EPD®

Certified Environmental Product Declaration

EPD® of Electricity from Vattenfall Nordic Nuclear Power Plants

UNCPC Code 17, Group 171 – Electrical energy

The International EPD® system, EPD International AB - In line with ISO 14025

S-P 00923

2019-12-31

Vattenfall AB - Vattenfall AB Nuclear Power

Confidentiality class: None (C1)

VATTENFALL

Contents

Preface

PRODUCER. Forsmarks Kraftgrupp AB (FKA) and Ringhals AB (RAB) are responsible for the electricity generation in Vattenfall's nuclear power sites. The sites are located north of Östhammar on the Swedish East coast and north of Varberg on the Swedish West coast. The companies are partly owned by Vattenfall AB SE–162 87 Stockholm, telephone +46 8 739 50 00, www.vattenfall.com. Both FKA and RAB have environmental and health and safety management systems certified and registered according to ISO 14001 and ISO 45001.

PRODUCT AND DECLARED UNIT, Electricity belongs to the product category UNCPC Code 17, Group 171 – Electrical energy. The declared unit is defined as 1 kWh net of electricity generated and thereafter distributed to a customer connected to the Swedish regional grid (70/130 kV). The two sites have together four Boiling Water Reactors (BWR) and three Pressurised-Water Reactors (PWR) with a common generating capacity of about 7200 MW. On an average year they generate approximately 47 TWh of electricity. The reactors are of type generation II and once-through fuel cycles are applied, i.e. there is no reprocessing of fuel. Both Forsmark and Ringhals are base load plants.

THE INTERNATIONAL EPD® SYSTEM
The international EPD® system, administrated by EPD International AB, is based on ISO 14025, Type III Environmental Declarations. The relevant governing documents in hierarchical order are: Product Category Rules UN CPC 171 and 173, version 3.1, General Programme Instructions for an environmental product declaration, EPD® version 2.01, ISO 14025, ISO 14040, ISO 14044.

ENVIRONMENTAL PERFORMANCE BASED ON LCA
See below for a summary of methods and results. For more information, see section 3.

System Boundaries. The EPD® comprises the generation of electricity in the nuclear power plant; Upstream processes i.e. uranium fuel production and production of auxiliary supplies; and Downstream processes i.e. distribution of electricity. Further construction and dismantling of the nuclear power plant and the facilities for radioactive waste handling has been included in Core – Infrastructure. The use stage of electricity at the consumer level is not included. The technical lifetime is 60 years. The geographical scope for electricity generation and management of spent nuclear fuel and radioactive waste is within Sweden, whilst the nuclear fuel is produced world-wide.

Environmental Information. A short summary of compiled data is presented below, per generated and distributed kWh electricity.

Upstream	Mining & milling, refinery and conversion, enrichment and fabrication of nuclear fuel. Production of auxiliary substances and chemicals for Nuclear Power Plant (NPP) operation and radioactive waste treatment.
Core	Operation of NPP and facilities for handling radioactive waste and spent nuclear fuel. Incineration or deposit of conventional waste from operations.
Core infrastructure	Construction and decommissioning of the nuclear power plant and radioactive waste facilities, including necessary reinvestments.
Downstream	Operation of electricity networks, i.e. emissions from inspection trips, production and emissions of oils. Extra generation in NPP to compensate for losses in distribution system.
Downstream infrastructure	Includes manufacturing of materials (for lines, cables, pylons, transformers, buildings, and switching stations), ground work and handling of discharge material incl. transportation.

Distribution of electricity implies losses, which must be compensated for by increased generation. The loss to an average large industrial customer connected to the regional distribution network (70/130 kV) amounts to 3% (included in the downstream column below). The losses are different for different types of customers and often higher in the countryside. The average loss to a household customer varies between 7-9%.

Ecoprofile

Input

Resources	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Copper in ore	g	2,02E-03	3,65E-06	1,64E-03	**3,66E-03**	1,11E-04	6,79E-03	**1,06E-02**
Fossil energy resources	MJ	2,04E-02	3,74E-04	3,73E-03	**2,45E-02**	1,57E-03	1,61E-02	**4,21E-02**
Gravel, stone & sand	g	3,29E+00	5,58E-02	6,34E+00	**9,69E+00**	2,91E-01	1,08E+00	**1,11E+01**
Iron in ore	g	3,34E-02	0	5,54E-02	**8,88E-02**	2,80E-03	5,76E-01	**6,67E-01**
Limestone	g	2,12E-01	2,34E-03	7,43E-01	**9,57E-01**	2,89E-02	2,38E-01	**1,22E+00**
Potential energy through hydro turbines[2]	MJ	2,80E-03	1,50E-03	1,31E-03	**5,61E-03**	1,70E-04	7,12E-04	**6,49E-03**
Renewable fuel (biomass)	MJ	1,04E-04	1,58E-06	1,32E-03	**1,42E-03**	4,38E-05	2,65E-04	**1,73E-03**
Soil	g	1,04E-01	1,50E-02	8,20E-01	**9,38E-01**	2,81E-02	0	**9,66E-01**
Uranium in ore	g	1,88E-02	4,15E-06	6,27E-06	**1,88E-02**	5,65E-04	8,77E-07	**1,94E-02**
Zirconium sand	g	5,77E-04	1,39E-07	2,04E-05	**5,98E-04**	1,80E-05	4,51E-06	**6,20E-04**
Electricity use in the power plant[3]	MJ	0	1,36E-01	0	**1,36E-01**	4,09E-03	0	**1,40E-01**
Water, different sources	g	2,99E+04	1,05E+04	2,98E+03	**4,34E+04**	1,25E+04	1,61E+01	**5,59E+04**
Other input (agg. of remaining substances)	g	5,46E-02	3,82E-04	3,11E-02	**8,60E-02**	2,68E-03	5,11E-02	**1,40E-01**

Output: emissions

Pollutant emissions	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Global Warming Potential	g CO_2-eq. (100years)	1,87E+00	1,76E-01	4,30E-01	**2,48E+00**	2,17E-01	1,44E+00	**4,13E+00**
Global Warming Potential incl. biogenic CO_2	g CO_2-eq. (100years)	2,01E+00	2,32E-01	5,21E-01	**2,76E+00**	2,26E-01	1,45E+00	**4,44E+00**
Acidification Potential	g SO_2-eq.	4,97E-03	1,28E-03	2,36E-03	**8,61E-03**	4,12E-04	9,43E-03	**1,85E-02**
Photochem. Ozone Creation Potential	g Ethene-eq.	4,88E-04	9,76E-05	1,77E-04	**7,63E-04**	5,45E-05	1,32E-03	**2,14E-03**
Eutrophication Potential	g Phosphate-eq.	2,85E-03	2,93E-04	4,05E-04	**3,55E-03**	1,45E-04	4,87E-03	**8,56E-03**
C-14 to air	kBq	5,13E-05	6,46E-02	1,43E-05	**6,47E-02**	1,94E-03	2,05E-06	**6,66E-02**
Kr-85 to air	kBq	2,88E-02	4,71E-02	1,23E-04	**7,59E-02**	2,28E-03	4,87E-07	**7,82E-02**
Rn-222 to air	kBq	1,18E-02	2,71E-03	5,50E-03	**2,01E-02**	6,09E-04	4,68E-04	**2,11E-02**
Particulate matter to air	g	3,27E-03	1,52E-04	4,71E-04	**3,89E-03**	1,31E-04	7,24E-03	**1,13E-02**
Polyaromatic hydrocarbons	g	3,42E-07	1,09E-07	1,93E-07	**6,45E-07**	2,02E-08	2,93E-06	**3,60E-06**

Output: waste

Waste and material subject to recycling	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure[7]	Total - distributed
Hazardous waste								
Hazardous waste to disposal	**g**	2,35E-03	8,45E-04	7,78E-06	**3,20E-03**	9,59E-05	0	**3,29E-03**
Hazardous waste to Incineration	**g**	5,79E-03	1,83E-03	0	**7,62E-03**	2,29E-04	0	**7,85E-03**
Radioactive waste								
Volume of deposit for high-level radioactive waste[4]	**m³**	6,05E-13	2,26E-09	7,06E-15	**2,26E-09**	6,78E-11	0	**2,33E-09**
Volume of deposit for low/medium-level radioactive waste	**m³**	3,57E-11	4,21E-08	5,03E-08	**9,25E-08**	2,77E-09	0	**9,52E-08**
Low-level radioactive waste without further treatment	**g**	1,92E-02	9,02E-04	3,69E-05	**2,02E-02**	6,06E-04	0	**2,08E-02**
Spent fuel[5]	**g**	0	3,08E-03	0	**3,08E-03**	9,24E-05	0	**3,17E-03**
Uranium in spent fuel	**g**	0	2,72E-03	0	**2,72E-03**	8,15E-05	0	**2,80E-03**
Waste to recycling[6]								
Aluminium	**g**	0	0	2,45E-04	**2,45E-04**	7,35E-06	0	**2,53E-04**
Crushed concrete	**g**	0	0	6,75E-01	**6,75E-01**	2,03E-02	0	**6,96E-01**
Copper scrap	**g**	0	1,82E-06	2,32E-03	**2,32E-03**	6,97E-05	0	**2,39E-03**
Lead scrap	**g**	0	0	1,25E-03	**1,25E-03**	3,75E-05	0	**1,29E-03**
Steel scrap	**g**	1,41E-04	5,98E-05	7,12E-02	**7,14E-02**	2,14E-03	0	**7,35E-02**
Other waste to recycling	**g**	1,99E-02	1,22E-01	2,74E-03	**1,44E-01**	4,33E-03	0	**1,49E-01**
Other waste								
Waste to disposal	**g**	1,25E+01	6,27E-02	1,57E+00	**1,42E+01**	4,25E-01	0	**1,46E+01**
Waste to incineration	**g**	2,53E-04	1,08E-02	3,42E-02	**4,52E-02**	1,36E-03	0	**4,66E-02**
Waste water	**g**	6,16E+03	7,45E+00	1,10E+04	**1,72E+04**	5,31E+02	5,21E+03	**2,29E+04**

[1] Distribution losses of 3% of generated electricity are included in the Downstream column.
[2] Hydropower is reported as used potential energy (1 kWh hydroelectricity = 1,14 kWh potential energy).
[3] It is assumed that this electricity is generated by the NPP itself. The environmental impact is accounted for since this amount of electricity has been subtracted from the reference flow.
[4] High-level radioactive waste from electricity generation in upstream processes is assumed to be further processed and is not classified as waste in the generic data.
[5] Spent fuel includes the entire uranium fuel in g UO_2. The fuel assemblies (steel, zircalloy and Inconel components) are included in the volume deposit categories above.
[6] Use of recycled material is classified as secondary resources according to GPI.
[7] All waste flows are transformed into resource use and emissions through appropriate waste management processes. Thus, no waste amounts reported from Downstream infrastructure.

Conclusions of the LCA

The major environmental impact from nuclear power, in terms of emissions such as greenhouse gases, eutrophying and acidifying substances and potentially ground-level ozone creating substances, is attributable to the activities in the upstream processes, especially during mining of uranium and enrichment processes. The biggest contribution to emissions in the uranium extraction and milling phase comes from the uranium extraction activity and electricity consumption, while it in the enrichment phase derives from the electricity consumption. All in all, upstream processes contribute to 23-45% of the impact depending on impact category.

If the distribution of electricity is also included, the environmental impact from nuclear power is mainly caused by construction and decommissioning of the grid for distribution of the electricity generated. The downstream processes contribute to 38-64% of the total impact, depending on impact category. See section 3.4.5 for a dominance analysis of the results

The greenhouse gas emissions from generation and distribution of electricity are just above 4 g CO_2e per kWh which is slightly lower than compared to last update of the EPD. See section for 3.4.6 for a description of the largest contributions to this difference.

ADDITIONAL ENVIRONMENTAL INFORMATION

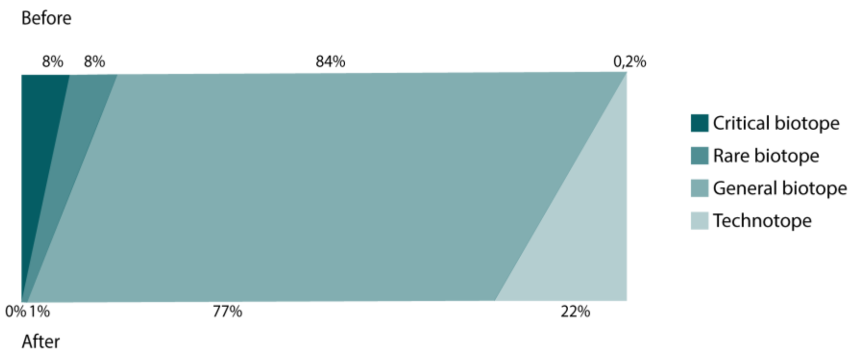
The complete certified declaration also contains descriptions of environmental risks, ionizing radiation issues and impacts on biodiversity in accordance with the EPD® system instructions.

Land use and Impact on Biodiversity

Vattenfall's Biotope Method is used to quantify impacts on biodiversity as a direct consequence of the utilisation of land and water for economic activities. Affected areas are categorised into Critical biotope, Rare biotope, General biotope and Technotope. In the table and figure below the identified biotope changes are shown. See section 4.1 for more information.

	Biotope Change (ha)	Biotope Change Allocated (ha)	Allocated areas (m^2/kWh el)		Biotope Change per kWh electricity (m^2/kWh el)
			Before After	Before After	
Critical Biotopes	-44 310	-6	8%	0%	$-2\cdot10^{-6}$
Rare Biotopes	-2890	-5	8%	1%	$-2\cdot10^{-6}$
General Biotopes	-770	4	80%	80%	$3\cdot10^{-7}$
Technotopes	8090	7	0,2%	20%	$4\cdot10^{-6}$

Biotopes allocated to Vattenfall production (m^2/kWh el)



Safety, Barriers and Radiation

The nuclear power industry is strictly regulated and closely monitored by authorities. The operator of a NPP is the owner of and responsible for the nuclear fuel from mining to final repository. In addition to strict design criteria including redundant control systems there are safety considerations at three levels. See section 4.2 for more information.

Radioactive substances in various forms are handled during normal operation by facilities in the nuclear fuel cycle. These substances emit ionizing radiation that may result in doses to the people working in the facility (dose-to-personnel), and to people outside the facility (dose-to-third party).

Dose to personnel. The table below show the average dose to personnel at the different facilities in the nuclear fuel life cycle.

	Unit	Upstream facilities	NPP-operation	Nuclear waste handling
Average individual dose	**mSv**	0,07 – 1,8	0,96 – 0,98	0,1 – 1,5

Dose to critical group/dose to representative individual is an assessed effective dose (mSv) that is received by an individual living in the vicinity of the facility. This is commonly a hypothetical individual that is assumed to represent a person that is more exposed due to its habits and consumption pattern, the critical group /representative individual may be defined differently between countries due to the type of facility, the emissions as well as the surrounding environment.

Maximum calculated annual effective dose 2018 from FKA and RAB was 0,00014 respectively 0,00029 mSv to a 7-12-year individual in the critical group. For comparison, if you live in Sweden the annual radiation dose is about 0,6 mSv from naturally occurring radioactive substances in soil and building materials. The total dose varies, but the average is about 4 mSv including for instance medical radiation and radon in homes.

Environmental Risk Assessment

The conclusion is that environmental risks in the nuclear fuel chain have low probability according to acceptance criteria set by the regulatory body. See chapter 4.5 for more information.

Noise

Noise has been measured in the surroundings of the NPPs. Beside the level of noise generated at the original source, the noise level at a specific measuring point is also dependent on external circumstances such as for example wind direction and temperature. Maximum noise levels have been measured to be kept within the environmental permits for the nearest households in the vicinity of the power plant, which are 40 dB(A) (night) and 50 dB(A) (daytime) for Forsmark, and for Ringhals 43 dB(A) (night) and 50 dB(A) (daytime).

1. Introduction

1.1. Declared Unit

This document constitutes the certified Environmental Product Declaration EPD® of electricity from the nuclear power plants (NPP) Forsmark and Ringhals operated by Vattenfall AB.

The declared unit is 1 kWh net electricity generated and thereafter distributed to a customer connected to 70/130 kV

Forsmark and Ringhals nuclear power plants are base-load plants of the Swedish electricity system meaning that they provide a continuous supply of electricity throughout the year with some minimum power generation.

1.2. The Declaration and the EPD® system

Environmental Product Declaration is recognised as a tool for industry for the communication of the environmental impact of products and services.

This Environmental Product Declaration is an EPD® in accordance with the system administered by EPD International AB (www.environdec.com). EPD® is an international application of ISO 14025, Type III environmental declarations. The International EPD® system and its application are described in General Programme Instructions.

The hierarchic structure of the fundamental documents for the EPD® system is:

- Product Category Rules UN CPC 171 AND 173 (for preparing an environmental product declaration for Electricity, Steam and Hot/Cold Water Generation and Distribution), version 3.1.
- General Programme Instructions for the International EPD® System (GPI), version 2.01.
- ISO 14025 on Type III environmental declarations.
- ISO 14040 and ISO 14044 on Life Cycle Assessments (LCA).

This EPD® contains an environmental performance declaration based on a life cycle assessment. Additional environmental information is presented in accordance with the Product Category Rules (PCR):

- Information on land use:
    - an assessment of impact on biodiversity based on The Biotope Method, (Grusell E. et al, 2015),
    - a categorisation of land use according to Corine Land Cover Classes, land occupation time, periods and exploitative activities,
    - a description of visual impacts,
- Information on radiology, doses to personnel, doses to third party.
- An Environmental Risk Assessment (ERA) for the potentially environmentally or human toxicologically harmful emissions that may result from abnormal incidents and accidents.
- Electromagnetic fields, a description of measures to keep fields low and some information on limits and recommendations by different bodies.
- Noise.

1.3. Vattenfall, LCA and EPD®

Vattenfall has applied LCA for several years for different energy sources and has accumulated competence and experience in this field. The additional development through the EPD® enhances the ability to inform objectively about the complex environmental issues associated with the generation of electricity.

There are multiple reasons to environmentally declare electricity, most significantly:

- Electricity is used in the manufacturing of virtually every product. Information regarding the environmental footprint in electricity production is pivotal to LCAs for other products. This has generated an increased interest in the market for this type of information primarily because users need certified and modular life cycle data that are possible to sum up as inputs to their own EPD® and LCA.
- EPD® provides a basis for professional procurement, private as well as public sector, in allowing comparison of different power sources, heat production technologies, and different producers. This creates an incentive for producers to reduce their use of resources and the impact on the environment caused by their systems.
- EPD® is an effective instrument in the continuing environmental efforts within Vattenfall, the objective being constant improvement and being in line with ISO14001.
- The Directive 2009/72/EC requires member states to introduce systems for customer information regarding the origin of the electricity and, at a minimum, provide figures on CO_2 and radioactive waste. The information given in an EPD® is of a high quality and exceeds the requirements in the Directive.
- The demand for Climate Declarations. The International EPD® system has issued so-called climate declarations as the first example of single-issue EPDs. It describes the emissions of greenhouse gases, expressed as CO_2-equivalents for a product's life cycle, based on verified results from LCA – based on information in accordance with ISO 14025.

Nuclear power differs from other power technologies e.g. in that:

- The nuclear fuel cycle and the technology are complex, and fuel is produced and refined in various locations.
- Radioactive substances are formed during the process.
- Ionizing radiation can neither be seen, heard nor felt.
- The general public worries about accidents and long-lived radioactive waste.

2. Producer and product

2.1. Producer

2.1.1. Vattenfall Nuclear Power Plants (NPP)

The product (electricity) described in this EPD is generated in the NPP´s Forsmark and Ringhals. They are two of the largest power plants in Sweden and important base load plants of the Swedish electricity system, contributing to approximately 42% of the annual production in the country in the year 2018. Forsmark power plant is situated on the east coast of Sweden, in the region of Uppland, some 70 km northeast to the city of Uppsala. Ringhals power plant is situated on the west coast of Sweden, close to Varberg in in the region of Halland, some 60 km south of Gothenburg, see map in *Figure 4*.

By the end of 2019 one of the reactors at Ringhals (R2) will be taken out of operation, and another reactor (R1) will be taken out of operation the subsequent year. These reactors are included in this EPD and their generation has been adjusted to their actual lifetimes.

Forsmark power plant is owned and operated by Vattenfall AB (66%) and a number of private and public energy utilities under the name of Forsmarks Kraftgrupp AB (FKA). The company was formed in 1973. Ringhals power plant is owned and operated by Vattenfall AB (70,4%) and Sydkraft Nuclear Power (29,6%) and goes under the name of Ringhals AB (RAB).

FKA and RAB have a common organisation and one CEO. The CEO of FKA and RAB carries the ultimate responsibility for operations. Environmental Supervisory and controlling support, including reactor safety and radiological protection, is managed by internal functions at the power plants. Monitoring of environmental work and reporting to authorities is managed by the environmental departments. FKA and RAB, as plant owners, are by Swedish law responsible for paying for any radiological damage in case of an accident with releases to the environment.[1]

[1] Law (2010:950) on responsibility and compensation for radiological damage. (Swedish: Lag (2010:950) om ansvar och ersättning vid radiologiska olyckor)

Procurement of nuclear fuel requires a permit issued by the Swedish Government in accordance with present legislation (Kärntekniklagen). Permits are only granted to operators of NPPs. The Operators Ringhals AB and Forsmark Kraftgrupp AB as well as Vattenfall Nuclear Fuel AB have received such permits and are the owners of the uranium from cradle to grave, i.e. from natural uranium to final repository of nuclear waste. SKB has a permit to operate the waste facilities on behalf of Vattenfall.

2.1.2. Vattenfall AB, and Subsidiaries

The majority owner of FKA and RAB, Vattenfall AB, is one of the largest producers of electricity and heat in Europe. Net sales amounted to 156,824 billion SEK 2018 (app. 14,4 billion EUR). Although Vattenfall is owned by the Swedish government, it is not only present in Sweden, but also in Denmark, Finland, Netherlands, Germany and the UK. Vattenfall´s purpose is to Power Climate Smarter Living and the ambition is to enable fossil free living within one generation. This means that Vattenfall is committed to contribute to the climate agenda and reduce its environmental footprint. The work that Vattenfall does within LCA and EPD is very important in this context. Vattenfall has set ambitious goals to transition to fossil free energy production in line with science on climate change.

In 2018 Vattenfall generated 130,03 TWh electricity of which 31,6 TWh was fossil power, 55,0 TWh nuclear power, 35,5 TWh hydro power, 7,8 TWh wind power and 0,4 TWh electricity from burning biomass and waste. Furthermore, Vattenfall produced 18,9 TWh heat and had net sales of 57,2 TWh gas during 2018.

