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# Challenges in Planning of Integrated Nuclear Waste Management

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**Abstract:** Planning for integrated nuclear waste management (INWM) entails consideration of all generated waste from energy generation, nuclear fuel cycle and institutional facilities as well as waste from decommissioning and remediation of nuclear facilities, legacy waste, and eventual accident waste and requires establishment of different planning scenarios as well as control milestones to allow for adequate flexibility to address inevitable changes. An early assessment of waste management needs from development and use of advanced reactors and innovative nuclear fuel cycles is required to aid design and operation of such facilities as well as to understand their impact to overall waste management planning. Major prerequisites for approach to planning and establishment of INWM plans are discussed briefly. It is pointed out that five most important challenges in establishing and implementing the INWM plan needs to be addressed: (i) inventory; (ii) time frame for an integrated plan; (iii) assessment of facility needs; (iv) costs estimation (life-cycle cost analyses) and (v) funding and financing. The INWM has to promote strategic thinking within a broad framework resulting in a sustainable and sensible outcome for nuclear waste management at a strategic and national level.

**Keywords:** nuclear energy; nuclear waste; nuclear waste management; policy and strategy; integral planning



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## 1. Introduction

Nuclear energy is now an integral part of civilization with numerous nuclear applications ranging from medicine which includes both diagnostics and treatment to power generation including large scale nuclear power plants (NPP) and autonomous power generators used in difficult-to-access terrestrial locations and space exploration. Currently operating 433 nuclear power reactors have the total net installed capacity to generate 387,998 MW (e) of electricity with 57 new power reactors under construction to further add 59,009 MW (e) of installed capacity worldwide which shows a growing pace of peaceful nuclear energy use [1]. Utilization of nuclear energy in any form inevitably leads to the generation of some radioactive or contaminated materials for which no use is foreseen thus termed nuclear waste (NW) which includes spent (used) nuclear fuel (SNF) when not considered as a resource to be reprocessed [2,3] although the amount of such materials is minuscule compared with other industries. Indeed, the volume of nuclear waste generated within the nuclear industry is orders of magnitude smaller compared with waste generated by non-nuclear practices. For example, a typical NPP generating ~1 GW (e) for one year produces at average ~25 tonnes of SNF which can be considered as a nuclear waste stream (alternatively the SNF can be reprocessed [3]) and a few hundred cubic meters of low and intermediate waste (LILW) to be finally disposed of. On the other hand, a coal-fuelled power station of the same capacity generates annually ~6.5 × $10^6$ tonnes of $CO_2$, plus more than 300 × $10^3$ tonnes of ash. It is notable that, in reality, the ash waste from coal-fuelled power plants typically contains some ~400 tonnes of toxic heavy metals including radioactive U and Th, and more than 5 × $10^3$ tonnes of noxious gases which as a rule need purification before discharge [4]. The most important lesson learned from the past 60 years of the peaceful use of nuclear energy is to consider and account for nuclear waste management (NWM) even before the waste is generated and then integrate its management at the country level to provide trust to stakeholders which usually perceive nuclear waste as a problematic issue [5–7]. Indeed, adequate and highly effective NWM technologies are already developed and used both at international and national levels within most of the countries which use to a certain extent nuclear energy [8–13]. Sustainability of nuclear energy is however impossible without assuring the general public that the nuclear waste is a manageable issue and is not a real burden to future generations which would otherwise contradict the fundamental safety principles of nuclear energy [14]. The direct consequence is that developers of more sustainable innovative reactors, advanced nuclear fuel cycle technologies, and novel nuclear applications should be fully aware of the importance of NWM including decommissioning phase waste and address it early on, in fact in the research and development (R & D) phase [7].

The IAEA issued dedicated guidance document on policies and strategies for radioactive waste management (RWM) in 2009 [15]. This was the result of a joint effort of Nuclear Energy and Nuclear Safety departments done in a wide consultation with Member State (MS) representatives. The document was aimed on how to set out nationally agreed position for managing radioactive waste, and to provide visible evidence of the concern and intent of the government and the relevant organizations to ensure radioactive waste will be properly taken care of. That was a move in the right direction and was well received by many MSs, which then tried to set up their national policies and start working on adequate RWM strategies to define the goals and requirements for the safe management of radioactive waste and spent fuel if this is declared as a waste. However, guidance on elaboration of national policy and strategy as well as implementation of it was left to discussions and actions between various state agencies of jurisdiction, national regulator and variety of waste generators and operators (license holders) in MSs.

The aim of this paper which follows our brief presentation at the International Conference on Radioactive Waste Management: Solutions for a Sustainable Future [16] is to analyse and highlight the challenges of integrated nuclear waste management (INWM) plans including major prerequisites for establishment of an INWM plan.

## 2. Nuclear Waste Management (NWM) and Its Planning

The nuclear waste lifecycle comprises several distinct stages with the life end point being disposal as illustrated by Figure 1 which demonstrates that prior to the disposal, the waste usually goes through a number of steps such as pre-treatment, treatment, conditioning, storage and transport with characterization utilised within the entire lifecycle.

