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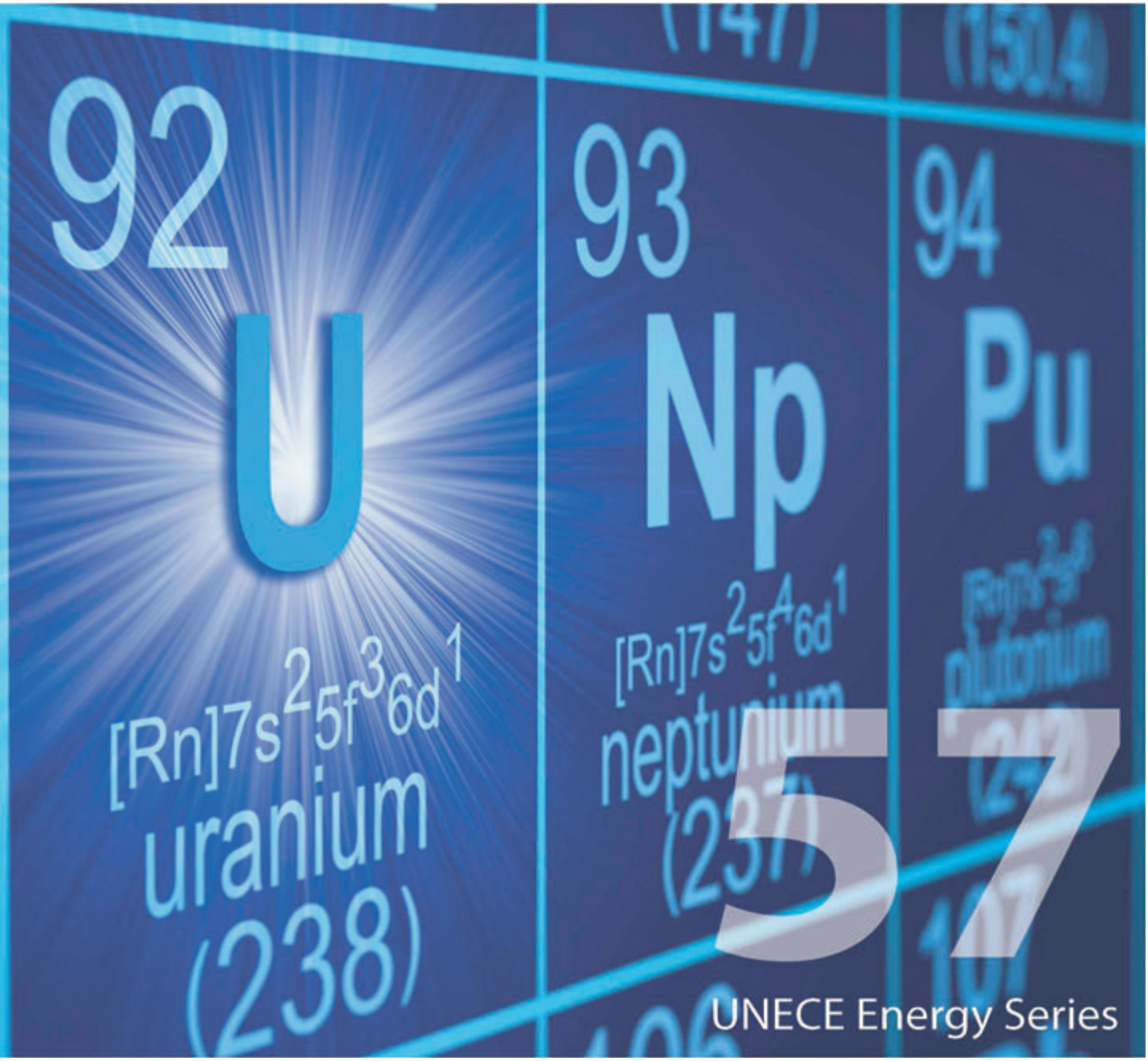
Redesigning the Uranium Resource Pathway

Application of the United Nations Framework Classification for Resources for Planning and Implementing Sustainable Uranium Projects



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Application of the United Nations Framework Classification for Resources for Planning and Implementing Sustainable Uranium Projects

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Foreword

As the world's population continues to grow and with a strong demand for a higher quality of life for all, access to clean and affordable energy is increasingly critical for sustainable development. The realities of anthropogenic climate change require all countries to seek increased use of low-carbon energy sources. These two realities reinforce the argument that good social outcomes should shape how energy and raw materials are managed and used responsibly in the future.

The ECE region is a leading producer of uranium, with significant production coming from Canada, Kazakhstan, Russian Federation, Ukraine, United States of America and Uzbekistan. Globally, uranium resources are mainly treated as a mineral commodity with little recognition of their contribution as fuel for affordable and low-carbon electricity production. The reality that nuclear energy reduces or displaces carbon emissions is becoming more widely recognized. Over 30 countries rely on nuclear power to meet their energy needs, and several others plan to join this group. On the other hand, some countries have chosen to not pursue nuclear energy because of the risks of incidents or accidents, the high cost and lengthy commitment nuclear power requires or because of the long-term waste disposal challenges and have announced phase-outs of this energy source.

Uranium resources fuel 452 reactors with a total net capacity of 399 GigaWatt (electric), which represents approximately 10 per cent of global electrical generating capacity. This capacity has an availability factor of 80 per cent or more. Global nuclear capacity has the potential to increase significantly by 2030. China, for example, is putting a new nuclear reactor into operation every two months. New nuclear unit construction is also progressing in other countries, including in Belarus, France, Finland, Russian Federation, Turkey, United Kingdom, India and the United Arab Emirates.

This publication examines uranium in the context both of its contributions to climate action as a low-carbon, small-footprint energy material and of the value of applying the United Nations Framework Classification for Resources (UNFC) to planning and implementing transparent, sustainable uranium projects. Specifications and guidelines for the management of nuclear fuel resources, according to UNFC, are available. Use of UNFC can enable countries and companies to consider fully the socio-economic viability, environmental sensitivity, technological maturity and level of knowledge at a project level to ensure that uranium resources contribute to sustainable development and attainment of the 2030 Agenda for Sustainable Development.

I am pleased to note that this publication is part of ECE's ongoing efforts to focus on responsible production and consumption of resources. It was prepared by the ECE Expert Group on Resource Management. The Expert Group's Working Group on Nuclear Fuel Resources developed the report under the leadership and support of the International Atomic Energy Agency (IAEA). I thank all the experts involved and, in particular, IAEA for its continued invaluable support of and cooperation in our work on sustainable resource management. I recommend this publication for extensive discussion, review and feedback.

Olga ALGAYEROVA

Under-Secretary-General, United Nations
and
Executive Secretary, United Nations
Economic Commission for Europe

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Acronyms

0W . . . . . .Zero waste
AMV . . . . . .Africa Mining Vision
BECCS . . . . . .Bioenergy Carbon Capture and Storage
BRICS . . . . . .Brazil, Russian Federation, India, China and South Africa
°C . . . . . .Degrees Celsius
CAPEX . . . . . .Capital expenditure
CAREM. . . . . .Central Argentina de Elementos Modulares
CCUS . . . . . .Carbon capture, utilisation and storage
CMIC . . . . . .Canada Mining Innovation Council
CNEA. . . . . .National Atomic Energy Commission - Argentina
CRIRSCO. . . . .Committee for Mineral Reserves International Reporting Standards
CRR . . . . . .Comprehensive resource recovery
CX . . . . . .Comprehensive extraction
ECE . . . . . .United Nations Economic Commission for Europe
EMS . . . . . .Environmental Management System
EPC . . . . . .Engineering, procurement and construction
ESIA . . . . . .Environmental and social impact assessment
EU . . . . . .European Union
FIPR . . . . . .Institute Florida Industrial and Phosphate Research Institute, United States of America
GEA . . . . . .Global Energy Assessment
GHG . . . . . .Greenhouse gas
GT . . . . . .Grade thicknesses
GWe . . . . . .Gigawatt electrical
HELE . . . . . .High-efficiency, low-emissions
HSE . . . . . .Health, Safety and Environment
HTGR . . . . . .High-temperature gas-cooled reactors
IAEA . . . . . .International Atomic Energy Agency
ICMM. . . . . .International Council on Mining and Metals
IEA . . . . . .International Energy Agency
IIASA . . . . . .International Institute for Applied Systems Analysis
INDCs . . . . . .Intended Nationally Determined Contributions
IPBES . . . . . .Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
ISL . . . . . .In-situ leaching
ISO . . . . . .International Organization for Standardization
ISR . . . . . .In-situ recovery
KPI . . . . . .Key Performance Indicator
JUMCO. . . . . .Jordanian Uranium Mining Company
MEM . . . . . .Ministry of Energy and Mines
MENA . . . . . .Middle East, North Africa
MWe . . . . . .Megawatt electrical

NEA . . . . . .OECD Nuclear Energy Agency
NGSA . . . . . .Nigerian Geological Survey Agency, Nigeria
NORM . . . . . .Naturally occurring radioactive material
NPPs . . . . . .Nuclear power plants
OECD . . . . . .Organization for Economic Co-operation and Development
OPEX. . . . . .Operating costs
PFN . . . . . .Prompt fission neutron technique
PPM . . . . . .Parts per million
PWR . . . . . .Pressurised Water Reactor
ROI. . . . . .Return on Investment
SDG . . . . . .Sustainable Development Goal
SEEA . . . . . .System of Environmental-Economic Accounting
SGS . . . . . .Saudi Geological Survey, Saudi Arabia
SLO . . . . . .Social license to operate
SMR . . . . . .Small modular reactor
TAEC . . . . . .Tanzania Atomic Energy Commission
TBL . . . . . .Triple Bottom Line
ToR. . . . . .Terms of Reference
tU . . . . . .Tonnes of uranium
U . . . . . .Uranium
UDEPO . . . . .World Distribution of Uranium Deposits Database
UNESCO . . . . .United Nations Educational, Scientific and Cultural Organization
UNFC. . . . . .United Nations Framework Classification for Resources
UNFCCC . . . . .United Nations Framework Convention on Climate Change
UNRMS . . . . .United Nations Resource Management System
UPSAT . . . . . .Uranium Production Site Assessment Team
URT . . . . . .United Republic of Tanzania
USEPA . . . . . .United States Environmental Protection Agency
WNA . . . . . .World Nuclear Association
WWII . . . . . .World War II

Executive Summary

The trigger for writing this publication was the recognition that the adoption of the Sustainable Development Goals (SDGs) (2030 Agenda for Sustainable Development) requires a ground-up review of all resources critical for the successful delivery of the SDGs in general, but most notably SDG 7, safe affordable energy, and the role of uranium resources in realising it, as a clean, low-carbon energy source. Any discourse on the future of the uranium industry that sets itself outside or at odds with the purposes of the 2030 Agenda and the Paris Agreement on Climate Change for a realistic 2°Celsius (2C) pathway, and, if possible, a more demanding 1.5°C goal, would be derelict in its duty to address the gravity of the situation the world now faces in regard to urgent and transformative climate action. Unless and until the sustainable energy paradigm for a low-carbon future is set, the triad of proposed benefits from SDG compliance to "People, Planet and Prosperity" will remain largely out of reach.

Regarding "People", the objective of this report is to provide decision makers with the best technical advice on options for and benefits of the use of uranium as an energy resource as a key component in the 2°C low-carbon stabilization pathways, as called for by the SDGs. The decisions taken are not just concerned with meeting the immediate technical objectives of providing safe, affordable and accessible energy for all through the selection of a locally or nationally appropriate portfolio of energy technologies but also with how best to communicate both the potential advantages but also the related challenges of including uranium in the energy mix. Of the potential advantages, three stand out. First, of critical significance to public health and safety in urban communities, in which more than 50 per cent of the world's population now lives, is the urgent need to reduce or eliminate the dependency on hydrocarbon fuels which are dominant sources of urban air pollution. Secondly, as rapidly growing urban communities are experiencing ever greater stresses on land use, uranium as by some distance the densest of energy resources can contribute very significantly to reducing the percentage of land required in densely populated areas for energy generation by fuelling nuclear power plants. Thirdly, the rapidly growing evidence assembled by the conflict over land use for the achievement of food and energy security objectives is causing a major threat to biodiversity on the planet, demands a response as immediate and transformative as climate action. Of the disadvantages, one stands out by far, mistrust and fear of the real intentions of those advocating and using nuclear power. Unless stakeholders can feel reassured and that trust in the safety of nuclear power is assured, it is likely that they will turn against it. What does it take to gain and retain that trust? How can the role of uranium as an energetic resource in helping establish a new environmental-economic equilibrium that simultaneously addresses the demands of climate action, land use and biodiversity be best explained and sustained?

Regarding "Planet", the objective is to align the future uranium resources pathway to the SDGs commitment as follows:

> *"We are determined to protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources and taking urgent action on climate change, so that it can support the needs of the present and future generations."*

While some countries choose to pursue nuclear energy with a view that it can play an important role in their energy mix, other countries have decided not to depend on nuclear energy because of concerns about its medium and long-term safety, for example as related to short- to medium-term operating risks and, long-term, to waste storage and treatment. This report will assist countries which have already included nuclear energy along with other sources of low-carbon energies in their Intended Nationally Determined Contributions (INDCs) explain their position in a more comprehensive manner, taking into account issues

such as urban public health and land use management, while also meeting the needs of newcomer countries to nuclear fuels and nuclear energy, especially those for which the availability of national uranium resources may be the decisive factor in entering into the nuclear energy space for the first time.

More widely the report shows how integrating uranium resources into the full range of options for sustainable natural resource management as part of climate action and protecting biodiversity can create an innovative platform developing a low-carbon energy plan for sustainable development. Hence it argues that the conventional model of uranium as an energy commodity needs to give way to a new model of uranium as a "critical raw material", as defined on the basis of potential supply risks and strategic need for meeting the objectives both of SDG 7 and SDG 13, with profound consequences for the future economics of uranium resource recovery and management.

Regarding increased "prosperity" for all as the desired outcome from the 2030 Agenda, the publication of this report as a joint undertaking of ECE and IAEA, is expected to contribute to ECE's efforts to develop standards and best practices for sustainable energy for current and future generations. Much will depend in the coming few years on decision-makers understanding better why uranium and thorium as potentially infinite fuel resources matter so much to the future prosperity and environmental health of the planet and hence why there is so much to be gained from redesigning the uranium resource pathway both in tangible and intangible terms. Substantial and well-coordinated investment in the main intangible – the global capability to recover and use uranium safely and beneficially – will be the key to future success with a return on investment stretching out long after 2030. How the first steps towards a very significant enhancement in capabilities are already being taken in various countries around the world is one of the significant factors behind the confidence presenting this report for review and comment. Regarding tangibles, perhaps the most promising developments are those associated with developing Small Modular Reactors (SMRs) which are being designed to offer much lower investment thresholds for countries starting in nuclear power generation and an overall more affordable life cycle cost of ownership.

Among the most significant policy initiatives, bringing intangibles and tangibles together in a new paradigm, are those addressing the need for "zero waste" outcomes in all resource recovery and use projects, not just uranium. The policy initiatives include the need to rewrite the uranium narrative in a manner that meets stakeholders needs. It should also address their understandable fears and reasons for their mistrust and highlight the connectivities and co-dependencies between all available sources of energy as well as frame energy policies and good practices according to local and national needs and priorities as much as global principles. In that way, a coherent but locally differentiated set of capabilities and solutions will emerge of direct and significant benefit to the timely delivery of the 2030 Agenda for Sustainable Development.

This document does not assume, still less take for granted, that uranium resources will in future be included in the set of energy resources the world chooses to rely on. However, it does assume that the argument that has been made to date for its inclusion is at best significantly underperforming, and at worst is significantly flawed such that it is no longer fit for purpose. Hence, improving both the communications strategy and its core narrative(s) is perhaps the single most pressing need when it comes to addressing the questions from decision makers as to why they should persist with, and indeed expand, their investment in uranium as a sustainable, low carbon,[1] energy source.

