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Nuclear Decommissioning Profile Switzerland

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1 Introduction

Similar to other countries, Switzerland started to pursue nuclear energy after the end of the Second World War (IAEA 2022a). The Manhattan-project and the American nuclear technology development had a decisive influence on the development of nuclear technology in Switzerland (Wildi 2003). The state was heavily involved in the early stages of nuclear technology development but it soon moved to the peripheral role of a moneylender. The construction of the five commercial nuclear reactors in Switzerland was therefore initiated by the private industry and not by state-governed projects (Wildi 2003). In 1969, Beznau 1 started operating commercially as the first official Swiss nuclear power plant (NPP)[1] (swissinfo 2016). Currently, the NPP fleet of Switzerland is among the oldest worldwide (Schneider et al. 2021). Table 1 shows the Swiss nuclear power reactors in detail.

Table 1: Nuclear power reactors in Switzerland

Nuclear Power Reactor	Grid connection	Type[1]	Net Capacity [MW(e)]	Status
Beznau-1	1969	PWR	365	Operational
Beznau-2	1972	PWR	365	Operational
Gösgen	1979	PWR	1010	Operational
Leibstadt	1984	BWR	1220	Operational
Mühleberg	1972-2019	BWR	373	Permanent shutdown

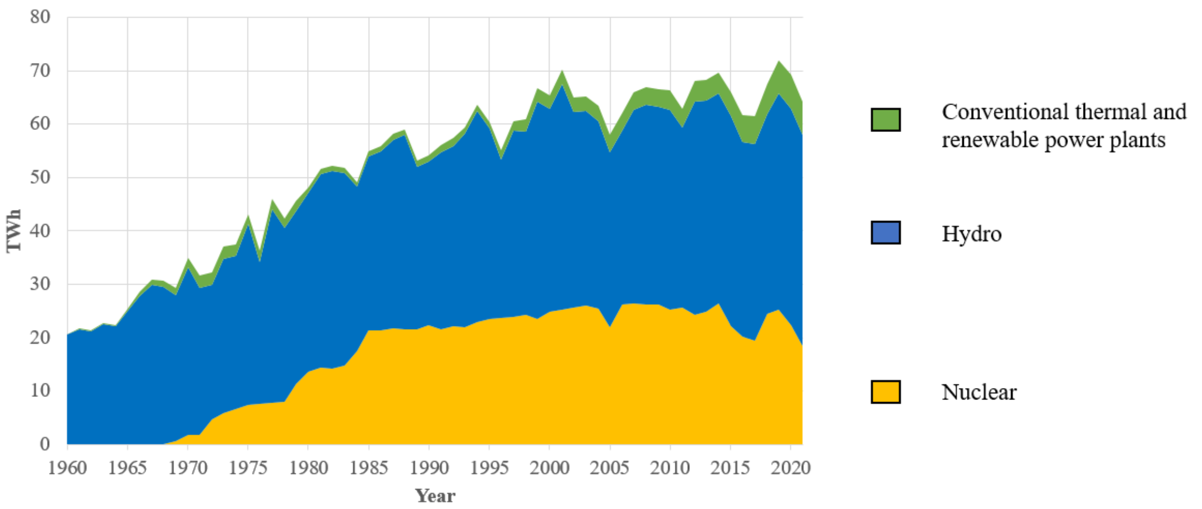
[1] There are two types of Light Water nuclear reactors in Switzerland: Pressurized water reactors (PWR) and boiling water reactors (BWR).

Source: Own compilation based on IAEA (2022b).

NPPs are still an important source of electricity in Switzerland today. In 2020, the share of nuclear energy in the electricity production mix was around 32.9%. In addition to nuclear energy, Switzerland also generates electricity from hydropower plants (58.1%), fossil fuels (2.3%) and various renewables such as solar, wind and biomass (6.7%) (BFE 2021). As visible in Figure 1, the share of non-hydro based renewable electricity in the mix has been increasing slightly in recent years.

[1] Note that even though Beznau-1 is the first official commercial Swiss NPP it was not the first Swiss NPP connected to the electric grid. In 1960, a Swiss NPP was constructed in an underground rock cavern in Lucens (VD). The reactor was a heavy-water reactor and was connected to the electric grid in 1968 (Buser, Lambert, and Wildi 2020; Wildi 2003). However, the project was abandoned after a collapse of the cooling system released a high amount of radioactivity in the cavern in 1969. After the accident, the decommissioning process started right away and was finished in 1995 (Wildi 2003). For more information about Lucens, see Buser, Lambert, and Wildi (2020); ENSI (2012) and Wildi (2003).

Figure 1: Swiss electricity generation by source (1960-2021)



Source: Own depiction based on data from Bundesamt für Energie (BFE) (2022c).

Swiss electricity consumers face a mixed electricity market structure, both monopolistic and competitive. The market for large-scale consumers[2] was liberalized in 2009. Thus, these consumers are able to freely choose their electricity provider and buy the electricity they need on the electricity market (AEW 2021). In contrast, small consumers (which correspond to 99% of all end users) cannot buy their electricity on the market. They are bound to their local electricity provider (AEW 2021). However, plans exist for a possible full liberalization of the Swiss residential electricity market in the near future (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation (UVEK), 2020).

In the monopolistic market structure for private consumers, the price of nuclear energy is regulated and determined by the electricity generation costs ("LCOE") of the NPP. These costs include the degree of capacity utilization; construction and capital costs; operating costs; and fuel costs (mainly disposal costs). The electricity generation costs of NPPs in Switzerland have decreased over time as the capital costs are being repaid. Currently, the costs are approximately 0.04 CHF/ kWh[3] for the older Swiss NPPs (swissnuclear 2018). Large-scale consumers can purchase electricity at market prices which are not regulated and NPPs acting in the market receive the respective wholesale market price which is subject to fluctuations. Consequently, future market developments might improve or damper the profitable production of nuclear electricity (swissnuclear 2017a). For 2022, the Swiss Federal Electricity Commission ElCom reports a slight increase in electricity prices (ElCom 2021).

This report provides an in-depth overview of the nuclear decommissioning landscape in Switzerland. This report will cover the nuclear legal framework, decommissioning regulation, financial regulation and current decommissioning status.

[2] Annual consumption of more than 100'000 kWh (AEW 2021).
[3] 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).