2.1.3. Forsmark and Ringhals Nuclear Power Plants (NPPs) –Technical information

Forsmark consists of three boiling-water reactors (BWR) of the light-water type (LWR). Two of the reactors, Forsmark 1 and Forsmark 2 are practically identical and Forsmark 3 is of a more recent model. Ringhals has one boiling-water reactor (BWR) Ringhals 1, and three pressurised-water reactors (PWR) of the light-water type (LWR). Two of the reactors, Ringhals 3 and Ringhals 4 are practically identical and Ringhals 2 is of an earlier design. As mentioned above, R1 and R2 will be taken out of operation after 2020 and 2019 respectively but are included in this EPD. The calculation of the total lifetime production takes into account their respective closing dates.

The reactors are cooled with seawater (Forsmark reactors with 150 m^3 per second and Ringhals reactors with 170 m^3/second) and the temperature of the outlet water is 10 °C higher when it is released to the Bay of Bothnia and Kattegatt, North Sea respectively. In the BWR type reactors, 20% of the fuel is replaced during revision every summer and in the PWR type reactors 25% is replaced.

The power output, annual average generation, average efficiency and total fuel loads are listed for each reactor in **Fel! Hittar inte referenskälla.** Also, the commissioned year and the planned closing-down year are listed for each reactor.

Table 1 Forsmark and Ringhals technical data

Reactor unit	Power output (MWel.)	Average generation[1] (TWh)	Average efficiency [2] (%)	Total fuel load (tonne UO_2)	Commissioned (year)	Planned close down
Forsmark 1	965	7,7	33	134	1980	2040
Forsmark 2	1 099	8,3	34	134	1981	2041
Forsmark 3	1 157	7,9	35	138	1985	2045
Ringhals 1	881	6,2[3]	33	125	1976	2020
Ringhals 2	852	5,0[4]	33	83	1975	2019
Ringhals 3	1 063	7,8	32	82	1981	2041
Ringhals 4	1 103	7,9	32	82	1983	2043
Total	**7 120**					

[1] Forsmark 1-3 and Ringhals 3-4 average from 2014-2018
[2] Based on the thermal energy in the reactor.
[3] Planned annual production for 2019 and 2020. Ringhals 1 will be closed after 2020.
[4] Planned production 2019 (Jan-Oct). Ringhals 2 will be closed end of year 2019.

Figure 1 Forsmark 3, turbine hall

2.1.4. Environmental Management System

Since 1998 Ringhals and Forsmark have certified environmental management systems according to ISO 14001. Both power plants are also certified according to ISO 45001 for occupational health and safety.
The environmental and health and safety management systems are an integral part of the facilities' management systems, which comprises the whole organization, planning, accountability, routines, and processes.

2.2. Product System Description

2.2.1. The Nuclear Life Cycle

The nuclear fuel cycle describes all the different steps and activities that are undertaken when uranium is used for the generation of electricity. All the stages from "the cradle to the grave" are included in this life cycle inventory (in accordance with the PCR), hence the full path from mining of natural uranium, through production of uranium fuel and generation of electricity at the NPP to final repository of the spent fuel. These steps can be aggregated into three major processes: Upstream, Core and Downstream, and are briefly described below.

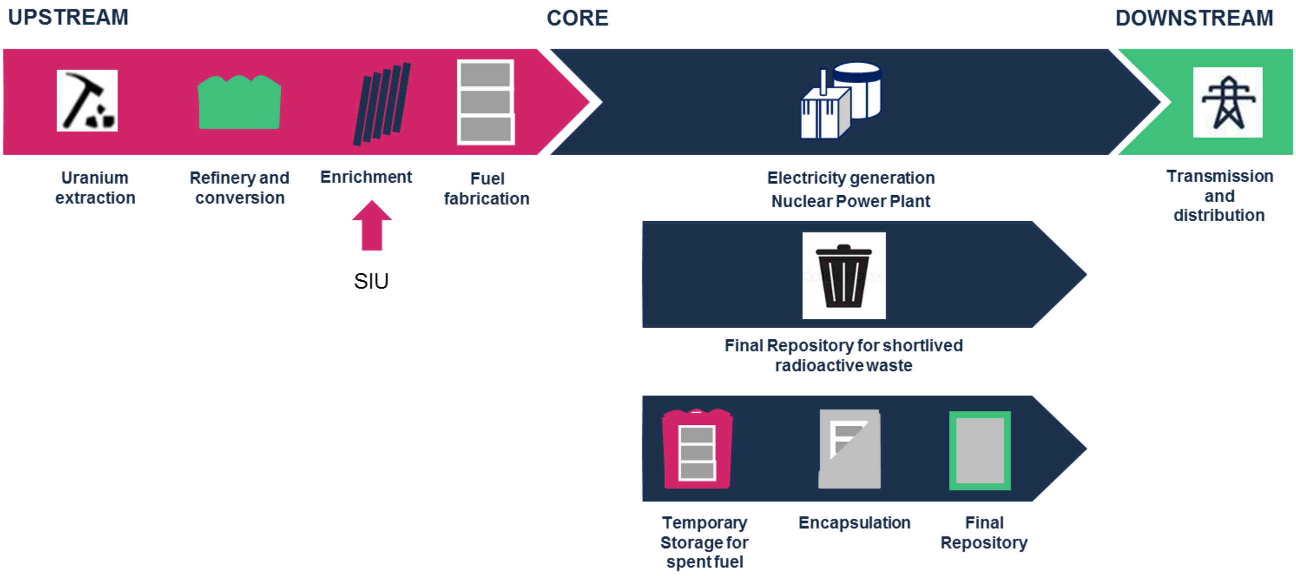


Figure 2 The nuclear value chain from mining of uranium ore to final repository and electricity distribution. Infrastructure for core processes and downstream processes are included.

Upstream Processes:

- **Uranium Extraction**
  The natural uranium ore is extracted via mining (in underground mine or open pit mine) and milling. Uranium oxide (U3O8) is produced, so called "yellow cake".
- **Refinery and Conversion**
  The "yellow cake" is converted (via a wet or dry process) into uranium hexafluoride UF_6. The content of the radioactive isotope uranium U235 is then less than 1%.
- **Enrichment**
  Through an enrichment processes (such as the centrifuge method) the content of U235 in the UF_6 is increased to 3-5%.
- **Fuel Fabrication**
  The enriched UF_6 is used for production of fuel pellets, consisting of uranium dioxide (UO_2), which are gathered in fuel assemblies, ready to use in nuclear power plants.
- **Reprocessed uranium**
  In some cases, one or more of the steps above can be replaced by reprocessing uranium. Vattenfall is, during the years of validity of this EPD, procuring reprocessed material in the form of Slightly irradiated uranium, SIU. If the SIU is enriched, the product can readily be used in nuclear plants. SIU is hence a waste-product that can replace mining, refining and conversion.

Core Processes:

- **Electricity Generation**
  Via fission processes in the nuclear power plant the nuclear energy in the fuel is converted into heat energy, which is turned into electric energy. Each fuel assembly can be used for approximately 4-5 years before it is removed from the reactor and stored as spent fuel at on-site storage pools at Forsmark and Ringhals for about 12-18 months.
- **Final Repository for Short-lived radioactive waste**
  The short-lived operational waste is transported to the rock vault repository in Forsmark, a facility called SFR. In the future, short-lived radioactive waste from decommissioning is also planned to be finally disposed of there.

- **Long lived radioactive waste** from dismantling and decommissioning of the NPP´s will be finally disposed of in SFL, a final repository not yet built, located or licensed, however it is planned to be established after 2040[2].
- **Temporary Storage for spent fuel**
  The spent fuel is transported to the central interim storage facility for spent nuclear fuel (CLAB). At CLAB the fuel is temporary stored in water pools for approximately 30 years. The purpose is to reduce the generation of heat from the spent fuel to a level necessary for disposal in a final repository.
- **Encapsulation**
  After interim storage the spent fuel will then be placed in copper canisters at an encapsulation plant adjacent to CLAB (which is not yet built).
- **Final Repository**
  The canisters with the spent fuel will be transported to the final repository where they will be deposited at about 500 meters depth, in the bedrock close to Forsmark NPP. They will be covered by bentonite clay (which is not yet built).

Downstream processes

- **Transmission and distribution**
  The electricity produced at the NPP is transmitted to the consumers/end users via the transmission and distribution grid.

2.2.2. Upstream Processes – Selected Suppliers

Vattenfall Nuclear Fuel, owned by Vattenfall AB, is commissioned by the NPPs to purchase the uranium fuel for Vattenfall's NPPs. There are several suppliers in the different stages in the uranium processing chain and the suppliers selected for this EPD® cover 94-100% of the uranium fuel used. Suppliers have been selected to cover the different technologies used in the different uranium processing steps, and different geographies.

The supplier selection in this EPD® is based on existing contracts for purchase during 2019-2022. Included suppliers and their representativeness are presented in the map and text below.

Figure 3 Upstream process facilities location worldwide.

The selected suppliers for the different process steps are listed with their representativeness and respective techniques below.

---

[2] As this facility is yet in the planning phase, the environmental data is not sufficient to evaluate land use and radiology impacts, and hence it has been excluded from chapter 4.1-3. The facility is however assed from a risk and LCA perspective.

Uranium extraction (Mining & milling)
The selected suppliers represent 94% of the fuel used.

- Cameco, Cigar Lake underground mine/McClean Lake milling, Canada
- Rio Tinto, Rössing, open pit mining, Namibia
- BHP Billiton, Olympic Dam, underground mine, Australia
- Tenex, SIU (Slightly irradiated uranium - reprocessed uranium), Russia

Refining & Conversion
The selected suppliers represent 100% of the refining & conversion service needed. They both use the wet process where the uranium oxide is dissolved in nitric acid.

- Cameco, Blind River & Port Hope, Canada
- Orano, Malvési & Tricastin, France

Enrichment
The selected suppliers represent 100% of the enrichment service needed. They use the centrifuge process for enrichment.

- Orano, George Besse II, France
- Tenex/UEIP, Novouralsk, Russia
- Urenco, Great Britain

Fuel Fabrication
The selected suppliers represent 100% of the service needed. The process is similar for all suppliers.

- Framatome, Lingen, Germany (BWR fuel)
- Framatome, Romans, France (PWR fuel)
- Westinghouse, Västerås, Sweden
- GNF, Wilmington, USA (chemical conversion)/Juzbado, Spain (fuel fabrication)

2.2.3. Core Process – NPPs and Management of Conventional and Radioactive Waste

The NPPs and the facilities for management of radioactive wastes included in this EPD® are presented and location shown in the map below.

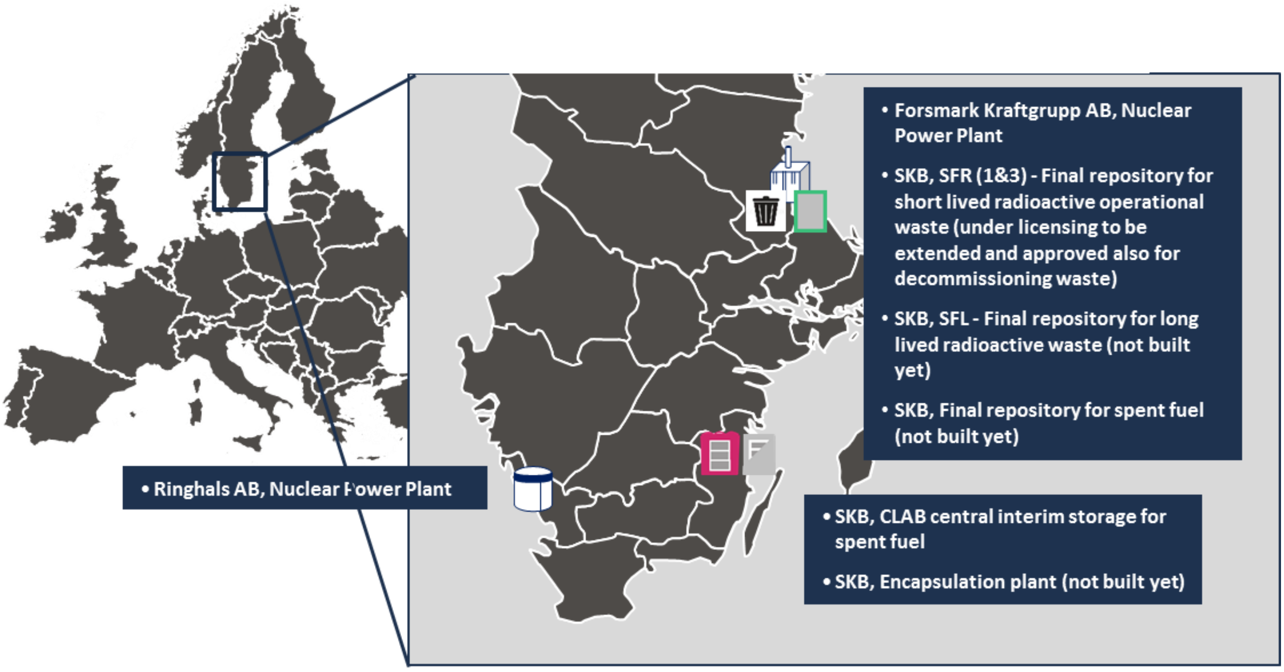


Figure 4 Core process facilities location

Included in this EPD® are the facilities for central interim storage (CLAB), encapsulation and final disposal of spent nuclear fuel, the final repositories for short-lived radioactive waste (SFR, existing) and long-lived radioactive waste (SFL, future facility), and the nuclear power plants. Waste from operation of the NPPs is transported to SFR and waste from dismantling of the NPPs is planned to be disposed at both SFR and SFL. The responsibility for developing and operating the system of facilities used to handle all waste from all the Swedish nuclear power plants lies within the Swedish Nuclear Fuel and Waste Management Company (SKB).

2.2.4. Downstream Process – Distribution of Electricity

The downstream process comprises the transmission and distribution of the product, electricity, to its end users via its distribution chain consisting of numerous lines, cables, transformers, and switchgears.

The national grid voltage (200-400 kV) is reduced to lower voltages (regional network 70-130 kV) for distribution over distribution networks (10–130 kV) and low voltage local networks (0,4 kV) to consumers. Large customers, e.g. certain industries, are frequently connected to the high or medium voltage distribution network (10–130 kV), while small users such as single households are connected at 0,4 kV to low voltage local networks.

During the transmission and distribution phases, losses of electricity occur. These losses depend on several factors such as distance, load, feed voltage, and user connection voltage. In general, the higher the voltage, the lower the losses. To an industrial customer connected to the regional network, the average distribution loss is 3% whereas the loss to a household customer in the countryside is 9%.

Figure 5 The distribution loss to an industrial customer connected to the regional network is 3% on average, whereas the loss to a household customer in the countryside is 9%.

Distribution losses lead to reduced delivery of useful electricity, which must be compensated for by additional generation in the power plant and consequently additional resource use and emissions.

In this study the losses are supposed to be compensated for through additional generation in Forsmark and Ringhals NPPs. In the downstream calculations, losses of 3% have been used, representing a typical industrial customer on the 70-130 kV distribution network.

Figure 6 Power lines.

3. Environmental Performance Based on LCA

3.1. Life Cycle Assessment Method

This EPD® for electricity from Forsmark and Ringhals NPPs is based on a comprehensive LCA. The declared unit is 1 kWh net generated at plant fed to the national grid and delivered to an industrial customer connected to the regional network (70/130 kV). The used net electricity generation is calculated as the net electricity generation for the year 2018.

The assessment comprises operation of all facilities in the nuclear fuel cycle. Construction and decommissioning of the nuclear power plant and waste facilities for radioactive waste are also included. The distribution of electricity has been included in terms of distribution losses as well as construction, operation phase and dismantling.

In summary the Ecoprofile has been determined as follows:

- The NPPs' share of the supplier in question has been calculated based on the average annual need for fuel during the reference period,
- The NPPs' operation has been inventoried with respect to use of electricity, fuels, auxiliary materials and chemicals, emissions and handling of conventional wastes as well as on-site transports and test operation of reserve power,
- The facilities for management of radioactive wastes have been inventoried individually along with necessary transportation of the waste,
- The NPPs' share of the different facilities for management of radioactive wastes have been calculated,
- Environmental impact per kWh of the lifecycle excluding infrastructure is the sum of the – to the NPPs' allocated – portions of the environmental impact of suppliers and radioactive waste management facilities and of the NPPs themselves (including necessary reserve power testing) divided by the reference flow i.e. the annual average electricity net generation during the reference period,
- Environmental impact per kWh of included lifecycle infrastructure (construction and decommissioning) is divided by the annual average electricity net generation during the reference period and the technical service life i.e. the assumed electricity net generation during the technical service life.

Excluded from the lifecycle:

- Impacts due to potential accidents, breakdowns, and leakages (included in Additional Environmental information, section 4.4).

3.2. Technical Service Life, Reference Flow, Reference Year

The technical service life time is different for different facilities in the NPPs life cycles. The technical service life time of the NPPs, as for all Swedish NPPs, influences the environmental impacts from infrastructure (construction and dismantling) and operation of the different facilities in the core process. Further, the technical service life time of suppliers' facilities vary. Since construction and decommissioning of those facilities are excluded, the technical service life time has no relevance on the LCA results, only on biotope impact, see chapter 4. Table 2 below provides an overview of reference flow data in the lifecycle.

Table 2 Reference flow data.

Description of reference flows used in the LCA	TWh
Average electricity generation in the NPPs (Vattenfall share)	30,0
Electricity generation in the NPPs during their technical lifetime (Vattenfall share)	1 835
Estimated total electricity generation in all Swedish reactors during their technical service life times	3 646
Electricity transfer during the technical service life time of the transmission grid 220/400 kV	4 892
Electricity transfer during the technical service life time of the regional network 70/130 kV	2 920

Table 3 Reference flow, technical service life time and reference year

Facility	Technical service life [years]	Infrastructure: Reference flow [TWh]	Operation: Environmental data, reference year	Operation: Reference flow [TWh]
Upstream				
Mines Refinery & Conversion Enrichment Fuel fabrication	Not applicable	Not applicable	Operational data from 2018[1]	30,0[2]
Core				
Ringhals 1,2 Ringhals 3,4 & Forsmark 1, 2, 3	44 60	1 835[3]	Operational data from 2018	30,0[3]
CLAB	86	3 646[6]	CLABs operational data from 2018	3 646[6]
Encapsulation plant	41		Estimated operational data for encapsulation of total spent fuel from all Swedish reactors during their technical service life times. The lifetime requirement of canisters and total lifetime production provides operating data per kWh	
SFR existing[4]	87		SFR's operational data from 2018	
SFR expansion[4]	47		No operation data available, data estimated from existing SFR[3]	
SFL[5]	9		No operation data available, data estimated from existing SFR[3]	
Final repository[5]	41		Estimated operational data for the deposition of total spent fuel from all Swedish reactors during their technical service life times. Estimated operating data for encapsulation is reported per canister.	
Downstream				
Transmission grid	40	4 892	Operational data from Swedish Vattenfall power networks (2008) Length and transferred energy from ENTSO-E and Svenska Kraftnät (2017)	122,3
Regional network	40	2 920	Operational data from Swedish Vattenfall power networks (2008) Length and transferred energy from Vattenfall Distribution (2018 and 2016)	73,0

[1] The supplier selection is based on existing contracts for purchase during 2019-2022.
[2] Converted to the needed amount of uranium, see Figure 7
[3] Vattenfall's share of the production at Forsmark and Ringhals
[4] In the previous version of the EPD, certified in 2016, SFR existing was called SFR1 and SFR expansion was called SFR3
[5] Not yet built. Technical service life time for these facilities have been estimated by SKB and for the final repository for spent fuels it represents the time after which all spent fuel has been deposited and the repository has been sealed. After sealing, the surface area can be used for other purposes.
[6] Vattenfall's share emanates to 50,3%

3.3. System Boundaries, Allocation and Data Sources

3.3.1. System Boundaries
Table 4 describes the life cycle in 13 phases from mine to final waste deposit and electricity distribution.

Table 4 Life cycle divided into 13 phases.

Process module	Process	Included environmental impact
Upstream	Uranium extraction	Includes use of fuels and electricity, raw materials, emissions and production of auxiliary substances and chemicals, transportation of exiting wastes, all available amounts of wastes.
	Conversion	Includes use of fuels and electricity, raw materials, emissions, production of auxiliary substances and chemicals, transportation of exiting wastes, and all available amounts of wastes. Transport from mines.
	Enrichment	Includes transport from conversion plant, use of fuels and electricity, raw materials, emissions and production of auxiliary substances and chemicals, transportation of exiting wastes, all available amounts of wastes.
	Fuel fabrication	Includes transport from enrichment facility, use of fuels and electricity, raw materials, emissions and production of auxiliary substances and chemicals, transportation of exiting wastes, all available amounts of wastes.
	Auxiliaries NPP	Production of auxiliary substances and chemicals used in NPP.
	Auxiliaries radioactive waste	Production of auxiliary substances and chemicals used in facilities for management of radioactive waste.
Core	Operation NPPs	Transport of uranium fuel and auxiliary substances and chemicals, to the NPP, on-site transports, operation of NPP and fossil fuelled reserve power, electricity, raw materials, emissions, transportation of radioactive waste and transportation and treatment of conventional waste.
	Operation of radioactive waste facilities	Includes use of electricity, raw materials, emissions, necessary transportation, transportation and treatment of conventional waste.
	Infrastructure – Construction/ Decommissioning of NPPs	Includes manufacturing of inputs (raw materials), ground work and handling of outputs incl. transportation.
	Infrastructure – Construction/ Decommissioning of waste facilities	Includes manufacturing of the major construction materials (followed from cradle to grave), necessary blasting and groundwork, and handling of outputs incl. transportation. Data for not yet existing plants, SFR expansion and SFL, has been estimated from SFR existing. Data for not yet existing encapsulation and final repository plants has been estimated by SKB.
Downstream	Operation distribution	Includes emissions from inspection trips, production and emissions of oils.
	Infrastructure – Construction/ Decommissioning distribution	Includes manufacturing of materials (for lines, cables, pylons, transformers, buildings, and switching stations), ground work and handling of discharge material incl. transportation.

	Distribution losses	Is calculated by “extra” generation in NPP to compensate for losses in the electricity distribution system, i.e. 3% of generated electricity.

Necessary transports are included.

Assumptions regarding transportation of uranium are based on average uranium fuel volumes and mix of suppliers during the years 2019-2022.

The geographical scope for electricity generation and management of spent nuclear fuel and radioactive waste is within Sweden, whilst the nuclear fuel is produced world-wide.

Conventional waste is handled according to the Polluter Pays principle within each process step.

Figure 7 under section 3.3.2 below presents a simplified process tree with system boundaries for the LCA for electricity from nuclear power.

3.3.2. Allocation Principles

The uranium quantities from each process from mining to final repository have been calculated according to the proportion of the NPP’s average annual requirement of fuel.

Whereas 100% of the NPP infrastructure is included, a portion of the waste facility infrastructure has been allocated to the lifecycle corresponding to the Forsmark and Ringhals NPPs’ life generation in relation to the whole generation of Swedish nuclear power. Total nuclear generation is calculated as the sum of expected life generation for each reactor by adding already produced electricity, plus estimated production until end of the technical service life.