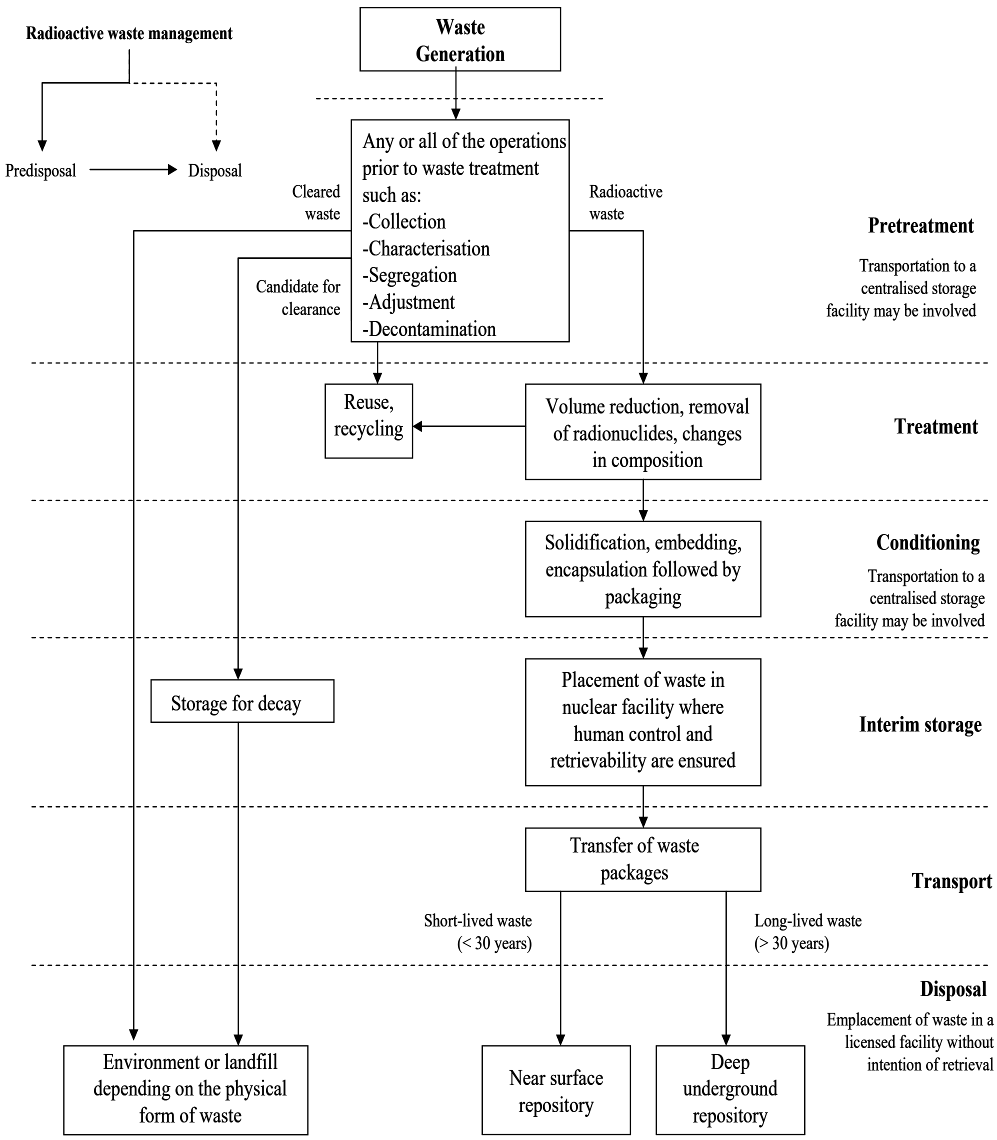


**Figure 1.** Schematic of nuclear waste lifecycle. Reproduced with permission of IAEA from [17].

As shown in the last (right hand) column of Figure 1 the life cycle of nuclear waste generated is typically comprising several distinctive steps [10,18]:

(I) Pretreatment. This step includes any operations prior to waste treatment, to allow selection of technologies that will be further used in processing of waste, i.e., treatment and conditioning.
(II) Treatment. It includes the operations which intend to improve safety or economy by changing the characteristics of nuclear waste. Some treatment may result in an appropriate wasteform [11,13,19] although the treated waste often requires immobilization and/or backfilling.
(III) Conditioning. This step produces a waste package suitable for handling, transportation, storage and/or disposal.
(IV) Storage. It provides confinement, isolation, environmental protection, and monitoring during certain periods of time (storage period) ensuring retrievability of waste packages.
(V) Transportation. It refers to the deliberate physical movement of nuclear waste in specially designed packages from one place to another.
(VI) Disposal. This is the end point of nuclear waste lifecycle and envisages emplacement of waste in an appropriate facility without the intention of retrieval [20,21].

Nuclear waste characterization is used as a necessary element from the beginning of the lifecycle to its end. Characterisation involves determination of the physical, chemical and radiological properties of the waste to establish the need for further adjustment, treatment, conditioning, or its suitability for further handling, processing, storage and disposal [10,22].

By definition the NWM comprises all administrative and operational activities involved in the handling, pretreatment, treatment, conditioning, transport, storage, and disposal of radioactive waste [1]. Administrative-related activities are schematically shown in Figure 2 and play a crucial role in ensuring the safety and effectiveness of operational activities.