2 Legal and Regulatory Framework

2.1 Governmental and regulatory framework

The first act on nuclear energy dates back to 1959 when the Swiss government passed a bill concerning the peaceful use of nuclear energy (Schweizerisches Bundesarchiv (BAR) 2020). Today, there are six main acts about the usage and organization of the nuclear industry in Switzerland (see the box for details). The main laws that govern the nuclear industry are a part of the Nuclear Energy Act (KEG). The KEG regulates the construction, operation, and decommissioning of NPPs (Bundesrat 2005).

Figure 2 shows all the important regulatory and governmental bodies and their respective influence on Swiss NPPs. Concerning governmental and regulatory bodies guiding the nuclear industry, the **Federal Council**, the Swiss executive branch, and the **Federal Assembly,** the Swiss legislative branch, are responsible for the peaceful usage of nuclear energy in Switzerland. Together, they define the regulatory and legal framework. The Federal Council and the Federal Assembly are also involved in the license approval process of Swiss NPPs as they grant the general license (Kernkraftwerk Gösgen 2020b).

The **Department of the Environment, Transport, Energy and Communication (DETEC),** whose head is one of the federal councilors, regulates the issuing of licenses concerning the construction and operation of NPPs (IAEA 2022a). The **Federal Office of Energy (SFOE)** has the competence to answer nuclear energy related questions on a political level. It is subordinate to DETEC (BFE 2022a).

Legal framework of Swiss nuclear industry

Energy Act (EG), SR 730.0: formulates Switzerland's requirements for its energy supply.

Electricity Supply Act (StrVG), SR 734.7: lays out the framework and tasks for all Swiss electricity providers.

Nuclear Energy Act (KEG) and Nuclear Energy Ordinance (KEV), SR 732.1 and SR 732.11: KEG regulates the usage of nuclear energy in Switzerland and determines the safety principles. KEV adds on to KEG and makes it more specific, e.g., concerning the transport of nuclear waste.

Radiation Protection Act (StSG), SR 814.50: regulates the radiation protection aspects for operators of nuclear facilities and for nuclear energy users in medicine, industry and research.

Nuclear Energy Liability Act (KHG), SR 732.44: regulates, among other things, who is liable for damages/ accidents tied to nuclear power plants.

Act on the Swiss Federal Nuclear Safety Inspectorate (ENSIG), SR 732.2: regulates the organization and tasks of the national inspectorate for nuclear safety (ENSI).

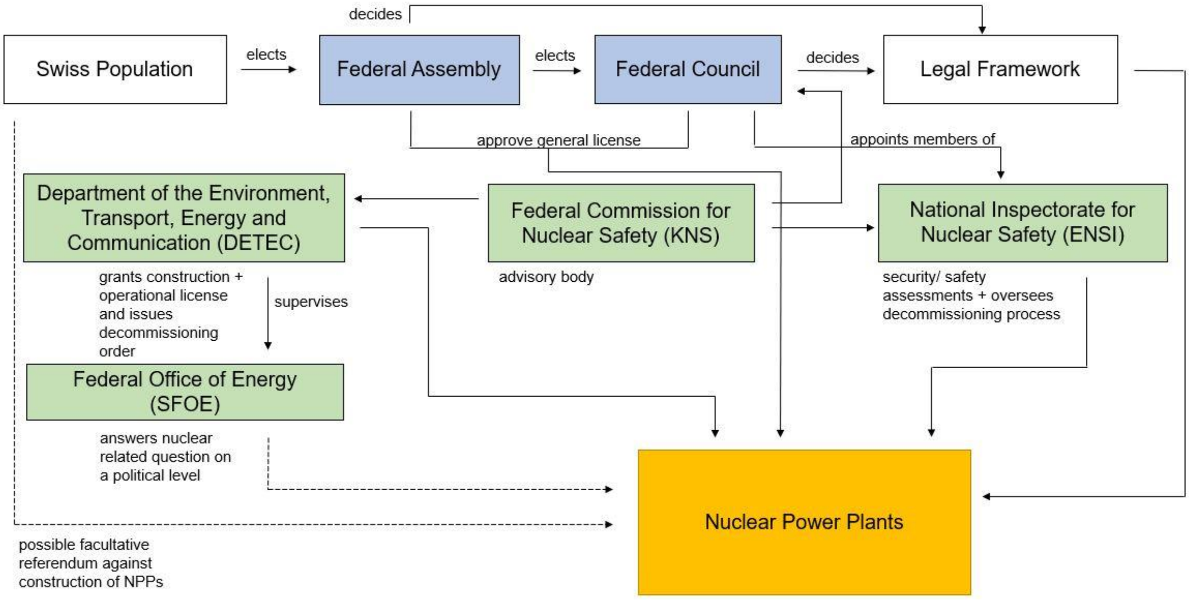
The main supervisor of the nuclear industry on a national level is the **National Inspectorate for Nuclear Safety (ENSI).** ENSI is independent from SFOE and supervised by an independent board whose members are appointed by the Federal Council (ENSI 2020a). Its tasks include inspections of the Swiss NPPs, surveillance of revisions, radiological survey, and safety assessments of the nuclear facilities. Thus, its area of competence is quite extensive, ranging from surveying operation and decommissioning NPPs to the transport of radioactive waste to nuclear research (ENSI 2020a).

Throughout the year, ENSI conducts over 400 on-site inspections and monitors the operation and organization of the nuclear facilities (ENSI 2020a; 2020b). In general, inspections are carried out without notifying the operator first (ENSI 2015b). Every ten years, the NPP operators must carry out a periodic safety review (a so-called "PSÜ"). The objective is a holistic safety assessment of the NPP by the operator. The task of ENSI is to examine the PSÜ thoroughly and to point out where retrofitting measures are necessary (ENSI 2012a).

Another regulatory body involved is the **Federal Commission for Nuclear Safety (KNS)**. KNS holds an consultative role and thus, advises the Federal Council, DETEC and ENSI in nuclear related issues (BFE 2020). There is no overlap between the membership of the boards of KNS and the independent board of ENSI (BFE 2020; ENSI 2020). As shown in Figure 2, the **Swiss population** also has the possibility of opposing the construction of an NPP by taking a facultative referendum. Further opposition measures include direct demonstrations as happened in Kaiseraugst.[4]

On an international level, Switzerland is a founding member of **IAEA** (International Atomic Energy Agency) and follows its regulations (Eidgenössisches Departement für auswärtige Angelegenheiten (EDA) 2017). For a complete overview over all the international treaties and conventions followed by Switzerland, see (IAEA 2022a).