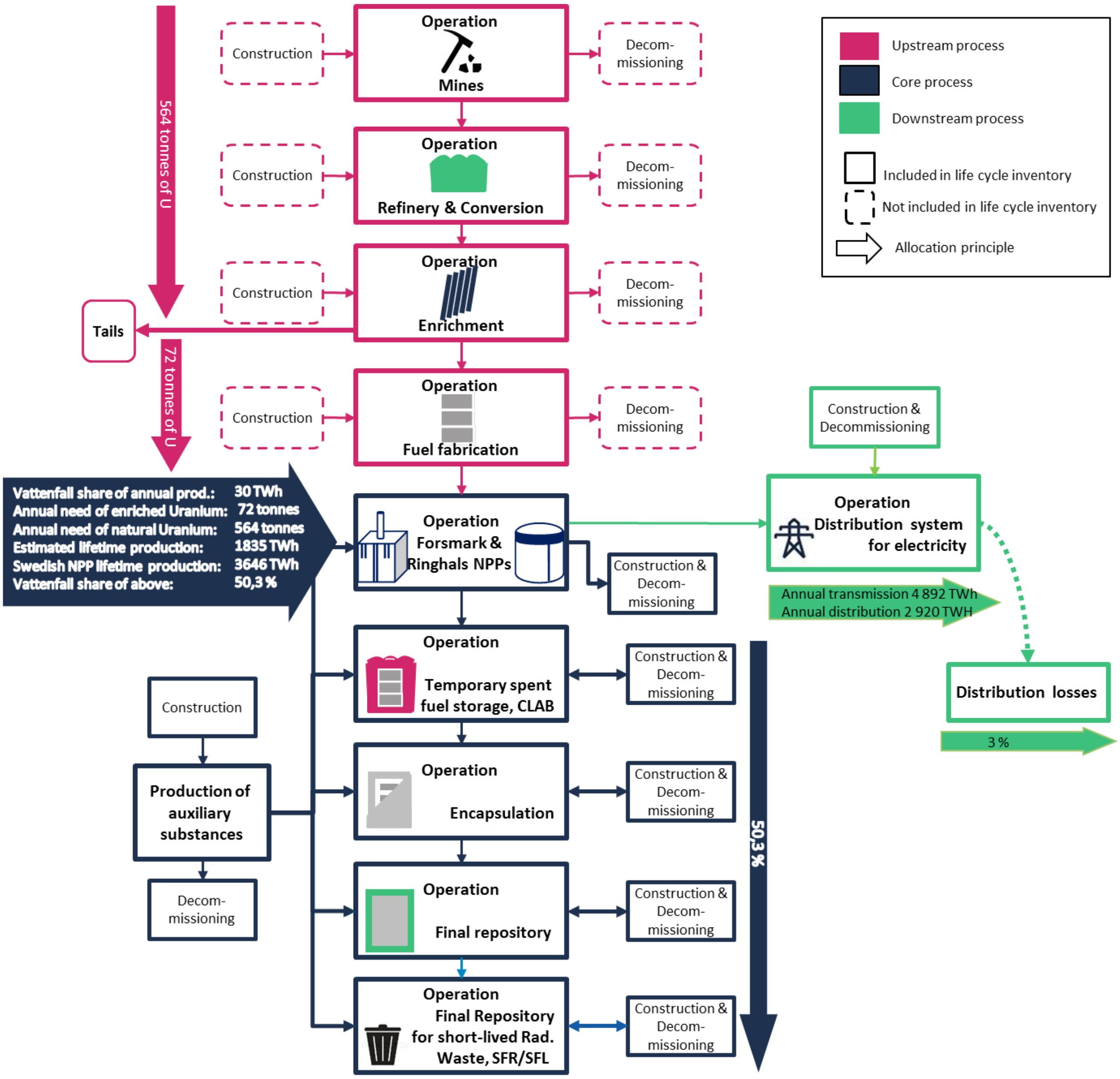


Figure 7 System boundaries and reference flow in upstream, core and downstream processes.

3.4. Environmental Information – Results from LCA

The assessment results are summarized in the Ecoprofiles below and commented in sections 3.4.1–3.4.6.

For the columns *Upstream*, *Core*, *Core – infrastructure* and *Total generated,* the numbers are expressed per 1 kWh generated electricity.

For the columns *Downstream*, *Downstream – infrastructure*, and *Total distributed* the numbers are expressed per 1 kWh electricity delivered to a customer connected to the 70/130 kV distribution network (distribution loss: 3% of generated electricity).

3.4.1. Ecoprofile Quality

In the Ecoprofile the result is given with two significant digits. It should be noted that data quality does not always motivate two significant digits.

3.4.1.1. Environmental Impact Categories, the 1% Rule

Core process and upstream processes

The EPD® system allows that maximum 1% of the total environmental impact for any impact category is omitted due to data gaps. The rule is related to the inflow and outflow of materials, chemicals, electricity, heat and fuels in the studied core process.

All inflows and outflows to the operation of the NPP, of CLAB, and of SFR existing reported in their Environmental Management System have been included in the LCA. Inputs and outputs from operation of not yet existing plants for handling of radioactive wastes i.e. encapsulation plant, and final repository are based on discussions with experts within SKB. The operation of the final storages for radioactive demolition waste, SFR expansion and SFL, will be of the same kind and order as the operation of SFR existing. Input and output data for SFR expansion and SFL is therefore estimated from SFR existing.

Major inputs and outputs necessary to construct, maintain and dismantle the infrastructure of NPP and waste management facilities for radioactive wastes have been included. The assumption regarding amounts of material is conservative. Production of raw material for buildings, machinery and components is included. The manufacturing process for large machines and components such as generators, transformers and turbines has been included. All known inputs and outputs of the uranium fuel subcontractors' operations have been included.

Infrastructure of the suppliers in the uranium fuel chain is not included. The plants for extraction, conversion and enrichment of uranium as well as production of fuel are used by many users other than Vattenfall. It is difficult to obtain data from the suppliers and the construction and demolition of these plants is assumed to have little impact on the final results regarding the studied environmental impact categories and is hence not included in this assessment. The infrastructure of other upstream processes is included in most cases since it is included in the LCI data from the used database (ecoinvent).

For included processes (excluding gravel, sand, earth, water, and energy resources) all resource flows from nature aggregate to app. 2,6 g/kWh electricity. The sum of all identified flows not tracked from the cradle is app. 0,0053 g/kWh, which is less than 1% of aggregated resource flows from nature.

The conclusion is that the known exclusions in the production stage (upstream and core processes) contribute to less than 1% to reported emission categories.

Downstream processes

In the distribution stage (downstream processes) construction, operation and dismantling of the power network is included as well as the distribution losses in terms of the extra generation necessary as compensation.

No data gaps have been reported in the documentation of the selected generic data used for construction and dismantling of the networks.

Operational data represent the conditions in the Vattenfall power network in the late nineties and comprise fuels and emission from clearing of power lanes, and from transportation during maintenance and inspections, consumption of oils, and specific emissions from pylons. There are more underground cables and less overhead power lines today and the latter require more maintenance, for example in connection with clearing of power lanes and repair related to storms. Hence used data are conservative.

For included processes (excluding gravel, sand, earth, water, and energy resources) all resource flows from nature aggregate to app. 0,9 g/kWh electricity. The sum of all identified flows not tracked from the cradle (from compensation of losses) is app. 0,0002 g/kWh, which is less than 1% of aggregated resource flows from nature.
The conclusion is that the known exclusions in the distribution stage (downstream processes) contribute less than 1% to reported emission categories.

3.4.1.2. Generic and Specific Data, the 10% Rule

According to the EPD® system General Programme Instructions, section 1, specific data shall always be used if available. If specific data is lacking, generic data may be used. There are two types of generic data: selected generic data and proxy data. Selected generic data is data from databases recommended in the PCR and can be used provided it is representative of the geographical area in question, there is a technological equivalence, there is a completeness of data regarding inputs and outputs, and the boundaries are equivalent. Proxy data is data from other databases or data from recommended databases that does not fulfil mentioned data quality rules.

Core process

Data for core process are specific, as specified in the PCR and the GPI.

Core – Infrastructure

Specific data has been used with respect to construction material amounts, excavated amounts, etc. Data for production of construction materials, vehicle operation, waste treatment, and generation of the electricity supplying the subcontractors is selected generic data. Other generic data has been used for diesel-fired machines, and vehicles used for groundwork such as excavating, transports, and handling of masses of stone and soil during construction.

Upstream processes

Specific data has been retrieved from the suppliers in the uranium fuel chain for operations related to mining, milling, refinery and conversion, enrichment and fuel fabrication.

Selected generic data (from recommended databases in the PCR) has been used for the European suppliers' upstream processes and for production of auxiliary material and chemicals for the NPPs.

Data for upstream processes for non-European suppliers has been retrieved from the database ecoinvent as Global or Rest-of-the-World average data. In some cases, European average data has been used for non-European suppliers, when other data has not been available. Most of the environmental impact from the upstream processes of non-European suppliers in the uranium fuel chain stems from electricity generation or fuel use, where the country specific data has been used.

Downstream processes

Specific data has been used regarding operation of the network, electricity transfer and regarding losses. Selected generic data has been used for construction and demolition.

The 10% Rule

The 10% rule says that no more than 10% of the impact in either assessed impact category can originate in proxy data. See Table 5 below for presentation of proxy data in all life cycle stages along with the total share of proxy data for the entire life cycle. As can be seen, no more than 10% originates in proxy data and the 10%-rule is therefore met for the entire life cycle

Table 5 Share of proxy data in all life cycle stages, along with in total

Impact category[1]	Unit/kWh	Share of proxy				
		Core	Core-infr.	Upstream	Downstream	TOTAL
GWP	g CO_2-eq. (100years)	0%	<10%	4,2%	0%	<3,1%
GWP incl bio	g CO_2-eq. (100years)	0%	<10%	4,6%	0%	<3,2%
AP	g SO_2-eq.	0%	<10%	0,9%	0%	<1,5%
POCP	g Ethene-eq.	0%	<10%	3,1%	0%	<1,6%
EP	g Phosphate-eq.	0%	<10%	7,5%	0%	<3,0%

[1] GWP = Global Warming Potential, AP = Acidification potential, POCP = Photochemical Ozone Creation Potential, EP = Eutrophication Potential

3.4.2. Resource Use

In Table 6 below, the input of resources to the ecoprofile per functional unit is presented.

Table 6 Ecoprofile input - Resource use

Resources	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Non-renewable material resources								
Aluminium in ore	**g**	7,64E-04	1,34E-05	2,72E-03	**3,50E-03**	1,06E-04	2,39E-02	**2,75E-02**
Bentonite, clay	**g**	1,07E-01	2,76E-04	2,56E-01	**3,63E-01**	1,09E-02	2,43E-02	**3,98E-01**
Basalt	**g**	7,78E-05	3,10E-07	1,30E-03	**1,37E-03**	4,20E-05	1,03E-04	**1,52E-03**
Chromium ore	**g**	2,08E-04	9,28E-06	2,01E-03	**2,23E-03**	6,80E-05	2,34E-04	**2,53E-03**
Copper in ore	**g**	2,02E-03	3,65E-06	1,64E-03	**3,66E-03**	1,11E-04	6,79E-03	**1,06E-02**
Dolomite	**g**	6,48E-03	3,00E-05	4,08E-03	**1,06E-02**	3,18E-04	1,77E-03	**1,27E-02**
Feldspar	**g**	5,20E-10	3,28E-13	1,58E-09	**2,10E-09**	6,33E-11	1,20E-09	**3,36E-09**
Fluorspar	**g**	4,12E-02	6,56E-06	1,43E-04	**4,14E-02**	1,24E-03	1,13E-04	**4,27E-02**
Gravel, stone & sand	**g**	3,29E+00	5,58E-02	6,34E+00	**9,69E+00**	2,91E-01	1,08E+00	**1,11E+01**
Gypsum	**g**	2,80E-04	2,89E-05	6,58E-03	**6,89E-03**	2,10E-04	2,06E-03	**9,16E-03**
Iron in ore	**g**	3,34E-02	0	5,54E-02	**8,88E-02**	2,80E-03	5,76E-01	**6,67E-01**
Lead in ore	**g**	4,21E-05	5,85E-07	0	**4,27E-05**	1,49E-06	4,21E-04	**4,65E-04**
Limestone	**g**	2,12E-01	2,34E-03	7,43E-01	**9,57E-01**	2,89E-02	2,38E-01	**1,22E+00**
Magnesium in ore	**g**	6,67E-04	4,58E-06	1,22E-03	**1,89E-03**	5,77E-05	8,01E-05	**2,03E-03**
Manganese in ore	**g**	3,99E-03	3,56E-06	5,78E-04	**4,57E-03**	1,38E-04	3,74E-05	**4,75E-03**
Molybdenum in ore	**g**	1,73E-04	6,75E-07	1,82E-04	**3,55E-04**	1,07E-05	1,02E-04	**4,68E-04**
Nickel in ore	**g**	1,71E-04	1,59E-06	3,70E-04	**5,43E-04**	1,74E-05	1,54E-03	**2,10E-03**
Olivine	**g**	1,16E-08	1,80E-11	2,85E-08	**4,02E-08**	1,42E-09	2,34E-09	**4,39E-08**
Salt	**g**	1,65E-02	6,64E-04	3,60E-03	**2,08E-02**	6,41E-04	4,18E-03	**2,56E-02**
Soil	**g**	1,04E-01	1,50E-02	8,20E-01	**9,38E-01**	2,81E-02	0	**9,66E-01**
Sulphur in ore	**g**	3,05E-05	1,09E-05	1,17E-05	**5,31E-05**	1,63E-06	3,74E-07	**5,51E-05**
Tin in ore	**g**	6,76E-07	1,31E-09	9,67E-08	**7,74E-07**	2,42E-08	4,32E-07	**1,23E-06**
Titanium dioxide	**g**	2,92E-06	1,49E-07	1,78E-04	**1,81E-04**	5,98E-06	3,71E-05	**2,24E-04**
Zinc in ore	**g**	5,27E-05	3,57E-08	0	**5,27E-05**	1,95E-06	6,63E-04	**7,18E-04**
Zirconium in sand	**g**	5,77E-04	1,39E-07	2,04E-05	**5,98E-04**	1,80E-05	4,51E-06	**6,20E-04**
Renewable material resources								
Wood[2]	**g**	4,96E-03	7,81E-05	6,52E-02	**7,03E-02**	2,16E-03	1,35E-02	**8,60E-02**
Non-renewable energy resources								
Crude oil	**g**	1,36E-01	5,40E-03	2,91E-02	**1,70E-01**	2,44E-02	5,55E-02	**2,50E-01**
Hard coal	**g**	2,56E-01	3,04E-03	7,08E-02	**3,30E-01**	1,05E-02	5,02E-01	**8,42E-01**
Lignite (wet)	**g**	2,56E-01	7,17E-04	1,12E-02	**2,68E-01**	8,35E-03	4,35E-02	**3,20E-01**
Natural gas	**g**	1,09E-01	9,68E-04	9,62E-03	**1,19E-01**	3,59E-03		**1,23E-01**
Uranium in ore[3]	**g**	1,88E-02	4,15E-06	6,27E-06	**1,88E-02**	5,65E-04	8,77E-07	**1,94E-02**
Uranium in ore, primary energy[3]	**MJ**	1,05E+01	2,32E-03	3,51E-03	**1,05E+01**	3,16E-01	4,91E-04	**1,09E+01**
Peat	**g**	2,35E-03	8,31E-04	4,71E-03	**7,89E-03**	2,39E-04	9,96E-05	**8,23E-03**
Renewable energy resources								
Bio mass (dry)	**g (DS)**	7,19E-03	1,09E-04	9,09E-02	**9,82E-02**	3,02E-03	1,83E-02	**1,20E-01**

Potential energy through hydro turbines[4]	**MJ**	2,80E-03	1,50E-03	1,31E-03	**5,61E-03**	1,70E-04	7,12E-04	**6,49E-03**
Solar electricity	**MJ**	1,45E-03	3,61E-04	9,00E-05	**1,90E-03**	5,73E-05	1,05E-07	**1,96E-03**
Wind electricity	**MJ**	2,27E-03	6,53E-04	7,81E-05	**3,00E-03**	9,06E-05	3,02E-05	**3,12E-03**
Electricity use in the power plant								
Electricity use in the power plant[5]	**MJ**	0	1,36E-01	0	**1,36E-01**	4,09E-03	0	**1,40E-01**
Water use								
Ground water	**g**	2,36E+00	1,33E+00	7,21E-02	**3,77E+00**	1,07E+00	2,52E-04	**4,83E+00**
River water	**g**	6,63E+03	3,87E+03	2,59E+03	**1,31E+04**	5,57E+02	3,97E-02	**1,37E+04**
Sea water	**g**	7,32E+00	1,85E+01	7,37E-01	**2,66E+01**	7,97E-01	9,30E-05	**2,73E+01**
Water, specified natural origin	**g**	8,41E+02	4,61E+02	3,61E+02	**1,66E+03**	6,71E+01	2,66E-02	**1,73E+03**
Water, unspecified origin	**g**	2,24E+04	6,18E+03	2,45E+01	**2,86E+04**	1,18E+04	1,61E+01	**4,05E+04**
Use of recycled material[6]								
Aluminium	**g**	0	0	1,10E-04	**1,10E-04**	3,30E-06	0	**1,13E-04**
Copper	**g**	7,09E-03	0	6,51E-04	**7,74E-03**	2,32E-04	0	**7,97E-03**
Steel	**g**	8,79E-04	0	2,20E-02	**2,28E-02**	6,85E-04	0	**2,35E-02**
Other input (agg. of remaining substances)	**g**	5,46E-02	3,82E-04	3,11E-02	**8,60E-02**	2,68E-03	5,11E-02	**1,40E-01**

[1] Distribution losses of 3% of generated electricity are included in the downstream column.

[2] A significant portion of the wood used as a material resource is incinerated in the end-of-life and connected to an emission of biogenic CO_2.

[3] Uranium in ore expressed in g uranium and MJ primary energy is not to be combined, it is the same uranium amount expressed in g and MJ.

[4] Hydropower is reported as used potential energy (1 kWh hydroelectricity = 1,14 kWh potential energy).

[5] The electricity used in the Nuclear Power Plant is assumed to also be generated by the NPP itself. The environmental impact is accounted for by subtracting the amount of electricity from the reference flow.

[6] Use of recycled material is classified as secondary resources according to GPI

Real volumes of material resources have been applied in the calculation of environmental impact, from production of raw materials for components and from plant operation. The amounts of recycled material used in construction and reinvestments are reported separately, and quantities are based on industry data on standard rates of scrap used in the production of the respective metal.

Excavation and blasting data are NPP-specific and the major construction materials have been followed from cradle to grave. Assumed reinvestments during the technical service life have been included.

Electricity consumption in the nuclear power plants' suppliers' factories and in other suppliers' processes is converted to renewable and non-renewable energy resources, as are fuels used in other processes. Hydropower is reported as potential energy (1 kWh hydroelectricity = 1,14 kWh potential energy), wind and solar power as electricity. The electricity consumption in the nuclear power plant is reported in the Ecoprofile although it is a lifecycle internal flow and has been environmentally accounted for.

Water consumption is reported in several categories, based on origin.

Some minor inflows have not been tracked from the cradle due to lack of data. The effect is an underestimation of environmental impact; see also section 3.4.1.1 on the 1% rule regarding data gaps.

3.4.3. Pollutant Emissions

In Table 7 below, the pollutant emissions contributing to the environmental impact categories assessed in this EPD® are presented.

Table 7 Pollutant emissions

Environmental impact categories	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Global Warming Potential	g CO_2-eq. (100years)	1,87E+00	1,76E-01	4,30E-01	**2,48E+00**	2,17E-01	1,44E+00	**4,13E+00**
Global Warming Potential incl. biogenic CO_2	g CO_2-eq. (100years)	2,01E+00	2,32E-01	5,21E-01	**2,76E+00**	2,26E-01	1,45E+00	**4,44E+00**
Acidification Potential	g SO_2-eq.	4,97E-03	1,28E-03	2,36E-03	**8,61E-03**	4,12E-04	9,43E-03	**1,85E-02**
Photochem. Ozone Creation Potential	g Ethene-eq.	4,88E-04	9,76E-05	1,77E-04	**7,63E-04**	5,45E-05	1,32E-03	**2,14E-03**
Eutrophication Potential	g Phosphate-eq.	2,85E-03	2,93E-04	4,05E-04	**3,55E-03**	1,45E-04	4,87E-03	**8,56E-03**

[1] Distribution losses of 3% of generated electricity are included in the downstream column.

3.4.3.1. General

Characterisation factors have been applied when contributions have been added to the environmental impact categories Global Warming Potential, Acidification Potential, Photochemical Ozone Creation Potential (ground level ozone) and Eutrophication Potential. Calculations and characterizations are in accordance with General Programme Instructions. Information provided in the diagrams is presented in accordance with the phases described in section Table 4 earlier in this report.

Emissions of radioactive substances are treated in section 4.2, Safety, barriers, and radiation.

3.4.3.2. Emissions contributing to Global Warming Potential

Figure 8 below presents the distribution contribution of emissions contributing to Global Warming Potential from different stages in the life cycle. Carbon dioxide is the dominating greenhouse gas, contributing with about 88% of total emissions. Emissions of greenhouse gases emanate mainly from use of fossil fuels in electricity generating processes or in other industry processes. Contributions from other greenhouse gases are mainly from methane (about 7%), sulphur hexafluoride (about 2%) and nitrous oxide (about 2%). The emissions of methane and sulphur hexafluoride occurs mainly in the downstream distribution of electricity, although large shares of methane derive from the electricity generation upstream as well, while nitrous oxide derives mainly from the uranium extraction phase (explosives) and the conversion phase (use of nitric acid). Transports account for about 1% of total emissions in this category.