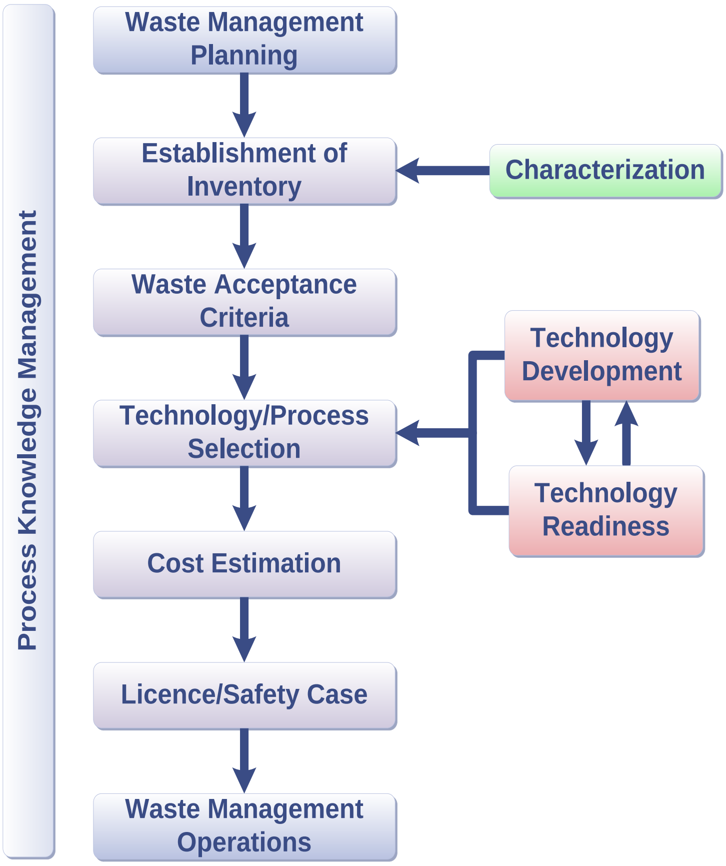


**Figure 2.** Schematic of nuclear waste management (NWM) administrative activities.

Implementation of NWM programmes is based on knowledge of inventory of nuclear waste streams in stock, forecast of waste streams to be generated during established timeline for integrated planning, assessment of needs for different waste management facilities and selection of technologies to deal with nuclear waste generated during the entire life cycle (so-called from cradle to grave) within the envisaged timeline, establishment of cost estimates and scenarios for different alternatives for waste management during planning period and approaches to funding for implementation. The integrated approach on NWM refers to a logical and preferably optimized strategy used in its planning and implementation as a comprehensive programme starting from waste generation and ending with disposal such that the interdependencies between the various stages (see Figure 1) are taken into account, and decisions made at one stage do not foreclose certain alternatives at a subsequent stage. For example, the generation of waste is highly dependent on the design, planning and operation of a nuclear facility. The INWM plans aim to ensure that the strategy of nuclear waste management addressing safety boundaries, environmental concerns and stakeholders' interest can be implemented on the level of the country as well as on the levels of individual actors such as waste generators, predisposal and disposal facility operators.

### 3. Policy and Strategy of Nuclear Waste Management (NWM)

NWM at the country level is organised following dedicated forms of policy and strategy for managing its spent fuel and radioactive waste which set out the nationally agreed position and plans for managing NW (comprising the SNF considered as waste and other radioactive waste) [15]. The policy of NWM is a set of established goals or requirements for the safe management of NW and normally defines national roles and responsibilities that are mainly established by the national government. The strategy is the means for achieving the goals and requirements set out in the national policy for the safe management of spent fuel and radioactive waste and is normally established by the relevant waste owner or operator, either a governmental agency or a private entity. Policies and strategies of NWM are evidence of the concern and intent of the government and the relevant national organizations to ensure that NW is properly taken care of [15]. The national policy may be elaborated in several different strategies which may address different types of waste (e.g., reactor waste, decommissioning waste, institutional waste, etc.) or waste belonging to different owners.

The IAEA issued the dedicated guidance document on policies and strategies for NWM in 2009 [15] which resulted from a joint effort of the IAEA's Nuclear Energy and Nuclear Safety departments done in a wide consultation with the international community via IAEA Member State representatives—experts including the authors of this work. This document has highlighted nationally agreed position for NWM with roles and responsibilities of the INWM key players as illustrated by the organigram shown in Figure 3.