Figure 2: Governmental and regulatory actors and their connection to Swiss NPPs



Overarching governmental bodies are marked blue; agencies and departments green; standard arrows reflect a direct influence by the actor on Swiss NPPs; dashed arrows reflect a possible or indirect influence. Source: Own depiction.

[4] The project of an NPP in Kaiseraugst began in 1969. In 1972, the official location permit was granted by the federal government. This decision was met by strong opposition of the local population that lasted for several years. On April 1st 1975 the conflict came to a head when around 18'000 activists occupied the site of the planned NPP in Kaiseraugst for eleven weeks. The goal was to stop construction work. Given the strong and well-organized local opposition, it became evident that the construction of an NPP in Kaiseraugst would not be feasible. The project was officially abandoned in 1988 (Kupper 1998).

2.2 License provision and extension

Art. 12-25 in the Nuclear Energy Act regulates the policies with regards to licenses for nuclear plants. The construction of a NPP demands three licenses: a general (Art. 12-14), a construction (Art. 15-18) and an operating license (Art. 19-25) (Bundesrat 2005). A particularity of the Swiss legal process is that the Swiss people may call for an optional referendum and therefore, decide on the construction of new nuclear facilities (IAEA 2022a).

The general license defines the holder of the authorization, location/ site, purpose of the unit, main features of the project (for NPPs this includes the type of reactor, capacity and type of main cooling system) and maximum radiation exposure for people living close-by. It is approved by the Federal Assembly and the Federal Council. However, the general license itself does not allow the NPP owners to begin construction. For that, DETEC must grant a construction license (Bundesrat 2005). DETEC will grant a construction license if the protection of humans and the environment is all but guaranteed; the project fulfills the nuclear safety requirements; no conflicts of interest are present (e.g., envisioned site of plant is not in a protected area); professional execution of the project is present; and there exists a plan for decommissioning. The construction license defines the holder of the authorization, site/ location, planned reactor output, relevant elements of technical realization, basic features of emergency protection, units and system parts that may only be built after approval of inspecting authorities such as ENSI (Bundesrat 2005).

The last license necessary for the actual operation of a NPP is the operating license. Again, DETEC is responsible for granting this license. The operating license defines the holder of the authorization, allowed reactor output, limits for radiation exposure of the surrounding environment, measures for surveillance of the surrounding environment, safety, and emergency measures that the holder of the authorization has to meet during the operation of the plant (Bundesrat 2005). There is no maximum duration of licenses, meaning that all currently active Swiss NPPs (Beznau 1 + 2, Gösgen and Leibstadt) have unlimited operating licenses. As long as the NPPs are deemed to be safe by inspections through ENSI, they are allowed to keep operating (ENSI 2020a; IAEA 2022a; UVEK 2017). In addition to safety issues, the Federal Council has the right to revoke the license if the requirements for issuance stated by the law are not currently, or no longer, met. The Federal Council may also revoke the license if the licensee fails to comply with a condition or an ordered measure despite a reminder (SR 732.1, Art. 67). Note, that the construction of new Swiss NPPs is forbidden by law (Art. 12a in SR 732.1) as of May 2017 (Bundesrat 2005).

Decommissioning law and regulations are also governed by ENSI, KNS, and DETEC under the Art. 26-29 of the Nuclear Energy Act determined by the Federal Council and Federal Assembly. A detailed discussion of the decommissioning process and its laws follows in Section 3.

2.3 Oversight

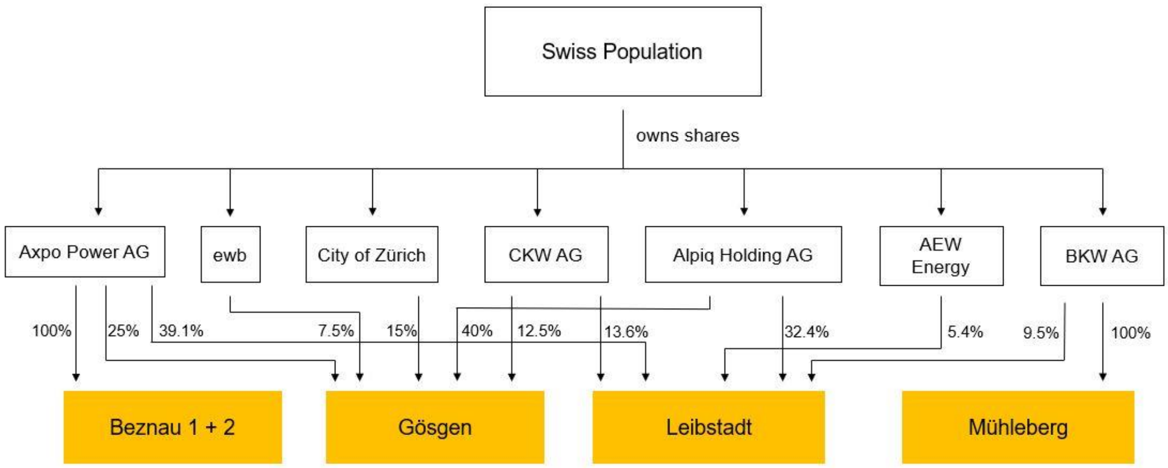
The main oversight in terms of granting licenses belongs to the Federal Council, the Federal Assembly, and DETEC, as they make the decision whether to issue a license or not (IAEA 2022a). While SFOE and ENSI are not part of the final decision to grant a license, they are both heavily involved in the supporting processes. For example, SFOE is the lead in all authorization procedures with respect to the three licenses and ENSI is involved in the safety assessments and examinations of the nuclear facilities (IAEA 2022a).

Oversight during operations is largely the responsibility of ENSI, which conducts safety and security inspections (ENSI 2020a). All NPPs are additionally subject to international inspections conducted by the International Atomic Energy Agency (IAEA).