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[1] The designation as a "low carbon" energy source takes into account the hydrocarbons that may have been used in mining and processing uranium and in related activities such as constructing and operating power plants and constructing and operating distribution grids.

1. Background

The decision to produce this report, Redesigning the Uranium Resource Pathway, was taken by the Working Group for the application of UNFC to Nuclear Fuel Resources in April 2017 in Geneva on the occasion of the annual meeting of the ECE Expert Group on Resource Classification.[2] The Working Group, which originated as a Task Force, was established in 2010 under the joint auspices of ECE and the International Atomic Energy Agency (IAEA).[3] Its status was subsequently changed to that of a Working Group. It meets annually in Geneva in the context of the Expert Group annual meeting.

1.1 Companion documents

The document is to be read as a companion piece to three other ECE publications developed by the Working Group, as follows:

(i) Bridging Document between the OECD NEA/IAEA Uranium Classification and UNFC [1]
(ii) Guidelines for the Application of UNFC to Uranium and Thorium Projects [2]
(iii) Application of UNFC[4] to Nuclear Fuel Resources – Selected case studies [3]

1.1.1 Bridging Document

The Expert Group approved the Nuclear Fuel Resources Bridging Document in April 2014. It aligns UNFC with other widely used resource classification systems for nuclear fuels, notably the "Red Book", co-published every two years since first appearing in 1965 by the Nuclear Energy Agency (NEA)[5] of the Organization for Economic Cooperation and Development (OECD)[6] and IAEA.

1.1.2 Guidelines

The Guidelines provide additional support for holistic resource management, taking into consideration all specific aspects of uranium as an energy fuel, thus setting it apart from other mineral commodities.

1.1.3 Case Studies

Some case studies were developed in parallel with the Guidelines to provide UNFC users with practical, worked examples of how to apply UNFC to specific projects and resources.

1.1.4 This document – the need for redesigning the uranium resource progression pathway

The decision to complement the Bridging Document, Guidelines and Case Studies with this fourth, forward-looking document was reached against the background of a significantly changed international and UN policy and market landscape, as defined and shaped most notably by the 2030 Sustainable Development Goals (SDGs)[7] [4] and the

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2 For ECE see https://www.unece.org/info/ece-homepage.html

3 For IAEA see https://www.iaea.org

4 The United Nations Framework Classification for Resources (UNFC) changed its name in April 2017. Prior to this, UNFC was known as the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009)

5 For NEA see https://www.oecd-nea.org

6 For OECD see http://www.oecd.org/about

7 For the UN SDGs see https://sustainabledevelopment.un.org/?menu=1300

Paris Agreement on Climate Change[8] [5]. This policy landscape sets uranium as an energy resource in the context of an urgent global need to decouple the provision and economics of energy generation capacity, and the concomitant security of ever-growing energy supply, from the dependency on carbon resources which has characterized global commercial energy provision since the beginning of the industrial revolution.

The uranium resource progression redesign proposed in this document is necessary, but probably not a sufficient condition for resolving a critical dependency for the nuclear energy sector worldwide. This is the safe, secure, transparent and fully traceable supply of uranium fuels for nuclear power plants, in a predictable, reliable and affordable manner as suited to the requirements of a "decoupled" low-carbon energy economy as called for by SDG 13, Climate Action but largely SDG 7 "Ensure access to affordable, reliable, sustainable and modern energy for all". That future will be determined by a yet untried combination of "why" factors, policy, economic, social and technological, which will determine if and only subsequently how (best) uranium resources will in future be recovered.

1.1.5 Direct and Indirect Benefits

Among these factors, some are already identifiable if needing further clarification. They may be broken out according to the direct and the indirect contributions uranium resources can make to a sustainable economy, as follows;

1. Direct
   - An indefinitely sustainable energy source
   - Fully decoupled from the energy-carbon economy, hence green
   - Low footprint, hence low land use penalty
   - Highly adaptable and modular, (if the SMR route is followed)
   - Localisable.

2. Indirect
   - Capacity to slow or reverse the urban pollution crisis caused by the use of hydrocarbon fuels, whether for transportation, cooking or heating
   - Consequent benefits to slowing or reversing the global deforestation and desertification crisis, as nuclear has a smaller land requirement
   - Consequent benefits to reversing the accelerating loss of biodiversity[9] by mitigating or eliminating conflicts over land use between food and energy security objectives [6]
   - Proportionately reduced or very low energy overhead the more the uranium is sourced as a co- or by-product
   - Concomitant opportunity for significant waste reduction in conventional mining where well over 99 per cent of mined rock may be designated "waste" once its uranium content is recovered.

In general, the less conventional, "solid" mining is required to recover uranium, with zero waste a possible outcome especially from *in situ* leaching (ISL), or put another way the more uranium is recovered as a co- and by-product, not the primary target, the more the environmental-economic equilibrium is maintained. Moreover, since the primary product incurs in full whatever waste externality there is a major overhead of conventional uranium mining, the tailings, that is removed from both the environmental and economic equation. In fact, for uranium as a by-product, the waste balance is net negative at least by the volume of by-product uranium recovered.

[8] For the Paris Agreement (UN Framework Convention on Climate Change (UNFCCC)) see http://unfccc.int/paris_agreement/items/9485.php

[9] For the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services see https://www.ipbes.net/document-library-catalogue/summary-policymakers-global-assessment-report-biodiversity-ecosystem

1.2 Basics

1.2.1 UNFC framework

UNFC is a multi-axial resource classification and progression tool for the balanced, transparent and integrated management of all resources. It aligns socio-economic, geological and techno-feasibility factors, together with the ability to manage and assess both uncertainties (aleatoric variables) and sensitivities (epistemic variables) involved in the classification of those resources whether in a primary (first use) state or a secondary (second and subsequent – circular use) state. This capability supports a conventional "resource progression" model – i.e. one that gives a degree of predictability and certainty to market access – but perhaps more significantly it enables full life cycle and materials flow modelling based on the premise that "End of Life" procedures for one cycle are simultaneously "Start of Life" procedures for the next, even when the cycles may have a significant interval of inactivity between them. This recognition that in one sense all "projects" are indefinite, but unpredictable in their cyclic periodicity, in and of itself makes space for non-resource-based factors to operate within UNFC.

1.2.2 UNFC – from Tool to Toolkit

UNFC, as it evolves from resource classification tool into a resource management toolkit, the UN Resource Management System (UNRMS), puts an ever-greater emphasis on accommodating social and environmental considerations at the centre of resource management. The outcome is that what started as a project- and the single resource-driven tool is transforming into a more comprehensive toolkit, with at least five main attributes:

- **Resource centred** (life cycle resource management, primary and secondary resources, circular economy, zero waste…)
- **Customer and service centred** (energy as service, the right to produce and sell energy and/or form local energy communities, inclusive artisanal resource management…)
- **Security centred** (maintaining the security of supply for food, energy, water, critical materials…)
- **Value centred** (ending poverty, new economic resources, equitable distribution of benefits, governance, transparency…)
- **Communications centred** (terminology, definitions, key participants/ stakeholders).

The purpose of the UNFC and UNRMS toolkit is first to provide decision and policymakers with the range of instruments, arguments performance indicators that create the necessary and sufficient conditions for cost-beneficial, socially accepted management of resources in general while meeting resource specific needs and eccentricities. Uranium has always been a very good reference material by which to test the UNFC value proposition both in general and in a resource-specific manner a process which now extends into the wider UNRMS space.

1.2.3 What is uranium?

The discovery of Uranium (U) in 1789 is credited to a German chemist, Martin Heinrich Klaproth, who named it after the freshly discovered planet Uranus. It was first isolated as a metal in 1841 by the French chemist Eugene Melchior Peligot. It is a silver coloured, radioactive energetic metal, the heaviest naturally occurring element, identified by the chemical symbol U with an atomic weight of 92, meaning it holds ninety-second place in the periodic table. Among its remarkable properties are its very high density, a melting point of 2805°C, and its extremely low solubility in reduced conditions but high solubility in oxidizing conditions.

Uranium generates a complex decay series containing elements with unique properties such as radon and radium. Its radioactive properties were first identified more than a century later by the French physicist Henri Becquerel, a discovery dated to 26 February 1896. This led to further investigation, including the properties of its decay products such as polonium and radium, by Marie and Pierre Curie, who extracted polonium and radium from ore to conduct their experiments. One outcome was the commercialisation of radium (Ra) the first industrial application of uranium ores, from 1908 the year of its discovery to World War II (WWII), mainly for medical purposes such as (Curietherapy), radiography, and luminous paints.

Uranium is all-pervasive in the earth's crust and found in abundance. It is especially enriched in the continental crust and still more in the upper continental (2.7 g/t on average). Estimates of how much U is stored in the earth's crust to a depth of approximately 25km range from 40 – 100 trillion tonnes. Some 4Gt are estimated to be dissolved in the oceans. 99.3 per cent of the naturally occurring uranium is the isotope U238. Typically, the element is found in very low concentrations and measured in parts per million (ppm). A very small number of deposits are known with extremely high concentrations, one of which contains 20 per cent U average grade and may reach 80 per cent U over a thickness of 15 m (McArthur River deposit, Canada[10]). This highly exceptional deposit has been in commercial production using automated, remote-controlled recovery technologies and ground freezing. However, for market reasons, as of early 2019 production remains suspended.

With respect to risks to people and biota, uranium's toxic properties as a heavy metal are generally of greater significance than its radioactivity. Most of the radioactivity of a natural uranium ore resides in its decay products such as radium.

1.2.4 Nuclear energy - "atoms for peace"

The potential of uranium as a fuel for nuclear power plants was developed in the aftermath of WWII, the end of which was precipitated by the bombs dropped on Hiroshima and Nagasaki. Under the "atoms for peace" programme proposed in 1953 by United States President Eisenhower uranium's use as a peaceful, energy resource was promoted as a way of channelling uranium applications away from the military towards economic development which relies on long-term stable base-load energy provision.

The first commercial nuclear power station, Calder Hall opened in the UK in 1956, with a dual military and energy generation function. The first exclusively commercial power plant using a Pressurised Water Reactor (PWR) was started up by Westinghouse in Rowe Massachusetts, United States of America, in 1960.

The IAEA rationale and vision for the peaceful uses of nuclear energy defines that: "Any use of nuclear energy should be beneficial, responsible and sustainable, with due regard to the protection of people and the environment, non-proliferation, and security". The basic principles on which nuclear energy systems should be based to help meet growing global energy needs include uses that are: (a) beneficial; (b) responsible and (c) sustainable. Due to the potential use of uranium in nuclear weapons programmes, uranium production is subject to an additional set of constraints not applied to other mineral developments overseen by the IAEA Safeguards Department. IAEA was created to allow countries with nuclear technology to share it with other countries in return for an agreement not to use that technology for weapons development. As a result, international trade in uranium requires that parties agree to IAEA safeguards. See [2] for more discussion on these aspects.

[10] See McArthur River/Key Lake
https://www.cameco.com/businesses/uranium-operations/suspended/mcarthur-river-key-lake

1.2.5 Classification and management of uranium resources using UNFC

As a classification system, UNFC may be applied to energy resources of all kinds, including oil and gas, renewable energy such as bioenergy, geothermal, solar and wind, nuclear fuel resources, mineral resources, injection projects for geological storage; and anthropogenic resources such as reusable raw materials recovered from residues and wastes. When UNFC is applied to uranium resources within the context of the SDGs, it offers the opportunity to redefine not just the way uranium resources are classified – the classification to date has focused almost exclusively on "peaceful" or "military/ strategic" – but how they are produced and utilized within a green, clean energy matrix.

With the global acceptance in late 2015 of the 2030 Agenda for Sustainable Development, it has become apparent that there could be a new era in uranium's history as an energetic resource. While natural resources are essential for the attainment of most of the SDGs, how, when and where these resources are discovered, produced and consumed are issues which have become central to the process of delivering many of the SDGs. In consequence, UNFC has become the comprehensive and integrated tool for classifying all resources that will play a part in achieving acceptable balanced and responsible socio-economic development.[11]

Diverging from the conventional resource classification approach which views uranium as just another mineral "commodity" that can be traded in the minerals market, UNFC presents policymakers and experts with a perspective to consider uranium as a low-carbon fuel that can contribute to achieving many of the SDGs, notably 7 and 13, and related climate action INDCs under the Paris Agreement. Based on this approach, UNFC specifications and guidelines can be used to define an environmentally and economically sound progression pathway for uranium projects producing energetic fuels.

The UNFC methodology for classification and resource management incorporates the application of considerations of E – Socio-economic viability; F – Field project status and feasibility and G – Level of Knowledge / Confidence in estimates. Simple, high-level definitions linked to the fundamental principles of UNFC together with detailed instructions for use in the form of specifications are provided for precise classification of resources.

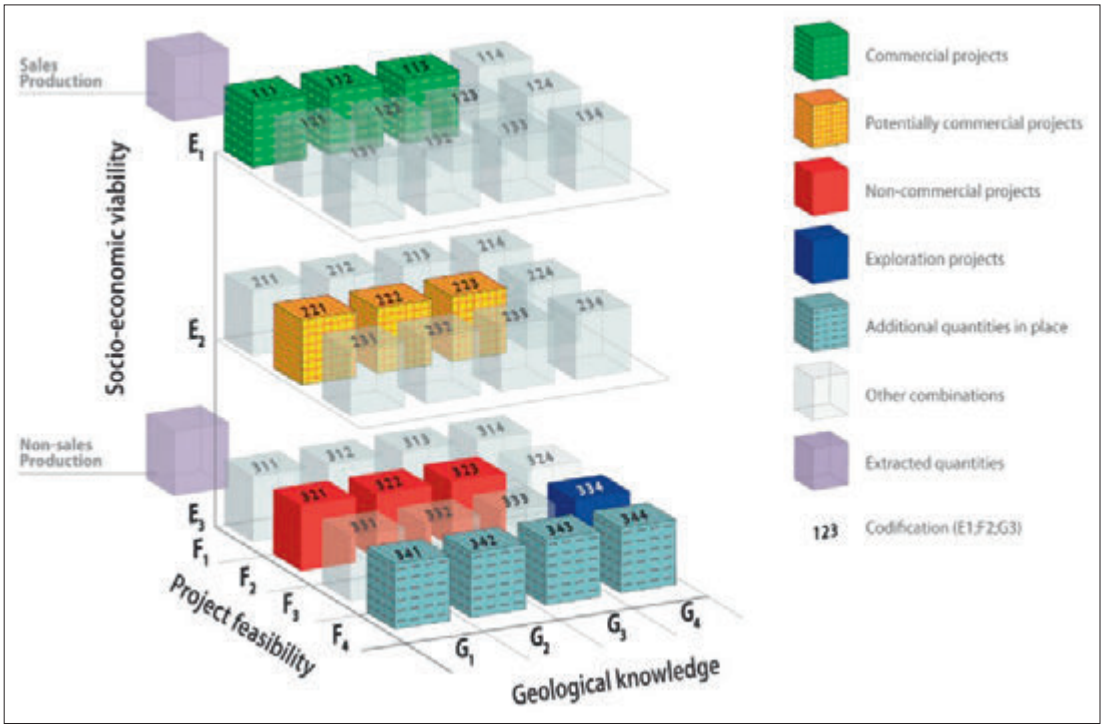
For uranium, the specifications are provided through a bridging document[12] between the "Red Book" published jointly by NEA and IAEA [1]. Apart from these specifications, additional information, with case studies and examples, are provided through the Guidelines for the Application of UNFC to Uranium and Thorium Projects[13] [2]. Their relative status then classifies projects according to alpha-numeric codes (Figure 1).

[11] In 2018, a decision was made by ECE to develop the United Nations Resource Management System (UNRMS) based on UNFC.