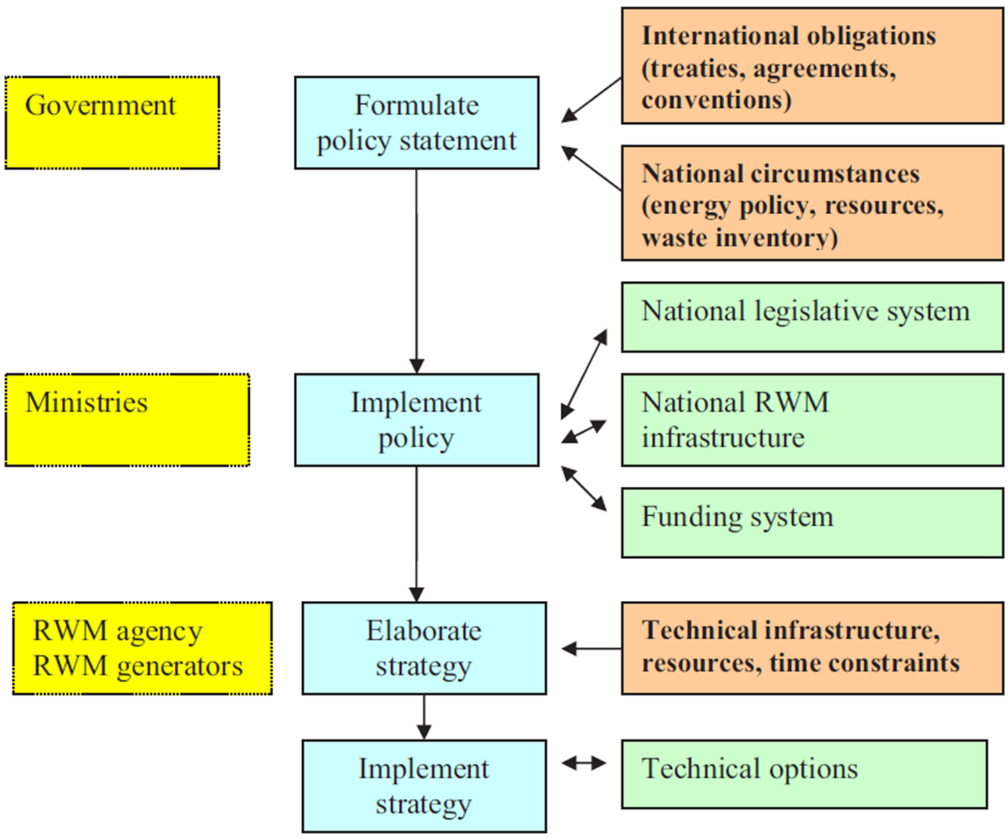


**Figure 3.** Distribution of roles and responsibilities of the key players of INWM. Reproduced with permission of IAEA from [15].

The IAEA is putting many efforts to keep updated the area of NWM within its activities including technical guidance publications, see, e.g., [23]. This includes organising on regular basis meetings and workshops focused on development of policies and strategies of NWM. Online activities available worldwide are notable contributing to upgrading state of the art approaches used within member states of IAEA, see, e.g., the dedicated IAEA policy and strategy course [24] offered as part of the SNF and NWM, decommissioning and environmental remediation curriculum [25]. The European Union (EU) has issued "Council Directive 2011/70/Euratom of 19 July 2011 establishing a community framework for the responsible and safe management of spent fuel and radioactive waste" which in essence identifies obligations of the license holders (Article 7) and defines content of the national programmes (Article 12). Directive details responsibilities of its MSs to establish policy and strategy to manage nuclear waste. However, similarly to the IAEA document it leaves its implementation to discussion and actions to various stakeholders. It should be pointed out that France and UK have achieved significant success in applying of INMW planning approach and principles as well as fully transparent reporting on NWM to the general public.

The challenges in setting up a national policy are to ensure proper understanding of NWM needs, options and timelines as well as identification and allocation of responsibilities among government bodies and different actors including stakeholders involved aiming to build and operate adequate NWM supporting infrastructure. The national policy also needs to account for inevitable changes at NWM planning stage being monitored and updated regularly. Elaboration of the strategy is typically initiated by the licensees, e.g., NW owners or operators of either a company or governmental agency. Evidently any declared policy may be elaborated in several or many different strategies that needs to address different types and origins of NW including, e.g., NW of NPP's and research reactor, disused sealed radioactive sources, decommissioning, and legacy NW. In this respect, coordination between policy and strategies developers is essential to address various challenges related to the adequacy of set goals and to select adequate technical options of INWM programmes based on a clear understanding of technical and economic feasibility of the NWM systems. This also indicates that the simple downward (so-called "top-down") approach as in the organigram presented within Figure 4 is not adequate, neither to setup meaningful national policy nor to elaborate on a national strategy and its implementation.

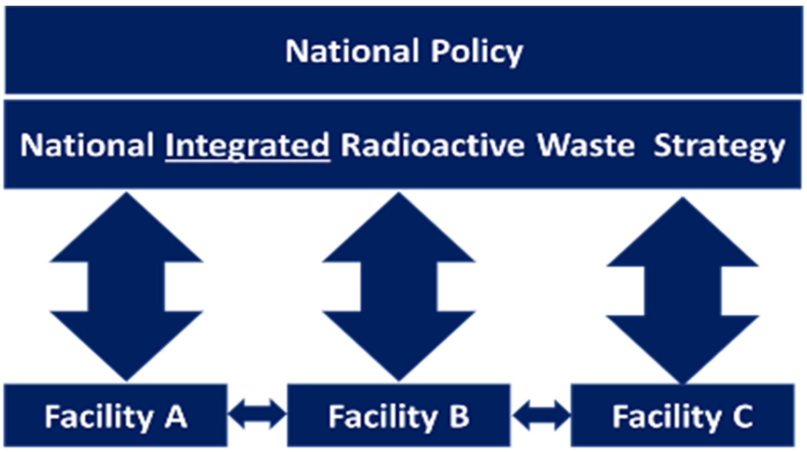


**Figure 4.** Schematic of INWM dialogues.

## 4. Elaboration of Integrated National Strategy

Depending on the scale of NWM programmes several strategies typically linked to major NW streams can be in place. The consequence of the presence of several individual strategies is that the overall national strategy can only be established by iteration between the upward (so-called "bottom-up") inputs from licensees (licence holders) and top-down approaches set by the national policy developers. The INWM strategy requires both top-down and bottom-up inputs and a continuous dialogue between all involved parties (actors). The INWM programmes shall be developed through an iterative, integrated and transparent process involving all stakeholders, and must be regularly updated (Figure 4).

In addition, the management of NW starting from generation ("cradle") and ending at a dedicated disposal facility ("grave") requires a continuous dialogue between waste generators, waste processors, storage, and disposal operators. The INWM programme cannot be focused predominantly on any one step in a waste management life cycle such as on the cradle, or on the grave. To avoid results considered as just collection of "lists of wishes" or declarations of different players, a commitment to develop an implementable "strategy" is essential.

