom Clay at a depth of 223 m below the Mol nuclear site to demonstrate the doability of the disposal structure and to conduct various *in situ* experiments at relevant scales. As an alternative host formation, ONDRAF/NIRAS is also investigating the suitability of Ypresian shales[38], which lie deeper. In particular, the Dutch province of Brabant is pushing to investigate this possibility because of the additional isolation and lack of fresh groundwater at that depth. ONDRAF/NIRAS is currently preparing a *methodological* safety and feasibility file for geological disposal, scheduled for 2025. This file will consider deep disposal at various depths between 200 and 600 meters in (unspecified) little hardened clay.

For all types of B and C waste, disposal concepts were developed that rely on concrete packages that ensure sufficient shielding to allow underground operations (Figure 29). Such packaging was also developed for the spent fuel that would not be reprocessed (Figure 30).

For high-level radioactive waste (category C heat-emitting waste), these containers are called "supercontainers. They essentially consist of an overpack in carbon steel placed in a prefabricated concrete buffer. The high pH environment in the concrete causes passivation of the carbon steel so that a very long containment time can be motivated, which must include at least the thermal phase[39]. A supercontainer can contain either 2 standard CSD-V canisters of vitrified waste (Figure 29 left), or 4 UOX

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[35] In doing so, ONDRAF/NIRAS will specifically monitor developments related to deep borehole salvage and advanced nuclear technologies.

[36] Little hardened clay refers to clays that are not compacted to the point of losing their plasticity. Plasticity provides great self-sealing ability.

[37] The Boom Clay is a Tertiary formation belonging to the Rupel Group, formed during the Early Oligocene (33.9 - 28.4 million years ago). It consists of alternating clayey silty and silty clay layers, with a high pyrite and glauconite content in the silty layers.

[38] Ieperian clay refers to the clay of the Kortrijk Formation, formed during the Early Eocene (about 52 million years ago). It is characterized by silty, sometimes sandy, intercalations, which become more important towards the east.

[39] Simply put, the thermal phase is the period during which the host formation, due to the decay heat generated by the waste, is significantly warmer than normal. For the (existing) vitrified waste, that duration is in the order of 800 years, for spent fuel several thousand years.

fuel bundles or 1 MOX fuel bundle (Figure 30). The higher heat dissipation in the case of MOX fuel (and rather low heat tolerance of clay as a host formation) ensures that its disposal density is limited.

For Category B waste, such as the existing reprocessing waste in standard CSD-C canisters consisting of sleeves and end pieces and other technological waste, and the drums containing historical bituminized waste, different types of "monoliths" are used accordingly. These are also concrete containers into which the canisters or drums are placed and the voids filled with mortar (Figure 29 right).

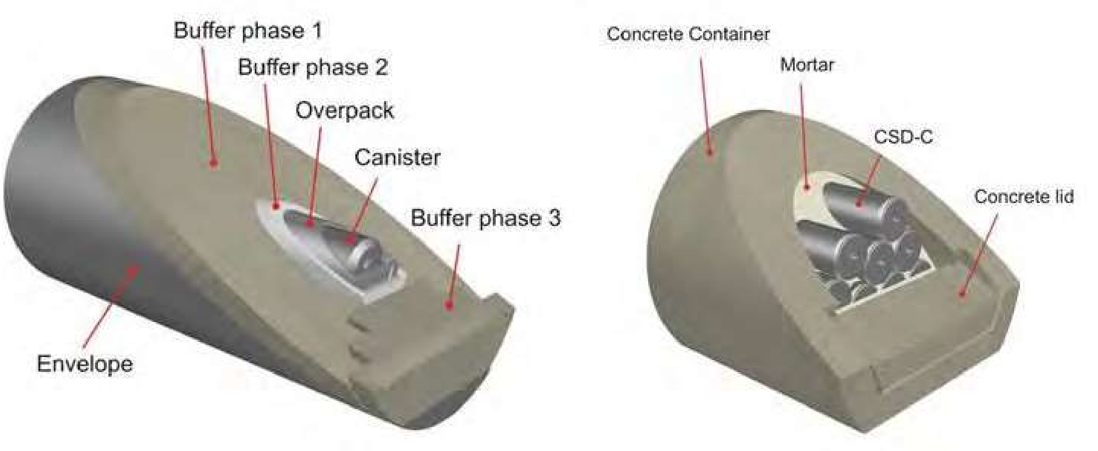

Figure 29: Supercontainer for vitrified waste (li nks)[lix] and monolith-B for compacted waste (right)[lx].

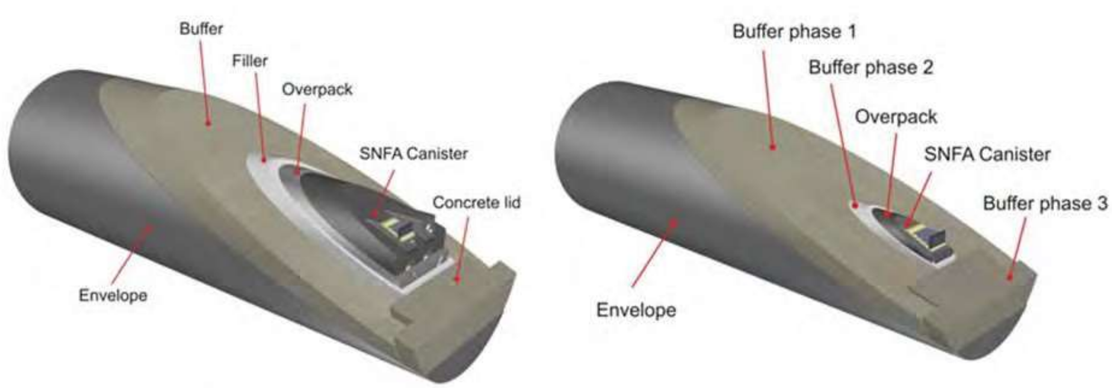

Figure 30: Supercontainers for spent fuel if considered waste: a supercontainer can hold 4 UOX fuel bundles (left) or 1 MOX fuel bundle (right)[lix].

The nature and quantities of the final B&C waste to be managed / disposed of depend on the choices still to be made in the context of the Belgian nuclear fuel cycle.

2.3.8 General methodology radioactive waste and spent fuel

2.3.8.1 Operational radioactive waste and spent fuel

For the radioactive waste and fissile materials section, the potential effects of the postponement of deactivation of Doel 4 and Tihange 3 compared to the reference scenario are budgeted as cumulative quantities accumulated during the ten-year extension of operation within the period 2025-2037. The effects of these additional quantities of waste and fissile material are assessed in light of the management measures discussed in §2.3.7.

2.3.8.2 Decommissioning

Regarding decommissioning, the longer lifetime of the Doel 4 and Tihange 3 reactors may give rise to a difference in the total activation of components, such as the tubular steel. Here it is not impossible that there would be a shift in volume distribution of category A and B waste from decommissioning. This is being investigated and tested based on activation calculations.