[12] See Bridging Document between the NEA/IAEA Uranium Classification and UNFC https://www.unece.org/fileadmin/DAM/energy/se/pdfs/comm23/ECE.ENERGY.2014.6_e.pdf

[13] See Guidelines for Application of UNFC to Uranium and Thorium Resources https://www.unece.org/fileadmin/DAM/energy/images/pub/1734723E_WEB.pdf

Figure 1. **UNFC system based on alpha-numeric codes**



The purpose of this classification is not just to satisfy a regulatory reporting need. Proper classification identifies the progression milestones achieved to date by a project according to the E, F and G axes and what is needed to progress the project to a stage where it can start delivering value at the market ready stage of E1, F1, G1. In that sense, UNFC is a resource management tool as it identifies the socio-economic, feasibility and knowledge parameters that are required to move the project forward, or when it warrants, backwards, to place a commercially active project back on hold, e.g. “care and maintenance”. The application of UNFC thus ensures the correct and timely channelling of capital investments to deserving projects and their protection if market conditions change unfavourably. While the bare commerciality of the project is thus satisfied, on other different levels, the social and environmental aspects of a project are also continuously monitored, assessed and clarified.

UNFC is a system that puts the resource base and its related projects in proper perspective, thus helping policymakers and financial decision makers to have the required understanding and knowledge to support efficient resource development resulting in enhanced prosperity. In a different dimension, the technical experts can assess the technological requirements for not only bringing the project to the production stage but also the innovative approaches required to reach the maximum efficiency in operations. The general public and other stakeholders are meanwhile assured that social and environmental aspects (people and planet) are being managed and addressed appropriately.

Accordingly, during 2017-2018, UNFC incorporated guidelines for accommodating social and environmental considerations in the process of resource classification and use which enable users of UNFC to capture all related aspects consistently, notably regarding the assessment of the E axis. UNFC guidance on alignment with the SDGs focuses on the responsible management of resources, as well as its contribution to the ideal of sustainable development. Instead of relegating SDGs to the periphery of resource management functions, UNFC seeks to place them at the very core of the system, making it a tool for transformative policymaking, strategic rather than commoditised government resource management, business process innovation and related financial management and reporting.

1.2.5.1 Target minerals

To date, one of the more common attributes of "conventional" commercial-scale uranium mining has been on the recovery of uranium from open pit rock deposits with very low concentrations of uranium as low as 100-150 ppm. This has meant that in those cases some 99 per cent plus of rock in mining becomes re-designated merely by the act of mining itself as "waste" (or, more neutrally "tailings"). The term "waste" or "waste rock" is used only because the mine operator has no further use for the rejected material not because the rock is any more dangerous than it was mined (if anything it is less so) nor that other uses will not in time be found. In consequence uranium tailings are found in many countries around the world and have caused significant social and environmental problems, some of which are only now starting to find solutions as pressure from communities living close such piles grow and more widely as circular economy policies start to be applied in order to reduce or eliminate wastes of all kinds.

Overall, mining industries worldwide are now under intense public pressure to reduce or eliminate waste. Leading mining nations such as Australia and Canada envisage reaching "zero waste" in the coming two decades. As a result, commitment to reducing or eliminating wastes and tailings, imposing costly and environmentally damaging burdens on future as well as present generations, has become the prime prerequisite for obtaining the "social licence to operate" (SLO) [7].

Taking the rise in significance of the SLO together with higher operating costs, weak uranium demand and low prices, the outcome has a significant sector-wide shift in the uranium industry to more efficient, less visibly invasive mining methods where uranium may be a co- or by-product of another higher volume resource. As an example, currently, the world's largest uranium deposit, Olympic Dam in Australia, is principally a vast copper-gold deposit which yields relatively large quantities of by-product uranium which is co-located with the copper-gold ore body. By-product uranium is likewise recoverable from gold processing, including tailings, the economics being co-dependent on both gold and uranium markets.

The most significant technological changes in the uranium sector of the past 20 years has been the transition from mining solid rock either by open pit or underground means, first, to liquid mining *in situ* leaching (ISL) or *in situ* recovery (ISR), using acid or alkaline leaching, and more recently (2016 onwards) to *in situ* recovery using less invasive bioleaching technologies[14] or recovery using carbon dioxide (CO_2) and oxygen (O_2). The outcome is that "liquid" mining, notably ISL, has now displaced solid mining as the predominant uranium recovery method, responsible for more than 55 per cent of all uranium recovery, with the outcome that tailings are now generated in far lower quantities than hitherto. Kazakhstan, where ISL is widely practised, is now the world's largest single uranium producer.

1.2.6 Why recover uranium?

For policy and decision makers, the question "why recover uranium?" may well be of far greater significance than "how to recover uranium?" It is hard to find reference works on uranium recovery, which offer guidance on the "Why?" question rather than the "How?"

For decision makers, there are some simple questions to address to respond to "why recover uranium?"

(i) Is uranium recovery for use within a planned or actual national nuclear power programme?

(ii) If so, is this programme aligned with SDG 7 on Affordable and clean energy, and SDG 13 on Climate Action and the Paris Agreement?

[14] Bioleaching is the recovery of metals from their ores through the use of living organisms. This is much cleaner than the many traditional leaching technologies.

(iii) If so, is this in part because of reasons of enhancing public acceptance and/or mitigating social risk and/or national reporting under UNFCCC?[15]

(iv) If not, is the objective purely to sell uranium on the open market?

(v) If so, or not is there a robust national capability for conducting a techno-economic feasibility study that can show that the case for engaging in uranium mining is justified.

(vi) If so, or if not, does the scope for the techno-economic feasibility study encompass options for recovery of co-located resources, especially where these comprise critical materials for the nuclear fuel cycle, within the context of policies of comprehensive resource recovery, zero waste and climate action?

(vii) If so, is the objective to enter a series of related long-term off-take agreements and/or memoranda of understanding with third parties, companies and/or countries, to be co-investors or supply-chain partners with and/or to them?[16]

(viii) If so, are the value at the source and local content key national policy objectives?

(ix) If so, are international standards for these local content policies, e.g. as set out by OECD [8], the broader SDG agenda and the Paris Agreement, being pursued.

1.2.7 The resource progression pathway – planning, workflow, milestones and decision gates

The science of project management of all types is commonly traced back to the work of Henry Gantt who is credited with the systematisation of large-scale projects, often military, but also applied to major civil engineering projects such as highways, according to scientific and engineering principles. Gantt's work is associated strongly with efficiency at work and has many similarities in its methodology with the work of Frederick Winslow Taylor [9] and Henry Ford,[17] who likewise broke tasks in complex systems into unitary, normalised activities, which could be replicated system-wide and be taught as standardised competencies. Gantt's model effectively mapped tasks as a journey through time, where groups of tasks rolled up into activities. When completed, these, like measurable points in a journey, were recorded as, or by, milestones. So, efficiency and performance could be in meaningful units of time and resource application.

Much less respected of Taylor's and Gantt's scientific project management principles, an omission that is now being, somewhat painfully redressed, is that successful projects need social acceptance and entailed social responsibility and equity. In Gantt's methodology, these socio-economic principles are in constant equilibrium with technical expertise and efficiency. Stable maintenance and application of that equilibrium depend critically in the immediate terms on the appropriateness and measurable quality of training offered to the workforce to execute the project. In the longer term - and a uranium project may have a project life cycle of one hundred years or more – the critical dependency for maintaining the equilibrium is the extent that institutional knowledge and experience, what Michael Polanyi was to call tacit knowledge [10] [11], is conserved and transferred within the capabilities of the system as a whole. Uranium projects are no exception. In consequence, even those countries with a long history of use of uranium as an energy resource have suffered significant and costly losses in institutional memory, which is proving stubbornly difficult to regenerate.

[15] For UNFCCC see https://unfccc.int

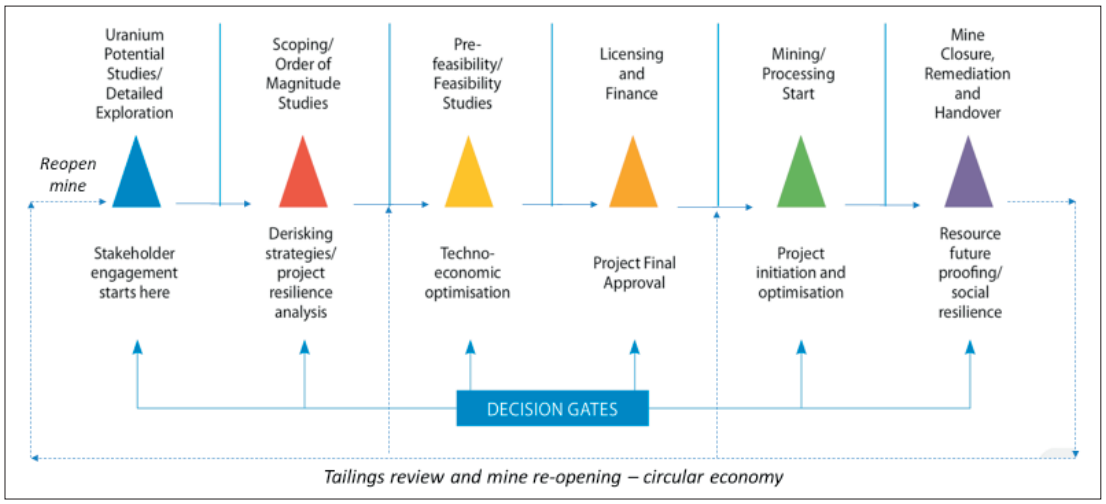
[16] For emerging concerns, e.g. in the United States of America, about security of fuel supply for nuclear power generation see http://www.world-nuclear-news.org/UF-US-government-to-investigate-uranium-imports-1907184.html

[17] Henry Ford is attributed with developing the socio-economic principles of "Fordism" by which mass production (such as in his car factories) combines with mass consumption to create sustained economic growth and widely shared material advancement, which in relation to the SDGs is termed "prosperity".

Milestones are all pervasive in the uranium sector, and it is much harder to find a project plan or performance report that does not use milestones than one that does. Since mining projects by nature are very long and very complicated, typically they will have a large number of milestones for project managers that may be advantageous. For policy and decision makers, this may be overcomplicated or just confusing.

This document hence uses the milestone model, but in two simplified "meta" ways. The first, see Figure 2, was developed for use during IAEA training missions on uranium resources. The purpose is to normalise and to explain to decision makers how the principal phases of a uranium project might unfold, from early exploration to eventual mine closure, decommissioning and handover. In the course of one such mission, to Niamey, Niger, one of the capital cities worldwide of uranium production, at the suggestion of the Niger authorities, the six key milestones identified – from exploration to closure – were complemented by the addition of a key dependency for successful passage of the decision gate at each separate milestone.

Figure 2. **Project milestones, dependencies and decision gates – for decision makers**[18]



In that way, the "rear-view" mirror nature of the Gantt milestone (where have I come from, where am I at the moment?) is complemented by a forward-looking analysis which identifies one of, or perhaps the main dependency for success as the particular episode of the journey is initiated. For example, it is now obvious that stakeholder engagement and social licence acquisition begins with the first boots on the ground of the exploration geologist, not with the award of a mining licence and the preparation of the mine site for resource recovery.

Meta-milestones (Figure 2) commonly double as "decision gates" - a point at which a state change in a project, typically associated with the transition to a new stage in the life cycle, is undergone, triggered by an active decision to proceed to enter the next major stage in the resource recovery process. Passing a given milestone signals that a new episode has *consciously* been initiated, not just passively observed. In effect, the first milestone may embed many other dependencies without any one of which the project cannot succeed, and each one of which entails a deeper level of investment and resource commitment, such as:

[18] The Milestones approach was first developed by Julian Hilton and Harikrishnan Tulsidas in support of the IAEA programme RAF 3007, in a Report entitled "Strengthening Regional Capabilities for Uranium Mining, Milling and Regulation of Related Activities", 14 December 2013 and the Decision Gates component was added at a regional meeting in Niamey, Niger, 1 December 2014.

(i) Generation of exploration targets
(ii) Selection of favourable areas
(iii) Official procedures in the targeted country
(iv) Regional exploration
(v) Detailed exploration
(vi) Project feasibility.

In the case of Niger, the suggestion to follow such a milestone/decision gate method was not made for theoretical reasons but was grounded in the findings of a government-led analysis of which uranium mining projects might underperform or fail, and why, based on 50 years of national experience of uranium mining.

Figure 2 sets out six "meta" milestones as simultaneous decision gates at which a decision will be made as to (a) IF AND WHY to proceed into the next stage of work, and hence investment and (b) IF SO, HOW? Two of these decision gates raise an issue extrinsic to the mine life and purpose, that of "resilience". The mining sector is dogged by cycles of "boom and bust"; all is well in the boom phase, but what happens not just to the mining community but to its whole supply chain and all its and their stakeholders in the bust phase.

A favourite question asked of visitors to Niamey is "what was the population of Arlit, a major uranium mining centre in Niger, 50 years ago?" Answer: "zero". With a current population of 200,000 supported directly and indirectly by the development of uranium mining, the question arises, as for any single resource-dependent mineral, what happens to that city when uranium mining stops abruptly. The problem can be understood from one perspective by realising that mine activity support directly some 2,500 employees, each of whom is directly or indirectly supporting a further 5-10 employed people, e.g. in service industries, or family members and dependents. Many of these have migrated for economic reasons to the city but live in extreme poverty.

Is this economy resilient? Not really, at least in the short term. Part of the answer to the question of longer-term resilience lies in planning for resilience before the mine opens, and investing in infrastructure including hospitals and education, that will enable the city to transition to other industries. However, it also may require a fundamental change of the mining life cycle model from linear to circular, beginning with resource future-proofing at the point of mine "closure" leading to the option to reopen the mine or revisit the tailings when economic and social conditions become propitious to do so.

1.2.8 Critical dependencies

A combination of good practices derived from successful uranium mining projects and related policy documents such as the Africa Mining Vision [12] have established a small but very significant number of critical dependencies. Decision makers may use these critical dependencies to validate for any given project or country, to assess whether or not the readiness to enter uranium mining or to licence projects is at a level that the decision maker can feel confident to proceed.

1.2.8.1 Capabilities and competencies

Does the country have the necessary capabilities and validated (certified) competencies to plan, evaluate and regulate uranium mining projects? If not, does it have access on a secure and affordable basis to these requirements through third parties, such as partner countries, independent consultants etc. such that it can proceed?

1.2.8.2 Infrastructure

Is the appropriate infrastructure for a project already in place (e.g. energy, roads, communications, healthcare, etc.) or is the expectation that the mining company will provide these? If so, does the government agency responsible understand what such infrastructure requirements will be and likely associated costs and performance standards?

1.2.8.3 Value (adding) at the source and local content

Does the country have the capacity/capability to undertake value-adding processing itself or is the expectation that yellow-cake will be shipped for processing out of the country?

If the shipment is intended, is the chain of custody and logistics requirement well understood and the shipment process robust and compliant with international standards and treaty obligations?

1.2.8.4 Health Safety and Environment

Does a suitable, internationally recognised, system of regulation, inspection and enforcement exist for all aspects of health, safety and environment as related to the project, with particular attention to the management and process of naturally occurring radioactive materials (NORMs), notably with respect to legacy tailings and wastes.

1.2.8.5 The social licence to operate

Is a "social licence to operate" in place for the proposed or actual project? If so, is that in the form of a formal "charter" (example Niger) or of an informal but binding understanding between the operator and the stakeholders? Is there a related transparent governance system in place for overseeing the project and reporting on its progress and performance in a competent, trustworthy and independent manner?

1.2.8.6 Transparent governance and elimination of corruption

Growing attention is being paid to the role of transparent governance and accountability in any large resource management project. Likewise, investors, donors and financial institutions are applying much more rigorous standards to the execution of such projects, especially when there may be linkages of various kinds to the potential for conflicts over the resources being mined or the purposes for which they are being recovered. UNFC and the UNRMS under development have these challenging issues very much in mind, especially where the project is presented as a contributor to sustainable development.

1.2.9 "Downsizing" – the rise of the small modular reactor?