Greenhouse gases
Total 4,1 g CO_2-eq./kWh$_{el}$ (Core 0,2 g CO_2-eq./kWh$_{el}$)

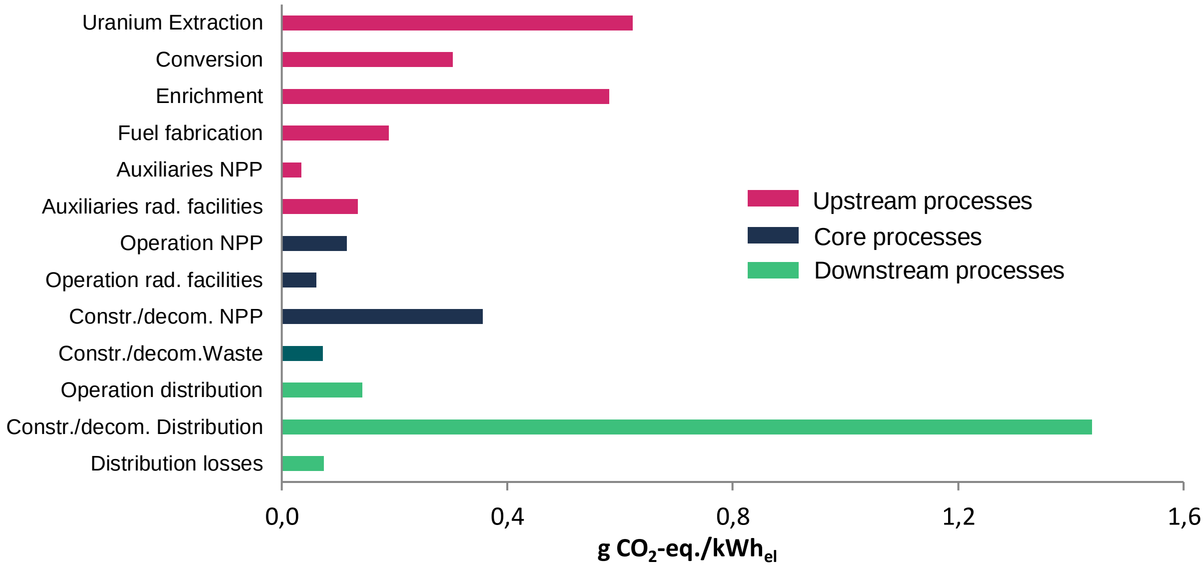


Figure 8 Greenhouse gas emissions (biogenic CO_2 is excluded) distributed on the life cycle stages

3.4.3.3. Emissions contributing to Acidification Potential

Figure 9 below presents the distribution contribution of emissions contributing to Acidification Potential from different stages in the life cycle. The dominant contributions are due to emissions of sulphur dioxide and nitrogen oxides, contributing with 55% and 37% respectively of total emissions. Remaining 8% emanates mainly from ammonia which contributes with a total of 4%. Most of the sulphur dioxide and nitrogen oxides emissions are related to construction of transmission grid, production and transportation of sulphuric acid used in the uranium extraction process, combustion of fossil fuels for electricity generation, and diesel combustion at power plants. Transports account for about 7% of total emissions in this category.

Acidifying substances
Total 0,018 g SO_2-eq./kWh$_{el}$ (Core 0,001 g SO_2-eq./kWh$_{el}$)

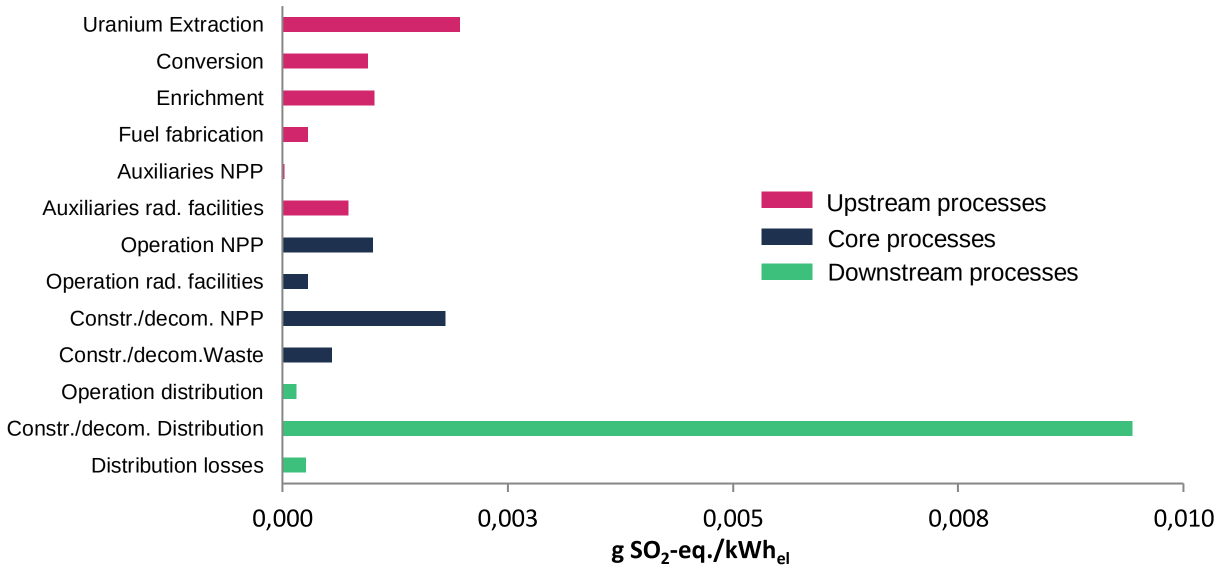


Figure 9 Acidifying substances distributed on the life cycle stages.

3.4.3.4. Emissions of substances contributing to Photochemical Ozone Creation Potential

In the presence of nitrogen oxides and sunlight, various types of hydrocarbons in the air may give rise to photochemical oxidants, primarily ozone. Hydrocarbon emissions result from vaporization of oil products and organic solvents and from incomplete combustion of fuels. In Figure 10 below, the distribution contribution of emissions contributing to Photochemical Ozone Creation Potential from different stages in the life cycle is presented.

In this category the major contributors are carbon monoxide (about 34%), unspecified non-methane volatile organic compounds (NMVOC, about 26%), sulphur dioxide (about 23%) and nitrogen oxides (about 13%). Another substance contributing in this category is methane with about 3% of total emissions in this category. Most of the emissions in this category derive from the downstream processes, from the construction of the electricity transmissions networks. Other contributing life cycle stages are the uranium extraction (mainly due to transport, electricity generation and diesel combustion) along with the construction of the nuclear power plants (mainly due to steel). Transports account for about 2% of total emissions in this category.

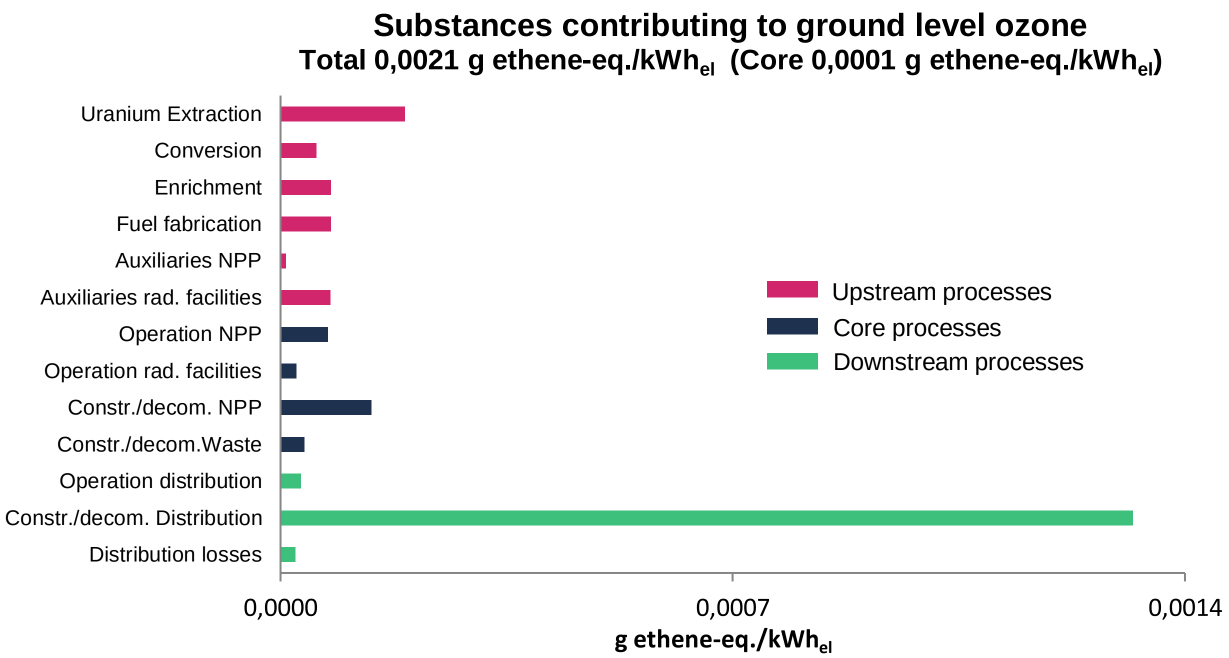
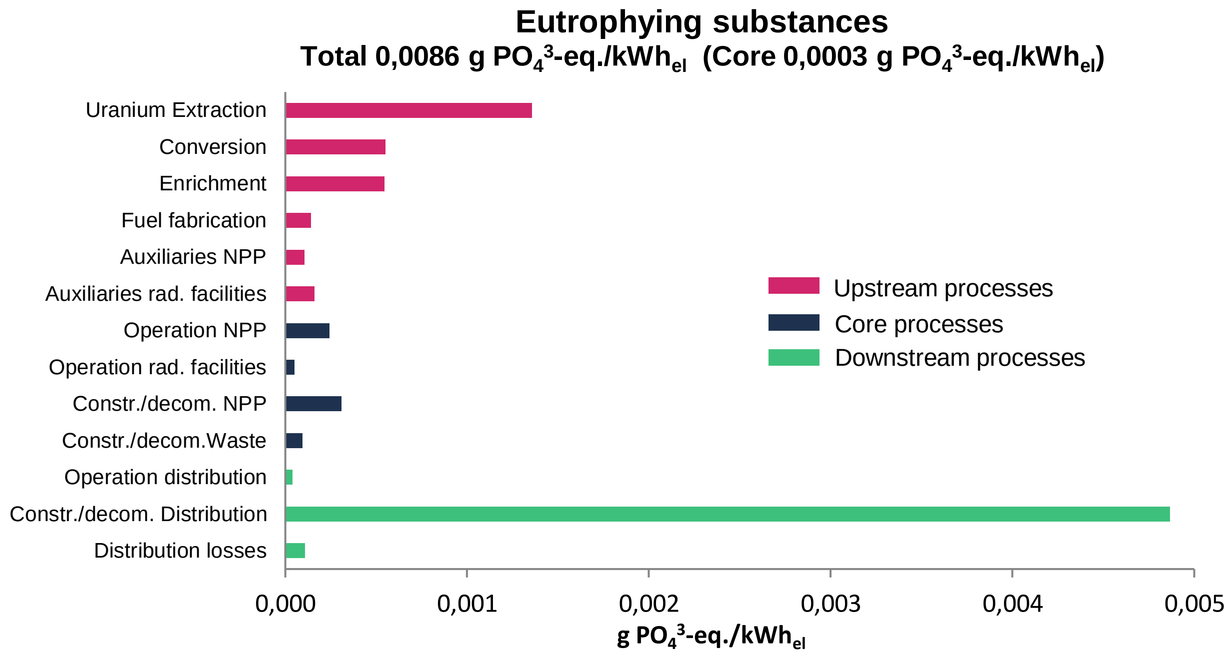


Figure 10 Substances contributing to Photochemical Ozone Creation Potential (ground-level ozone) distributed on the life cycle stages

3.4.3.5. Emissions contributing to Eutrophication Potential

Oxygen consuming substances like organic matter and nutrients like nitrogen and phosphorous compounds cause eutrophication. In Figure 11 below, the distribution contribution of emissions contributing to Eutrophication Potential from different stages in the life cycle is presented. The dominant substances are phosphate (accounts for about 40%), and nitrogen oxides (about 37%). Thereafter, ammonia and nitrogen account for about 5% each, while chemically oxygen demanding substances (COD) and nitrous oxide (laughing gas) contribute with additionally about 2% each.

The largest contribution comes from construction and decommissioning of the transmission and distribution network. One large part of the emissions in this category comes from the uranium extraction, where production of sulphuric acid together with electricity generation is large contributing factors. Transports account for about 2% of total emissions in this category.



3.4.3.6. Figure 11 Substances contributing to Eutrophication Potential distributed on the life cycle stages.

Emissions Contributing to Given Emission Categories

In Table 8 below, the main emissions contributing to the addressed impact categories are presented. The 26 parameters presented constitute 99-100% of the contributions to the reported impact categories: Global Warming Potential, Acidification Potential, Photochemical Ozone Creation Potential (ground level ozone) and Eutrophication Potential.

Table 8 Ecoprofile – Emissions contributing to given emission categories

Emissions contributing to given impact categories	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Alkane to air	**g**	2,05E-05	9,52E-07	7,79E-06	**2,93E-05**	3,78E-06	6,84E-05	**1,01E-04**
Ammonia to air	**g**	2,26E-04	5,69E-05	7,45E-05	**3,57E-04**	1,12E-05	1,21E-04	**4,89E-04**
Ammonia to water	**g**	2,63E-05	1,24E-05	5,11E-06	**4,39E-05**	1,41E-06	4,34E-06	**4,96E-05**
Carbon dioxide	**g**	1,70E+00	1,68E-01	4,02E-01	**2,27E+00**	1,28E-01	1,26E+00	**3,66E+00**
Carbon dioxide (biotic)	**g**	1,45E-01	5,56E-02	9,09E-02	**2,91E-01**	8,87E-03	1,73E-02	**3,17E-01**
Carbon monoxide	**g**	4,34E-03	5,93E-04	1,57E-03	**6,50E-03**	6,98E-04	1,98E-02	**2,70E-02**
Carbon tetrachloride (tetrachloromethane)	**g**	2,37E-07	3,97E-10	2,84E-10	**2,37E-07**	7,14E-09	4,14E-09	**2,49E-07**
Chemical oxygen demand (COD) to water	**g**	1,31E-03	1,44E-04	3,31E-04	**1,79E-03**	2,39E-04	6,65E-04	**2,69E-03**
HCFC-22	**g**	1,26E-06	1,45E-10	2,65E-09	**1,26E-06**	3,79E-08	4,50E-07	**1,75E-06**
Hydrocarbons (unspecified)	**g**	2,11E-06	5,83E-08	2,66E-06	**4,83E-06**	4,42E-05	1,29E-09	**4,90E-05**
Hydrogen chloride	**g**	1,50E-04	3,19E-05	1,25E-05	**1,94E-04**	6,20E-06	1,18E-04	**3,18E-04**
Hydrogen sulphide	**g**	1,07E-04	1,20E-06	3,17E-06	**1,12E-04**	3,36E-06	5,77E-06	**1,21E-04**
Nitrate to water	**g**	1,63E-04	4,47E-05	2,83E-05	**2,36E-04**	7,32E-06	1,35E-04	**3,78E-04**
Nitrogen to water	**g**	7,58E-06	6,73E-05	2,34E-06	**7,72E-05**	2,36E-06	1,26E-06	**8,08E-05**
Nitrogen oxides	**g**	3,74E-03	1,51E-03	1,45E-03	**6,70E-03**	3,14E-04	3,31E-03	**1,03E-02**
Nitrous oxide	**g**	2,28E-04	7,15E-06	1,79E-05	**2,53E-04**	7,77E-06	2,67E-05	**2,88E-04**
NMVOC (unspecified)	**g**	5,53E-04	1,75E-04	1,74E-04	**9,02E-04**	4,34E-05	1,71E-03	**2,65E-03**
Methane	**g**	3,80E-03	1,09E-04	7,48E-04	**4,66E-03**	1,69E-04	5,29E-03	**1,01E-02**
Pentane	**g**	1,79E-05	9,84E-07	3,57E-06	**2,24E-05**	2,05E-06	5,96E-06	**3,05E-05**
Phosphate to water	**g**	2,35E-04	2,20E-06	2,49E-05	**2,62E-04**	8,41E-06	1,10E-03	**1,37E-03**
Phosphorus to water	**g**	5,30E-07	1,05E-06	1,69E-07	**1,75E-06**	5,95E-08	5,28E-07	**2,33E-06**
Sulphur dioxide	**g**	3,66E-03	9,26E-05	1,18E-03	**4,92E-03**	2,21E-04	6,62E-03	**1,18E-02**
Sulphur hexafluoride	**g**	9,84E-08	7,06E-08	7,82E-08	**2,47E-07**	3,47E-06	4,39E-07	**4,16E-06**
Sulphuric acid	**g**	1,11E-06	1,62E-10	9,16E-07	**2,02E-06**	6,08E-08	2,23E-08	**2,11E-06**
Trichlorofluoromethane	**g**	3,90E-08	2,29E-10	2,47E-08	**6,39E-08**	1,99E-09	1,65E-06	**1,72E-06**
VOC (unspecified)	**g**	1,60E-04	1,42E-05	4,79E-07	**1,74E-04**	5,56E-06	9,61E-07	**1,81E-04**

[1] Distribution losses of 3% of generated electricity are included in the downstream column.

3.4.3.7. Emissions of Toxic and Other Substances to Air, Water and Ground

In Table 9 below, emissions of toxic and other substances to air, water and ground are presented.

Table 9 Ecoprofile – toxic and other substances

Emissions of toxic and other substances to air, water and ground	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[1]	Downstream - infrastructure	Total - distributed
Ammonia	g	2,52E-04	6,93E-05	7,96E-05	**4,01E-04**	1,26E-05	1,25E-04	**5,39E-04**
Antimony to air	g	1,93E-07	1,83E-09	1,63E-07	**3,58E-07**	1,44E-08	1,47E-06	**1,84E-06**
Arsenic	g	2,27E-04	6,70E-09	1,89E-04	**4,15E-04**	1,31E-05	5,63E-06	**4,34E-04**
Cadmium to air	g	1,11E-05	8,26E-10	9,28E-06	**2,04E-05**	6,13E-07	1,18E-06	**2,22E-05**
Carbon monoxide (biotic)	g	1,78E-05	1,92E-07	7,87E-06	**2,59E-05**	8,17E-07	2,68E-06	**2,94E-05**
Chromium (VI) to air	g	1,98E-09	2,05E-11	9,53E-09	**1,15E-08**	4,64E-10	2,14E-08	**3,34E-08**
Dioxine to air	g	6,08E-12	3,36E-13	3,99E-12	**1,04E-11**	3,14E-13	3,49E-12	**1,42E-11**
Lead	g	6,17E-04	1,35E-07	5,15E-04	**1,13E-03**	3,64E-05	1,13E-05	**1,18E-03**
Mercury to air	g	2,05E-05	1,71E-09	1,71E-05	**3,76E-05**	1,13E-06	7,02E-08	**3,88E-05**
Oil to ground	g	3,37E-04	1,32E-05	6,78E-05	**4,18E-04**	7,61E-05	1,83E-04	**6,77E-04**
Oil to water	g	3,24E-04	1,23E-05	6,38E-05	**4,00E-04**	6,99E-05	2,15E-04	**6,85E-04**
Particulate matter to air	g	3,27E-03	1,52E-04	4,71E-04	**3,89E-03**	1,31E-04	7,24E-03	**1,13E-02**
Polyaromatic hydrocarbons	g	3,42E-07	1,09E-07	1,93E-07	**6,45E-07**	2,02E-08	2,93E-06	**3,60E-06**
Sodium hypochlorite	g	5,62E-07	1,79E-08	4,27E-07	**1,01E-06**	3,02E-08	0	**1,04E-06**
C-14 to air	kBq	5,13E-05	6,46E-02	1,43E-05	**6,47E-02**	1,94E-03	2,05E-06	**6,66E-02**
Kr-85 to air	kBq	2,88E-02	4,71E-02	1,23E-04	**7,59E-02**	2,28E-03	4,87E-07	**7,82E-02**
Rn-222 to air[2]	kBq	1,18E-02	2,71E-03	5,50E-03	**2,01E-02**	6,09E-04	4,68E-04	**2,11E-02**

[1] Distribution losses of 3% of generated electricity are included in the downstream column.
[2] Do not include extra emission from mines due to land disturbance.

Antimony, arsenic, carbon monoxide, dioxins, lead, polyaromatic hydrocarbons, and oil are toxic substances reported as inventory results in the Ecoprofile, as are the emissions of radioactive isotopes required by the PCR. These emissions are limited and occur above all in conjunction with energy use during uranium extraction (not the mine itself) and processing of metals, production of cement, incineration and generation of electricity used in sub-contractor's processes.

Additional toxic emissions occur from old salt impregnated power poles. These poles are successively being replaced by other types. Salt impregnated poles emit arsenic, and galvanized steel poles release zinc and cadmium. Cables can cause small releases of heavy metals and older cables can release some lead. These impacts are, however, quite local, within 0,2 meters of source.

Emissions of particulate matter to air, presented in *Figure 12 Particulate matters* below, originate mainly from fossil electricity generation and uranium extraction (mining and milling) and during construction of distribution systems, but also from combustion of fuels. About 29% of the particles have a size of ≥10 micrometres, 14% are medium sized, and 13% are fine particulates (≤ 2,5 micrometres), while the remaining fraction is of unspecified size. The fine particulate fractions are most harmful to human health.

Emission of particles to air during construction and demolition of NPP and facilities for handling of radioactive wastes and during uranium extraction of uranium have not been considered in this EPD®.

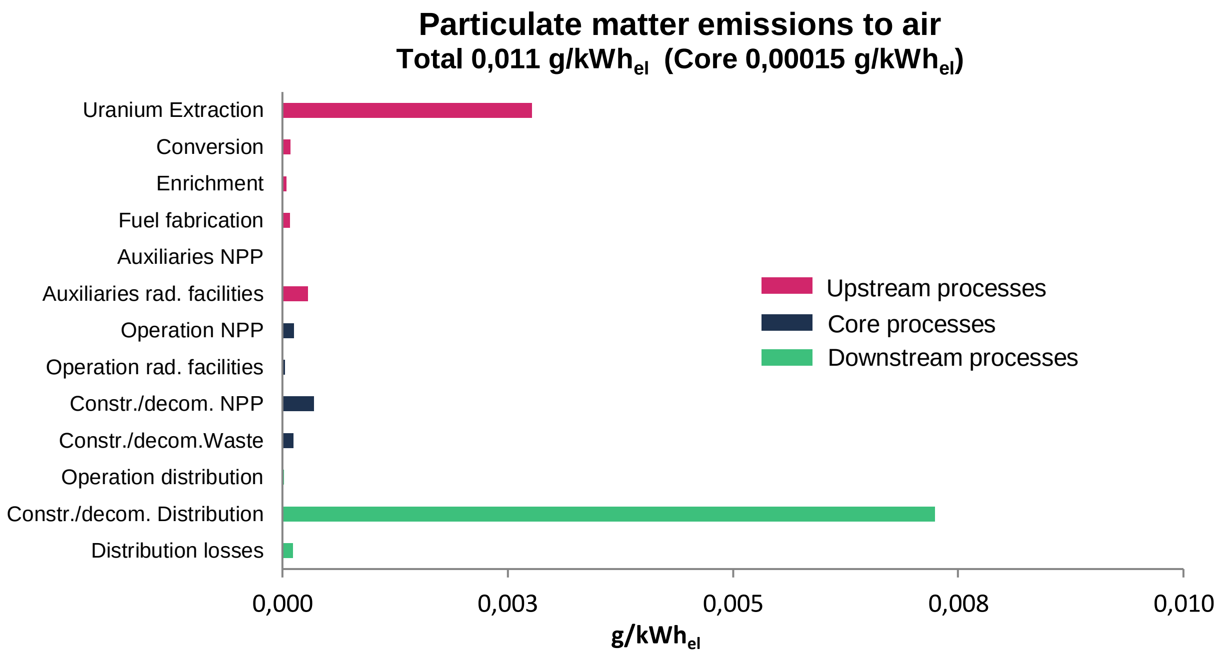


Figure 12 Particulate matters emission to air distributed on the life cycle stages

3.4.4. Waste and Material Subject to Recycling

Table 10 below presents the waste in relation to the production of 1 kWh electricity. In the subsequent sections each phase of the life cycle is commented. For some of the suppliers in the uranium fuel chain and for some other upstream processes, there has been no available information on how conventional waste is treated. In those cases, the waste is assumed to be deposited.