2.4 Ownership

Eighty-two percent of the Swiss NPPs belong to public authorities, in other words, these facilities indirectly belong to the Swiss citizens. Most shares in the operating electricity companies of the NPPs belong to the cantons. Foreign investors are not directly involved in the ownership of Swiss NPPs (Kernkraftwerk Gösgen 2020a). Figure 3 shows the operators and shareholders of the Swiss NPPs. Note that the nuclear reactors Beznau 1 + 2 are fully owned by Axpo Power AG and Mühleberg by BKW AG whereas Gösgen and Leibstadt are so-called partner plants (i.e., under shared ownership by multiple shareholders).

Figure 3: Swiss NPPs and their owners



Source: Own depiction based on Seidel and Wealer (2016).

In the following, the different owners of the Swiss NPPs (visible in Figure 3) are shortly described in more detail:

- **AEW Energie AG** is a public company and belongs to the canton of Aargau (AEW 2020).
- **Alpiq AG** is an international energy company, owned and controlled by different shareholders (Alpiq 2020). Major shareholders are EOS Holding SA and Swiss Power Plant Holding Ltd. (subsidiary company of CSA Energy Infrastructure Switzerland) with both owning 33.33% of Alpiq's shares (Alpiq 2020b).
- **Axpo Holding AG, Axpo Power AG, Axpo Solutions AG, Avectris AG** and **CKW AG** all belong to the Axpo group. The Axpo group belongs 100% to the North-East Swiss cantons and utilities (Axpo 2020).
- **BKW AG** is a public company. The majority of shares (52.54%) belong to the Canton of Bern (Kernkraftwerk Gösgen 2020). 10% belong to the Swiss energy utility company Groupe E AG (BKW 2019).
- **ewb** is a public company and belongs to the city of Bern (EWB 2020).
- **City of Zürich** is publicly organized. The City Council forms the government and is elected by the people of Zürich.

All utility holding companies described in this subsection also either operate their own or have shares in renewable energy sources such as hydropower, solar, wind power, and biomass. The companies are thus diversified in terms of their electricity sources. Further, the companies also have an international aspect to their portfolio as they own and invest in energy sources abroad (AEW 2020; Alpiq 2020a; 2020c; Axpo 2020; BKW 2020b; EWB 2020).

2.5 Liability

In general, the operators of the NPPs are liable for damages and events tied to the power plant (Art. 1, SR 732.44). The liability is unlimited (Art. 3, SR 732.44). It is valid for the operation of the power plant as well as when transporting fuel (e.g., from the power plant to the interim storage facility "Zwilag"). Furthermore, the unlimited liability is independent of negligence; in other words, it does not matter whether external factors or the operator were responsible for the damage, the operators are always liable (Art. 3, SR 732.44). Contrary to other countries, the operators are liable even when warlike events, terrorist attacks or extraordinary natural phenomena cause the damage (BFE 2011).

In the case of a nuclear accident, the operator of the power plant is fully liable for all costs related to the accident, also including the subsequent decommissioning of the plant. The mandatory liability insurance coverage for nuclear accidents currently lies at around EUR 1.2 billion for the operators of Swiss NPPs. The coverage is provided by the nuclear insurance pool, which was established in 1957. The members of the nuclear insurance pool are several private Swiss insurance companies such as Helvetia, Basler Versicherungen, AXA, die Mobiliar etc. (Nuklearpool 2021a; 2021b). If the damage exceeds the insurance coverage, the operator is liable with its complete company assets. To give an example, for hypothetical accidents at NPP Beznau and Mühleberg it is Axpo Power AG and BKW AG, respectively, who would be liable. According to the legislation, the law does not provide for any recourse to the shareholders (swissnuclear 2021a; BFE 2011).

In addition to the mandatory liability insurance coverage, the federal government set up a nuclear damage fund. The fund was established to cover the risks that the private insurance pool cannot insure, or cannot insure fully. Thus, these risks are expected to be covered or partly covered by the federal government. An example for such a risk is a core meltdown with an uncontrolled release of radioactivity (Bundesrat 2015). Furthermore, the federal fund operates as a risk hedge in the event of insolvency of the insurers and the liable operators. To secure the coverage, operators pay premiums, which flow into the federal nuclear damage fund. The fund contained around 520 million CHF at the end of 2020 (Bundesrat 2021). [5]

Switzerland also ratified two nuclear energy liability agreements of Brussels and Paris. With the additional agreement of Brussels, 1.5 billion € is now covered by private liability insurance and available to cover nuclear damages (compared to 1.2 billion € before) (BFE 2022b; Bundesrat 2021). There also exists a bilateral agreement with Germany on liability towards third parties in the field of nuclear energy dating back to 1986, which regulates the principle of equal treatment of nationals of both countries (BFE 2022b).

2.6 Nuclear Waste Management

Nuclear waste management is regulated by Art. 30-34 of the Nuclear Energy Act. According to the law, radioactive waste produced in Switzerland must *generally* be disposed of domestically. The operators of NPPs are obliged to dispose of their nuclear waste in a safe manner and assume the costs for disposal. The disposal obligation of the operators is fulfilled when a) the waste is disposed of in a deep geological repository and the financial means for its monitoring and closure are secured; b) the waste is disposed of in a disposal facility abroad[6] (Bundesrat 2005). ENSI makes sure that the operators meet these requirements and has therefore the main oversight with respect to nuclear waste management (e.g., transport of nuclear waste, interim storage, final repository) (ENSI 2020a).

All of the five Swiss NPPs have their own facilities to store all categories of radioactive waste (high, medium and low) on site. Spent fuel elements are first stored for a few years in the cooling pool at the power plant. Once the spent nuclear fuel has sufficiently cooled, it is packed into dry casks and transported to the interim storage facility "Zwilag" where it will be stored until its final deposition in

[5] 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).
[6] The conditions under which disposal abroad is sanctioned are not clearly stated in the law. For the purposes of commercial reactors, it is our understanding that waste must be disposed of domestically.

the geological repository (Zwilag 2021b). The only exception is Beznau. Beznau has its own interim storage facility on-site "Zwibez", where spent fuel elements and lower level waste are temporarily stored (Nagra 2022b). The construction of Zwilag began in 1996 and it started to operate gradually from 2001 onwards. The construction was financed by its shareholders, i.e., the operators of the Swiss NPPs[7], and to a lesser extent, the Swiss Confederation (Zwilag 2021a). The capital stock of Zwilag is proportionally distributed according to the individual capacity of the NPPs (Nagra 2020e). NPPs with higher capacity use more spent fuel and thus, produce more waste. Zwilag can be seen as a link between the generation of nuclear waste and its final long-term storage. It was built to store and process all categories of radioactive waste generated in Switzerland (Zwilag 2021b). The storage facility includes a plasma plant, which is the first of its kind to be used for nuclear waste vitrification. In the plasma plant, the lower-level radioactive waste is thermally decomposed. Through this process, the volume of the waste is reduced and thus, is made more compact and stable for final storage. The process does not reduce the radioactivity of the waste (Zwilag 2020).