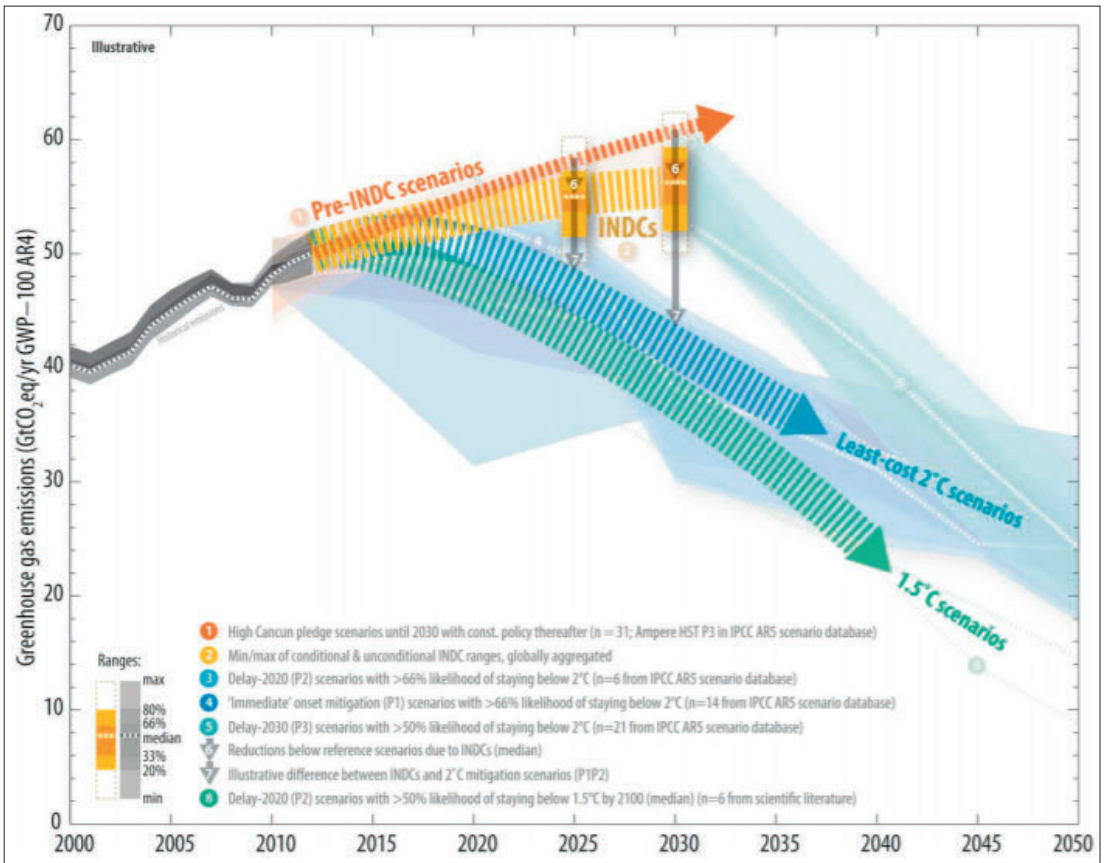
The tendency in design and operation of nuclear power plants (NPPs) has been towards centralised, ever higher generation capacities, partly determined by the fact that the national grid distribution infrastructures, on which power supplies to homes and businesses depend, predated the nuclear reactor as an electricity generation technology. The rapid rise of more localised, renewable sources of power, such as solar panels, has opened up space for alternate models of localised energy provision. In retrospect, 2018-2019 may turn out to be a significant tipping point for nuclear power in which the much less capital intensive, technologically perhaps more innovative SMRs started a new phase of very intensive development.[19]

[19] A useful snapshot of the diversity of work worldwide in SMR development as of early 2018 may be found at http://namrc.co.uk/intelligence/smr

1.3 Climate Action – the new crossroads for nuclear power

In the wake of the Fukushima Daiichi event of 11 March 2011 – where the term "event" includes both the impact of the naturally occurring earthquake and tsunami and the man-made failures at the Fukushima Daiichi nuclear reactor site – many operational nuclear reactors around the world are either being taken out of service ahead of time or being scheduled for accelerated retirement. These trends have brought both the global nuclear energy and uranium fuels industries to "a new crossroads" that could mark either the start of a new "green world"[20] renaissance for nuclear energy or a slow decline to at best a regional market, mostly in Asia.

Figure 3. **Comparison of global emissions in 2025 and 2030 resulting from the implementation of INDCs and under other scenarios**



Sources: Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report scenario database, 1.5 °C scenarios from scientific literature, IPCC historical emission database and intended nationally determined contribution quantification.
Abbreviations:
AR4 = Fourth Assessment Report of the Intergovernmental Panel on Climate Change
GWP = Global warming potential
INDC = intended nationally determined contribution
IPCC AR5 = Fifth Assessment Report of the Intergovernmental Panel on Climate Change
n = number of scenarios
yr = year

[20] The term "green world" is taken from Jacqui McGill, Uranium a Tale of Two Tails, 28 November 2017, https://www.bhp.com/media-and-insights/prospects/2017/11/uranium-a-tale-of-two-tails

In 2012, the Global Energy Assessment (GEA) of the International Institute for Applied Systems Analysis (IIASA) brought together some 500 authors and reviewers from across the world to provide comprehensive, science-based perspectives on sustainable energy futures, quantitative pathways, and the policies needed so they could be achieved [13] and [14]. GEA pathways, in general, and the six related to SDG 7, portray possible futures which are premised on a large share for nuclear energy in the sustainable energy mix.

As of the end of October 2016, 163 INDCs were submitted representing 190 countries and covering almost 99 per cent of global emissions. However, only ten countries (Argentina, Belarus, China, India, Islamic Republic of Iran, Japan, Jordan, Niger, Turkey and the United Arab Emirates) indicated that nuclear energy would play a role in their INDCs [15]. Initial INDCs fall well short of meeting the Paris Agreement targets [16]. Other countries that currently use nuclear power (a total of 30) do not exclude the possibility of including nuclear power in the strengthening of their climate actions. Furthermore, another 30 countries that are either considering or planning to include nuclear power in their energy mix are actively working with IAEA [17]. The future of nuclear energy will depend on how many of these countries will introduce nuclear energy in the next two or three decades.

While energy efficiency and emission reductions through the acceleration of low-carbon technologies, such as renewable energy, nuclear energy and carbon capture and storage (CCS), are included in most of the 2°C scenarios (Figure 3), progress on all these fronts is being questioned. In the majority of the scenarios, the share of low-carbon electricity supply (comprising renewable energy, nuclear energy and CCS) should increase from the current share of approximately 30 per cent to more than 80 per cent by 2050. A big bet is sometimes placed on energy efficiency and renewable energy [16]. Specific energy technologies (for example, CCUS, shale gas, investing in high-efficiency, low-emissions (HELE) technology, or nuclear power) are excluded in the formulation of some national sustainable energy strategies for reasons of public perception, politics, or imposed market distortions [14].

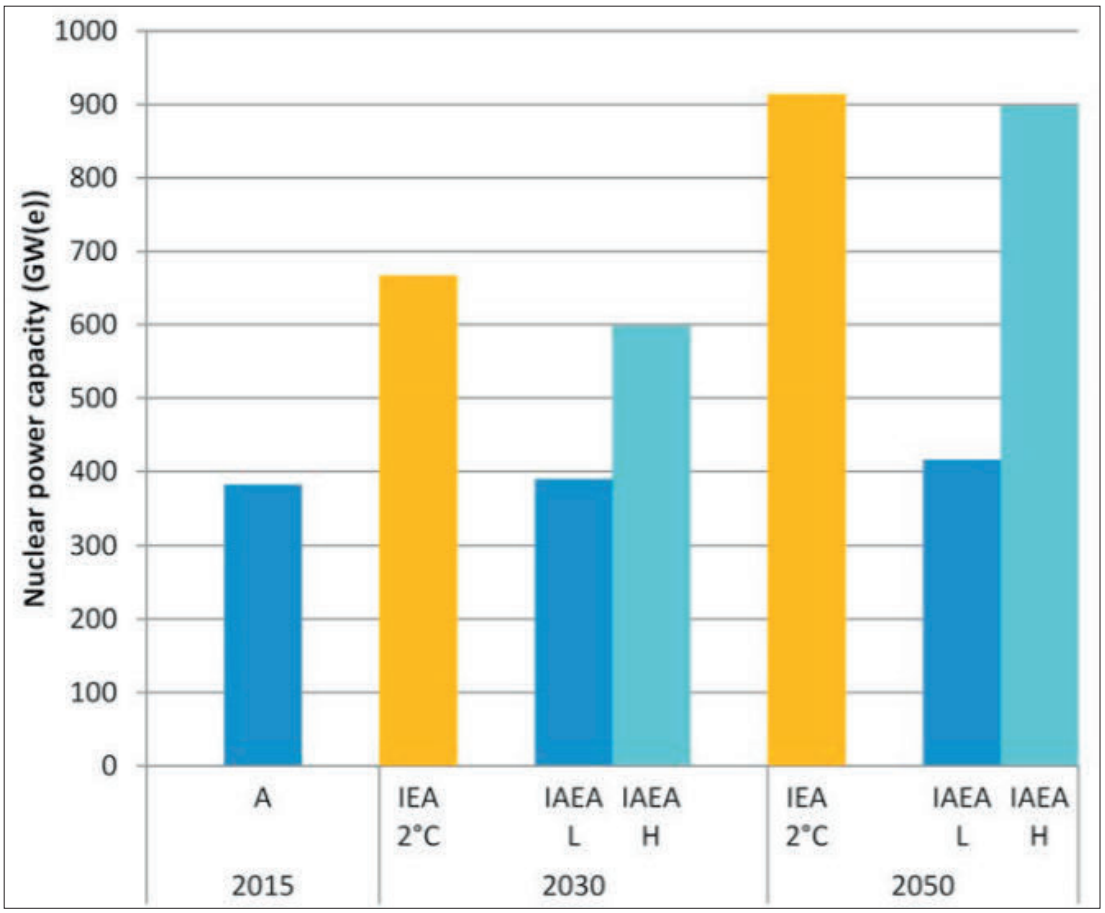
Moreover, the switch from one energy source to another does not happen very quickly [18] [19]. The progress of SDG 7 targets to 2030 highlights the concern that the world is falling short on renewable energy and energy efficiency [20]. Thus by 2040, about 75 per cent of global energy demand will still be met by fossil fuels, with renewable and nuclear contributing only 25 per cent [21].

The integrated assessment models for the 2°C pathways require storing 1,300 billion tonnes of CO_2 by 2100. Of this target, 700 billion tonnes should come from Bioenergy Carbon Capture and Storage (BECCS), which will require a land area twice the area of India to implement. Currently only four CCS projects of 1 million tonnes CO_2 per year (or less) capacity are operational. To meet the required CCS targets by 2050, there would need to be approximately 15,000 of such projects. However, the outlook remains bleak in some regions such as in Europe, where "the realisation of large-scale CCS projects … has been challenging, with many projects being slowed down by financial restrictions, public acceptance and also lack of incentives".[21]

As seen in Figure 4, International Energy Agency (IEA) 2°C scenarios will require a significantly higher contribution by quantity and percentage from nuclear power than the "High scenarios nuclear capacities by 2030 and 2050" projected by IAEA [17]. A higher target for nuclear is also called for in other scenarios [22]. Though nuclear energy has been prominently considered in many of the 2°C scenarios, there are no specific targets set in the 2030 Agenda for Sustainable Development.

[21] Carbon capture, utilisation and storage
https://ec.europa.eu/jrc/en/research-topic/carbon-capture-utilisation-and-storage

Figure 4. **Prospects for nuclear power capacity worldwide: IAEA Low and High and IEA 2°C scenario projections of installed nuclear capacity**



The World Nuclear Association (WNA), through its "Harmony Programme" has set a goal of 25 per cent share of electricity generation from nuclear power by 2050. This will require 1,000 Gigawatt electrical (GWe) of new nuclear capacity to be installed by 2050[22] and be premised on there being a level playing field in energy markets. Such a level playing field supposes: (i) optimized, existing low-carbon energy; (ii) harmonized regulatory processes to provide a consistent, efficient and predictable nuclear licensing regime; and (iii) creating an effective safety paradigm focusing on genuine public wellbeing, where the health, environmental and safety benefits of nuclear energy are set out.

Natural gas, uranium (and thorium) and hydrogen may be more effective global foundational fuels for the twenty-first century [23]. Nuclear fission is a reliable, high-capacity, high-load mode of electricity generation, which means it could offer a good complement to various renewable conversion modes that still have mostly low-capacity, moderate-load, and unpredictably intermittent operation. If a new global nuclear era comes, it will have to be based on better, more efficient, and inherently more reliable and safe designs that have been under development for the past twenty-five years. This could also include an enhanced role for SMRs.

[22] The WNA Harmony Programme
http://world-nuclear.org/our-association/what-we-do/the-harmony-programme.aspx

1.3.1 The impact on non-technical factors

The main impact of the Fukushima Daiichi event on the looming choice as to which of the energy options is to be followed, while apparently having significant technical determinants such as efficiency and safety, is that non-technical factors will largely determine this choice. Of these, perhaps the most significant is that the Fukushima Daiichi event exposed a general communications failure by all the major stakeholders in nuclear power to win and retain the social licence to operate for nuclear power plants. This communications failure is nowhere more evident than in the persistently negative, but also deeply concerned, public opinions and perceptions about the intentions of the nuclear community, whether in government or in the private sector, which the Fukushima Daiichi event crystallised.

1.3.2 A new uranium narrative

UNFC and UNRMS can be used as a vehicle for structuring uranium's resource definition and classification narrative into a coherent "beginning, middle and end", where UNRMS can capture the management of a sustainable and secure progression of uranium as a critical nuclear fuel resource, resulting in an essential, transparently measurable and potentially significant contribution for uranium in helping to resolve the climate change crisis.

This means tracking uranium resource progress from exploration and discovery to production and eventual closure (Figure 2), i.e. the whole project life cycle, not from a mineral project "risk-benefit" perspective premised largely on a single measure of return – profit or return on investment (ROI) to an investor and/or operator. The alternative will be from a programmatic "risk-risk" perspective whose measures of return are based on a new equilibrium of environmental and economic outcomes as set out in the SDGs and the Paris Agreement, of which public and environmental health through green-world energy provision takes precedence.

1.4 Purpose – UNFC and uranium resources in alignment with the SDGs

To evaluate the contribution uranium can make to the new global goals of clean, secure, affordable and accessible energy requires the uranium resource progression pathway to be redesigned in compliance with the objectives and values of the SDGs, notably SDGs 7 and 13, as well as SDGs 14 and 15 on biodiversity.

By applying these objectives and values as the primary modifiers for how to apply UNFC's three-fold classification criteria, namely the socio-economic (E); the technical feasibility (F); and the inherent characterisation of the in-ground resources, including related uncertainties (G), it becomes possible to redesign and map a "balanced and integrated" pathway for sustainable uranium resource recovery in the future. The steps taken along this redesigned pathway will vary, sometimes significantly, from region to region or economy to economy, depending on locally available resources and capabilities. Whatever the setting, to deliver a low- or zero-carbon energy system an optimum mix of options will be needed. Depending on the country, that mix will be based on a combination of energy efficiency, renewable energy, high efficiency-low emissions (HELE) technologies in fossil fuel use, CCUS and nuclear energy.

Among the clean, "green" energy options, uranium has a positive role to play, in particular, where (a) the uranium recovery process focuses on uranium as a co- or by-product of recovering other resources, such as copper, gold, phosphates, REE or vanadium (b) land use is a key determining factor premised on the scarcity of available land in an energy-intensive urban or peri-urban environment. Uranium is one of the most energy-intensive

fuels and thus requires a small volume of fuel to be managed and transported. A nuclear power station has a very limited surface footprint compared to all other energy sources, also requiring fewer materials and metals for its construction, as well as fewer copper lines for its collection. From a life cycle cost analysis perspective (LCCA), the long life (up to 100 years) of nuclear power stations, especially the news ones, offers many advantages once the challenge of the initial capital outlay has been met. Positioning uranium resources within the new global policy landscape rather than as competitors for mineral project investment funding enables this report to offer an alternative, high-level pathway for uranium recovery to the conventional uranium project mode.