Table 10 Ecoprofile – Waste and material subject to recycling

Waste and material subject to recycling[1]	Unit/kWh	Upstream	Core	Core - infrastructure	Total - generated	Down-stream[2]	Downstream - infrastructure	Total - distributed
Hazardous waste								
Hazardous waste to disposal	g	2,35E-03	8,45E-04	7,78E-06	**3,20E-03**	9,59E-05	0	**3,29E-03**
Hazardous waste to incineration	g	5,79E-03	1,83E-03	0	**7,62E-03**	2,29E-04	0	**7,85E-03**
Radioactive waste								
Volume of deposit for high-level radioactive waste[3]	m^3	6,05E-13	2,26E-09	7,06E-15	**2,26E-09**	6,78E-11	0	**2,33E-09**
Volume of deposit for low/medium-level radioactive waste	m^3	3,57E-11	4,21E-08	5,03E-08	**9,25E-08**	2,77E-09	0	**9,52E-08**
Low-level radioactive waste without further treatment	g	1,92E-02	9,02E-04	3,69E-05	**2,02E-02**	6,06E-04	0	**2,08E-02**
Spent fuel[4]	g	0	3,08E-03	0	**3,08E-03**	9,24E-05	0	**3,17E-03**
Uranium in spent fuel	g	0	2,72E-03	0	**2,72E-03**	8,15E-05	0	**2,80E-03**
Waste to recycling								
Aluminium	g	0	0	2,45E-04	**2,45E-04**	7,35E-06	0	**2,53E-04**
Crushed concrete	g	0	0	6,75E-01	**6,75E-01**	2,03E-02	0	**6,96E-01**
Copper scrap	g	0	1,82E-06	2,32E-03	**2,32E-03**	6,97E-05	0	**2,39E-03**
Lead scrap	g	0	0	1,25E-03	**1,25E-03**	3,75E-05	0	**1,29E-03**
Steel scrap	g	1,41E-04	5,98E-05	7,12E-02	**7,14E-02**	2,14E-03	0	**7,35E-02**
Other waste to recycling	g	1,99E-02	1,22E-01	2,74E-03	**1,44E-01**	4,33E-03	0	**1,49E-01**
Other waste								
Waste to disposal	g	1,25E+01	6,27E-02	1,57E+00	**1,42E+01**	4,25E-01	0	**1,46E+01**
Waste to incineration	g	2,53E-04	1,08E-02	3,42E-02	**4,52E-02**	1,36E-03	0	**4,66E-02**
Waste water[5]	g	6,16E+03	7,45E+00	1,10E+04	**1,72E+04**	5,31E+02	5,21E+03	**2,29E+04**

[1] The table includes both waste that has been followed to the grave, meaning that the treatment of the waste is included in the LCA, and waste that has not been followed to the grave.
[2] Includes operation and distribution losses
[3] High-level radioactive waste from electricity generation in upstream processes is assumed to be further processed and is not classified as waste in the generic data.
[4] Spent fuel includes the entire uranium fuel in g UO_2. The fuel assemblies (steel, zircalloy and Inconel components) are included in the volume deposit categories above.
[5] Includes emissions of *waste water* as well as all emissions of *water* that are not further specified.

3.4.4.1. Core Process

Waste and residues from operation of NPP and facilities for handling of radioactive wastes are reported under this heading. Wastes to be landfilled, deposited or incinerated have been followed to the grave, and residues to be recycled have been followed to a collection site.

Spent fuel with uranium content is reported, followed by radioactive wastes that is to be deposited.

3.4.4.2. Core – Infrastructure

Waste and residues from construction, reinvestments and decommissioning of NPP and facilities for handling of radioactive wastes is reported under this heading.

In the process of manufacturing of steel, plastic and copper the waste is not followed to the grave. Wastes to be land filled, deposited or incinerated have been followed to the grave, and residues to be recycled have been followed to a collection site.

3.4.4.3. Upstream Processes

Most waste flows in the upstream processes have been followed to the grave. Reported amounts are mainly generated at the supplier in the uranium fuel chain, where the treatment of generated waste is not known. For some of the suppliers in the uranium fuel chain and for some other upstream processes, there has been no available information on how conventional waste is treated. In those cases, the waste is assumed to be deposited.

All depleted uranium (tails) is reported as hazardous non-radioactive waste, despite the fact that a considerable part of it is warehoused awaiting higher uranium prices. In this regard, the depleted uranium could be considered as "by-product". Concentrations of less than 0,1% U235 precludes economically viable enrichment of tails, which consequently must be classified as hazardous waste.

3.4.5. Dominance Analysis and Conclusions

Contributions to the studied environmental impact categories are distributed between the life cycle stages as presented in Table 11 below. As is made clear, the uranium extraction and enrichment phase, along with the construction and demolition of distribution networks, make the most significant contributions in all address impact categories.

Table 11 Dominance analysis.

Legend: >25% | ≤25% | ≤10% | ≤3%

Dominance analysis[1]	Uranium Extraction	Conversion	Enrichment	Fuel fabrication	Auxiliaries NPP	Auxiliaries rad. facilities	Operation NPP	Operation rad. facilities	Constr./decom. NPP	Constr./decom.Waste	Operation distribution	Constr./decom. Distribution	Distribution losses
GWP	15%	7%	14%	5%	1%	3%	3%	1%	9%	2%	3%	35%	2%
GWP incl. bio	14%	7%	15%	5%	1%	4%	3%	2%	10%	2%	3%	33%	2%
AP	11%	5%	6%	2%	0%	4%	5%	2%	10%	3%	1%	51%	1%
POCP	9%	3%	4%	4%	0%	4%	3%	1%	7%	2%	1%	62%	1%
EP	16%	6%	6%	2%	1%	2%	3%	1%	4%	1%	0%	57%	1%

[1] GWP = Global Warming Potential, AP = Acidification Potential, POCP = Photochemical Ozone Creation Potential and EP = Eutrophication Potential

Electricity consumption and fuel use in the uranium extraction, conversion and enrichment of uranium, dominate the emission categories in the upstream processes (Uranium Extraction – Auxiliaries radioactive waste facilities). The biggest contribution to emissions in the uranium extraction and milling phase comes from the uranium extraction activity and electricity consumption, while it in the enrichment phase derives from the electricity consumption. Amongst the radioactive waste facilities, it is the encapsulation plant that accounts for the largest share of emissions, and this is mainly due to the use of copper and steel in the canisters. All in all, upstream processes contribute to 23-45% of impact depending on impact category.

The operation of the NPP causes 3-5% of the total emissions in each impact category. All in all, the core processes (Operation NPP – Operation radioactive waste facilities), including handling of the different waste streams, contribute to between 3-7% depending on impact category. Construction, reinvestments and decommissioning of NPP and facilities for handling of radioactive wastes (Core – infrastructure) contribute to 5-13%, depending on the impact category.

Construction of transmission and distribution networks is a dominating impact contributor in the downstream processes. The environmental impact due to distribution losses in Table 11 above is caused by the extra electricity which is necessary to generate in order to compensate for losses in the distribution network. All in all, the downstream processes contribute to 38-64% of the total impact, depending on impact category.

3.4.6. Differences vs. earlier version of Vattenfall's EPD®

There are some differences in the results between this EPD® and the earlier EPD®s for electricity from Vattenfall's Nordic nuclear power plant, certified in 2016, see Table 12 below and clarifications in the subsequent sections.

Table 12 Differences vs. earlier version, excluding downstream

		EPD® of Electricity from Vattenfall Nordic NPPs (excl. distribution)	
Environmental impact categories	**Unit/kWh**	**2019**	**2016**
Global Warming Potential	**g CO_2-eq. (100years)**	2,5	NR[1]
Global Warming Potential incl. biogenic CO_2	**g CO_2-eq. (100years)**	2,8	4,2
Acidification Potential	**g SO_2-eq.**	0,009	0,039
Photochem. Ozone Creation Potential	**g Ethene-eq.**	0,0008	0,0028
Eutrophication Potential	**g Phosphate-eq.**	0,0036	0,0084

[1] NR = Not reported

General

The largest reduction in the above environmental impact categories takes place upstream, which is related both to an updated supplier mix and that the impact of some suppliers has been reduced. When it comes to Global Warming Potential, the main reduction takes place in mining and enrichment of uranium mainly due to the following reasons:

- Mining
    - A smaller share originates from open pit mining, which generally is connected to a higher impact
    - 40% of the uranium originates from reprocessed uranium
    - Improved energy efficiency of suppliers
- Enrichment
    - Update of data sets for the electricity consumption, where the reference year was updated from 2008 to 2014/2016 and the country electricity grid mixes have improved substantially for some of the assessed countries during this period

All ecoinvent data has been updated from ecoinvent 3.1 to ecoinvent 3.5, which usually is an important factor in the changes in environmental impact. In addition, the data set selected for the electricity consumption at the suppliers was updated from Ecoinvent to Thinkstep when available, and when Thinkstep was judged to have more recent data. Characterisation factors for all impact categories have been updated in accordance with latest version of CML. In addition, few minor errors have been detected and corrected in the LCA model in GaBi.

The reference flow, meaning the electricity generated in the power plants, is with the case of Forsmark calculated as the average generation from the years 2014-2018. In the case of Ringhals, this is calculated rather differently as R1 and R2 will be closed during the validity period of the EPD®. Therefore, the value is based on forecast production for the years 2019-2022. The fuel purchases are also based on expected costs during these years. In 2016, the method used for Forsmark has now been applied for both Forsmark and Ringhals. This is not considered to impact the results substantially.

Uranium extraction and Milling

There have been several changes in suppliers of uranium extraction since 2016. Cameco remains to be a supplier, but Key Lake mine has been changed to Cigar Lake mine, while McArthur River mill has been changed to McClean lake mill. The supplier Billiton from Australia, with the Olympic Dam mine/mill is included once again (as it was during certifications in 2013, but not in 2016). Rio Tinto's Rössing still remains a supplier, but with a smaller share of uranium supply than previously (about 70% less) thus having a smaller impact than in 2016. The share from open-pit mines has been reduced, which in turn reduces the environmental performance since open-pit mines in general have a higher impact. About 40% of the uranium is from Tenex, but no longer from the Dalur site – as it was in the EPD® of

2016 – but is instead reprocessed uranium. Hence the impacts from the processes of mining, milling, refining and conversion are avoided through the use of this recycled uranium.

Overall, the impacts from uranium extraction are lower than the earlier version for all assessed impact categories.

Conversion

As mentioned in the section above, one major difference in this EPD of 2019 is that about 40% of the uranium comes from recycled uranium sourced from Tenex, thus avoiding the impacts from the processes of refining and conversion of this uranium. Apart from this, no major differences have been made for refining and conversion since 2016. Cameco remains a supplier for these processes, along with Orano (previously Areva). As in 2013, Orano supplies more than half of these services and therefore makes a higher contribution to most of the emissions in this phase. On a whole, the impact from refining and conversion has remained largely the same since 2016 in regard to Global Warming Potential and Eutrophication Potential, while it for Acidification Potential and Photochemical Ozone Creation Potential has decreased.

Enrichment

The same three suppliers are present in this study compared to 2016, although the Tenex site has changed from Zelenogorsk to Novouralsk. In addition, the distribution of their contribution to the fuel fabrication for Vattenfall has altered somewhat.

Tenex and Orano (previously Areva) contributes to about 20% and 45% more than in 2016, while Urenco's contribution has decreased by about 30%. Overall, the impact from enrichment has decreased for all impact categories since 2016. This is mainly driven by an update of data sets for the electricity consumption, where the reference year was updated from 2008 to 2014/2016 and the countries' electricity grid mixes have improved substantially during this period.

Fuel Fabrication

Genusa GNF is included in the assessment (as it also was for the certifications in 2013), along with the already assessed Westinghouse and Framatome (previously Areva). Overall, the contribution from the fuel fabrication phase to emissions phase is similar to the levels in 2016 in regard to Acidification Potential, while it has increased for the remaining impact categories assessed.

Nuclear Power Plant

Somewhat lower electricity generation compared to earlier version. This results in a somewhat higher share of impact from the construction and decommissioning of the nuclear power plants.

Waste handling

No differences in waste management allocation procedures since 2016 but selected generic data for waste handling has been updated (to ecoinvent 3.5).

Distribution

Selected generic data updated, resulting in differences compared to earlier version.

4. Additional Environmental Information

4.1. Land Use and Impact on Biodiversity

4.1.1. The Biotope Method

The Biotope Method (Grusell E. et al, 2015) is a systematic procedure developed by Vattenfall for the quantification of impact on biodiversity following the exploitation of land and water. It is based on comparisons of the prominence of various types of biotope *Before* and *After* project development. According to the Biotope Method, *Before* is the situation before the start of the construction work and *After* is a selected time when a biotope has stabilized in relation to the new conditions. The fundamental assumption is that the changes in biodiversity, which are caused by the utilisation of land and water, are reflected in the losses and gains of various types of biotope. Affected areas are identified, measured and characterised based on biological value.

The Biotope Method considers impacts on biodiversity that can be directly related to a specific activity. Indirect impacts, e.g. fragmentation and barrier effects are outside the scope of the method.

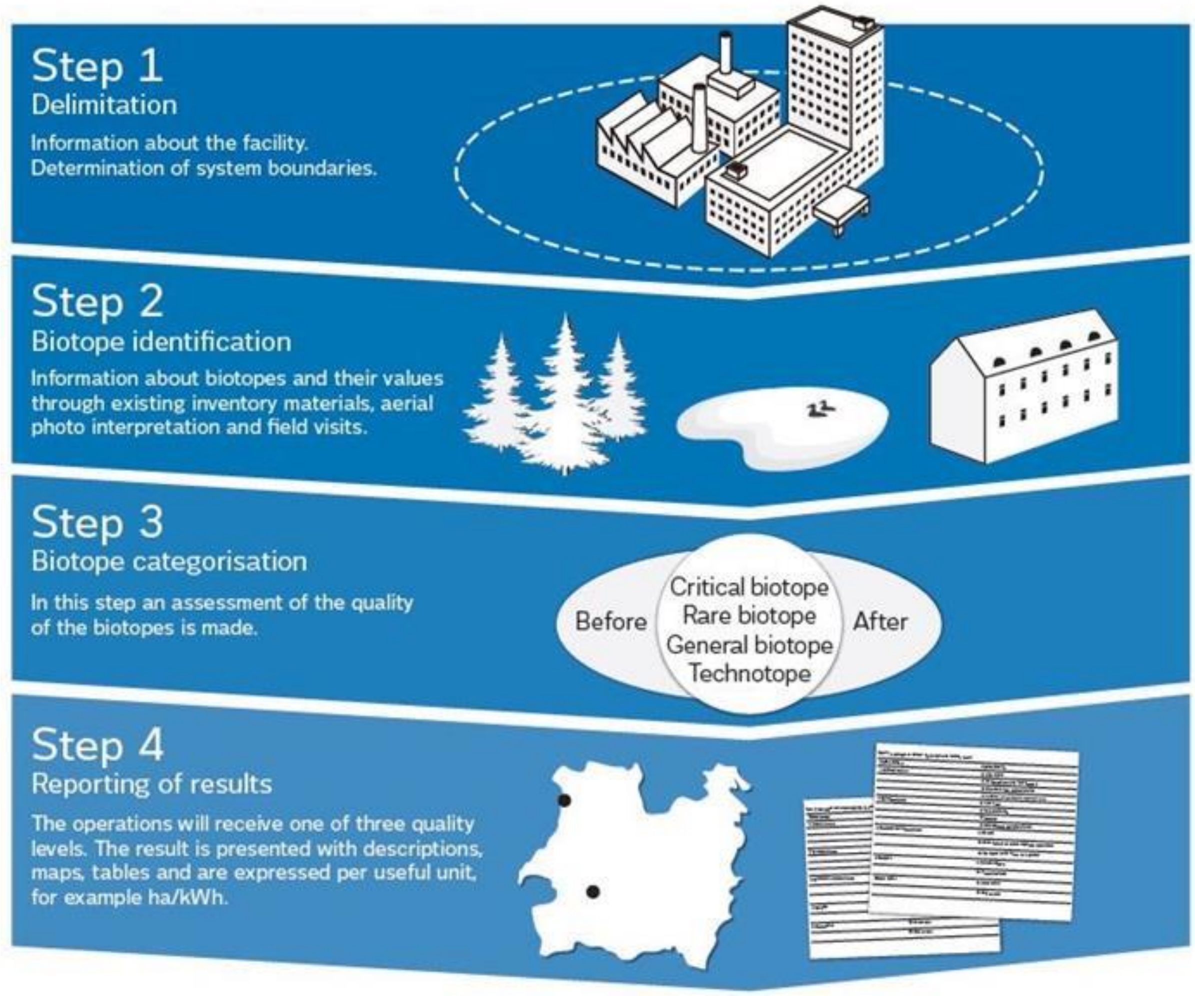


Figure 13 The four steps in the biotope method

Biotopes are divided in the following categories:

- **Critical Biotope, CB** – A critical biotope is an area that by its structure, species content, history and physical environment has a very high significance for flora and fauna. It harbours, or can be expected to harbour, red-listed species.
- **Rare Biotope, RB** – A biotope that differs from its surroundings through a high richness in species or through the existence of regionally rare species or species with key features.
- **General Biotope, GB** – Other biotopes, i.e. those that cannot be assigned to any of the other categories.
- **Technotope, T** – Areas without preconditions for biological production (e.g. hard-made surfaces and buildings).

The figure below represents the changes in categories between the *Before* and the *After* situations in principle.

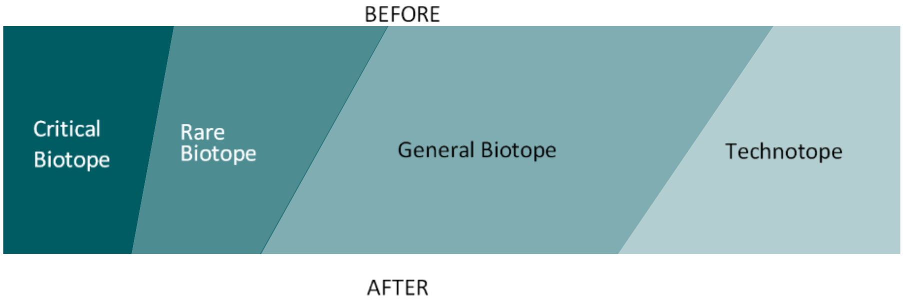


Figure 14 Biotope method Before – After

The quality of the results depends on the quantity and quality of the underlying data. The method is designed to result in a higher reported impact if input data is of lower quality (no biotope inventory on site + meagre data as for the rest = higher impact).

The highest quality level is A, and the lowest is C (tables 13-14). If there is a lack of information, various tools such as area-specific standard charts and assignation keys may be used. The highest quality level justifies three significant digits for data on area, whereas the lowest levels should only be reported on with one significant digit.

Table 13. Quality levels and requirements for inventory material for the "Before" and "After" states.

Quality level	Before	After
A	• Inventories in the field or • Satisfactory inventory material or • Aerial photography interpretation, incl. verification of red-listed species and values	• Site visit (though exceptions are possible) and • Inventories in the field or • Satisfactory inventory material or • Aerial photography interpretation, incl. verification of red-listed species and values
B1	• Inventories in the field or • Satisfactory inventory material or • Aerial photography interpretation, incl. verification of red-listed species and values	• Categorisation key
B2	• Categorisation key	• Site visit (though exceptions are possible) and • Inventories in the field or • Satisfactory inventory material or • Aerial photography interpretation, incl. verification of red-listed species and values
C	• Categorisation key	• Categorisation key

Table 14. Weighed quality levels of total areas

Quality level Weighted	Explanation
A	≥ 75% of the total area has been carried out as in A
B	≥ 75% of the total area has been carried out as in A or B (A+B ≥ 75%)
C	Other cases

4.1.2. Land inventory and data quality
This section is based on a separate report, where the application of the method used is described in more detail.

The Biotope Method 2015 has been applied on the total allocated area. The data quality levels vary, where the NPPs, one of the fuel fabrication facilities, two of the four mines, and SFR have the highest level, A (Table 15). B2 is applied on CLAB, and the lowest, C is applied on all others. For level C the *Before* situation is set to 40% critical biotope, 40% rare biotope and 20% general biotope, and the *After* situation is 100% technotope. For waste facilities not yet built the total area has been estimated.

Table 15 Quality levels on land use inventory

Process module	Process	Facility	Quality level
Upstream	Uranium extraction	Cigar Lake	C
		McClean Lake	C
		Rössing	A
		Olympic Dam	A
	Refinery & Conversion	Blind River	C
		Port Hope	C
		Malvési	C
		Tricastin	C
	Enrichment	Novouralsk	C
		Capenhurst	C
		George Besse II	C
	Fuel fabrication	Lingen	C
		Westinghouse	A
		Wilmington	C
		Juzbado	C
Core	NPP	Forsmark	A
		Ringhals	A
	Waste facilities	SFR, Forsmark	A
		CLAB, Oskarshamn	B2
		Encapsulation	C[1]
		Final repository	C[1]

[1] Not yet built.

4.1.3. Description of Land Use – Upstream, Mining
For the production of electricity at Forsmark and Ringhals, uranium has been extracted from the following mines: Cigar Lake, McClean Lake, Rössing, and Olympic Dam. The mines at Rössing and Olympic Dam has quality class A.

Since there is quite detailed information made available regarding nature conservation values of these sites, there is a description of these areas below.

Rössing

The Rössing mine is situated in the Namibian desert in south western Africa and exploits a 2549 ha land area with a hot desert climate and meagre precipitation. The prevailing conditions are extreme as with monthly average temperatures of +23,8 °C (May) and 15,4 °C (October) and with monthly maximum temperatures between +31,8 °C (July) and +39°C (January). Annual precipitation is a scant 30-35 mm, while evaporation amounts to 3150 mm (*Ashton et al 1991*). A decisive factor for flora and fauna is the fog, which regularly rolls in from the Atlantic Ocean some 60 km to the west. The moist air creates condensation on the ground and in the vicinity of the mine this condensation can go up to as much as 180 mm per year, although more modest amounts are normal.

The mining field is at 575 above MSL (Mean Sea Level) in a peneplain with a slight relief to the west, north, and northeast. To the south and southeast the terrain is more dramatic with several steep canyons. The river beds are usually dry and only heavy rains inland generate short periods of water flow toward the ocean.
The vegetation is typical for desert areas; only a limited number of mainly low growing plants sustain the extreme conditions. Various succulents and lichens clearly dominate the barren environment of mountainous hills and plains. The situation in the river valleys is different; water accumulated in the sediment during periods of water flow is exploited by a number of perennials, among them several species of Acacia, that are important for the fauna. Land use is dictated to available natural resources, mainly mining and extensive animal grazing.