As of right now, Switzerland does not have any final repository for radioactive waste. Nagra (the National Cooperative for the Storage of Radioactive Waste) proposed two possible construction plans for the final disposal of radioactive waste: (1) a combination repository for high active (HAA) and low/ medium active (SMA) nuclear waste and (2) two separate repositories for HAA and SMA waste, respectively (Nagra 2020d). The process of choosing a site for the final repository or repositories took around 15 years. In September 2022, Nagra made its final choice and selected the site "Nördlich Lägern" to host a combination repository. According to Nagra, they choice the site over the other two candidate sites because of the superior geological conditions. Currently, Nagra is working on the procurement of general licenses, which have to be submitted to the Government until 2024. It is expected that the first waste will be stored in the final repository in 2050 (Nagra 2022a).

[7] BKW Energie AG (10.7%), Kernkraftwerk Gösgen-Däniken (31.2%), Kernkraftwerk Leibstadt (33.8%) and Axpo Power AG (24.3%).

3 Decommissioning Regulation

3.1 Decommissioning policy

In Switzerland, two types of decommissioning strategies are allowed: “direct dismantling” and “deferred dismantling after safe enclosure.” Mühleberg, the first commercial NPP being decommissioned in Switzerland is using the direct dismantling strategy.

The strategy of direct dismantling requires that the power plant be dismantled right after it’s shutdown. The entire decommissioning process is estimated to take around 10-15 years. Advantages of this strategy include expediency; the presence of the long-term working force who have a deep knowledge about the specific NPP; and the fact that the infrastructure is still in good condition. But, because there is little time for the short-lived radioactivity to decay, costs may be higher[8] and workers are exposed to greater amounts of radioactivity (TÜV 2016).

In the strategy of deferred dismantling, the dismantling of the NPP starts later on (around 30-60 years after the shutdown). This strategy allows radioactivity levels to decrease over time and therefore, the workers are subject to less radioactivity than in the direct dismantling strategy. Further, the strategy also bears the advantage that money in the decommissioning fund can accrue more interest. A big disadvantage of safe enclosure is uncertainty about future conditions (i.e., continued financial viability of the business owning the liability; political environment; being able to retain and recover the relevant knowledge after a long period) (Pomfret, Nash, and Woollam 2002; TÜV 2016).

There is also a third strategy that is sometimes used in decommissioning NPPs called “safe entombment.” According to this strategy, the NPP is safely enclosed in cement and encapsulated from the natural environment. In Switzerland, the method has previously been used to decommission an experimental reactor in a rock cavern in Lucens (ENSI 2012b). Currently, safe entombment is not allowed as a strategy for the decommissioning of commercial reactors in Switzerland.

3.2 Regulatory and legal process

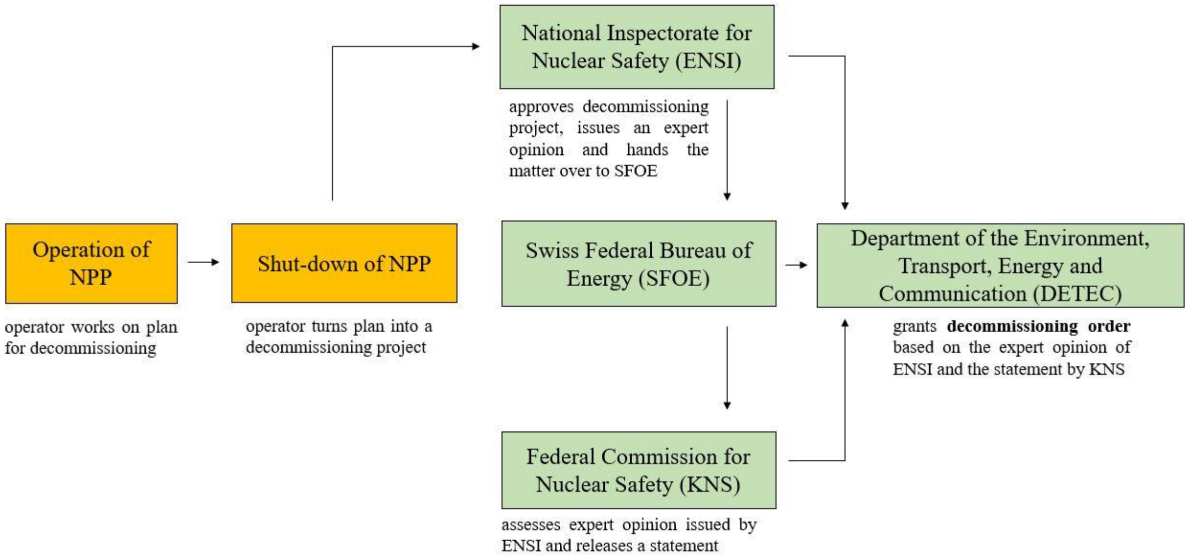
The decommissioning of nuclear plants is regulated in Art. 26-29 of the Nuclear Energy Act. According to Art. 26, the operator must decommission its plant if it decides to shut the plant down or if the operational license has been revoked. Throughout operation, the operator of the power plant is working on the decommissioning plan. The plan needs to be detailed and specify aspects such as the planned decommissioning work, the time required, a radiation protection plan, and information on the type and quantity of radioactive waste expected (Bundesrat 2005). When the shutdown is near, the operator concretizes its plan and turns the plan into a decommissioning project, which ENSI must approve. After that, ENSI issues an expert opinion and hands it over to the SFOE. The expert opinion of ENSI is

[8] There are other studies suggesting that the costs of immediate dismantling will be lower (e.g., Park et al. 2022; Suh, Hornibrook, and Yim 2018; OECD/NEA 2006; Short et al. 2011).

assessed by KNS who then releases a statement. Based on the expert opinion of ENSI and the statement released by KNS, DETEC issues the decommissioning order (BFE 2018; BKW 2020). The regulatory and legal steps necessary are summarized in Figure 4.