1.5 Nuclear energy and uranium production – current state

The current depressed state of the nuclear energy and uranium production landscape has been one of the points of departure in the preparation of this report. On 11 March 2011, the Fukushima Daiichi nuclear accident in Japan[23] abruptly ended an apparent renaissance in the nuclear power sector worldwide and triggered a general slowdown in the development of new uranium recovery projects. Effective 2018, most of the NPPs in Japan remain under extended shutdown while some major economies, among them Germany and South Korea, have announced a general phasing out of their nuclear energy capacity. New builds have been slowed down not least because of public concerns about safety.

This slowdown has been compounded since 2015 by the shale gas revolution which in some key markets such as the United States has ushered in a new era of very low energy prices. This has further weakened the market "push" case for uranium as an energy resource for baseload provision. Unable to compete financially with very low natural gas prices a few nuclear plants have announced shutdowns rather than undertake costly upgrades.

Uranium supply and demand were thought to be in balance as recently as 2013.[24] Since then the situation has changed into a state of significant oversupply.[25] Uranium prices in 2016, for example, were in the range of US$42 - US$75/kgU, the lowest since 2004 [24]. These intractably low prices have created such adverse financial consequences that many operating projects have been placed under care and maintenance or have undergone significant reductions in capacity utilization. This trend is affecting not just the more marginal projects. Late 2017 witnessed the suspension of McArthur River and Key Lake operations in Canada, knocking out approximately 7,000 tU annual production capacity.[26] Kazakhstan announced a 20 per cent cut in production from 2018 for the next three years, which amounts to a reduction of 4000 tU/y in annual production.[27]

This simultaneous closure of the world's richest and one of its largest uranium deposits and the slowdown in Kazakhstan has brought into sharp focus the primordial question of if, and if so, how uranium resource recovery should and could be redesigned for future sustainable operations.

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23 For the Fukushima Daiichi Accident see https://www-pub.iaea.org/books/iaeabooks/10962/the-fukushima-daiichi-accident

24 See World Nuclear News, Uranium supply and demand in balance for now. http://www.world-nuclear-news.org/ENF-Uranium_supply_and_demand_in_balance_for_now-1209137s.html

25 See World Nuclear News, Nuclear fuel report sees growth and gaps, http://www.world-nuclear-news.org/UF-Nuclear-fuel-report-sees-growth-and-gaps-1409177.html

26 See World Nuclear News, Cameco to suspend McArthur River and Key Lake, http://www.world-nuclear-news.org/UF-Cameco-to-suspend-McArthur-River-and-Key-Lake-09111701.html

27 See World Nuclear News, Kazakhstan to cut uranium production, http://www.world-nuclear-news.org/UF-Kazakhstan-to-cut-uranium-production-0412177.html

1.6 UNFC and nuclear fuel resources management

In 2014, a bridging document was developed and endorsed by the ECE Expert Group on Resource Classification (renamed as the Expert Group on Resource Management end-2018) for comparing the results between UNFC and the NEA/IAEA resources reporting scheme [1]. It provides detailed instructions and guidelines on how to classify uranium resource estimates using the UNFC numerical codes, information which is accordingly referenced but not duplicated here.

The mapping of NEA/IAEA results for individual deposits into UNFC requires the application of "Production Terminology", or production centre status, as defined in the "Red Book". This is a unique instance where the project maturity of UNFC is aligned to production readiness of another system related to mineral resources. Even though production readiness is not a part of the NEA/IAEA system as such, it is part of the "Red Book" reporting.

The proper bridging between the two systems would not have been possible without the use of production readiness, one of the meta-milestones, in the uranium resource-progression pathway. Such use of production readiness is absent from any other international mineral resources reporting system, but it necessarily carries over into the redesigned resource pathway as a critical decision gate. All that has to be modified with regard to provision of the necessary information and arguments for the decision to proceed to be taken in a transformative way will be the combination of soft socio-economic and hard climate-action technical factors. These, rather than any technical resource-recovery considerations, will weigh most powerfully with decision makers. What makes the decision itself intrinsically harder to make is that the risk/risk analysis required is not pitting like-for-like risks against each other. Instead, the perceived and sometimes intensely emotional risk of an acute, catastrophic nuclear event has to be assessed against the chronic risk of seriously diminished quality of life and life expectancy in serious decline in carbon-fuel polluted cities.

Production-centred status establishes that uranium resources are not just materials that can be "extracted" from the ground and then used. Uranium becomes a "resource" only when it can contribute to energy production. It is not a mere "commodity" that can be traded in the market but only truly derives value when seen as part of a larger value chain in clean energy provisioning. Seeing uranium as an essential energy resource elevates its status to that of a "critical raw material", on which the long-term energy security and overall sustainable development of a country may depend.

To further support the uranium industry, UNFC guidelines were also prepared in 2015 [2]. Their purpose was to provide non-mandatory guidance for the application of UNFC to uranium and thorium resources. The guidelines are intended to assist all those responsible for finding, classifying, quantifying, financing, permitting, mining, and processing these minerals such that they are fit to enter the nuclear fuel cycle. The application of the specifications outlined in UNFC, with assistance provided by the guidelines, provides a simple but powerful tool for classifying uranium and thorium resources.

The guidelines provide support for the adoption of milestone- and decision-gate-driven approaches to resource progression management in uranium mining and processing projects. These techniques can facilitate smooth project planning and operation across a complete project life cycle including eventual mine or mill closure, decommissioning and site handover. The methodology aligns with the three primary UNFC E, F, G criteria (socio-economic viability, project feasibility and geological knowledge), which likewise focus on key milestones in project life.

The guidelines underline that investment should result in increased, self-sustaining social capital, based on capacity-building, infrastructure development and long-term community/operator partnership. Success may manifest in outcomes such as technology transfer and technology spill-over. The investment must also result in internationally recognized health and safety standards. Equitable distribution of benefits between community and operator

over the short and the long-term should reflect evolving stakeholder needs and cultures. The guidelines also include comprehensive resource recovery as one of the options that can enhance the overall economics of a uranium project. Projects such as Olympic Dam, a giant copper mine with major co-product uranium resources, exemplify such opportunities.

1.7 Social acceptance

The so-called "social licence to operate" which has been under considerable and growing strain for many years in the minerals sector, has now entered an era of extreme difficulty. Opposition to mining or production of oil and gas (together known as the "extractive" industries) previously once came from disparate activist groups, often seen as fringe elements. Today, anti-mining sentiment has become a part of the wider public consciousness. Mining in general, and uranium production in particular, has become an undesirable activity with low or no social acceptance. Moratoriums on mining and uranium production existed in past times in certain provinces or districts that had poorly fared from poor practices or legacy wastes. Today, the movement to ban extractive industries altogether is creeping into public policy, some governments even imposing nationwide blanket bans on mining.

Previous fixes by the industry, for example from strengthening corporate social responsibility, or other similar stakeholder engagement efforts, have become less effective given the degree of public scepticism about extractive industries in general. When compounded by the communications failure suffered in some markets by the uranium industry, uranium resource progression and management require a complete rework. Along with global developments on sustainability and climate action, a new era is dawning on production and consumption of all raw materials, including energy resources.

This has led to a rethinking of how all natural resources are defined, managed and utilized. Redefining the resource pathways hence becomes not just the rational economic option based on clean energy, but also a matter of creating a paradigmatically new narrative for the resources industry within a wider global rewrite within the SDG framework. This paradigm change has to be anchored in a new "Nash" equilibrium, one in which environmental and economic outcomes are so closely coupled they become co-dependent. Such a new equilibrium has, fortunately, already been envisaged by the System of Environmental-Economic Accounting (SEEA) [25]. However, there is still much work to be done to realise the gains that SEEA anticipates and quantifies. One of the components of that required effort is to reconstruct the uranium resource progression narrative around the principle of indefinite sustainability that has to be coupled with the need for innovation and localisation in providing affordable and accessible energy solutions through SMRs integrated within an optimal energy mix.

1.8 Respecting the rights of indigenous populations

Uranium project development can also have complex social impacts related to displacement, land rights, cultural heritage, and other rights of indigenous populations. Therefore, it is well recognized that rights-based social safeguards, inclusive dialogue and risk management principles should be applied to uranium projects to ensure that it benefits the poor, leaves no one behind, and respects human rights. Chief among these is the need for inclusive, participatory, transparent, and ongoing stakeholder consultations to be built into infrastructure planning processes. On broader terms, uranium project development should be strictly based on free, prior and informed consent, in line with the UN Declaration on the Rights of Indigenous Peoples.[28]

[28] See United Nations Declaration on the Rights of Indigenous Peoples https://www.un.org/development/desa/indigenouspeoples/declaration-on-the-rights-of-indigenous-peoples.html

1.9 Uranium, UNFC, the Paris Agreement and the Sustainable Development Goals

As the human population is projected to grow to approximately 10 billion by 2050, the planet is seeing a transformation unparalleled in its history. Human beings are now recognized as a formidable geological agent, instrumental to major planetary-wide changes, especially related to large volume generation of residuals. Often termed as 'wastes', these process residues and rejects are overwhelming the lithosphere, hydrosphere and the atmosphere and impacting the ecosystems. They are also one of the central themes of SEEA – how to map, quantify and valorize them.

Scientists call this new geological age the Anthropocene, the age of humanity. One of the most significant geological features of the current age is increasing atmospheric carbon dioxide content, the most 'visible' residual of this age. During the past, one million years atmospheric CO_2 varied from 180 to 280 ppm. Today anthropogenic net emissions have increased from the pre-industrial equilibrium of 280 ppm to approximately 397 ppm. Most of this increase is due to the combustion of fossil fuels such as coal, oil, and gas, although smaller fractions are the result of other factors, such as cement production and land-use changes.

While climate warming is one of the obvious impacts of the rising CO_2 level in the earth's atmosphere, other issues are also important. Extreme weather patterns, rising sea-levels, and ecosystem impacts, such as ocean acidification and terrestrial and marine biodiversity loss, are becoming evident. The adverse impact on coral reefs of rising temperature levels in the oceans has triggered new worries about the sustainability of whole marine ecosystems, which are already under serious pressure from the build-up of plastic wastes across all marine waters.

Carbon is not the only residual that is seen as a major issue. Human civilization is built on materials - be it structural materials, fuels for energy or fertilizers for food production. Extraction of raw materials and its processing create massive volumes of residuals in its value chains. The guiding principle of the past age was that these residuals do not have any further value and hence are to be released into the environment or disposed of in some form. Now the focus is shifting to achieving value restoration to and release from these residuals. This not only reverses the economic trend from value-destructive, one-directional linear processing models for extractive industries, back towards conservation and restoration of economic value (CAPEX restoration) while also eliminating avoidable operating costs (OPEX savings), it also sets up a completely new materials management model which takes as its cardinal principle the retention of all resources within the resource management system boundaries rather than transiting whatever is left over from extracting primary virgin resources from the "resource" (or asset) column to the "waste" (or liability column) merely because the primary owner has no purpose for these discarded materials even when they retain inherent value for other uses.

While human activities, and related resource classification and decision-making procedures, can be a cause of such major negative impacts if adequately defined, managed and directed they also have the potential to become drivers for mitigation and transition, as required under the Paris Agreement [5]. This harnessing of human commitment and creativity can underpin the development and adoption of innovative, transformative technologies, and through the integration of diverse approaches and meticulous planning on a global scale, a sustainable environmental-economic equilibrium can, at least in theory, be restored.

The assumption of the SDGs is that of a responsible redirection of human effort towards the achievements of measurable benefits to "people and planet" resulting in rising, equitably shared "prosperity". However, this redirection process, as with the successful delivery of

the Paris Agreement, will require extensive and sustained effort. This need was identified prior to 2015. Already with the publication in 2009 of the Africa Mining Vision (AMV)[29] [12] the critical dependencies for success were identified as investment in three priority areas – first, capacity-building and capability development, secondly, in infrastructure, including affordable, clean energy provision and communications, and thirdly, in local content, and value-add processing at source. There is a natural hierarchy in this investment process as, without the achievement of capacity and capability, investment in infrastructure is unlikely to achieve appropriate returns, and in the absence of measurable benefits, starting with improved infrastructure from which all can benefit, value-add processing will not be deliverable.

It is a fundamental part of the hypothesis at the heart of this document, that the uranium narrative now has the opportunity to be fundamentally revised, that the context for its future created by the SDGs, UNFCCC and policy statements such as the Africa Mining Vision is now favourable and positive to an extent never before seen in its history as a potentially infinitely productive carbon-neutral energy source. This narrative – while of course peaceful in its desired outcome – will be driven by considerations of climate action, public health and energy security but not by “atoms for peace”.

[29] See Africa Mining Vision, http://www.africaminingvision.org

2. Current State

Sustainable development is fundamentally linked to shared access to and affordability of energy itself and to the strategic and critical raw materials, among them, uranium, from which, or with the help which energy can be generated, stored and distributed. Uranium, perhaps of all energy resources is the one which most exhibits the attribute of indefinite sustainability, its attribute that is the key to stocking and securing the nuclear energy fuel cycle.

2.1 Stocking and securing the fuel cycle

Uranium resource supply is a small but mission-critical aspect of the nuclear fuel cycle. The currently defined global resource base is more than adequate to meet high case uranium demand through 2035 but doing so will depend upon timely investments to turn resources into refined uranium ready for nuclear fuel production. Challenges remain in the global uranium market with high levels both of oversupply and inventories, resulting in continuing pricing weakness. Other concerns in mine development include geopolitical factors, technical challenges and increasing expectations of governments hosting uranium mining.

2.1.1 Uranium resource base

What is the uranium resource base, and how is it currently assessed and managed?

The total identified uranium resources (reasonably assured and inferred) as of 1 January 2017 amounted to 10, 652,900 tonnes of uranium metal (tU) in the <USD 260/kgU category [26]. Of these quantities, 7,988,600 tU are estimated to be recoverable, and 2,664,300 tu are estimated to unrecoverable. Total undiscovered uranium resources (prognosticated resources and speculative resources) as of 1 January 2017 amounted to 7,530,600 tU.

Significant quantities of uranium are found in many “unconventional” resources (Table 1) [26]. Seawater has long been regarded as a possible source of uranium because of the large amount of uranium it contains (more than 4 billion tU) and its almost inexhaustible nature. However, because seawater contains such a low concentration of uranium (3-4 parts per billion), developing a cost-effective method of extraction remains a largely techno-economic challenge.

What exactly is meant by “unconventional” uranium resources is not fully defined, and subject to change whether (a) by what the ultimate source may be of the uranium, or (b) the means of recovery? From a provenance perspective, “conventional” uranium resources refer primarily to those recovered by traditional mining techniques, i.e. from the various deposit types whose primary characteristic is that their primary value to the mining company is their uranium content.

By contrast, “unconventional” uranium typically includes resources from which uranium is recoverable as a low-volume co- or by-products, such as from phosphate rocks, non-ferrous ores, peralkaline intrusions and carbonatite, monazite, black shale and lignite. How useful the “conventional” versus “unconventional” distinction is from a classification perspective is highly questionable, relying taxonomically on a difference between operator intentions or perceptions (which resource is my main target, and which is of secondary interest?) rather than on any inherent properties of the uranium itself or its co-located resources.

Nowhere is the taxonomic weakness more evident than (i) in the case of what is after all the world’s largest uranium mine, Olympic Dam. This is (a) primarily a copper and gold mine and which (b) recovers uranium above all to remove it as a “contaminant” of the copper recovery process, but in such large quantities that its value as a co-product exceeds the nuisance cost of recovering it; and (ii) that the world’s largest known uranium deposit is actually in Morocco by virtue of the very large quantities of co-located uranium contained in

Moroccan phosphate deposits and others of similar sedimentary types especially across the Middle East, North Africa (MENA) region.

Quantities shown in Table 1, below, for unconventional uranium resources are largely incomplete, as many potential co- or by-product uranium resources are not assessed properly and reported. Moreover, because Olympic Dam recovers uranium in a "conventional" manner, its vast uranium resources are, at least to date, generally not included from a resource perspective as part of the "unconventional" grouping. Perhaps the best approach will be simply to stop making such a distinction in future between conventional and unconventional since the underlying reason for its original introduction appears to be based on the degree of techno-economic risk in recovery not an inherent attribute of its geology. That is, "conventional" mining meant simply a method markets and investors were familiar with, mostly solid, open pit, while unconventional was "liquid" and increasingly in situ. If production volumes are factored in, ISL is now the "conventional" method and open pit the "unconventional".