Olympic Dam

Olympic Dam is situated in the inland of South Australia. The exploited land area is 2905 ha. The climate is of a desert like inland type with summer temperatures reaching +35 °C. Precipitation is irregular and sparse - approximately 160 mm annually. The area has been used for grazing grounds for animals since the middle of the 19th century. The settlers influenced flora and fauna by introducing grazing animals and rabbits. The regional flora is characterized by sparse and arid-zone vegetation. Some areas, particularly dune fields, are host to Acacias and tall shrubs, and other areas to white cypress pines.

Large quantities of water are used in the mine and in the living areas. Supply is limited and consists mainly of fossil ground water from the Great Artesian Basin. Water is pumped to the surface from a number of wells and fed to the mine and living quarters through pipelines. There is proof of diminished or ceased natural water flow at two wells. These wells were however already damaged by farmers and did not harbour any of the endemic species as found in some of the other wells. Ground water from the Great Artesian Basin has been used in the area for a long time, particularly for farming purposes. The use of ground water for the mine, including the city of Roxby Downs, constitutes less than 2% of the total ground water use in the area. The problem of diminishing water flow is recognized, and old farming wells are being sealed whilst efforts are made to increase flow from some wells. Various joint programs, some in collaboration with authorities, are aimed at a reduction of daily water usage by 37 million litres. This would more than compensate for the daily 32 million litres consumed by BHP Billiton/Roxby Downs.

4.1.4. Description of Land Use – Core, Forsmark & Ringhals

Underlying material for the inventory consists of aerial photographs, maps of different kinds, GIS-material, Environmental Impact Assessments, other types of environmental investigations, inventories, technical descriptions, verbal information, photos and on-site observations. The following two maps show the Forsmark area pre- and post-exploitation.

The following two maps show the Forsmark area before and after exploitation.

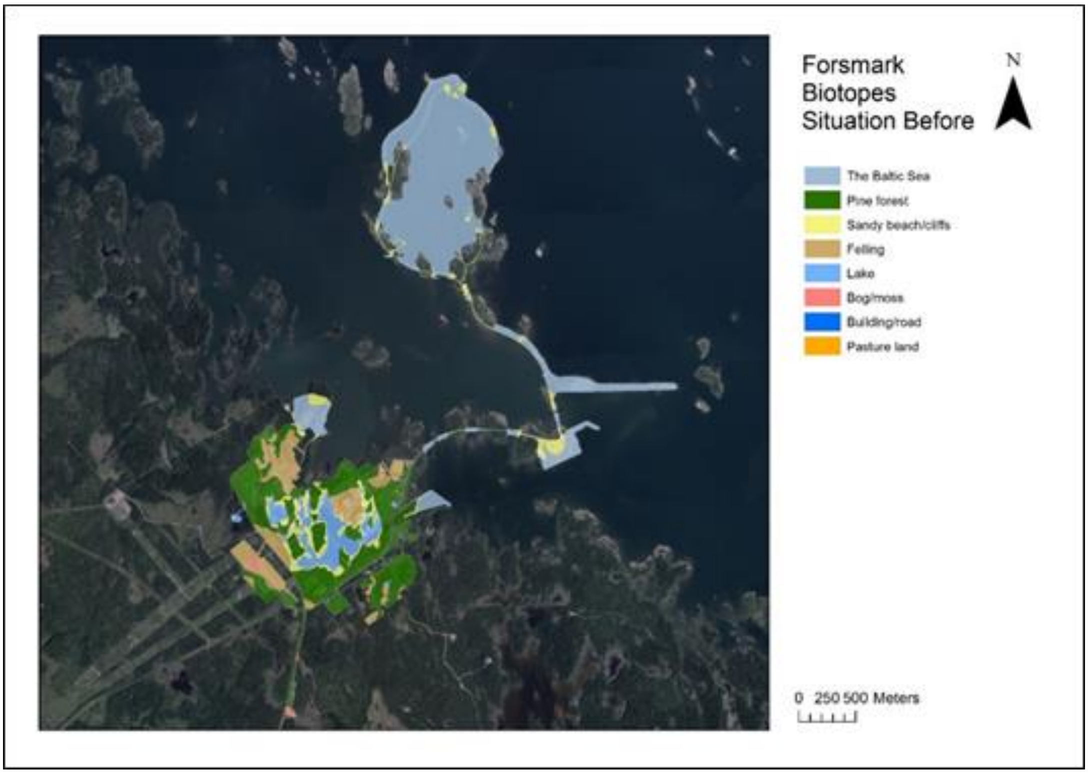


Figure 15 Forsmark area before exploitation.

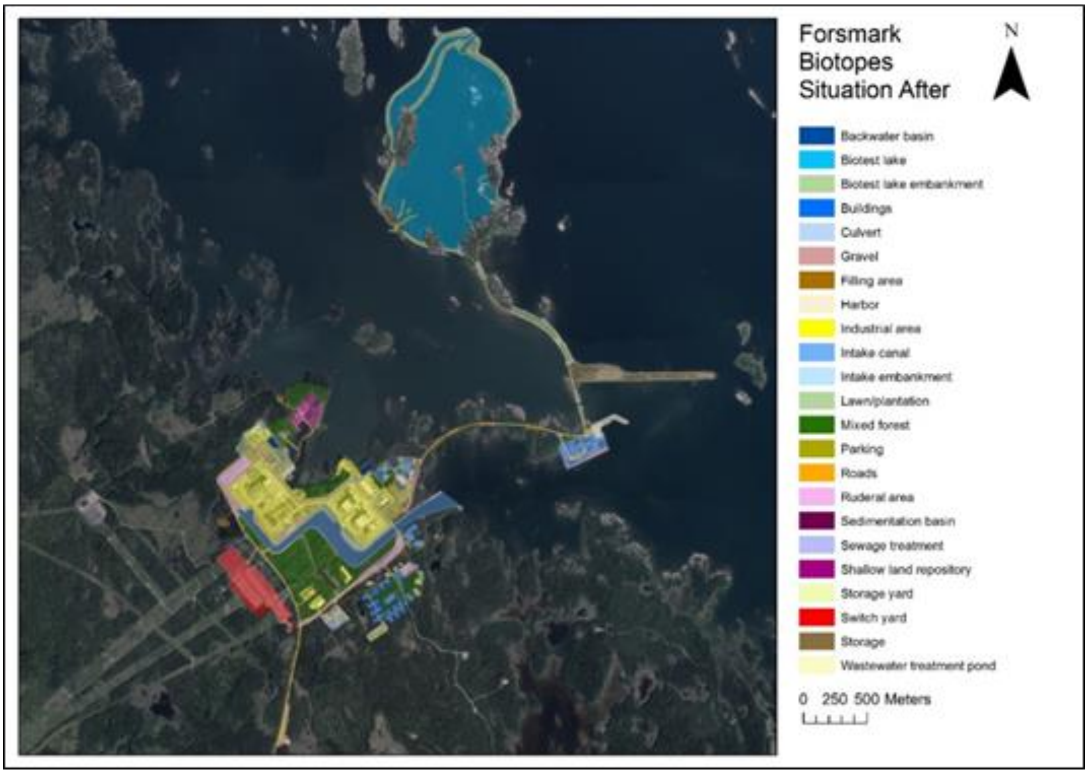


Figure 16 Forsmark area after exploitation

The following two maps show the Ringhals area before and after exploitation.

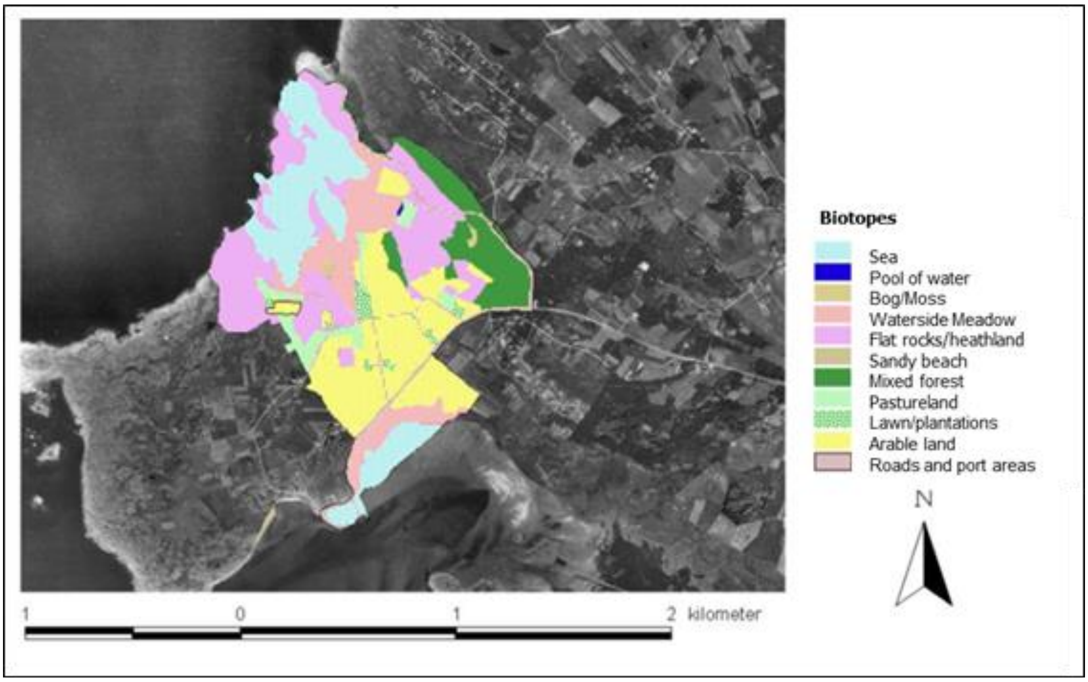


Figure 17 Ringhals area before exploitation.

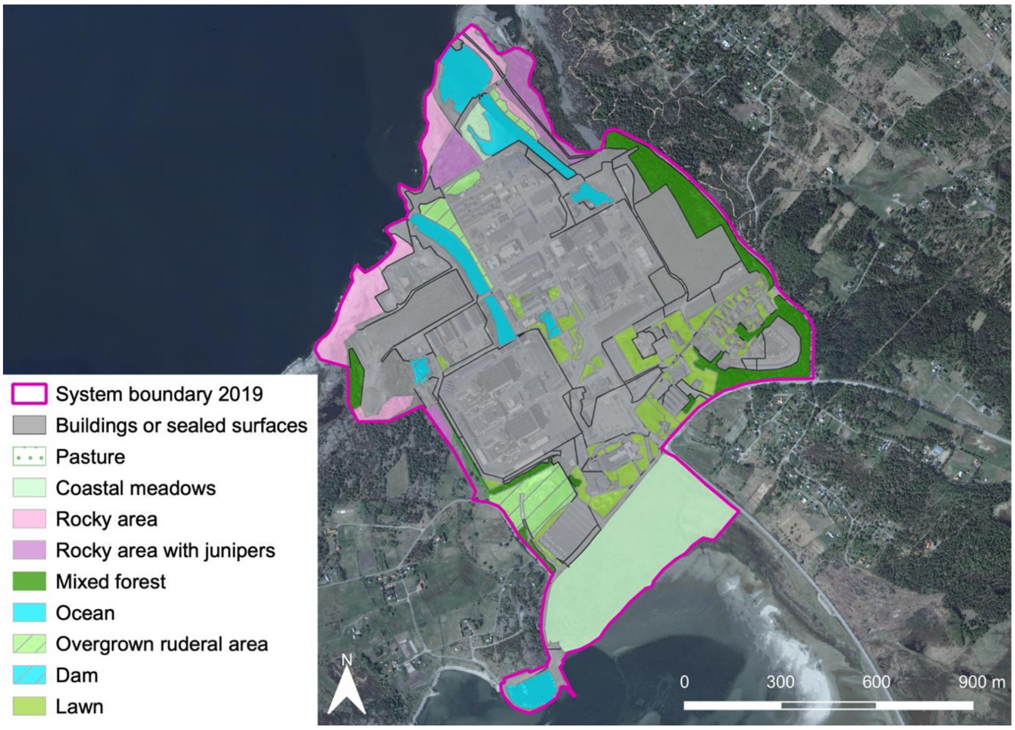


Figure 18 Ringhals area after exploitation

4.1.5. Land Use, Downstream Processes – Electricity Distribution

The power grid also has an impact on biodiversity, but no quantitative results from the application of the Biotope Method are included in this study from the distribution stage, and no classification of occupied areas according to the EU land cover categorisation system Corine has been made.

Lanes are regularly cleared creating a possible habitat for species that normally inhabit meadows and pastures. In addition, lanes constitute ecotones, where two biomes meet and integrate. These are generally considered more bio-diverse than homogenous areas. Wider lanes can constitute barriers that may cause fragmentation for some woodland species. In a cultivated landscape the lanes do not have any particular impact on biodiversity, positive or negative.

4.1.6. Results Biotope Method - All Phases

The graphs to the left below (Figure 19 and Figure 20) show that the uranium extraction facilities use considerably more land than other facilities. The relative contribution to land use of the mines decreases considerably after allocation, since their allocated share of the total production is between 2,3% and 17,6%. Instead, the NPPs are responsible for the largest part of land use after allocation, as is shown in charts below to the right (figures 19 and 20).

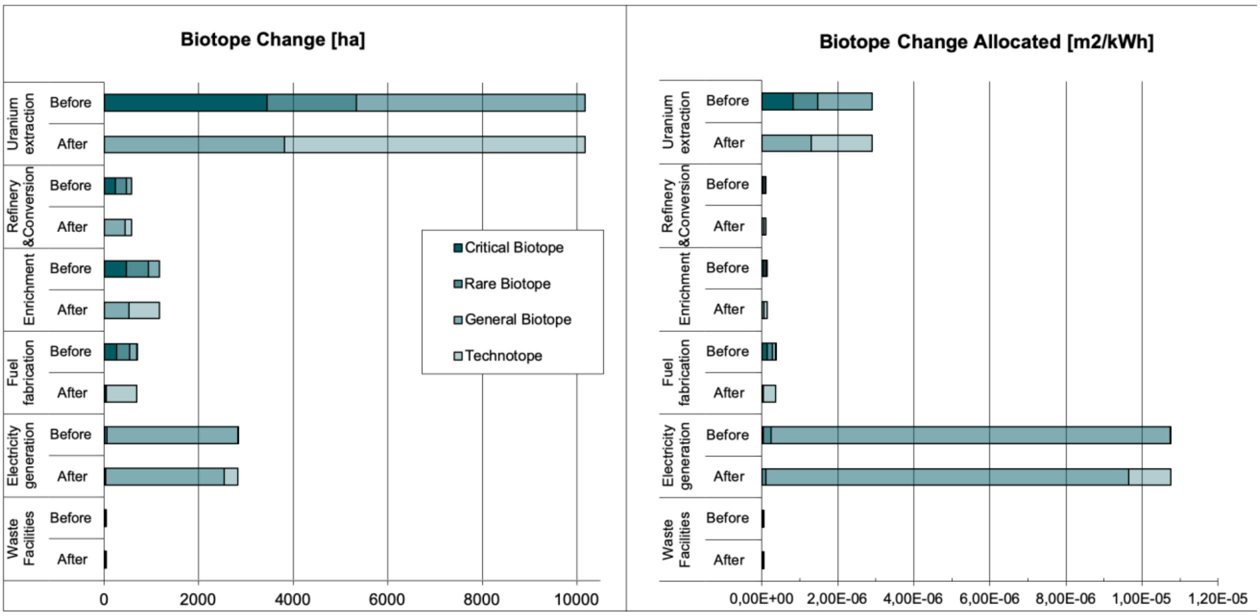


Figure 19 Biotope change in the nuclear fuel cycle before (left) and after (right) allocation. (1 ha = 10 000 m²)

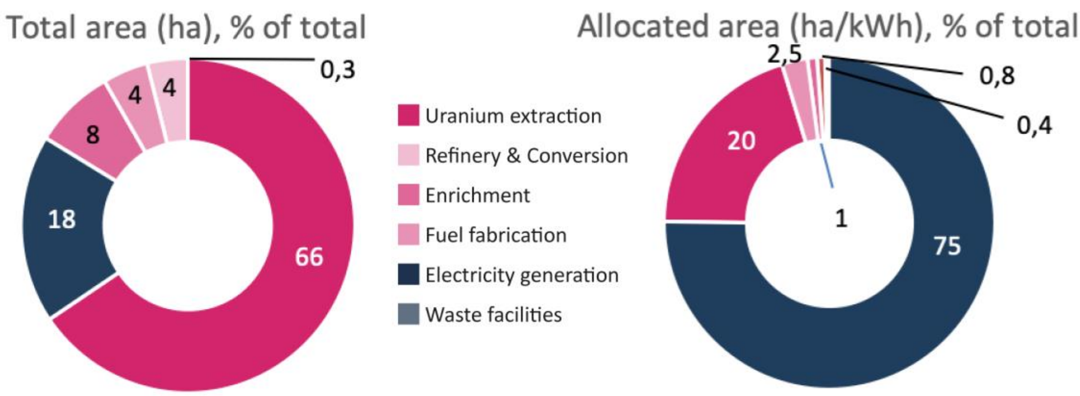


Figure 20 The proportion of the different facilities in the nuclear fuel cycle without (left) and with (right) allocation.

As can be seen from the figures above, land use before allocation is dominated by uranium extraction mines. When land use is allocated, the NPP facilities instead dominate with 75%, while the mines only make up 20% of the total area, see Figure 20. The total area claimed by Forsmark and Ringhals is 1203 and 1624 ha respectively, the largest component being the seawater surface plume[3], 890 ha and 1400 ha, respectively.

These results are quite different compared to the last update of this report in 2016. The main reason for this is that some facilities have been replaced. Because of this, the total land area has increased by over 2000 hectares. The area used by enrichment facilities has increased more than threefold, and the area used for fuel fabrication has increased by more than 11 times over. This is reflected in the proportions of the total land area claimed by different facilities.

The quality levels of the land use inventory are shown in Table 15.

The Biotope Method has been applied to all facilities. 64,4% of the facilities are assessed at level A, 0,1% are assessed at level B2 and 35,5% at level C. Therefore, the quality level of the total result of this study will be level C. To get level A for the total area, > 75% of the facilities should be assessed in quality level A (see table 14). To get level B, > 75% of the facilities should be assessed in quality level B. The highest quality level justifies three significant digits, whereas the lowest levels should only be reported with one significant digit.

The results of the biotope categorizations are shown in Table 16**.**

[3] **Plume definition**: 1 °C above ambient water temperature at 1 m below surface.

Table 16 Impact on biodiversity, before (ha) and after (m^2/kWh) allocation (due to rounding the numbers do not always add up).

	Uranium extraction		Refinery & Conversion		Enrichment		Fuel Fabrication		Electricity Generation, NPP		Waste facilities	
Before	**ha**	**m^2/kWh**	**ha**	**m^2/kWh**	**ha**	**m^2/kWh**	**ha**	**m^2/kWh**	**ha**	**m^2/kWh**	**ha**	**m^2/kWh**
Critical Biotope	3450	8E-07	230	4E-08	470	5E-08	270	1E-07	10	3E-08	10	9E-09
Rare Biotope	1890	6E-07	230	4E-08	470	5E-08	270	1E-07	50	2E-07	10	9E-09
General Biotope	4840	1E-06	120	2E-08	230	3E-08	140	7E-08	2760	1E-05	20	4E-08
Technotope	0	0	0	0	0	0	0	5E-11	7	3E-08	0	0
TOTAL	**10 170**	**3E-06**	**580**	**1E-07**	**1160**	**1E-07**	**690**	**4E-07**	**2830**	**1E-05**	**50**	**6E-08**
After												
Critical Biotope	0	0	0	0	0	0	0	0	0,0	0	0	0
Rare Biotope	0	0	0	0	0	0	2	2E-10	30	1E-07	0	0
General Biotope	3810	1E-06	440	6E-08	530	5E-08	50	4E-08	2510	10E-06	9	2E-08
Technotope	6360	2E-06	140	5E-08	640	8E-08	640	3E-07	290	1E-06	40	4E-08

Table 17 show a summary of the biotope change due to Vattenfall's nuclear electricity production in Forsmark and Ringhals. Since the majority of the allocated area is assessed at quality level C, the results are given in one significant digit (when allocated per kWh). For facilities with quality level C, the assignation key of the Biotope Method is used, which leads to a likely overestimation of Critical and/or Rare Biotopes in the *Before* situation. With that in mind, the results show that the largest land change has occurred in critical biotopes, followed by rare biotopes, both before and after allocation. Whereas there is a decrease in general biotopes before allocation, the general biotopes later increase somewhat after allocation. This shows that Vattenfall's share of the total production mainly originates from sites where critical and rare biotopes are turned into general biotope (and to some extent technotope) rather than where general biotope is turned into technotope. This highlights the importance of considering Vattenfall's share of the total production of different facilities to more accurately reflect their impact on biodiversity.

Table 17 Condensation of impact on biodiversity both with and without allocation to Vattenfall´s share of the electricity generation at Forsmark and Ringhals NPPs, based on the entire nuclear fuel cycle.

	Biotope Change (ha)	Biotope Change Allocated (ha)	Allocated areas (m^2/kWh el) Before	After	Biotope Change per kWh electricity (m^2/kWh el)
Critical Biotopes	-44 310	-6	8%	0%	$-2 \cdot 10^{-6}$
Rare Biotopes	-2890	-5	8%	1%	$-2 \cdot 10^{-6}$
General Biotopes	-770	4	80%	80%	$3 \cdot 10^{-7}$
Technotopes	8090	7	0,2%	20%	$4 \cdot 10^{-6}$

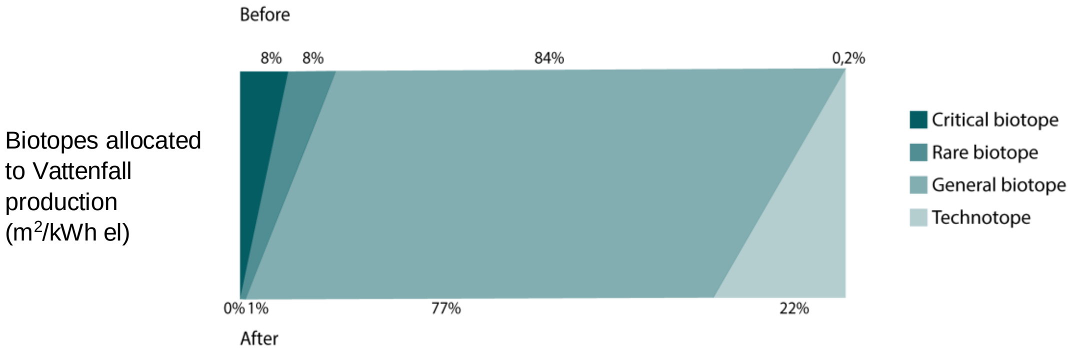


Figure 21. The allocated biotope change.