Once the NPP is shut down and no longer generates any electricity, the power operation of the NPP is considered to be permanently discontinued. The operator then prepares the power plant for dismantling and the post-operational phase. When this work is finished, and the operator has obtained the necessary legal document (the decommissioning order), the actual decommissioning process commences (ENSI 2021) .

Figure 4: Regulatory and legal steps necessary for decommissioning



Source: Own figure.

The post-operational and radiological decommissioning phases are scheduled to take approximately twelve years following shut down, after which conventional dismantling starts. Conventional dismantling no longer falls under the decommissioning order and thus, a second application must be submitted to the SFOE outlining how the operator intends to use the site in the future (BKW 2021; swissnuclear 2017b). The site of the former NPP may be reused for other purposes. If there are no parts left of the NPP on site, the location is called a “greenfield”. In contrast, a “brownfield” categorization indicates that there are still some remaining, though entirely decontaminated, structures from the power plant (BKW 2021). In Switzerland, there are three defined decommissioning targets, which are more nuanced. Target 1 foresees the release of the site from nuclear energy legislation, that is, only radiological decommissioning. Target 2 corresponds to the complete dismantling including the removal of foundations and concrete construction down to two meters from the top edge of the terrain. Lastly, target 3 requires the complete deconstruction including removal of all foundations of all facilities

(= greenfield). There is no legal obligation to officially adopt a specific target beyond Target 1, which is required by law. However, Target 3 is indicated as the base project in the cost study (see Subsection 4.1 for details on the cost study) (swissnuclear 2021b).

3.3 Oversight

In terms of decommissioning and the dismantling of Swiss nuclear facilities, ENSI has the main oversight. The decommissioning plans are reviewed regularly by ENSI and as steps in the decommissioning plan are undertaken, ENSI makes regular inspections (ENSI 2020a). Furthermore, the decommissioning work done in Switzerland follows the international recommendations of the IAEA and WENRA (Western European Nuclear Regulators Association) (ENSI 2015a).

4 Financial Regulation

4.1 The funding of decommissioning

The financing of decommissioning and waste disposal is established in Art. 77-82 of the Nuclear Energy Act and further in the Ordinance on the Decommissioning Fund and the Waste Disposal Fund for Nuclear Facilities (Bundesrat 2005; 2008). The operators of the NPPs are financially responsible for the disposal of spent nuclear fuel elements as well as the disposal of radioactive waste from operation (e.g., contaminated clothes) and decommissioning of their power plants. To ensure the financing of decommissioning and disposal of waste, two separate funds are in place: a decommissioning fund (established in 1985) and a waste disposal fund (established in 2001) (STENFO 2020).

These funds are centrally managed by STENFO's management body, the Administrative Commission, which collects, pools, and manages the individual contributions from each NPP. The pooled decommissioning funds must cover all decommissioning and dismantling costs, including associated decommissioning waste (i.e., contaminated concrete, etc.), of the NPPs (STENFO 2021g). The pooled waste disposal funds cover the costs of the final disposal of operational waste and spent fuel elements. The main cost elements are: transport and storage, processing, disposal of fuel elements, interim storage, and deep geological disposal of radioactive waste in one or two deep geological repositories (STENFO 2021b). Disposal costs that occur during the operation of NPPs must be paid by the operators on an ongoing basis and are not covered by the funds (Subsection 4.3). Similarly, the operators must also pay directly for the costs during the post-operational phase (i.e., the period from the decommissioning of a plant to the start of the defined decommissioning work) (STENFO 2021c).

The operators of the Swiss NPPs contribute yearly to these decommissioning and waste disposal funds. Zwilag only contributes to the waste disposal fund (STENFO 2020). The money from all contributors is collected in one account (one account each for decommissioning and waste disposal) and managed collectively by the Administrative Commission. The Administrative Commission is the management body of the funds. The supervision of the two funds belongs to the Swiss government. Fees for the decommissioning fund and the waste disposal fund are calculated based on routine cost studies. Every 5 years, each operator of a Swiss NPP reports its decommissioning and waste disposal costs to swissnuclear. After that, swissnuclear prepares a comprehensive cost study detailing the estimates for the plans for decommissioning the individual plants and for the deep geological repository that it submits to the Decommissioning Fund for Nuclear Facilities and Waste Disposal Fund for Nuclear Power Plants (STENFO). STENFO then releases a summarized cost study that includes all the relevant details reported by the operators (STENFO 2021d). The cost assessment will be discussed in more detail in Subsection 4.3. If there is money left over in the fund, i.e., if the decommissioning costs of an operator are lower than previously calculated, the money will be redistributed to the operator. However, this can only happen at the time when all of the NPPs have been fully radiologically decommissioned. No premature reimbursements are allowed (UVEK 2019).

4.2 Current balance in funds

As of December 31, 2020, the accumulated *decommissioning* fund capital, including annual contributions, amounted to CHF 2,822 million (previous year: CHF 2,724 million). This corresponds to an increase of 7.55% or CHF 198.2 million above the set target amount per 31st of December 2020 (STENFO 2021e). The accumulated funds for *waste disposal* (current amount), including annual contributions, amounted to CHF 6,030 million (previous year: CHF 5,768 million). This corresponds to an increase of 12.49% or CHF 669.5 million above the set target amount per 31st of December 2020 (STENFO 2021e).[9] Table 2 shows the current balances in the decommissioning and the waste disposal fund. As the Zwilag itself does not produce any radioactive content but stores the radioactive material of the NPPs, it does not need to contribute to the waste disposal fund.

Table 2: Current balance in the funds for individual NPPs and Zwilag (in million CHF, price level 2020)

Current balance as of 31/12/2019	Beznau (1&2)	Gösgen	Leibstadt	Mühleberg	Zwilag	Total
Decommissioning fund	895	602	678	486	45	**2,706**
Waste disposal fund	1,855	1,594	1,473	808	-	**5,730**
Total	**2,750**	**2,196**	**2,151**	**1,294**	**45**	**8,436**

Note: 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020). Source: STENFO (2021f).