## 5. Integrated Planning and Implementation of Integrated National Strategy

The INWM plan objective is to ensure that the chosen strategies for NWM are properly addressing safety boundaries, environmental concerns, and stakeholders' interests. The INWM programmes are developed so that they:

- Can be implemented on the level of individual waste generator, processor and disposal operators, and
- Are iteratively balanced on the level of the country and agreed with national regulator.

It is imperative that the INWM programmes should define how to:

- Deliver NWM goals in a defined time frame;
- Involve systematic analysis of all factors;
- Explore linkages, evaluates trade-offs and allow comparison of consequences;
- Confirm path to implementation of national policy goals;
- Ensure top-down and bottom-up input in an iterative manner assuming being regularly updated.

## 6. The Need for Integrated Nuclear Waste Management (INWM) Plan

An INWM plan is needed because a robust, national integrated NWM plan, updated on a regular basis, is key to maintaining the visibility, understanding and importance of safely managing the end-of-life liabilities from the peaceful uses of technology.

The INWM plan provides for the following:

- Enhances transparency and involves all stakeholder and interested parties
- Drives consideration of waste optimization before the waste is generated (pro-active waste management not reactive)
- Provides a robust planning basis to identify and ensure adequate provision of funds
- Serves as a tool to ensure continuity of intent during successive government administrations and personnel changes
- Is a key tool to either confirm goals in a declared national policy and declared strategies or to correct these to achievable/realistic deliverables.

## 7. Integrated Planning Process

Understanding of an overall NWM programme and its cost enables adequate and effective administrative and operational actions based on "informed decisions" in respect of the following crucial aspects:

- Advantages of NW minimisation at the source during operation and by the design of facilities;
- Limitations, and restrictions for development of a flexible plan to address envisaged needs;
- NW from decommissioning and remediation of nuclear facilities, legacy and eventual accidental NW;
- Need for an early assessment of NWM needs from development and use of advanced reactors and innovative NFC's that will aid design and operation of such facilities as well as to understand their impact to overall NWM planning.

The INWM plan requires establishment of different planning scenarios as well as milestone controlling steps (so-called "holding points") to allow for adequate flexibility aiming to address inevitable changes during the envisaged time frame.

Key factors to be addressed in the INWM planning process are as follows:

- Integration aiming to include top-down and bottom-up approaches;
- Transparency of processes involving all stakeholders;
- Driven by NW hierarchy principles during the operational and design phases;
- Incorporation of all NW in the country as well as decommissioning, legacy, and potential accident waste;
- Maintenance of flexibility by using hold points to accommodate inevitable changes;
- Inclusion of an early assessment for innovative reactors and fuel cycles;
- Underpinning by a robust cost estimate and adequate funds.

The INMW plan needs to be focused on integration of top-down and bottom-up approaches and be a transparent process involving all engaged parties as illustrated by Figure 5.

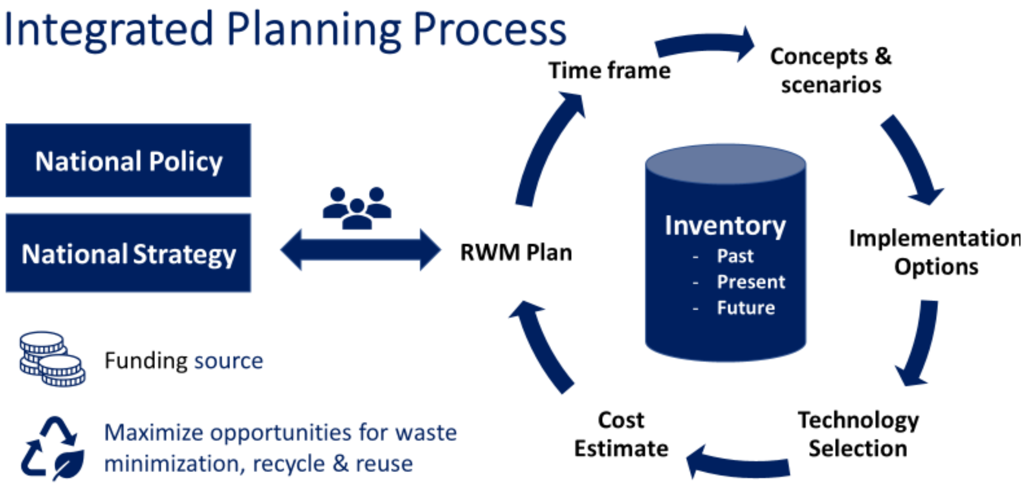


**Figure 5.** Flow sheet diagram of an integrated planning process.

The public's confidence of effectiveness and safety of INWM can be enhanced by the fact that substantial fund is already established, or it can be provided since an integrated plan exists. Considerations for INWM planning require proper balance between satisfying today's needs without closing off future options, realistic estimate of resources including human, technical and financial support to ensure the plan is resilient and adaptable. The INWM plan must respect expectations and interests of stakeholders meaning that it should be transparent and understandable. It shall always rely on good practices that incorporate good waste management practices around the world related to NW generation avoidance, optimization, and minimization.

## 8. Challenges of Integrated Nuclear Waste Management (INWM) Plan

Based on the discussion above, it is clear that developing and establishing an INWM plan requires careful consideration of a number of important aspects including waste inventory, timeframe, facility needs, cost estimation, as well as funding and financing. Each of these aspects has its own set of key concerns or challenges that need to be taken into account and addressed satisfactorily in order to establish a viable and effective INWM. These challenges are highlighted and further discussed below.