4.1.7. Corine Classification – Upstream and Core Processes

The classification according to Corine (http://www.eea.europa.eu/publications/COR0-landcover) has not been possible to perform on all facilities due to lack of information. Where classification data is missing the occupied areas are reported as "unspecified". It must be stressed that these areas could be significantly overestimated. All of the land used by the core activities have been classified according to Corine. However, there was not enough information to classify all of the land used by the mines. This is instead reported as unspecified. The unspecified land use for mines in the *Before* situation is 25% of the total land use and 18% in the *After* situation.

The final repository and encapsulation facilities are not yet built but the expected total area has been estimated by SKB. The total area for these facilities in the *Before* situation is specified in the category Unspecified, and the total area *After* is specified as Artificial surfaces.

All three reactors in Forsmark will be in operation for 60 more years. Ringhals 1 and 2 are closed down after 44 years in operation, whilst Ringhals 3 and 4 will also be operating for 60 more years. The land areas will be occupied during those 60 years, and also during the time for building and decommissioning, which accounts for another 10-20 years. After decommissioning, the land areas can be rehabilitated or used for other industrial purposes. The same can be applied for the waste facilities.

For the operational lifetime of waste facilities, see Table 3. These plants also occupy the land area some years before and after the service lifetime and will be rehabilitated or used for other industrial purposes after decommissioning.

Occupied land area is presented in hectares allocated to Forsmark's and Ringhals' share of the facilities during their lifetime in Table 18. Artificial surfaces have increased the most in the *After* situation compared to *Before*. Apart from unspecified land, forests have decreased the most in the *After* situation.

Table 18 Forsmark and Ringhals – Allocated hectare used of specified land category according to Corine Land Cover Classes. Note that the total area per column has been rounded to contain one significant digit, and therefore does not match the sum of the separate numbers in each column.

							Waste [ha]					
		Mining [ha]	Refinery & Conversion [ha]	Enrich-ment [ha]	Fuel fabrication [ha]	Electricity generation [ha]	CLAB [ha]	SFR [ha]	Final Repository & Encapsu-lation [ha]	**TOTAL [ha]**	**TOTAL $[m^2]$**	**CHANGE $[m^2]$**
BEFORE	**Artificial Surfaces**	0	0	0	0	0,1	0	0	0	0,1	1050	105 880
	Agricultural	0	0	0	0	1	0	0	0	0,5	5000	-3200
	Forest	3	0	0	0	3	0	0	0	6	55 570	-46 080
	Wetland	0,1	0	0	0	0	0	0	0	0,1	1650	-1650
	Waterbodies	0	0	0	0	30	0	0,1	0	30	291 720	-9280
	UNSPECIFIED	10	0,3	0,4	1	0	0,04	0	0,2	10	142 620	45 640
	TOTAL	15	0,3	0,4	1	32	0,04	0,1	0,2	50	497 600	
AFTER	**Artificial Surfaces**	6	0,1	0,2	1,0	3	0,03	0,1	0,2	10	106 900	
	Agricultural	0	0	0	0	0,2	0	0	0	0,2	1790	
	Forest	0	0	0	0	0,9	0	0	0	0,9	9490	
	Wetland	0	0	0	0	0	0	0	0	0	0	
	Waterbodies	0	0	0	0	30	0	0	0	30	282 440	
	UNSPECIFIED	9	0,2	0,2	0,1	0	0,01	0	0	10	96 980	

4.2. Safety, Barriers and Radiation

To prevent any major impact that the site might have on the environment, safety is always top priority at the nuclear power plant. Production output and economic factors are never permitted to jeopardize the safety of environment, personnel or facilities – this is imprinted in the mind of every employee and subcontractor.

4.2.1. Regulatory Authorities

The nuclear power industry is closely regulated by several laws, which concern environment, water, hazardous materials, nuclear technology, and radiation[4]. In addition, there are regulations from the Swedish Radiation Safety Authority (SSM).

Various decisions and licenses issued by authorities also regulate the industry. These are concerned with reactor safety, radiological environment as well as with the external conventional environment. In addition to these controls, the management of Vattenfall has objectives of its own. To secure uncompromising implementation all routines and procedures are documented in the Management & Quality Manual.

4.2.2. Safety at Three Levels

Design and operation of nuclear power plants must incorporate maximum protection against technical failures as well as external events such as fire, lightning, and sabotage. If something goes wrong the safety systems must prevent radioactive and other harmful substances from reaching the environment.

- **Preventative level**
  Safety is a design criterion for the NPPs. In addition to expert staff the crucial factors in accident prevention are operating routines, maintenance, and safety assessments.

- **Monitoring level**
  The second level of safety is designed to prevent failures that occur, despite preventative measures, from developing into accident scenarios. There are safety and monitoring systems and all the important systems have redundancy. Simultaneous system failures are avoided by diversification of technical solutions, e.g. independent electrical and hydraulic systems. Systems are furthermore located in different areas of the facility, to reduce the risk of fire damage. In the case of a serious failure the reactor(s) are automatically shut down.

- **Consequence-relief level**
  The third level is designed to control the radioactive and other harmful substances even if all other systems have failed and the fuel core is melting. The reactor containment is an important barrier made of steel and pre-stressed concrete. In the event of a serious accident the surrounding strong building is automatically sealed to prevent radioactivity from reaching the environment.

4.2.3. Barriers and safety systems

To protect the radioactive substances from reaching the environment there are several independent barriers and safety systems.

The barriers are described below and illustrated in *Figure* 22.

- **The fuel**
  The fuel itself is a barrier. The uranium fuel pellets are sintered to high chemical and mechanical stability, virtually insoluble in water and air with a melting point of 2 800 °C.

- **Fuel rods**
  The fuel pellets are encapsulated in strong tubes of zirconium alloy, which is particularly suited for nuclear applications due to high resistance to corrosion and they are completely gas proof.

---

[4] Swedish legislation: Miljöbalken, and specific to nuclear activities: Kärntekniklagen and Strålskyddslagen.

- **Reactor vessel**
  The reactor vessel and associated pipe systems is designed for high pressure. The wall of the vessel surrounding the fuel core is made of 15-20 cm thick steel.

- **Reactor containment**
  The reactor vessel and associated pipe systems is surrounded by the reactor containment which is made of metre-thick pre-stressed concrete “reinforced” with gastight steel plates.

- **Reactor building**
  The reactor building is made of steel and concrete and is designed to withstand strong forces from both inside and outside. It is also an obstacle to forced entry. For PWR, the reactor containment and the reactor building are one and the same.

There are multiple safety systems for cooling the reactor core and preventing radioactive substances from reaching the environment. To protect radioactivity to reach the environment even in the case of a core meltdown, the reactors are equipped with safety filters. The reactor containment is protected from over-pressure by releasing steam and gas to the filter, which takes care of at least 99,9% of radioactive substances.

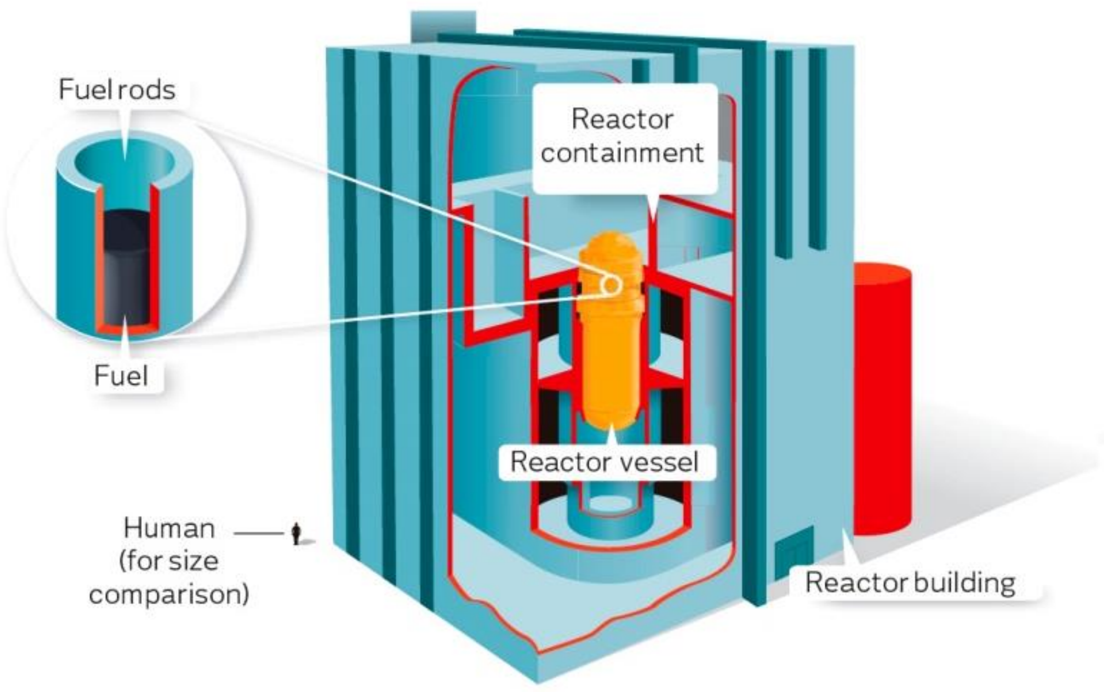


Figure 22 Barriers against radioactive emissions

4.3. Ionizing Radiation

Radioactive substances in various forms are handled during normal operation in facilities within the nuclear fuel cycle. These substances emit ionizing radiation that may result in doses to the people working in the facility (dose-to-personnel), and to people outside the facility (dose-to-third party). Radiation from normal operation is minor compared to natural background radiation, and results in annual doses of less than 0,001 mSv to persons living in the vicinity of the NPPs.

4.3.1. Dose-to-personnel

This section concerns dose-to-personnel for all facilities in the nuclear fuel cycle. The table below shows how high a dose should be allocated to generated electricity in terms of an average dose to an individual.

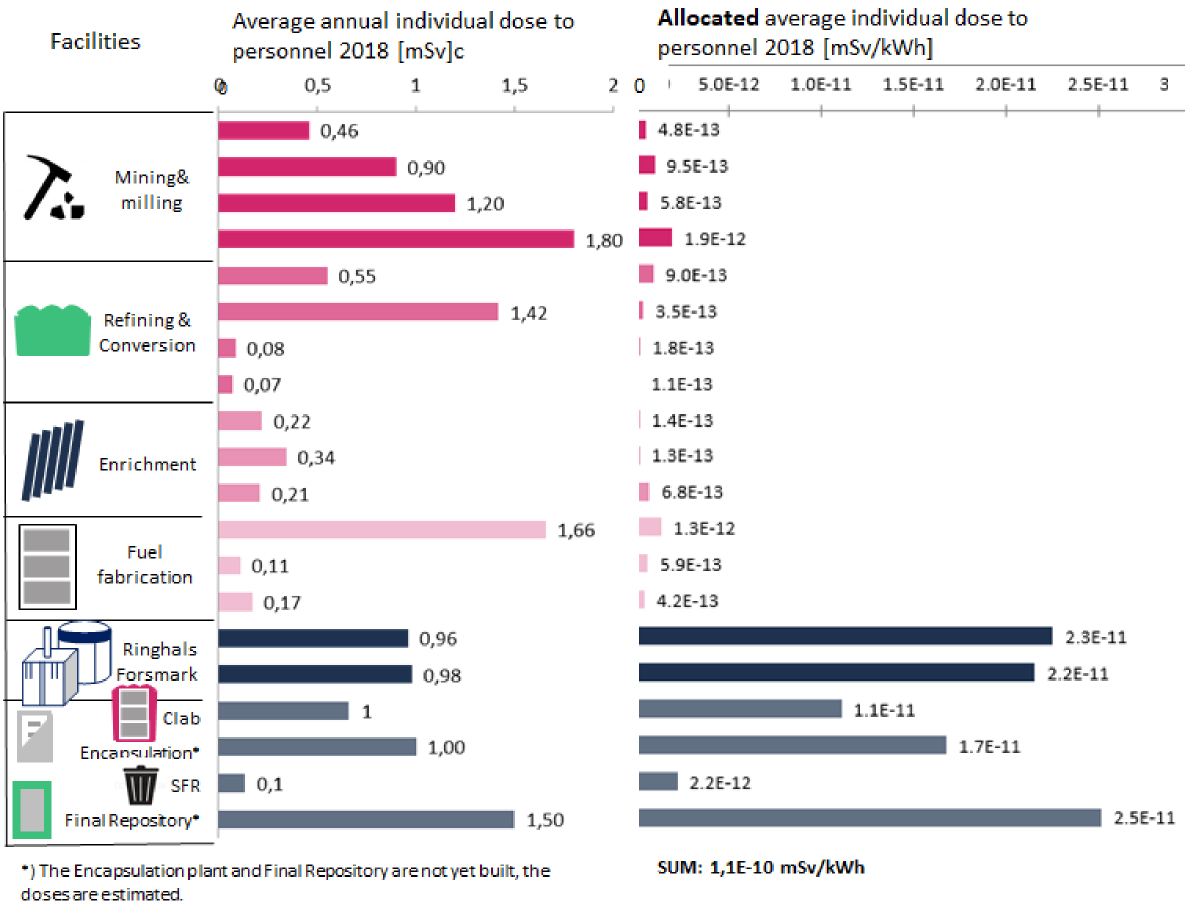


Figure 23 Allocated and average individual annual dose-to-personnel at the facilities in the nuclear fuel cycle.

4.3.2. Public exposure

Controlled release of radioactive substances to air and to water is normal during operation of facilities in the nuclear fuel cycle. Laws, regulations, and licenses in the respective country dictate permitted emission levels. Swedish NPPs report emissions to the Swedish Radiation Safety Authority (SSM) on a scheduled basis. The emissions will affect people living in the vicinity of the facilities (local effect). Some of the released substances with longer half-lives may affect the global population.

The internal exposure of man by ingestion of water and food goes via dispersion, deposition, transportation, and receptor uptake. The deposition on water in a normal situation is of marginal importance compared to land.

The path from release to dose (to third party) goes via dispersion, deposition and uptake. Man takes up radioactive substances from water and food. Man is also subjected to natural background and other irradiation. Conclusively, man is externally and internally exposed to low amounts of radioactive substances released from nuclear facilities during normal operations.

Dose to third party is assessed as:
- dose to critical group/dose to a representative individual
- collective dose

Dose to critical group/dose to representative individual is an assessed effective dose (mSv) that is received by an individual living in the vicinity of the facility. This is commonly a hypothetical individual that is assumed to represent a person that is more exposed due to its habits and consumption pattern. The critical group /representative individual may be defined differently between countries depending on the type of facility, the emissions as well as the surrounding environment.

Maximum calculated annual effective dose 2018 from FKA and RAB was 0,00014 respectively 0,00029 mSv to a 7-12-year individual in the critical group. For comparison, if you live in Sweden the annual radiation dose is about 0,6 mSv from naturally occurring radioactive substances in soil and building materials. The total dose varies, but the average is about 4 mSv including for instance medical radiation and radon in homes.

Collective dose (manSv) is the product of average effective dose and the number of exposed individuals in a specific area. The dose is calculated either from measured data (occupational exposures) or from estimated doses (public exposures) with mathematical modelling.

4.4. Environmental Risk Assessment

Events not considered as normal operation, and thus not included in the LCA part of the EPD, belong to the environmental risk assessment. In risk assessments, the probability that a hazard will turn into a negative event is estimated, and in general risk is defined as the probability of an undesired event multiplied by the consequences of the event. Both conventional and radiological environmental risks are considered in this report. Accidents and incidents due to sabotage, acts of war or terror are not included in the assessment.

Available information for this EPD on risks in the nuclear fuel cycle are of diverse kinds, from qualitative reasoning to detailed and quantitative analyses. For mining, refining, conversion, enrichment, and fuel fabrication a qualitative reasoning is primarily made, while for nuclear power plants and waste management quantitative methods are also presented to a greater extent.

The main source of information for this section is communication with the suppliers. Certain information is classified as confidential. This section should be viewed as a summary of separate risk assessments in the nuclear fuel cycle. The degree of detail in the provided material differs between the suppliers and consequently this is reflected in the text below.

4.4.1. Risk Assessment and the Nuclear Sector

Before construction of a NPP, risk analyses are performed in order to prove that the plant design is safe and has an ability to handle major incidents, such as large pipe-breaks and loss of external power. These analyses are called deterministic risk analyses and aim to prove that after a presumed large pipe-break or other major incident, no other single failure of any component will lead to core damage and radioactive releases to the environment.

Since the 1970's, Probabilistic Safety Assessment (PSA) has been applied in the nuclear power and other industries. It is a systematic approach to calculate the ability for a facility to withstand incidents and breakdowns, and answers the following questions:
- What incidents may occur, and how frequently?
- What barriers are required to contain the incident, and what is the probability of barrier malfunction?

For conventional risks, with non-radiological consequences, the nuclear industry uses various methods and risk management systems to map, evaluate and act on unacceptable risks.

4.4.2. Summary of Environmental Risks in the Nuclear Fuel Cycle

Before it is used in a nuclear reactor, uranium is only slightly radioactive, and its chemical toxicity is more significant. Accidents with environmental impact in the extraction, milling, conversion, and enrichment phases are predominantly chemical, such as accidents during shipments of chemicals or minor leaks from tanks and waste depots. No probable scenarios with sizeable consequences have been identified in these phases, and incidents lead to local impact only.

Systematic and detailed assessments have been made for the nuclear power plants. These assessments show that accidents with consequences for third parties have low probability, but the consequences might be considerable should they occur.

For the waste, assessments of the final repository show that even a hypothetical scenario, with severe damage on all copper canisters and failure of the bentonite clay buffer, would result in a dose to third party below the level of the natural background radiation in Sweden (natural background radiation of 0,5-1 mSv annually).

The conclusion is that risks in the nuclear fuel chain have low probability according to acceptance criteria as set by the regulatory body.

4.4.2.1. Mining

Vattenfall uses suppliers that extract uranium from underground and open pit mines.

Waste from uranium mines is similar in many ways to waste from other types of mines. Occasionally other substances are mined besides uranium. Waste from uranium mines contains radioactive substances, but also other materials such as heavy metals and acids that require action to prevent impact on the environment within the vicinity of the mine.

Tailings from the mining and milling are the leftover materials that remain after uranium is extracted. They are deposited as sludge in pits or dams. The tailings are radioactive; they contain radium which decays to form radon and other potentially hazardous elements such as molybdenum, selenium, uranium and thorium. The tailings must be managed to reduce the risk of spreading to the surrounding environment.

In order to prevent radioactive particulates from being wind-spread as well as to limit radon emissions, crushed aggregate and filled tailing dams are covered with a 1-2 m thick stratum of soil and gravel. This is an effective way of preventing dispersion of radioactivity, and it is employed by all mines in the nuclear fuel cycle.
Storage of mining waste in exhausted open pit mines and underground pits below the water table is a method that prevents oxidation and consequently production of acids, whilst simultaneously reducing the risk of human intervention as well as eliminating dust formation.

Below are risks that can lead to soil and/or water contamination, and negative impact on flora and fauna:

- Insufficient cleaning of water
- Accidental emissions to air such as particles and sulphur dioxide
- Spills and leakages of chemicals such as sulphuric acid and hydrocarbons
- Radioactive releases through accidental emissions or spills of process compounds
- Leakage from landfills and sludge ponds

Incidents during the past five years with impact on the environment reported from the suppliers include flooding, insufficient purification and cleaning processes, and leakages/spills of chemicals (e.g. ammonia) and radioactive substances.

4.4.2.2. Refining and Conversion

Vattenfall's suppliers use two different refining and conversion processes. In one of these, yellowcake is converted to uranium trioxide, and further to uranium hexafluoride (UF_6) and uranium dioxide (UO_2). In the second type of process, natural uranium is converted to uranium tetra fluoride (UF_4) and further to UF_6.The main risks in these processes relate to leakage of UF_6 and hydrogen fluoride (HF). HF is highly toxic, volatile and corrosive and is used in the conversion process. UF_6 is highly corrosive. The chemical toxicity of hydrogen fluoride (HF) is more adverse from a human health perspective than the radiation dose from the UF_6.

Risks noted by Vattenfall's suppliers include release of UF_6, HF and ammonia.

4.4.2.3. Enrichment

No chemicals are added in the enrichment process. Gaseous uranium hexafluoride – UF_6 (natural U-235 concentration) – is separated into two fractions in the process. One of these fractions has a lower concentration (depleted) and is called tails, and the other leaves the process enriched with a higher concentration of U-235 (typically 3-5%). At gas centrifuge facilities, pressure inside gas pipes is maintained below atmospheric pressure in order to prevent UF_6 from escaping. Sections of the facility containing high-pressure piping are equipped with airtight containment and the air inside is re-circulated to recover any escaped gas.

From a non-proliferation standpoint (i.e. calling for an end to the acquisition of nuclear weapons by additional nations), uranium enrichment is a sensitive technology needing to be subject to tight international control.

Risks assessed by Vattenfall's suppliers of enrichment services include spillage, leaks and emissions of UF_6, oil and other chemicals and substances.

4.4.2.4. Fuel Fabrication

Risks in the fuel fabrication stage relate mainly to the handling of hazardous substances (toxic and flammable) such as solvents, and radioactive materials.

Risk scenarios identified by Vattenfall's suppliers that can result in emissions include:

- Criticality accidents
- Release of uranium hexafluoride and the formation of hydrofluoric acid
- Emissions of ammonium
- Hydrogen explosion
- Release of uranium powder
- Methanol fire
- Ammonium fire and the creation of nitrous oxide

Risk assessments have shown that effects from release of chemicals dominate over the radiological effects in case of an accident.

4.4.2.5. Electricity Generation

Risk assessments regarding emissions of radioactive substances to the environment were made prior to the actual construction of the nuclear power plant. The results have influenced the construction of the facilities, which are built to contain a core melt with only minor radioactive emissions. Conventional risks have also been studied, and the major environmental aspects have been identified. Risk assessments have been performed whenever justified and they are continuously updated.

Conventional Environmental risks

Conventional risks are assessed partly using a risk matrix based on probability and consequence, partly using a scenario analysis method. The scenario analysis describes all the risks in financial terms, which the matrix-based method does not do, however the basic description of the risks is useful for gaining an understanding of the risk.

In the scenario method, three scenarios are created that represent events with varying degrees of probability. Event/scenario No. 1 can be expected to occur every two years, No. 2 every 10 years and No 3 every 100 years. The scenarios should be typical and representative for the risk situation discussed. From these events a distribution is created, and an expected mean value along with other estimates can be determined. Only the nuclear sites have been assessed using the scenario method.

Many different chemical substances are used at a nuclear power plant. Substances listed below have been selected for a risk assessment, since they a) occur in large quantities and b) may have negative effect on the environment (as well as on humans):

Oil/diesel. Many scenarios can be found, e.g. minor oil-spills, leakage from oil tanks, oil leakage from spare transformer.

Firefighting water. In the case of a fire, firefighting water may reach the environment. Depending on the burning object and depending on the method for fighting the fire, the amount and the substances present in the water may vary.

Ethanol. In Forsmark there are fuel tanks for petrol, diesel and ethanol. The largest risks associated with them are related to filling of the 5m^3 ethanol tank.

Sodium hypochlorite. Used for chlorination of auxiliary cooling water in Ringhals. The substance is stored in three tanks of 30 m^3 each.