4.3 Cost assessments

Every five years, the operators of the Swiss NPPs estimate the decommissioning and waste disposal costs of their respective NPP and report the costs to STENFO. The cost studies serve as the basis for determining the contributions to the funds. The contributions to the funds are calculated with the help of a financial model, which is reviewed by an external expert and approved by the Administrative Commission. The model is based on an operating life of 50 years, an investment return of 2.1% and an inflation rate of 0.5% per year (STENFO 2021f; 2021d). The Administrative Commission submits a proposal on the amount of the provisional fund contributions to DETEC. Once DETEC accepts the proposal, the fund contributions are binding for the NPP operators (swissnuclear 2016). Currently, the operators of the Swiss NPPs are paying their contributions to the funds based on the 2016 cost study. The new cost study 2021 will serve as the basis for the contributions for the years 2022-2026 (STENFO 2021a). The following Table 3 shows the cost elements covered by the decommissioning fund and the waste disposal fund respectively.

[9] 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020).

Table 3: Cost elements included in decommissioning and waste disposal funds

Decommissioning costs	**Waste disposal costs**
Administration costs	Administration costs
Insurance	Insurance
Official authorizations and supervision	Official authorizations and supervision
Radiation and occupational safety measures	Radiation and occupational safety measures
Planning, design, project management and supervision	Planning, design, project management, construction, operation, dismantling and monitoring of waste disposal plants
Plant-related preparation for decommissioning	Transport and disposal of radioactive operational waste
Containment, maintenance and guarding of the facility	Transport, reprocessing and disposal of spent fuel
Decontamination or disassembly and crushing of activated and contaminated parts	A 50-year monitoring phase for a deep geological repository
Transport and disposal of radioactive waste as a result from decommissioning	
Demolition of all technical equipment and buildings and the dumping of inactive waste	
Decontamination of the site	

Source: STENFO (2021b).

Waste disposal costs that arise during the operation and during the post-operational phase are covered directly by the operator. This includes the following cost (STENFO 2020):

- The processing of spent fuel elements
- Research and preparatory work by the National Co-operative for the Disposal of radioactive waste (Nagra)
- Construction and operation of a central interim storage facility (Zwilag in Würenlingen)
- Construction and operation of the fuel element wet storage facility at Gösgen NPP
- Measures after the decommissioning of a plant to maintain nuclear safety and radiation protection and to operate the infrastructure until the fuel elements have been safely removed

Table 4 shows the total estimated costs for decommissioning and waste disposal based on the latest estimates of the cost study 2021. In the table, the costs for decommissioning reflect the costs for the base project "Target 3". Similarly, waste disposal costs are indicated for the base project "waste disposal with a 75% chance for a combination repository."

Table 4: Total costs for decommissioning and waste disposal (in million CHF, price level 2020)

Costs for decommissioning and waste disposal	Beznau	Gösgen	Leibstadt	Mühleberg	Zwilag	Total
Decommissioning costs target 3 (green field)	950	894	1,016	591	184	**3,635**
Waste disposal costs for disposal with a 75% chance for a combination repository	4,462	5,086	5,453	2,070	.	**17,071**
Total	**5,412**	**5,980**	**6,469**	**2,661**	**184**	**20,706**

Note: 1 CHF corresponds to 0.9342 EUR and 1.0665 USD (yearly average exchange rate 2020). Source: swissnuclear (2021b).

4.4 Cost experience and accuracy of assessments

As no commercial NPP has been completely decommissioned in Switzerland, it cannot be said whether the costs assessments are accurate. So far, only one commercial NPP (Mühleberg) is undergoing decommissioning. According to the operator of Mühleberg, BKW AG, the financing is on track so far (BKW 2020; VSE 2020). In terms of determining the accuracy of their cost studies, STENFO recruits independent external experts to verify the cost estimates. By doing so, STENFO aims at making sure that experience from home and abroad is considered (STENFO 2022).

4.5 Funding Liability

In terms of costs for decommissioning and waste disposal, the operators are fully financially responsible. If the money that the operator has put in the fund is not enough the operator has to pay out of his pocket. If this is still not enough, the pooled fund is used to make up the missing amount. Then, the operator must pay back the money plus interest within a certain timeframe set by the Federal Council. If the operator of a power plant is insolvent, or no longer exists, and cannot pay the money back, the operators of the other Swiss NPPs are liable. If the other operators do not have the means to pay the debts the government is liable as a last resort (swissnuclear 2020).

5 Production

5.1 Overview

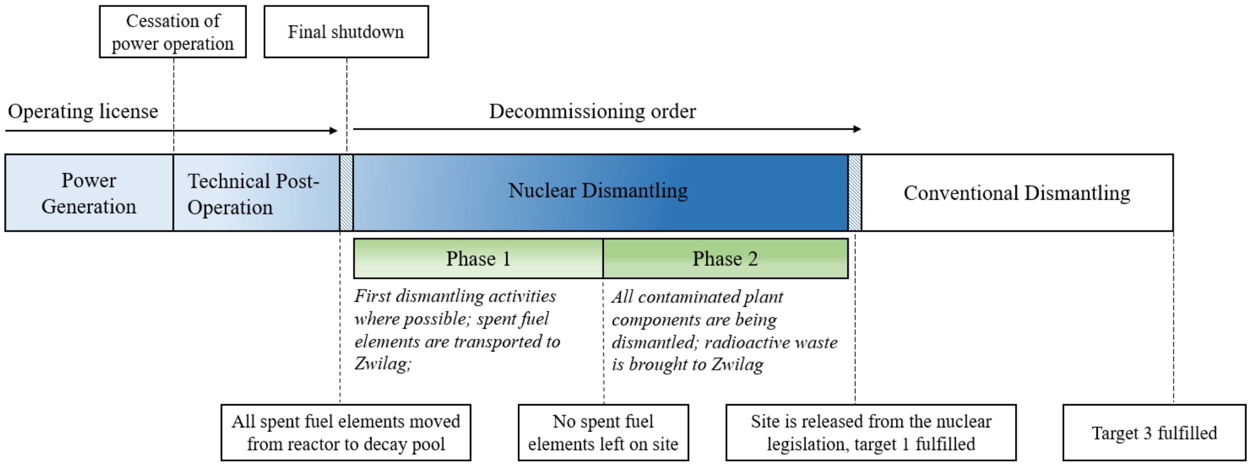
As of 2022, Switzerland has shut down one commercial nuclear plant: Mühleberg in December 2019. Since the shutdown of Mühleberg is very recent, decommissioning work only just begun and is in its early stages (BKW 2020a). Switzerland has some limited decommissioning experience with respect to research reactors. However, it must be made clear here that decommissioning a commercial reactor and decommissioning a research reactor differ greatly in terms of scale, financial incentives, regulation, and difficulty. Even so, some valuable decommissioning experience can be gathered from decommissioning projects of research reactors. Up until now, two research NPPs (AGN-201-P of the University of Geneva and AGN-211-P at the University of Basel) and one experimental reactor in Lucens, Canton of Vaud, have been successfully decommissioned (Hoskyn 2021; ENSI 2012b; 2013). Further, three research reactors are currently being decommissioned: DIORIT at the Paul-Scherrer-Institute (PSI) (since 1994; biological shield was dismantled in 2013), SAPHIR at PSI (since 2002; decommissioning process is almost finished) and PROTEUS at PSI which has been shut down and is currently in the first phases of decommissioning, i.e., the nuclear dismantling of the plant has begun (ENSI 2013; PSI 2022).