Table 1. **Unconventional resources of uranium (tonnes of U)**

Country	*Phosphate rocks*	*Non-ferrous ores*	*Monazite*	*Carbonatite*	*Black schist/ shales, lignite*
Brazil	28 000 – 70 000	2 000		13 000	
Chile	400	800			
Columbia	20 000 – 60 000				
Egypt	35 000 – 100 000				
Finland	1 000			2 500	35 000
Greece	500				
India	1 700 – 2 500	6 600 – 22 900			4 000
Indonesia			27 000		
Jordan	100 000				
Kazakhstan	58 000				
Mexico	240 000	1 000			
Morocco	6 526 000				
Peru	41 600	140 – 1 410			
South Africa	180 000				70 700
Sweden	42 300				1 012 000
Syria	60 000 – 80 000				
Thailand	500 – 1 500				
United States	576 500	1 800			19 014 000
Venezuela	42 000				
Viet Nam					500

Source IAEA [26]

Table 2 shows the quantities of unconventional uranium reported in UDEPO as of 2018 [27] [28]. Apart from these deposit types, re-processing of previous tailings, wastewater, and residues (such as coal ash) can also be a source of "unconventional" uranium. Historically, significant quantities of uranium have been recovered from phosphoric acid, notably through the commercial-scale application of solvent extraction processes integrated into the phosphoric acid production flowsheet [29].

In the United States from the early 1970s to the late 1990s some 17,150 tonnes of uranium were recovered in the course of "wet process" phosphate fertiliser production in Florida [30]. Gold tailing projects in South Africa are another source that has contributed by-product uranium recovery in significant quantities, a process which continues to date, though at reduced volumes [31].

Table 2. **Unconventional uranium resources as in IAEA UDEPO (2018)**

Deposit Type	*Resources (tU) in UDEPO*	*Grade (ppm)*	*Number of deposits in UDEPO*	*Number of Known World Deposits*
Intrusive plutonic	1,949,000	10-300	43	1660
Polymetallic Iron-oxide Breccia Complex	2,560,000	30-250	18	Less than 100
Paleo-Quatrz- Pebble Conglomerate	2,036,000	20-500	116	150
Surficial-Placers	67,000		13	~1000
Coal-Lignite	7,420,000	1-500	76	1600
Phosphate	14,300,000	50-150	69	1635
Black Shale	22,850,000	10-200	76	Several hundreds
Total	52,170,000		411	6-7000

The distinction between "conventional" and "unconventional" has become further blurred with regard to the applicable resource recovery technologies applied by the rise of "unconventional" uranium leaching recovery technologies, notably mining using in situ "liquid" leaching (ISR) methods and now less invasive methods with microorganisms, CO_2 and O_2.

2.2 A changing energy supply and demand landscape

The changing narrative of uranium (the new tale of the resource pathway), driven from within by innovations in both the sources of uranium accessed and the means of extraction employed, is also modified by changes in the wider energy landscape of which the most profound perhaps is a decoupling of oil and gas prices as one consequence of the decoupling of the energy economy from carbon fuels.

One of the most important intermediate "decoupling" changes is the shale gas revolution that began in 2010. This socio-economic and technological revolution has reset the balance of energy supplies, as a result casting a long shadow over all other energy sectors, with nuclear energy proving no exception. This system reset had significantly affected supply-side energy forecasts, among other things leading to the return of the United States to the ranks of net energy exporters after a long period when it was dependent on imports from third countries. This has already had and continues to have broader geopolitical and economic consequences.

First, energy prices in some, but not all, markets are likely to remain relatively low over the long-term. Secondly, energy resources from a paradigm of scarcity, in some markets have now become superabundant. Thirdly, it is becoming evident that even in traditional industries technological innovation, such as 3D printing, can be embraced at exponential speeds within the energy supply chain, opening alternate means of distribution and access. Fourthly, production patterns themselves can become nimbler and more flexible, responding more adaptably to market signals.

This also brings into focus other opportunities of compounding nature. As the footprint of operations becomes smaller, capital and operational expenditures could be reciprocally smaller. New technologies and their resultant efficiencies can be flexible but need not reduce or eliminate jobs and opportunities. Such gains may, however, can be compounded by gains in environmental protection and waste reduction performance. For uranium, within the new paradigm of grounding the uranium tale in its potential as an energy resource of indefinite sustainability, such compounded gains will have significantly positive consequences for its social acceptance.

2.2.1 Supply side

There has been a drastic decline in the quality of new uranium mineral discoveries in recent years. There are only a few, rare high-grade mineral deposits that at short notice can be moved into production. However, focusing on uranium exploration only on a few high-quality discoveries will bring many technical challenges and may prove to be too risky for conventional investment or project financing models. Exploration expenditures have been drastically reduced in recent years, and there has been more than one attempt to move away from greenfield to brownfield exploration. Results are inconclusive, as for example, the plan to reopen the Salamanca Uranium mine in Spain[30] which started in a mood of optimism, then was refused a permit on the grounds of local opposition and, as of March 2019, is hoping to get the licence refusal reversed following additional studies.

Against that background, there is increasing difficulty for companies to raise capital targeted for greenfield exploration activities. The reductions in capital raised and spent on exploration call into question the ability of "project-driven" miners and operators to find additional low-cost reserves to remain competitive, as well as their ability to respond to eventual increases in uranium demand.

If uranium exploration expenditures continue to follow the "boom and bust" cycles of the market, a few years of active exploration will be consistently followed by a fallow period, degrading rapidly the putative asset value of the projects while also degrading the even more valuable but intangible asset of the knowledge of how to open and manage such "unconventional" "mines". This creates considerable pressure on keeping uranium exploration talent and experience available on a long-term basis, i.e. on enhancing its resilience.

As existing projects become depleted, new resources must be brought into, or at least readied for, production. This requires not only continued exploration but also keeping adequate resources in the production pipeline, probably increasingly by digital means. Smart, software-based modelling together with the more sophisticated and accurate exploration and recovery techniques can greatly enhance the planning and management of a mine allowing future mines to be designed and tested online rather than in the ground. Such a "smart" transition is urgent in that current models of on/off uranium exploration and development are neither resource-efficient nor economically sustainable. The degree of urgency is, however, already translating to action with the lead being taken by well-led engineering/EPC contracting companies such as FINE, China, part of China National Nuclear Corporation (CNNC).

2.2.2 Demand side

As of 1 January 2017, it is estimated that about 62,825 tU are required annually [26] for a total of 449 commercial nuclear reactors that are connected to the grid with a net generating capacity of 391 GWe, This amounts to an average requirement of approximately 160 tU/GWe/year. The projected uranium requirements by 2035 will be 53,010 tU in the low case scenario and 90,820 tU in the high case scenario [26].

Demand for uranium has been further depressed by nuclear utilities deciding to keep lower inventories. Before the Fukushima Daiichi incident, the general practice in many countries was to have at least three reactor loads in inventory. In the current, oversupplied market, uncertainties concerning the security of supply have significantly diminished, leading to many utilities changing their inventory policies to keep only one reactor load on demand in store. In the short term, this has lowered the demand for uranium.

[30] See Berkeley Energia for the Salamanca project, https://www.berkeleyenergia.com

Improving efficiency in uranium utilization in the fuel cycle itself has similarly reduced uranium demand, along with contributory factors such as fuel cycle length, burn-up, improved fuel design, and market-technical strategies employed to optimise the relationship between the price of natural uranium and enrichment services. From a previous average of some 175 tU /year for 1 GWe capacity, the current requirement is only 160tU/year [26]. Such increases in uranium use efficiency mirror broader resource efficiency gains in the so-called "4.0" industrial economy.

World production in 2017 decreased and amounted to just over 59 000 tU. Further decreases in world production are expected because of the continued depressed uranium market [26]. The changes are principally the result of decreased production in Australia, and lower uranium mining output from Brazil, the Czech Republic, Malawi, Namibia and Niger. Kazakhstan produced approximately 24,575 tU in 2016 but then reduced output by 10 per cent in 2017 and a further 20 per cent reduction in 2018.[31,32]

Before the 2011 Fukushima Daiichi event, uranium miners vigorously – in retrospect over-optimistically – responded to the market signal of increased prices and projections of rapidly rising demand and invested in new projects. Since then, uranium market prices have drifted almost continuously lower, a trend compounded by lingering uncertainty about nuclear power development, even in countries ostensibly committed to nuclear expansion. This has reduced uranium demand and requirements, further depressing prices and slowed the pace of mine production and investment in new uranium project development.

This decline has significantly impacted the likely relative contributions of conventional and the unconventional resources in future uranium supply scenarios. Large, commercially-funded uranium production facilities will stay in operation only if sufficient long-term contracts are available. With interest in small, modular, less capital-intensive reactor fleets strengthening,[33] higher flexibility and adaptability to volatility in production and supply will inevitably be required both of uranium miners and nuclear engineers.

2.2.3 Small- and modular reactors as change agents?

If demand for SMRs increases, as seems likely if nuclear energy is to reinvent itself technologically, the uranium demand scenarios could be impacted substantially. Small reactors have a longer refuelling cycle, up to 10 years, rather than the 12 to 18-month refuelling cycle of large NPPs. It makes more sense to consider the lifetime uranium fuel requirement for a small reactor, rather than its annual needs. For example, a CAREM 25 MWe reactor will require 600 tU for its 40-year operating life. Nuclear utilities owning or leasing SMRs will consider it optimal to contract fuel supply for the entire lifetime of the reactor, rather than buying on an annual basis.

Assuming a significant increase in the availability of small- and medium-scale (27kW to 300 kW) reactors, which will also significantly lower the entry threshold requirements for countries not yet engaged in developing nuclear power programs to do so, there could be an upsurge in demand for uranium, whether based on an annual supply-contract or a supply contract aligned to the life cycle of the reactor. From the security of fuel supply perspective, the whole life cycle supply model is preferable.

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31 See World Nuclear News, Oversupply prompts Kazakh uranium production cut, http://www.world-nuclear-news.org/UF-Oversupply-prompts-Kazakh-uranium-production-cut-1001177.html

32 See World Nuclear News, Kazakhstan to cut uranium production, http://www.world-nuclear-news.org/UF-Kazakhstan-to-cut-uranium-production-0412177.html

33 See for example the United Kingdom investment announced December 2017 https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

2.3 The Trend to In-Situ Recovery 4.0 – a new environmental-economic equilibrium?

Demand for resetting the environmental-economic equilibrium as a basis for promoting more sustainable development, especially the provision of sustainable energy has led to a refocusing of interest in the development of commercial-scale uranium recovery projects towards ISL techniques applied to deposit types best suited to that recovery method notably so-called roll-front deposits.

2.3.1 Geology and mineralization

Uranium roll-front deposits are also known as ore-rolls, solution fronts, geochemical cells and/or reduction-oxidation fronts. These deposits are typically formed by mixing groundwater fluids of varying chemistry, such as oxidizing groundwater interfacing/mining with reducing groundwater, in transmissive fluvial and/or marine host sandstones with porosity of about 20 per cent (these can range from 10 -30 per cent) and permeability of about 200 millidarcy (mD) (possible range 50 - 500 mD). Typical groundwater parameters of known roll-front deposits show bulk groundwater flow rates of about 58 m^3/yr through 1 m^2 with a typical groundwater velocity of about 290 m/yr. Much lower flow rates can occur, for instance in the outback of South Australia (approximately 15 m/yr). Typical roll-front groundwater has an oxygen content of about 5 ppm and uranium content of about 50 ppb. A typical rate of roll-front advance is about 1.4 cm/yr. The period required to form a 10-km-long oxidized roll-front tongue is about 700,000 years. A 10m wide roll-front deposit with a 0.26% U_3O_8 ore grade, a typical deposit of this type, requires about 50,000 years to form.

The mineralization of uranium roll-front deposits typically consists of uraninite (UO_2, pitchblende) and coffinite [$U^{4+}((SiO_4)(OH)_4$], commonly as amorphous coatings on sand grains (quartz, feldspar) and fillings in interstitial spaces. Typical ore grades of roll-front deposits range between 0.05 and 0.26 % U_3O_8 but can be as much as 7 % U_3O_8. The size of known uranium roll-front deposits ranges from 2 to 13+ mt of U_3O_8. Many uranium roll-front deposits occur at the relatively shallow depths of 60–600 m.

Typical uranium roll-front deposits are narrow (3–40 m wide) but long, stretching over many kms and often across regional or national boundaries, though not with equal ore-quality along their length. In map view, many roll-fronts are complex and show extreme sinuosity. In the cross-sectional view, roll-front deposits are typically 2–8 m thick and crescent-shaped, (convex down-dip), often presenting as a complex stacked system of multiple roll-fronts.

2.3.2 Host rock

The host rock for a sedimentary uranium deposit typically includes a hydrogeological 'trap' with a focused groundwater flow (i.e. confined aquifer, bounding shales/clay, paleochannel system) and a reduction-oxidation interface. Sufficient time with favourable conditions, such as a regional chemically reducing environment, is needed to build the deposit.

Paleochannel uranium deposits suitable for ISR often occur in buried paleo-fluvial river sediments, as ancient river channel fillings (paleochannels). They are often situated at the confluences and intersections of fluvial channels and/or near bends, typically associated with an abundance of organic material and pyrite, the predominance of coarse-grained sediments, and basement scours [32]. Typical large paleochannels are 5-10 km wide, ~200 km long, joined by smaller tributaries, and show typical vertical gradients of 1.2 to 2.1 m/km. The general shape and orientation of the channels are often controlled by basement rocks and geological structures, such as where a channel breached a ridge along a fault zone. Other paleochannel sites can be significantly smaller and shallower.

Features may include uranium-mineralized sand and mudstone that eroded into organic-rich clay-mudstone (e.g. plant fragments, carbonized wood), with anomalously high uranium concentrations at bends and/or points of confluence with tributaries, and channels up 1 km wide and 80–150 m thick.

2.3.3 Exploration

Exploration of sedimentary uranium deposits is typically conducted by tightly spaced exploration drilling grids, relative drill grid spacing depending on the level and accuracy of resource classification sought. Mineral resource exploration of roll-fronts and paleochannel uranium deposits requires dense exploration and infill grids so that the roll-front and paleochannel geometry can be identified; a dense grid typically results in substantial drilling exploration costs. A significant saving in drilling exploration costs for paleochannel uranium deposits can be accommodated by applying a 3D seismic exploration and/or shear-wave seismic exploration survey, as these techniques are capable of cross-stratigraphic channel imaging and can obtain high target resolution. As digital artificial intelligence (AI) driven mining techniques evolve, so predictive/probabilistic resource modelling will rapidly improve.

2.3.4 Estimation of quantities

Estimation and reporting of uranium resources for ISR projects differ from hard-rock mining projects due to the need for quantitative estimation of the geotechnical and hydrogeological parameters, which are specific for ISR technologies [33]. The conversion of uranium resources to uranium reserves by applying the modifying factors is somewhat more complex. Modifying factors for converting resources to reserves are verified and corrected by using field leach trials of uranium ore horizons; field leach trials are a strictly applied requirement for all ISR projects.