Hydrazine. This is used to reduce oxygen in water and thereby reducing corrosion. Ringhals 2-4 each have a 13 m^3 tank close to the turbine hall.

The emission risks for the substances, according to the three scenarios, are summarised in Table 19 and 20.

Table 19 Forsmark. ERM emission risks for oil/diesel, fire-fighting water and ethanol as percentiles.

	Median values (50-percentile)	**10-year-value (90-percentile)**	**100-year-value (99-percentile)**
Oil/diesel	10 litres	500 litres	5 000 litres
Firefighting water	0 litre	100 litres	10 000 litres
Ethanol	0 litre	0 litre	10 000 litres

Table 20 Ringhals. ERM emission risks for oil/diesel, fire-fighting water and ethanol as percentiles.

	Median values (50-percentile)	**10-year-value (90-percentile)**	**100-year-value (99-percentile)**
Oil/diesel	10 litres	500 litres	5 000 litres
Sodium hypochlorite	0 litre	0 litres	500 litres
Hydrazine	0 litre	50 litres	200 litres

The most significant conventional environmental risks identified at Forsmark and Ringhals using the risk matrix are:

- Release and contamination of process chemicals.
- Storage and handling of ammonia and/or hydrazine: When hydrazine is decomposed, ammonia and other volatile chemicals are formed and released in the air and water.
- Release of heated cooling water: The water is heated to about 10 degrees before it is released to the sea, which (negatively and positively) affects animal and plant life in the sea.
- Leakage of sodium hypochlorite: Sodium hypochlorite is added to prevent mussels and sea turtles from growing on surfaces of the cooling water system that cool the security system. In turn, this follows the cooling water released back into the sea.
- Release of cleaning balls: These are used to keep the cooling water tubes in the condensers free from fouling. The cleaning balls are run through the tubes and may come out into the sea, which may affect wildlife and cause littering.
- Emissions from sanitary sewage treatment plant: The sewage treatment plant entails emissions of mainly organic and oxygen-consuming substances.
- Fires, e.g. fire in transformer, turbine hall, electronic components and flammable chemicals.
- Fuel truck accident.

Ringhals is classified according to Seveso's higher level, which requires additional reporting on the use of Seveso chemicals. In addition to the risks already identified above, risk scenarios according to Seveso include acetylene leakage, storage and transport of diesel oil, gasoline storage, fire or explosion caused by hydrogen gas accidents.

Radiological environmental risks

Probabilistic Safety Analysis (PSA)

Central components of the PSA method are event trees and fault trees. A fault tree is basically a logical map of each safety function and its components. An event tree is a logical map of a sequence of events. Event trees and fault trees are universally applicable.

Fault trees demonstrate which components and systems can be used to cope with an event, which systems are interdependent, in what manner a component can malfunction (components can exhibit multiple malfunctions), and how frequently malfunctions occur when the component is required to function as intended. Boolean algebra is applied to calculate the probability for system malfunction.

Event trees demonstrate which systems and interventions that must work in order for the reactor to safely shut down after a disturbance. An event tree starts with an individual initiating event such as a pipe fracture or power failure. A number of trees are connected and a resulting frequency (measure of probability) is calculated for various scenarios.

PSA-studies are conducted at three levels. Level 1 concerns incidents up to the point where the fuel in the reactor core is subjected to conditions beyond its design parameters, core damage. Level 2 concerns assessment of the possibility of incidents, which lead to a major breakdown and ensuing emissions to third party. A breakdown involving core meltdown does not necessarily lead to emissions to third party as illustrated below. Level 3 concerns probability and environmental impact of radioactive emissions (i.e. possible doses to third party depending on weather conditions after a specific accident scenario). PSA Level 1 and 2 studies are performed regularly at the NPP while level 3 studies are less frequent.

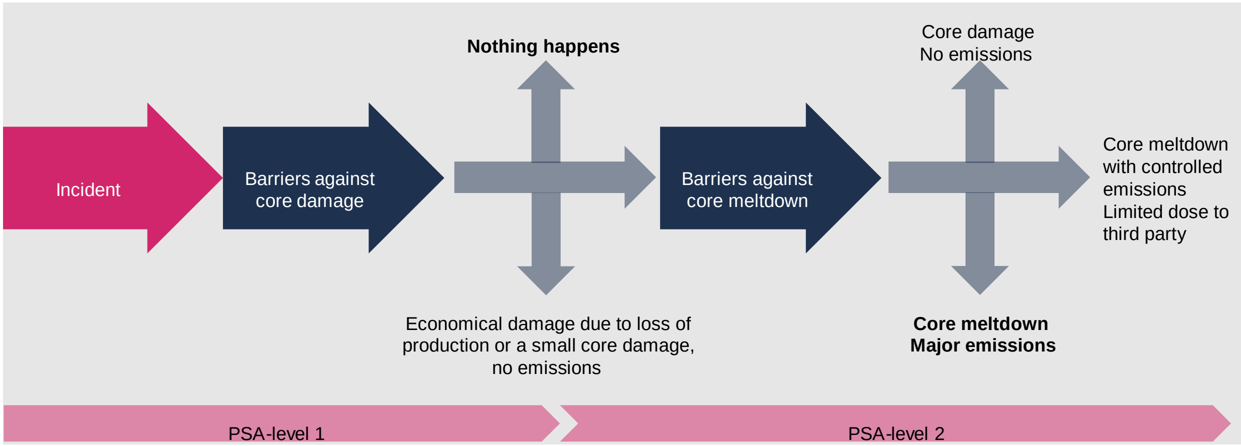


Figure 24. PSA levels and process tree.

PSA results

PSA is a quantitative risk analysis and the numeric data is necessary, however to focus on the actual quantitative result could be misleading as there is a degree of uncertainty in all such numbers. One reason is because incident frequencies as well as failure probabilities of systems and actions are estimated. The purpose of PSA is not primarily to calculate exact figures, but rather to identify dependencies and weaknesses at a facility. The PSA method however provides a systematic approach and the possibility to collect all information in a computerized model. This provides the possibility to evaluate and give priority to safety measurements. You can also trace dependencies between functions, components and systems.

PSA level 1 – Core damage frequency

Forsmark: The total calculated core damage frequency during power operation is estimated to approximately 0,01 times per 1000 years (F1-F3). Internal events, i.e. initiated from an event coupled to the process systems such as loss of coolant to the reactor, dominate in the contribution to the frequency. Analysed sequences involving fire and flooding which are area events have had a limited contribution to the core damage frequency.

Ringhals: The total calculated core damage frequency during power operation is estimated to between approximately 0,01 – 0,05 times per 1000 years (R1-R4). Internal events dominate in the contribution to the frequency. Analysed sequences involving fire which is an area event, also contributes to the core damage frequency.

PSA level 2 – Incidents leading to unacceptable emissions of radioactive substances to third party

Core damage frequencies in the PSA for the operational mode are subsequently (re)classified to reflect the actual state of the reactor unit when core damage is a fact. Classification parameters are e.g. state of containment, available cooling, etc. Depending on which functions and systems that are available during the accident scenario, the size of the emission and time to release will differ. These main functions and barriers are:

- Insulation of the reactor and the containment
- Recovery of reactor core cooling
- Physical phenomena that challenges the containment function (such as hydrogen explosions)
- Containment spray
- Filtered ventilation of the containment
- Filtered ventilation of diffuse leakage to the reactor building

Forsmark: The non-acceptable release frequency is calculated to less than 0,0003 per 1 000 years and the frequency of major releases to the environment is less than 0,00006 per 1 000 years (this is a share of the "non-acceptable release").

Ringhals: The frequency for non-acceptable releases is 0,001-0,005 per 1 000 years. The most likely release mode is filtered releases.

4.4.2.6. Waste Management

Land Repository
Both NPP´s have implemented an on-site repository for low level radioactive waste, which is used periodically. Conventional environmental risks connected to the land repositories include breakthrough in waterproofing, impaired function in infiltration bed, fire and flooding.

Regarding radiological risks, a number of extreme scenarios have been designed in order to calculate the maximum doses of exposure. Examples of analysed scenarios are intrusion into landfill, extreme fire, and construction of well in the repository. For all identified extreme scenarios, the resulting doses to the public will be low, at the most 10 µSv/year, even when making very conservative assumptions about the impact on waste and repository.

SFR (Final Repository for Radioactive Operational Waste)
Operational waste (Low and Intermediate Level Waste) from Swedish nuclear power plants and similar waste from industry, health services, and research facilities is deposited at SFR. The facility is located in bedrock some 60 meters below the sea floor and the water depth is five meters. The location was selected after geological examination. Seismic activities as well as the probability of tremor-related displacements are very low in the Forsmark area.

The most serious incident identified during operation would be if a waste container dropped from a lifting device. Clean-up personnel could then be subjected to irradiation if the container is damaged. The calculated sum of doses to all personnel is 15 mmanSv (no dose to the public).

Chemical risks are considered negligible since only minor quantities of chemicals are involved.

The risk of future generations being exposed to radioactive substances have been analysed for extreme scenarios:
- Radioactive particulates and contamination from waste can only propagate via the ground water, which attaches major importance to its flow in the bedrock. One thousand years after sealing off the facility, the calculated flow of ground water will be 5 litres/m^2 annually. As the land-elevation continues, the flow will reach 15 litres/m^2 annually, approximately 2500 years after sealing. Chemical examinations of the ground water show that present water flow through the rock is very limited, 0,2 litres/m^2 annually.
- The repository will remain covered by saltwater for the first 1000 post-sealing years. A fresh-water ecology implying downstream wells may have evolved after 2500 post-sealing years. The first 1000 years are called the saltwater period, during which the direct migration path for radioactive substances to humans via drinking water can be excluded.
- In a realistic scenario, where the barriers are intact, the maximum dose to an individual occurs approximately 100 years post sealing and is calculated to be 0,0001 mSv/year. This can be compared to the natural background radiation of 0,5-1 mSv annually.

Clab (Central Interim Storage Facility for Spent Nuclear Fuel)
Spent fuel will be stored at Clab in cooled water pools for several years. The water in the pools acts as radiation shielding as well as a coolant for the hot fuel. The quantity of water is large enough and evaporation gradual enough for a temporary disruption of the cooling to not pose any danger. It will take a full month before enough water has evaporated to uncover the top of the fuel assemblies. A fundamental design principle is the duplication of essential safety arrangements, e.g. power supplied by independent sources.

The bedrock site provides ample protection against intrusion, theft, sabotage, and other acts of violence as well as protection against acts of war. The storage area and cooling systems are designed to withstand the effects of anticipated Swedish seismic activity without damage to the spent fuel.

The assessed incidents are related to emissions of radioactivity. Chemical risks have not been analysed, as there are only minor amounts of hazardous chemicals at Clab. The dose outside the facility has been estimated based on conservative assumptions regarding release of radioactive substances. Most of the radioactivity inside the fuel has subsided while resident in the on-site storage pool at the NPP before transportation to Clab. Activity and temperature are still high, requiring shielding as well as cooling.

Doses to the environment are based on emissions from 20 m height and lasting one hour. Examples of analysed events are fire, loss of cooling or electricity supply and mishaps/failure of components in the management of fuel. All identified events are considered acceptable. Either the probability of occurrence is extremely low, or the consequences can be mitigated and are below the set criteria. The maximum effective dose at a 200 m distance was calculated to be 0,013 mSv. This can be compared to the natural background radiation of 0,5-1 mSv annually.

Encapsulation Plant

An encapsulation plant will be built that is integrated with Clab. Here, the spent fuel, after interim storage at Clab, will be encapsulated before final disposal. Clab and the encapsulation plant will then be operated together as one unit called Clink.

A risk assessment, similar to that of Clab, has been made for the future encapsulation facility. The assessment considers possible incidents during the operating lifetime of the facility regardless of the expected frequencies and consequences. The more probable incidents neither cause damage to the fuel within the facility, nor lead to consequences for the environment. Critical functionality affected by incidents can either be handled by other systems or temporarily suspended.

Various incidents are considered, such as fire, handling mishaps regarding fuel elevator cage, fuel assembly, receiving dock, insert, and transport cask and external incidents. None of these incidents are estimated to result in serious consequences for the surroundings. The residual heat (in the spent fuel) is considerably lower in this facility than in Clab, which results in slower processes in case of incidents. Consequently, available time for corrections increases proportionately.

Final Repository

SKB has concluded that a very suitable site for the final repository for spent nuclear fuel is available adjacent to Forsmark. Applications for necessary permits to build and operate this repository have been submitted to The Land and Environment Court and The Radiation Safety Authority (SSM) in 2011. Negotiations have been held in the Environmental court (2017) and the following year SSM and the Environmental Court gave their statements to the government, where the repository system was approved however on the condition to further investigate the copper canisters and their corrosion stability.

Different kinds of disruptions and mishaps can occur during the time the plant is in operation, i.e. during the time that the deposition is ongoing. After the core components of the decommissioning of the NPPs have been deposited, the plant will be closed (it has gone 40 years after the last reactor ceased operations in Sweden).

Conventional environmental risks are described and evaluated for all stages of the facility, i.e. construction, operation, decommissioning and closure. The risks are evaluated in order to see which ones are of a more serious nature. A very large proportion of the risks that occur is emission of oil or gas, primarily on land. In general, the risk is present mainly in connection with the construction phase and then is no different from the risks involved at every major construction project. With a good organization and a high environmental profile, emissions can be minimized and if necessary, decontaminated. Also, some of the other risks can be reduced significantly through preventive measures.

Risks evaluated to be of high priority (red) are:

- Lack of knowledge of the land (risk of harming valuable environments and species)
- The model of the geohydrological balance is incorrect (greater groundwater immersion and saline penetration)
- Powerful water-carrying crack is missed in front of tunnel operation
- Temporary fuel tanks
- Nitrogen contamination from blasting that remains on rock masses that are deposited

- Sealing work/injection resulting in groundwater immersion
- Emissions from components/vehicle

No event that would damage the canister during operation has been identified. A hypothetical case has been created where one assumes that the capsule breaks and activity leaks through a crack. One must assume that not only the canister is damaged, but also the equipment inside, as well as damage to the fuel cladding. Only gaseous activity can be released. This hypothetical case gives a dose of 0,04 mSv to a person standing in the same tunnel as the canister for one hour immediately after the capsule break.

The principal acceptance criterion, expressed in SSMFS 2008:37, concerns the protection of human health and requires that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". "Harmful effects" refers to cancer and hereditary effects. The risk limit corresponds to an effective dose limit of about $1{,}4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the effective dose due to natural background radiation in Sweden. Furthermore, the regulation SSMFS 2008:21 requires descriptions of the evolution of the biosphere, geosphere and repository for selected scenarios; and evaluation of the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

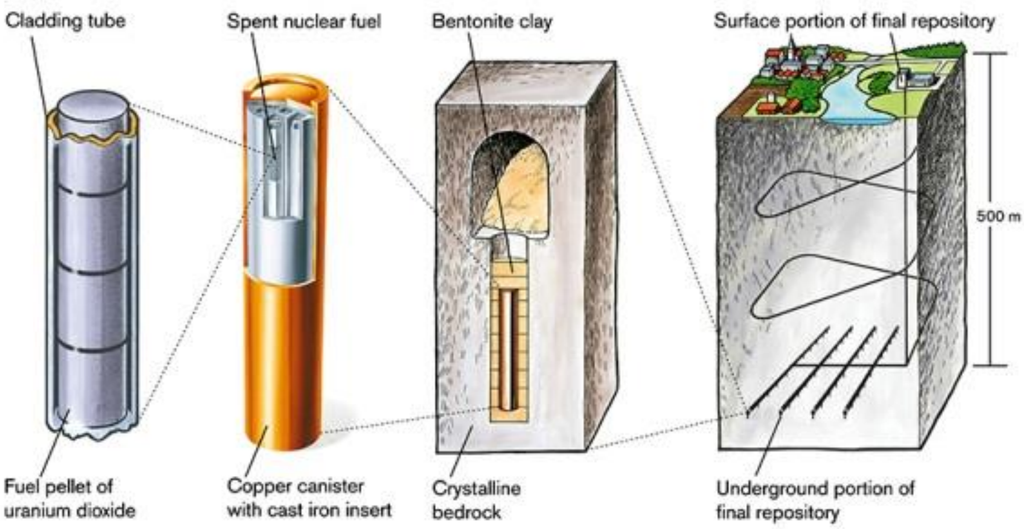


Figure 25. Physical Barriers.

4.4.3. Transportation

Worldwide, goods containing radioactive materials are routinely transported on public roads, railways and ships, and are thus consequently subject to general risks connected to goods transport. However, only about 5% of these transports are intended for the nuclear power industry.

Uranium is only weakly radioactive before it has been used as fuel, and its chemical toxicity is then more significant than its radioactivity and radiotoxicity. Transports within mining, refining, conversion, enrichment, and fuel fabrication takes place on land and at sea and accidents can occur, but consequences are minor.

The purpose-built ship Sigrid transports spent fuel enclosed in heavy-duty transport containers to Clab, with Sigrid providing radiation shielding and damage protection. The containers are robust and designed to withstand severe stresses, exceeding IAEA standards.

4.5. Electromagnetic Fields

Electromagnetic fields (EMF) appear in the vicinity of all electrical equipment and power lines. There are no binding limits regarding exposure to EMF. The International Commission on Non-Ionising Radiation Protection (ICNIRP), an independent body consisting of international experts, has however published recommendations[5] regarding acute health problems. The recommendations are based on knowledge about acute health problems due to changing magnetic fields and propose a limit of 1000 µT for people in the working environment, and for the general public they set a limit of 200 µT at 50 Hz. The EU Council of Ministers recommends a restriction of exposure to electro-magnetic fields in accordance with the ICNIRP:s recommendations.

High-frequency EMF has been found to be dangerous to human health. Effects on human health due to exposure of low-frequency EMF have been debated for a long time, the main concern being raised risks of cancer due to long-range exposure. The scientific research in this area is not conclusive and often contradictory. Despite extensive research, to date there is no evidence suggesting that exposure to low-frequency electromagnetic fields is harmful to human health[6]. According to ICNIRP, available research results on lesions due to long-range exposure, for example raised risk of cancer, does not suffice to establish limits. Vattenfall follows ICNIRP's, WHO's and OECD's work and recommendations in the area. At Vattenfall the precautionary principle is also followed, which implies reducing fields that deviate considerably from normality in each specific case.

4.6. Noise

Noise has been measured in the surroundings of the NPPs. Beside the level of noise generated at the original source, the noise level at a specific measuring point is also dependent on external circumstances such as for example wind direction and temperature. Maximum noise levels have been measured to be kept within the environmental permits at the nearest households in the vicinity of the power plant, which are 40 dB(A) (night) and 50 dB(A) (daytime) for Forsmark, and for Ringhals 43 dB(A) (night) and 50 dB(A) (daytime).

Power lines above 70 kV can generate corona noise levels of 45 dB(A) at a distance of 25 meters, however abating as distance increases.

4.7. Visual Impacts

Forsmark's and Ringhals' reactor buildings can be viewed from sea and land up close. Especially Ringhals can be seen from far out to sea. The visual impact from land is however limited as Ringhals nuclear power plant is located away from any municipality, in the vicinity of local industry, and Forsmark nuclear power plant is located in a forested area. The reactor buildings have a height of about 50-60 meters and are equipped with chimneys with a height of about 60 (pressurized water reactors, PWR) to 100 meters (boiling water reactors, BWR).

---

5 Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (1 Hz – 100 kHz), Health Physics Vol. 99, No 6, pp 818-836, 2010.

6 http://www.who.int/peh-emf/about/WhatisEMF/en/index1.html, http://www.who.int/peh-emf/standards/en/

Figure 28 Ringhals and Forsmark Power plants.

5. Information from the Certification Body and Mandatory Statements

5.1. Information on the Independent Verification of this EPD®

This EPD® has been verified within Vattenfall's EPD® Management Process. The independent verifiers Caroline Setterwall, ABB, and Lasse Kyläkorpi, Vattenfall AB, confirm that the product fulfils relevant process- and product-related laws and regulations and certify that this EPD® follows and fulfils all rules and requirements of the International EPD® system managed by EPD International AB (General Programme Instructions (GPI), version 2.01, 2013-09-18, and Product Category Rules (PCR) CPC 171 version 3.1, 2015-02-05). This certification is valid until 2022-12-31.

5.2. Verification of Vattenfall's EPD® Management Process

Vattenfall's EPD® management process is third party verified on annual bases, the last review was made 2019-10-17. Bureau Veritas Certification, accredited by SWEDAC, the Swedish Board for Accreditation and Conformity Assessment, hereby confirms that Vattenfall's EPD® Management Process follows the requirements in the GPI and the Process Certification Clarification (PCC) for the International EPD® system.

5.3. Mandatory Statements

5.3.1. General

To be noted: EPD®s within the same product category but from different EPD® programmes may not be comparable. When comparisons are made between different products in this product category it should be noted that energy can be supplied through different energy carriers like heat/steam or electricity, but the amount of kWh needed will differ with different energy carriers due to different energy quality and conversion/distribution efficiencies.

5.3.2. Omissions of Life Cycle Stages

The use stage of produced electricity has been omitted in accordance with the PCR since the use of electricity fulfils various functions in different contexts.

5.3.3. Means of Obtaining Explanatory Materials

ISO 14025 prescribes that explanatory material must be available if the EPD® is communicated to final consumers. This EPD® is aimed for industrial customers and not meant for private customer communication.

5.3.4. Information on Verification

EPD® programme: The International EPD® system managed by EPD International AB, Box 210 60, SE-100 31 Stockholm, Sweden. E-mail: info@environdec.com, www.environdec.com

Product Category Rules: Product Category Rules, CPC 171 Electrical Energy, version 3.1

PCR review was conducted by: The Technical Committee of the International EPD® system. Chair: Massimo Marine. EPD International AB. Full list of TC members available on www.environdec.com/TC

Independent verification of the declaration and data, according to ISO 14025, has been performed within Vattenfall's certified EPD® Management process.

X Internal (EPD process certification)

Internal and external verifiers: Lasse Kyläkorpi, Vattenfall AB, and Caroline Setterwall, ABB

Third party verification of Vattenfall´s EPD Management process has been conducted by the *accredited Certification body*: Bureau Veritas Certification

External verifier: Camilla Landén **This EPD® is valid until:** 2022-12-31

6. Links and References

Internet sites

www.vattenfall.com

www.environdec.com homepage of EPD International Ltd, where you can download supporting documents for this EPD®.

Databases:

Generic data mainly stem from the database Ecoinvent version 3.5 (2018) and GaBi Professional database 2019 Edition.

Contact information:

For questions concerning this EPD® and for general information on Vattenfall's work with EPD®, contact Lena Landström at Vattenfall, Lena.Landstrom@vattenfall.com

For additional information about Vattenfall, please visit our web site at www.vattenfall.com.

Specific questions regarding FKA's environmental topics should be directed to Rebecca Laitinen, e-mail: reb@forsmark.vattenfall.se.

Specific questions regarding RAB's environmental topics should be directed to Helene Holgersson e-mail: Helen.Holgersson@vattenfall.com.