5.2 Progress

Figure 5 shows the different stages of decommissioning. After the NPP has been shut down, i.e., stopped its electricity production, the NPP is in the technical post-operational phase. During this time, the plant is prepared for decommissioning. Further, spent fuel elements are unloaded from the reactor pressure vessels and moved to decay pools. There, they are stored to cool down. All of this work still falls under the operating license of an NPP. With the commissioning of the independent cooling of the decay pool, the plant is considered to be “finally put out of operation” (swissnuclear 2021b; ENSI 2022).

The final shutdown of the plant marks the expiration of the operating license and the decommissioning order attains full legal effectiveness. The decommissioning order is needed to start the actual dismantling of the plant (swissnuclear 2021b). During nuclear dismantling, the plant is dismantled step-by-step.

Figure 5: Overview over the decommissioning process



Source: Own depiction based on BKW (2022); swissnuclear (2021b); ENSI (2021).

In phase 1, first dismantling activities are carried out where possible. Also, spent fuel elements are packed into containers and brought to Zwilag. After all spent fuel elements have left the site, the NPP moves from phase 1 to phase 2 in the dismantling process. During phase 2, all contaminated parts of the plant (e.g., the reactor pressure vessel) are removed. If possible, the removed parts are cleaned and either brought to an interim storage facility or, after being tested for radioactivity, disposed of as regular waste (BKW 2022). At the end of the nuclear dismantling phase (around 10 years after final shutdown), the site is completely free of radioactive material. After ENSI has inspected and approved the site, DETEC officially releases it from nuclear legislation as the site no longer poses a radiological hazard. Then, conventional dismantling begins, which no longer falls under the decommissioning order (swissnuclear 2017b).

The entire decommissioning process (including technical post-operation and conventional dismantling phase) is estimated to take around 15-20 years (swissnuclear 2017b). However, the time varies according to the specific decommissioning target chosen (see Subsection 3.2 for details on the targets).

Mühleberg

BKW AG decided in 2013 to shut down and decommission its plant, Mühleberg, due to business reasons by the end of 2019 (BKW 2022). Phase 0, the technical post-operational phase, started on January 6th 2020 approximately three weeks after the final cessation of power production of the plant. The concept for phase 0 has been approved by ENSI in 2015 (swissnuclear 2021b). In 2020, all spent fuel elements were removed from the reactor into the decay pool (BKW 2022). ENSI confirmed the end of the technical post-operation phase with a final inspection in September 2020. The NPP moved from phase 0 to phase 1 in the decommissioning process. Currently, in 2022, Mühleberg is in phase 1. In this phase, dismantling activities in the reactor building are carried out where possible and spent fuel elements are transported from the decay pool to Zwilag. It is to be expected that all spent fuel will have left the plant by spring 2024 which will mark the end of phase 1 (BKW 2022).

5.3 Actors involved in the decommissioning process

Actors involved in the decommissioning process are the operator(s) of the specific plant (in the case of Mühleberg this would be BKW AG), the Zwilag, where most radioactive waste is stored, DETEC who issues the decommissioning order and finally, ENSI who oversees the entire process. While there is discussion of hiring external contractors to conduct some decommissioning work, as of this writing, no official plans or contracts are available to the public.

6 Country specific nuclear and decommissioning developments

An important turning point for the nuclear industry in Switzerland was the Fukushima nuclear accident in 2011. Following this accident, the political climate for Swiss NPPs has distinctively worsened and the public's resentment toward nuclear energy increased (ENSI 2012c). Shortly after the accident, the Federal Council introduced its "Energiestrategie 2050" which includes the support for the development and production of renewable energy with various measures including the phase-out of nuclear power (UVEK 2020). One of the measures is called the "cost oriented buy-back price." With this instrument, new biomass facilities, wind power plants, geothermal power plants, small waterpower plants and big photovoltaic facilities get a premium on their power input. Further instruments include federal investment contributions for biomass facilities and small hydro power plants and the introduction of a market premium for large hydro plants, which have to sell their power below their production costs. The Energiestrategie also requires all NPPs to be phased out at the end of their safe operating lifetime and prohibits the construction of new NPPs by law (Art. 12a SR 732.1) (BFE 2017; Verband Schweizerischer Elektrizitätsunternehmen (VSE) 2020).

Concerning nuclear decommissioning, Switzerland has limited experience. So far, only one commercial reactor, Mühleberg, has been shut down (BKW 2020a). The combination of the advanced age of the Swiss NPPs and the approved new federal energy strategy might encourage the shutdown of nuclear reactors in the near future. An additional push in that direction is given through high investment costs of nuclear power reactors (UVEK 2017). Axpo Power AG, the owner of Switzerland's oldest commercial NPP, Beznau, announced that they plan to definitely shut down their plant around 2030. To prepare Beznau for decommissioning, 10-12 people are working already today solely on this matter. As the NPPs Gösgen and Leibstadt are considerably younger than Beznau 1 + 2, it is expected that they will keep operating until the 2040s (SRF 2019). According to this information, Switzerland will have phased out of nuclear energy by 2050. However, recent global developments, especially related to energy security, sparked a discussion about constructing new NPPs in Switzerland and thus, challenging parts of the Energiestrategie 2050 (Hägler 2022).

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