### *8.1. Challenge I: Inventory*

A complete NW inventory should identify and quantify all NW streams [17,26,27]. The NW inventory typically consists of two main parts: (i) existing stocks of waste and (ii) forecasts of future arising during envisaged time frame. It is important to emphasise that the inventory challenge focuses on followings aspects:

- Having inventory of radioactive substances as appropriate rather than only NW including the location, amount, type and characteristics of existing and future radioactive substances to be generated in accordance with the existing waste classification scheme;

- Establishment of an NW inventory needs to be conducted by step wise approach in a systematic way;
- NW inventory is a simpler task for the existing NPP and NFC facilities regardless of larger scale of application since the NW arising is much more predictable except for emerging innovative type reactors and advanced NFC's which are currently in the R & D phases [26];
- Due to variety of applications, experiments in R & D of research reactors and future programmes, more challenges for NW forecast are envisaged with institutional waste owners regardless of much smaller volumes to be handled.

### *8.2. Challenge II: Time Frame for an Integrated Plan*

The time frame determination for an INWM plan accounts for the following:

- Owners of NPP and NFC facilities are looking for minimal over 100 years planning window of active NWM operations not counting close out of disposal facilities;
- Monitoring and close-out of disposal facilities can add up 300 years or even more;
- There are neither other programmes nor many experiences that need to take such planning time frame into account;
- Integrated plan for DSRS and institutional waste owners in many cases could be for a lesser time.

### *8.3. Challenge III: Assessment of Facility Needs*

The following activities are necessary during the envisaged planning time frame of an INWM programme:

- Determination of timing for NW facilities needed and their availability based on selection of technologies, but also regarding their refurbishment, replacement and decommissioning based on assessment of NWM planning needs [17,26];
- Establishment of NWM scenarios and milestones (holding points) related to consideration of alternatives;
- Setting timing of the facility need by completion time frames required ("just-in-time" approach);
- Consideration of availability of resources;
- Assessment of future capacities and selection of technologies for forecasted novel NW types;
- Establishment of locations for NW facilities—centralized vs. decentralized, modular, fixed vs. mobile [17,28,29];
- Account that longer-term planning should include consideration of more than one alternative scenario to address needs;
- Consideration of safety, environmental impact, legislation, regulations requirements;
- Accounting for stakeholder engagement and acceptance of waste facilities [30].

### *8.4. Challenge IV: Costs Estimation (Life-Cycle Cost Analyses)*

Meaningful INWM plans must be based on accurate cost and all resources estimate relevant to waste management needs in determined time frame [17,31,32]. These plans require establishment of methodology for performing country-specific economic analyses for various NWM options. It aims to assess the impact of variable waste generation volumes by addressing how much will NWM cost in total, how the future costs are estimated, when and how much money will be needed, which technology will be finally used in each step of NWM and assess whether technical solutions devised today will be accepted by society in the future. The methodology for performing country-specific economic analyses requires:

- An approach for developing alternative plans and costs for NWM;
- Performing an initial screening of alternative projects, technologies, processes and alternative life cycle management options using high level overnight cost estimates;

- Detailed costs estimate to develop the total overnight costs and cost flows of NWM for a particular NW stream.

Cost estimate accuracy should be maintained as recommended for the revision of the INWM plan. The social and political environment may dramatically change in the future. Moreover, a lesson from past is that severe economic setbacks and political or social changes cannot be ruled out for extended future. The cost estimation of future liabilities contains considerable uncertainties as they are projected over many years into the future. There are large gaps in time between receipt of the revenue out of which NWM costs will need to be covered and the actual costs incurred. Another issue could be related to the control costs of the waste generating firms which are generally high and there could be cases of potential collusion between inspectors and managers of these firms, see, e.g., [33].

### 8.5. Challenge V: Funding and Financing

Sustainable mechanisms for long-term funding of nuclear liabilities (financing mechanism) need to be established [17,26,32]. Although financing of future liabilities for NWM can be from more than one system, questions relevant to planning are always the same, namely as follows [16]:

- How are the necessary means collected?
- How are the funds (if any) managed?
- How secure in the future will be the value of money if sets aside today?
- How the risk concerned with the adequacy of the fund is handled (long term liability)?
- How high will yield of this money be, if any?
- Which institutional arrangement is most likely to endure during the coming changes?

In countries where funds earmarked for these purposes do not exist it has to be assumed that funds will be provided when required either from the utilities' general revenues or by government—in such cases understanding of cost and its timing is even more important (such is mostly case for institutional NW owners).

The NWM has a certain cost which must be covered either by "polluter pay principle" or by the respective State Budget. It is necessary to integrate implementation plan with available and needed resources including funding needed. Accuracy of sources of funding can only be achieved if needs are integrated with resources required in the defined time frame. Moreover, even systems performing as intended would most likely undergo changes in the course of time to adapt to a changing context. There is no optimal financing scheme, a recipe leading to good results in all countries.

Monitoring and reporting on funds utilization and fund performances should be done on at least yearly basis.

## 9. Conclusions

The major prerequisites or necessities for establishment of INWM plans are based on knowledge of inventory of nuclear waste streams in stock, forecast of waste streams to be generated during established timeline for integrated planning, assessment of needs for different waste management facilities and selection of technologies to deal with nuclear waste generated during the entire life cycle (so-called from cradle to grave) within the envisaged timeline, establishment of cost estimates and scenarios for different alternatives for waste management during planning period and approaches to funding for implementation.