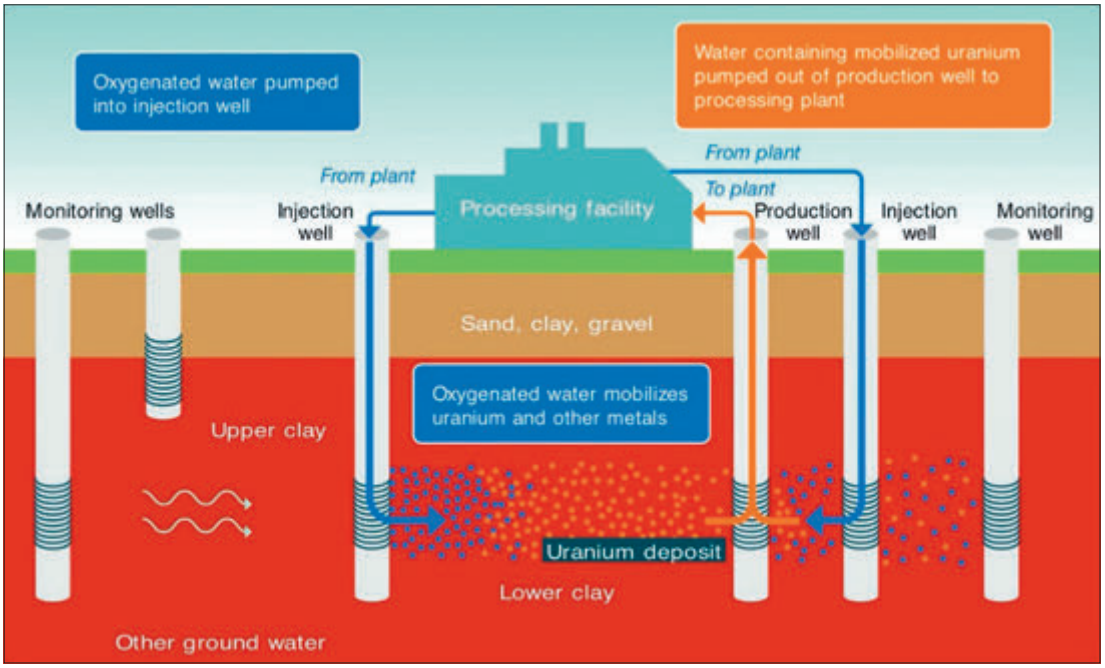
One specific challenge for resource estimation of near-surface ISR projects (<100 m depth) is water saturation of the mineralized zone. Uranium sedimentary ore deposits <60 m in depth are of particularly high risk for ISR as a minimum of about 60 m hydraulic head is required for ISR due to the water saturation specifications for extractor wells. Uranium roll-front and/or paleochannel deposits of shallow depths may not be economically recoverable via ISR technology, which has a significant effect on the reserve estimate of the ore deposit.

2.3.5 The Rise of In-situ Recovery (ISR) or In-situ Leaching (ISL)

ISR or ISL (Figure 5), is a generic ore recovery technology suitable in the case of uranium for application to sandstone-hosted deposits below the water table in weakly lithified or non-consolidated sands [33]. Such deposits include roll-front, tectonic-lithologic, basal channel, and tabular types containing approximately 33 per cent of the world's known uranium resources (7,360,255 tU).

The ISR concept is based on dissolving uranium ore minerals, which usually occurs as coatings on quartz and feldspar minerals in the host rocks (i.e. in place not in an attack tank or leaching column), liberating the uranium by reactive solutions that are injected through drill holes (injectors). The dissolved solution (pregnant lixiviant) is then pumped to the surface through discharge drill holes (extractors) (Figure 5).

Figure 5. **The uranium ISR process – US Environmental Protection Agency model**



The uranium grade is determined by down-hole geophysics, specifically by prompt fission neutron technique (PFN), coupled with systematic sampling and assaying of the drill core. The main ISR parameters to be considered are [33]:

(1) Uranium ore grade, the geometry of the ore body, and the type of mineralization. The accuracy of the ore grade estimate must be sufficient for supporting 'remote' mining.

(2) If the ore grade is estimated by gamma logging, then the disequilibrium is to be studied and reported.

(3) Accurate determination of the hydrogeological confinement of the mineralized horizon.

(4) Accurate determination of the permeability of the mineralized horizon.

(5) Careful characterization of the composition of the host rocks (particularly the carbonate content) to estimate if the uranium mineralization is amenable to dissolution by acid or alkaline solutions.

(6) Determination of the groundwater flow.

(7) Determination of the aquifer salinity.

(8) Determination of the rate of *in situ* dissolution of the uranium minerals by various lixiviants.

Some critical ISR mining considerations include:

– High-grade 'limb-ore', which can occur in mudstones (or with organic material) that is not suitable for ISR, but is often considered for conventional open pit or underground mine planning

– Minimum cut-off grade thicknesses (GT), typically 0.09% U_3O_8 for depths <300 m, and a minimum of 0.15 per cent U_3O_8 for depths >300 m

– Saturated, porous and actively permeable aquifer host sand units (i.e. those with a high percentage of actively exchangeable pore volume), and not containing an abundance of organic matter or mudstones

– The use of standardised production patterns such as 5-point cells (= 1 production cell/extractor and 4 injection wells/injectors) which commonly address a resource of about 2,000 - 4,000 kg (5,000 to 10,000 lb) U_3O_8.

2.3.6 Efficiency and economics

A reasonable and thorough assessment of ISR efficiency and economics requires abundant ISR leach simulations and testing to quantify the critical parameters; this also requires field leach trials.

Typical effective rates for U leaching and recovery from an ISR operation range between 0.001 and 0.01 d^{-1}/70%. Pore volume exchange rates are typically 0.06 d^{-1} but can vary between 0.015 and 0.15 d^{-1}, and average approximately17 days (with a range of 7–66 days). A wellfield life cycle may vary from 1–10 years. Among the most significant uncertainties affecting the life expectancy of such wellfields are the reaction kinetics for pyrite, organics and the oxidant concentration.

The current dominance of ISR is mainly due to increased production in Kazakhstan, but the method is widely used, e.g. in Australia, China, Russian Federation, USA, and Uzbekistan.

ISL continues to dominate uranium production, accounting for approximately 48 per cent of world production as of 2017 (see also Table 3) [26]. Underground mining (31.9 per cent), open pit mining (13.7 per cent) and co-product and by-product recovery from copper and gold operations (5.8 per cent), heap leaching (<1 per cent) and other methods (<1 per cent) accounted for the remaining uranium production shares. *In situ* bio-leaching using CO_2 and O_2 is now substituting for more environmentally invasive acid and alkaline leaching, a trend likely to grow.

Table 3. **World uranium production by technology (2017) [26]**

Uranium production method	*Per cent of global Uranium production (%)*
ISR/ISL	48.1
Underground	31.9
Open pit	13.7
Co-product/by-product recovery	5.8
Heap Leaching	0.5
Other methods	0.1

Initially the ISR case has been driven by an environmental imperative to eliminate all the very long-term and extremely costly “waste” problems caused by conventional uranium mining whether expressed as issues of tailings from open pit mining, such as in the Příbram Region, Czech Republic (Figure 6) or in Tajikistan (Figure 12), or from open pit/underground mines such as Ronneburg, run by Wismut GmbH in Germany [34] (Figure 7).

Just how widely distributed in a given uranium province mining activities can be is well illustrated in Figure 8 showing deposits by production volumes in the Czech Republic.

Inevitably, such mining activities in the “linear” project model left behind a major tailings legacy as is well illustrated by the distribution of such legacies in the Czech Republic, for example in one of the most significant centres, the Příbram Region (Figure 9).

Figure 6. **Uranium tailings (unremediated), Příbram Region, Czech Republic**

Figure credit: Jiri Muzak, DIAMO State Enterprise, Czech Republic

Figure 7. **Uranium mine remediation and restoration, Ronneburg, Wismut GmbH, Germany**

Figure 8. **Uranium deposits by production volume, Czech Republic**

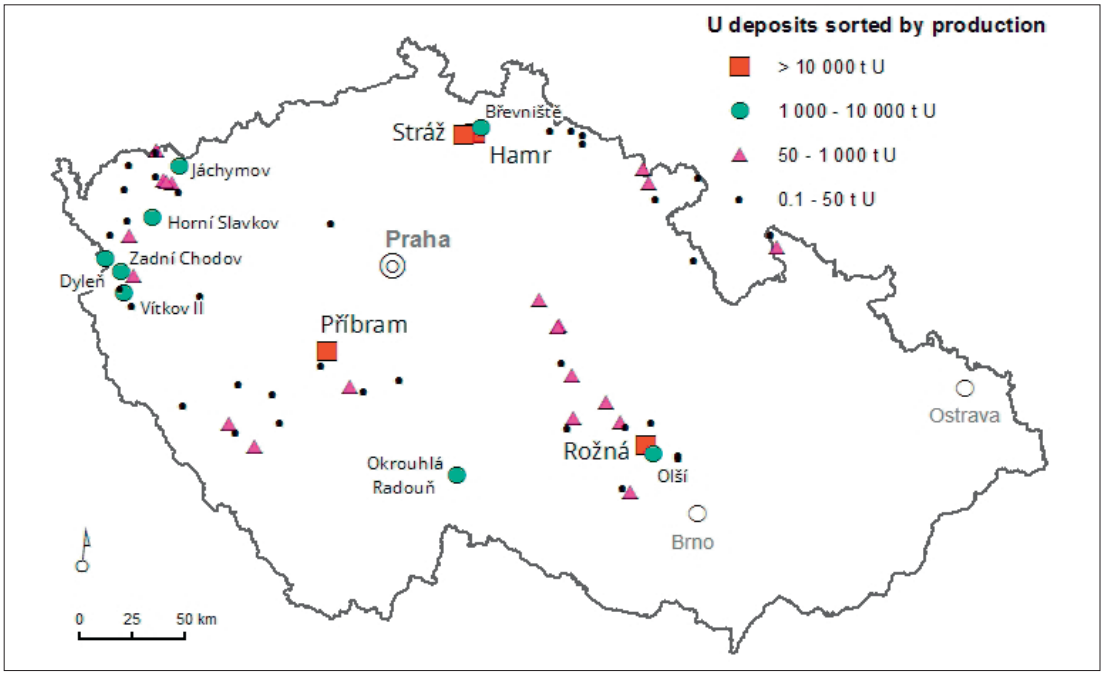


Figure credit: Jiri Muzak, DIAMO State Enterprise, Czech Republic

Figure 9. **Uranium mine tailings (red dots) and other mineral tailings (blue dots) Příbram Region, Czech Republic**

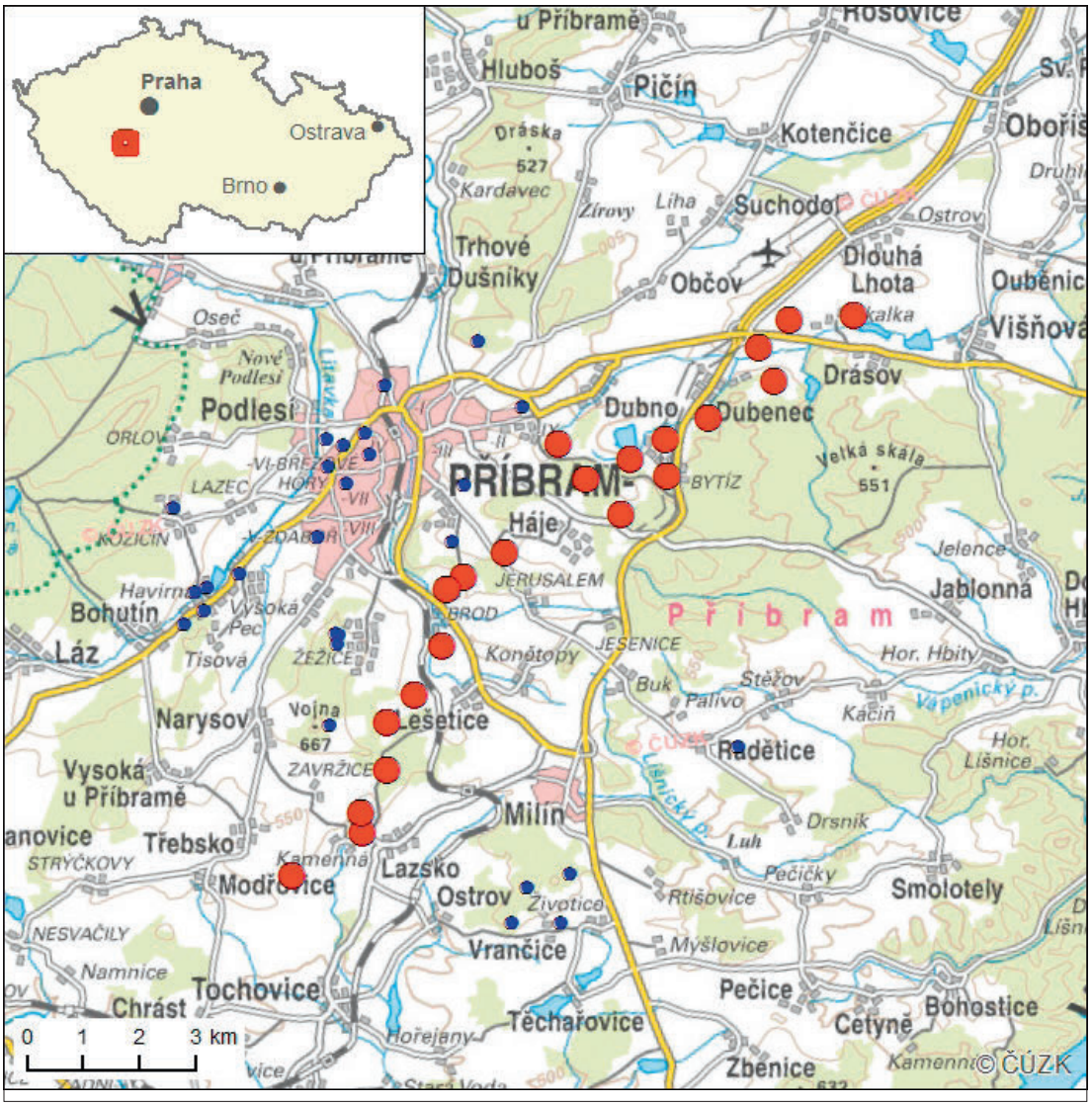


Figure 9 shows uranium tailings in the area as red dots and other minerals tailings in blue.

Committing, even in retrospect, to the principles of zero waste and the circular economy offers a major opportunity to revisit these resources from the perspective of reuse rather than disposal, with the major secondary objective of returning the valuable land to stressed communities to economically productive not sterile use.

2.3.7 Case study: Beverley and Four Mile mines, Australia

Among the most modern ISR uranium production centres are the Beverley and Four Mile mines in South Australia.[34] These combined have an average recovery rate of about 65 per cent at 0.26% U_3O_8 ore grade (including combined losses due to ISR mining and hydrometallurgical processing. The ISR process used comprises the following steps [35]:

a) The aquifer groundwater in the confined sandstone units is pumped to the surface.

b) A small amount of sulphuric acid and oxidant is added to the recovered water.

[34] As of the date of publication the mine is under care and maintenance.
See http://minerals.statedevelopment.sa.gov.au/mining/mines_and_quarries/beverley_and_beverley_north_mines

c) The now acidic and oxidizing water mixture (lixiviant) is pumped back into the aquifer through 'injector' (wells), mainly as 5-point or 7-point leaching cells.

d) The lixiviant next dissolves the uranium mineral.

e) After dissolution, the 'pregnant lixiviant' contains the uranium in liquid form, which is pumped back to the surface through the 'extractor' wells.

f) At the surface the uranium is extracted from the 'pregnant lixiviant' by ion-exchange columns; it is then thickened, washed and dried to a marketable product, so-called yellowcake.

g) The remaining process water is then recycled back into the aquifer, i.e. the processing cycle restarts to step b) with the addition or more sulfuric acid and oxidant.

Apart from the actual recovery operation, the ISR process requires a comprehensive network of aquifer monitoring wells, which monitor the pathways of the uranium, acid, and oxidant.

3. Scoping Uranium 4.0 – The prospect of indefinite sustainability

The case for the future use of uranium as a key component of a base-load energy provision portfolio rests on its position as a low- or zero-carbon, small footprint, indefinitely sustainable energy mineral that can increasingly be recovered as a co- or by-product of another resource recovery project, whether, copper, gold, phosphate or other. This positioning, combined with techniques such as ISR that hold out the promise of very low environmental impact and the potential for on-demand recovery, makes uranium a very attractive energy resource regarding fulfilling the requirements of the new point of environmental-economic equilibrium, for example in regard to energy density, on which sustainable development and maintenance of biodiversity depends. This can be characterized as uranium 4.0 or 4G. Presenting the advantages regarding climate action, public health and energy security is the concomitant narrative challenge which moving to uranium 4.0 (U4G) entails.