Iterative nature of planning process focusing on integration of downward ("top-down") and upward ("bottom-up") approaches is discussed emphasizing the advantages of waste minimization at the generation stage during nuclear application use (operation phase) and by the design of facilities, as well as limitations and restrictions, to develop a flexible plan to address envisaged needs. Approaches to planning for nuclear fuel cycle and nuclear power plant waste versus institutional waste and impact of these differences on integrated plan is also pointed out and potential solutions proposed. The INWM plan needs also to consider the nuclear waste from decommissioning and remediation of nuclear facilities, legacy waste and eventual accident waste. The INWM plan requires establishment of different planning scenarios as well as milestones ("holding points") to allow for adequate flexibility to address inevitable changes. In addition, an early assessment of nuclear waste management needs from development and use of advanced reactors and innovative nuclear fuel cycles is required to aid design and operation of such facilities as well as to understand their impact to overall waste management planning.

The IAEA has focused for many years on NWM technical guidance on how to characterize, process, store and dispose radioactive waste, as well on development of waste management safety standards and guidance, see, e.g., [17]. Nowadays, it is also needed to additionally focus on "soft issues" to address planning challenges which require more guidance to be developed, discussed, and shared with IAEA member states. Revision or update of published policy and strategy document [15] to address lessons learned in setting up updated policies and strategies as well as powerful analysis tools and methods [7,26,34,35] will contribute to implementation of integrated planning concept and to overall sustainability of NWM.

An accurate country level NWM reporting cannot exist without establishment of iterative top-down and bottom-up processes related to integrated planning to be utilized by NW generators, operators, regulators, and state functions. The INWM promotes strategic thinking by governments, senior sponsorship of projects or programmes within a broad framework where an agreed outcome at a strategic or even a national level is obtained. In addition, and wherever possible, national plan should strive towards transparency in its decision making and overall progress on key radioactive waste matters that should be regularly and transparently reported. INWM planning is a demanding work which should be done professionally and needs to be thorough auditable. Revision of integrated plans on every three years basis seems logical step forward if no significant changes are occurring. Changes require immediate revisions if plans are not flexible and adaptable to the change (e.g., predefined holding points, alternative scenarios, cost estimates for alternatives). The defendable INWM implementation plan is even more important in a case where funds earmarked for these purposes do not exist (such is mostly the case in countries with institutional waste only).

In summary, the main conclusions of this study are as follows:

- Safe and effective management of nuclear waste is facilitated by an integrated planning approach that covers all generated waste including waste from past, current and forecast future activities, and encompasses all stages in the life cycle of waste from generation to disposal.
- Development of INWM plan should be pursued by all users of nuclear technologies and generators of nu-clear waste.
- INWM promotes strategic thinking within a broad framework resulting in a sustainable and sensible out-come for nuclear waste management at a strategic and national level.
- Such a plan should be developed through an iterative, integrated and transparent process involving all stakeholders, and must be regularly updated.
- Waste inventory, overall timeframe, facility needs, cost estimation, as well as funding and financing are amongst the important challenges to be considered and addressed while developing an INWM plan.

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## Nomenclature

| | |
|---|---|
| IAEA | International Atomic Energy Agency |
| EU | European Union |
| INWM | integrated nuclear waste management |
| LILW | low and intermediate level nuclear waste |
| MS | Member State |
| NPP | nuclear power plant |
| NW | nuclear waste (same as radioactive waste) |
| NWM | nuclear waste management |
| R & D | research and development |
| RWM | radioactive waste management |
| SNF | spent (used) nuclear fuel |

## References

1. PRIS, Power Reactors Information System. Available online: https://pris.iaea.org/pris/home.aspx (accessed on 22 September 2022).
2. IAEA. IAEA Safety Standards Series GSR Part 3. In *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*; IAEA: Vienna, Austria, 2014.
3. *IAEA Nuclear Safety and Security Glossary*; The radioactive waste is the material that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body for which for legal and regulatory purposes no further use is foreseen. The terms "radioactive waste" and "nuclear waste" are generically used as synonyms in the context of safety and waste management; IAEA: Vienna, Austria, 2022.
4. Chapman, N.; Hooper, A. The disposal of radioactive wastes underground. *Proc. Geol. Assoc.* **2012**, *123*, 46–63. [CrossRef]
5. Rohlig, K.-J. *Nuclear Waste. Management, Disposal and Governance*; IOP Publishing Ltd.: Bristol, UK, 2022; pp. 7.1–7.19.
6. Pershukov, V.; Artisyuk, V.; Kashirsky, A. Paving the Way to Green Status for Nuclear Power. *Sustainability* **2022**, *14*, 9339. [CrossRef]
7. Phillips, J.R.; Korinny, A.; Depisch, F.; Drace, Z. Update of the INPRO Methodology in the Area of Waste Management. *Sustainability* **2018**, *10*, 970. [CrossRef]
8. Ahn, J.; Apted, M.J. *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste*, 2nd ed.; Elsevier, Woodhead: Cambridge, UK, 2017; 778p.
9. National Research Council. *Waste Forms Technology and Performance: Final Report*; National Academies Press: Washington, DC, USA, 2011; p. 308.
10. Ojovan, M.I.; Lee, W.E.; Kalmykov, S.N. *An Introduction to Nuclear Waste Immobilisation*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2019; 497p.
11. Hyatt, N.C.; Ojovan, M.I. Special Issue: Materials for Nuclear Waste Immobilization. *Materials* **2019**, *12*, 3611. [CrossRef] [PubMed]
12. Nabakhtiani, G.; Giorgadze, I.; Ojovan, M.I. IAEA Assisted Treatment of Liquid Radioactive Waste at the Saakadze Site in Georgia. *Processes* **2021**, *9*, 1679. [CrossRef]
13. Ojovan, M.I. *Handbook of Advanced Radioactive Waste Conditioning Technologies*; Woodhead Publusing: Cambridge, UK, 2011; 512p.
14. IAEA. IAEA Safety Standards Series No. SF-1. In *Fundamental Safety Principles*; IAEA: Vienna, Austria, 2006.
15. IAEA. IAEA Nuclear Energy Series No. NW-G-1.1. In *Policies and Strategies for Radioactive Waste Management*; IAEA: Vienna, Austria, 2009.
16. Drace, Z.; Ojovan, M. Prospects of integrated waste management planning. In Proceedings of the International Conference on Radioactive Waste Management: Solutions for a Sustainable Future, IAEA, Vienna, Austria, 1–5 November 2021. IAEA-CN294, ID313, 7p.
17. IAEA. *Selection of Technical Solutions for the Management of Radioactive Waste*; TECDOC-1817; IAEA: Vienna, Austria, 2017.
18. IAEA. International Predisposal Network. Available online: https://nucleus.iaea.org/sites/connect/IPNpublic/Pages/default.aspx (accessed on 23 October 2022).
19. Ojovan, M.I.; Lee, W.E.; Sobolev, I.A.; Dmitriev, S.A.; Karlina, O.K.; Klimov, V.L.; Petrov, G.A.; Semenov, C.N. Thermochemical processing using powder metal fuels of radioactive and hazardous waste. *J. Process Mech. Eng.* **2004**, *218E*, 261–269. [CrossRef]
20. IAEA. Disponet. Available online: https://nucleus.iaea.org/sites/connect/DISPONETpublic/Pages/default.aspx (accessed on 23 October 2022).
21. Ojovan, M.I.; Steinmetz, H.J. Approaches to Disposal of Nuclear Waste. *Energies* **2022**, *15*, 7804. [CrossRef]

22. IAEA. Labonet. Available online: https://nucleus.iaea.org/sites/connect/LABONETpublic/SitePages/Home.aspx (accessed on 23 October 2022).
23. IAEA. *Options for Management of Spent Fuel and Radioactive Waste*; NW-T-1.24; IAEA: Vienna, Austria, 2018.
24. IAEA. Course on Policies, Strategies and Prerequisites for Radioactive Waste Management. Available online: https://www.iaea.org/online-learning/courses/355/course-on-policies-strategies-and-prerequisites-for-radioactive-waste-management (accessed on 24 October 2022).
25. IAEA. E-Learning on Spent Fuel and Radioactive Waste Management, Decommissioning and Environmental Remediation. Available online: https://www.iaea.org/services/education-and-training/online-learning/spent-fuel-and-radioactive-waste-management-decommissioning-and-environmental-remediation (accessed on 24 October 2022).
26. IAEA. *INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Waste Management, INPRO Manual*; IAEA-TECDOC-1901; IAEA: Vienna, Austria, 2020.
27. IAEA. Draft TECDOC. Methodology for Inventory and Waste Management Needs Assessment. Robbins, R.A., IAEA, Vienna, Austria, *Unpublished Technical Report*.
28. IAEA. IAEA Nuclear Energy Series No. NW-T-1.4. In *Modular Design of Processing and Storage Facilities for Small Volumes of Low and Intermediate Level Radioactive Waste including Disused Sealed Sources*; IAEA: Vienna, Austria, 2014.
29. IAEA. IAEA Nuclear Energy Series No. NW-T-1.8. In *Mobile Processing Systems for Radioactive Waste Management*; IAEA: Vienna, Austria, 2014.
30. IAEA. Methodology for Development of Waste Acceptance Criteria. Draft TECDOC. Dragolici, F.N., IAEA, Vienna, Austria, *Unpublished Technical Report*.
31. IAEA. Organization, Principles and Technical Options for Waste Minimization. Draft TECDOC. Robbins, R.A., IAEA, Vienna, Austria, *Unpublished Technical Report*.
32. IAEA. Economics of Nuclear Waste. Draft TECDOC. Robbins, R.A., IAEA, Vienna, Austria, *Unpublished Technical Report*.
33. Accinelli, E.; Carrera, E.; Policardo, L. On the dynamics and effects of corruption on environmental protection. In *Modelling, Optimization and BioEconomics, I*; Pinto, A.A., Zilberman, D., Eds.; Springer Proceedings in Mathematics & Statistics: Berlin/Heidelberg, Germany, 2014; Chapter 3; Volume 73, pp. 23–42.
34. Diaz-Maurin, F.; Ewing, R.C. Mission Impossible? Socio-Technical Integration of Nuclear Waste Geological Disposal Systems. *Sustainability* **2018**, *10*, 4390. [CrossRef]
35. Munda, G. Multi-criteria Evaluation in Public Economics and Policy. In *New Perspectives in Multiple Criteria Decision Making. Multiple Criteria Decision Making*; Doumpos, M., Figueira, J., Greco, S., Zopounidis, C., Eds.; Springer: Cham, Switzerland, 2019. [CrossRef]