The transition to U4G is most a step change, away from the current paradigm of open pit or underground uranium production extracting uranium from typically very low-grade ores and leaving vast piles of tailings as legacy “wastes” in their wake. In response to the flexibility and nimbleness required to meet the uranium demand of the future, defining characteristics of the Uranium 4.0 will be:

- Discovery and management of new economic resources
- Comprehensive recovery premised on the delivery of a “cluster of values” associated with a range of minerals co-located in the same deposit
- Integrated energy management
- Small and efficient footprints
- Zero waste and zero harm
- Uranium as a service
- Focus on key outcome– indefinite sustainability
- In essence, the U4G end-point is to transform the uranium production cycle from producing uranium into a speculative uranium commodity market to securing the supply of uranium into an integrated, indefinitely sustainable, energy-provision system in which the price of uranium recovery is simply another OPEX cost.

3.1 Fundamental criteria for the Uranium 4.0 industry

Recognition and adoption of leading principles from which a redesigned Uranium 4.0 pathway can be charted will be necessary [36]. The redesign of uranium industry does not happen in a vacuum but will depend upon assimilating and applying lessons learned and adopting what is available from changes supplied by wider gains made in industry 4.0 in general, such as smart, digital mining.

Fundamental cornerstones of the 4.0 Uranium industry will address in the equal and co-dependent manner the social, environmental and economic aspects of an operation. The key to success is an equitable distribution of benefits from mining and recovery of uranium resources to all stakeholders, beginning with local communities dependent on, or perhaps displaced by, the mine. This is a fundamental assumption for social acceptance. More widely, commitment to mining 4.0 includes the active search for, and documentation and implementation of, those practices and principles that prove most effective in improving the social, environmental and economic performance of a mining and processing operation [37], updating and upgrading these whenever operational enhancements can be identified.

The guiding principle for the peaceful use of nuclear energy defines that "any use of nuclear energy should be beneficial, responsible and sustainable, with due regard to the protection of people and the environment, non-proliferation, and security" [38]. Based on this principle, the criteria for Uranium 4.0 are well defined as:

(i) Beneficial
(ii) Responsible and
(iii) Sustainable.

Uranium 4.0 will depend on improved recovery techniques and continued exploration and development of new ore bodies as older ones are depleted. At the end of mine life (if mine it is), some degree of decommissioning and remediation of facilities will still be required [39]. Each "End of Life" step will, however, be treated simultaneously as a resource future-proofing process, ie that part of the operation that seeks indefinite, if intermittent, continuity through the stewardship and enhanced understanding and mapping of known resources complemented by the discovery and development of new ones, including new types of resource not just more of known and existing types.

3.2 Principles for Sustainable Development Performance

The International Council on Mining and Metals (ICMM) has developed the Ten Principles for Sustainable Development Performance [40]. The World Nuclear Association (WNA) has published "Sustaining Global Best Practices in Uranium Mining and Processing", which sets down a corresponding set of principles applicable to the worldwide uranium production industry [41]. The application of these principles for a project will start at the conceptual phase and continue throughout a project such conceptual design and/or exploration; feasibility studies; construction; operation; remediation; closure; and post-closure stewardship/ resource future-proofing. These leading practices will be continually developed and improved upon for Uranium 4.0 projects as they pass the milestones of the life cycle and as more information is collected and better understood.

3.3 Baseline data collection

In managing the life cycle, most notably towards "circularity", the essential first and last steps will be baseline data collection. Baseline information will be required to characterize both the physical and social environment before project development and before project restart. Typically, baseline studies will be required to understand the pre-development conditions and to integrate information into project supporting documents. Public and stakeholder consultation processes will commence and will be managed in parallel with the baseline data collection programme during the exploration or conceptual design stage. Recognition and response to stakeholder concerns and expectations will minimize the potential for conflict and be of mutual benefit to the communities and the operators. Such concerns will develop and evolve through time, and even when the social licence to operate is initially won, it can easily be lost again if stakeholder interests and concerns are not respected.

3.4 Impact and risk assessments

The environmental and social impact assessment (ESIA) process will identify potential adverse impacts of the project. Amongst other tasks, a well-conducted ESIA is a process of identification, communication, prediction and interpretation of information to identify potential (both adverse and beneficial) impacts through the life of a project and determine

measures to manage these impacts. Impacts will be predicted based on the comparison of baseline information and anticipated future conditions both with and without the project occurring.

Undertaking a formal risk analysis will be a fundamental component of the decision-making process for the operation of a Uranium 4.0 project. The risk assessment will be used to determine the existing level of risk to the social, environmental and economic aspects of a project. Risk assessments will also be used to evaluate the relative risk reduction achieved by various risk management options, which while generic in their objectives typically manifest themselves in site- or project-specific ways. Uncertainty and sensitivity (aleatoric) analysis may be used to examine how robust any alternatives or random variables may be to changes in the information or assumptions used in the original analysis while techno-economic (epistemic) evaluation of best available resource recovery strategies and technologies will define operational choices once the generic project risk-profile is characterised.

A great challenge to operational design is that many, if not all operational and health, safety and environment (HSE) standards will continue to evolve. Uranium 4.0 design, closure and subsequent remediation strategy will anticipate and allow for, and maybe necessarily attempt to lead, changes in legislative and regulatory requirements, as well as evolving community expectations.

As with any disruptive technology, Uranium 4.0 will entail a change of regulatory approach. It will only be possible to affect the successful adoption of such technology using constructive cooperation between the operator and regulator. This cooperation will have several points of focus such as reducing negative environmental impacts, e.g. changing from acid/alkaline ISR to bio-leaching, enhancing stakeholder acceptance and the SLO, promoting and/or protecting biodiversity at resource recovery sites and preserving/protecting related resources such as groundwater.

Accordingly, Uranium 4.0 projects will incorporate an Environmental Management System (EMS) into the operation. Two series of ISO standards are particularly relevant in this regard are the ISO 9000 and 14000 series. The ISO 9000 series focuses on quality while the ISO 14000 series defines an EMS based on a commitment to continuous improvement. Another operational management tool that will be key performance indicators (KPIs). KPIs are targets that may be either quantitative or qualitative, and, in contrast to ISO 14000, will be used to measure performance against specific objectives or set values.

3.5 End of Life and Wastes

Management systems are necessary for waste products associated with a mine or processing facility are site-specific and in some rare instances region specific. Typically, regional optimization of waste management is not feasible, and each site will manage their waste streams, which generally include water, waste rock, process residues and radiologically and chemically contaminated equipment. For Uranium 4.0 projects, this waste management will be led by the guiding principle of zero waste and zero harm.

Continued care and future-proofing of an operation post-closure will be required to meet the requirements of sustainable development. This care will consist of but not be limited to ongoing monitoring; collection and treatment of contaminated water; management and storage of water treatment sludges; and maintenance of facilities such as water diversion structures. Uranium 4.0 operation will, however, look beyond linear closure and remediation into regenerating the site itself for new “circular” economic activities. This is linked to the discovery and management of new economic resources and setting the project on a new trajectory, made feasible through new technologies and business models.

3.6 Uranium Resources Management 4.0: Regional Perspectives

Often regional perspectives, e.g. those of Europe, Africa, Asia or Latin America, when mapped to the uranium life cycle milestones as shown in Figure 2, differ significantly according to their respective stages in mineral development, their difference in experience notably with regard both to uranium mining and nuclear power, but also because of their differing policy frameworks. Regional social and economic imperatives may vary widely.

3.6.1 Europe

In Europe, where mining including for uranium has a long history and where the activities peaked some time back, the emphasis is now on innovation-friendly approaches not a continuation of the old extractive industry models. The flow of new ideas from other sectors to mining as well as a reverse flow of mining innovations to other industries are essential in this context. Rather than having a short-term approach, the European Union (EU) places more emphasis on strategic considerations and new, more sustainable energy-provision paradigms. The EU made €80 billion funding available to innovation through the "Horizon 2020" programme 2014-2020, and a further €100 billion will be available for 2021-2027 through the proposed "Horizon Europe" programme.[35] As shown by the size of investment in these programmes, research and innovation are central to the EU's energy strategy.[36]

Unlimited production and consumption patterns are being substituted with alternative approaches that hinge on a circular economy[37] and increasing efficiencies (SDG 12). Such methods can lead to complex value chains that are initially either unfamiliar or hard to understand and manage or both. For instance, balancing policy objectives such as zero waste, the recovery and reuse of secondary resources (comprehensive recovery), the security of supply and strategic requirements for critical/key raw materials, and optimal land use is all of the high impacts on the value chain, with both positive and negative potential outcomes. As a performance indicator, lack of understanding of these issues and how they relate to each other may help to explain an apparent contradiction that high exploration success rates do not necessarily translate into commercial mining success. For all minerals including uranium, it may require as many as a thousand exploration projects to generate one commercially successful, operational mine. The pathway from an exploration success to a producing mine is tortuous and full of pitfalls.

Today geologists, mining and processing specialists spend more time than ever before in communicating with non-specialists. The results are not always encouraging. Training is a two-way process – now, complex ideas can be presented to non-specialists and educators; while professionals are also trained in the rudimentary tools of the trade in communicating science. At the heart of the communications is the SLO. SLO is a requirement and no longer seen as an add-on to a successful mining project but rather as its defining condition. "No SLO, no access to resources" is the watchword. Winning and keeping the SLO needs to be integral to a project's DNA, as well as to company business processes and procedures, investor values and expectations and to government's approach to resource management.

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35 See European Commission, Horizon 2020, https://ec.europa.eu/programmes/horizon2020/en/news/commission-proposes-most-ambitious-research-and-innovation-programme-so-far

36 See European Commission, Energy Strategy, http://ec.europa.eu/research/energy/index.cfm?pg=policy&policyname=energystrategy

37 As an example of the "circular" economy in policy formation see "Closing the Loop", the European Union policy consultation, http://ec.europa.eu/environment/circular-economy/index_en.htm

"Policy needs data", is the usual refrain, especially when it concerns a complex issue such as mining, but to derive information from data much higher skills are needed. Currently, many of the data sources do not provide the required level of disaggregation in data, which often makes the data of less value. Expertise-led raw material communities in which intangible value progressions from data to information to knowledge can happen effectively are now being fostered in Europe.

3.6.2 Asia

In Asia, uranium raw material scarcity contrasts with growing demand. Nuclear growth in both China and India is not matched by domestic uranium availability, requiring both countries to adopt a three-pronged approach to security of supply: (i) increasing primary production, (ii) exploring secondary production or co-product uranium, e.g. from phosphates, and (iii) seeking global access. Financing mineral projects in a conventional, market-driven manner could be a challenge, as this sector is viewed as a high-risk industry, so alternative financing mechanisms are being actively sought.

When a government depends on stable growth, employment and non-fluctuating revenues, unexpected market swings and volatility make even the best-laid plans go awry. Operating companies also have issues with regulatory multiplicity and inconsistencies, often compounded by a breakdown of communications between the governments, investors and themselves. This becomes more acute as transformations are sweeping through all levels of the employee base, causing each to address a need to break out of traditional operational mechanisms, cost structures and communications channels for addressing such matters. While roles and responsibilities need to be better clarified, building on higher (or often repairing damaged) levels of trust between stakeholders is becoming a critical success factor. One example of diverging government and company views is on how reserves and resources are assessed, the difference mostly resting on how much material that is recoverable versus non-recoverable. The government gives importance to mineral conservation; hence, the government's estimates of a resource base is sometimes higher than company estimates. A better understanding of the shared concerns in maximizing resource recovery always leads to a good relationship.[38]

3.6.3 Africa

Africa provides another extreme of various pressures at play. Maximizing revenues with scant regard to a better fiscal regime has plagued the region for a long time. Many countries in the region stand out for their lack of policies in mineral development and still depend on negotiating mineral development contracts on a case by case basis. With the lack of negotiating and contract writing experience, many countries stand in a weak position vis à vis the commercial operator or investor. Hence the first contract negotiated, however unfair or flawed it may be, becomes the template for all subsequent contracts. Former UN Secretary-General Kofi Annan pointed out at the scale of revenue loss in Africa caused by this weakness, which if plugged, could make Africa effectively non-aid dependent.

3.6.4 Regional and inter-regional collaboration

All regions now place high attention to multiple issues peculiar to their regions and their unique solutions. The EU, the African Union, and multi-lateral formulations such as the BRICS (Brazil, Russian Federation, India, China and South Africa) block (now proposed to be enlarged to include Pakistan, Bangladesh, Iran, Nigeria, South Korea, Mexico, Turkey, Indonesia, the Philippines and Vietnam) are making rapid strides in tackling common issues through regional and inter-regional collaboration. It is well recognized that many of the challenges are not within the remit of individual countries to address while collective efforts bear fruits.

[38] See Igor Shupurov, News ways of applying UNFC for harmonizing of relations between the State and investor in producing countries, https://www.unece.org/fileadmin/DAM/energy/se/pp/unfc_egrc/egrc9_apr2018/25.04/9_Igor.Shpurov_E.pdf

3.6.4.1 UNFC as a Facilitating Tool for Collaboration

Collaboration and transparency are prerequisites of standardization, which is where UNFC may apply as a facilitating tool, allowing partners in projects to make common assessments of any resource they are recovering and using. Using UNFC in mineral resource management is now recognized as valuable by the European Commission, African Union Commission[39] and by major resource producing and consuming countries such as the Russian Federation, China and India. UNFC provides the necessary framework for sustainable mineral resource management to avoid multiple issues as previously described and to derive new opportunities such as:

- Fostering a culture of innovation
- Accelerating the process from exploration to mining
- Mineral resource conservation, comprehensive recovery and zero waste
- Availability of disaggregated data on socio-economics, feasibility and estimates of quantities
- Harmonizing rules and regulations
- Integrating SLO to policies, business process and project operations
- Leveraging government-company-investor communications
- Strengthening innovative financing
- Building non-traditional competencies in mineral resource management.

Geological and political boundaries often do not coincide, and where two or more countries share access to and ownership of a distinctive geological formation or province, collaboration to optimise returns on a regional basis may well yield better outcomes for all partners than the competition with each other.

3.7 New economic resources and the circular economy

The extent to which "new economic resources" from residuals can be generated is debated. Paul Romer, an economist at New York University who specializes in the theory of economic growth, says sustainable economic growth does not stem from new resources but from existing resources that are rearranged to make them more valuable [42]. Brian Arthur, an economist at the Santa Fe Institute who specializes in the dynamics of technological growth, argues likewise that all new technologies derive from a combination of existing technologies [43]. The degree to which the uranium tale needs reconstruction to take advantage of the new conditions within which it can be told might suggest that for some existing resources the only alternative is to imagine they are entirely new. Such a process is driven by intangible factors, notably the creative power of the imagination. In that regard, strategies using digital technology to deconstruct existing narratives into their constituent elements, so they can be reimagined, not just recombined, in new, disruptive ways out-perform strategies that merely ring the changes on old themes.

Perhaps unusually for a profession generally assumed to be conservative in its way of thinking, the recalibration by accountancy professionals of economic value in general, and for-profit companies in particular around intangibles rather than tangibles could be interpreted to mean that Romer and Arthur are wrong. Of course, at one level they are right – managing resources to which discrete labels in the periodic table are assigned, such as uranium does not mean that we wake up each day to new elements being added to

[39] The African Union Commission Calls for Mining Professionals and Experts to Develop African Mineral and Energy Resources Classification (AMREC) and Management System in line with the Africa Mining Vision Principle, https://au.int/en/pressreleases/20180423/african-union-commission-calls-mining-professionals-and-experts-develop

the table. It risks, however, understating the role of innovation in creating new assets from transformative combinations of minerals.

Revolutionary devices such as the smartphone, which cannot function without many little known elements of the periodic table, derive their impact simply from rearranging various materials, notably rare earth elements, in such a way that our phones are now equally cameras, navigation instruments, lifestyle and diet managers and multimedia communication instruments. In that sense, thanks to the astonishing gains delivered by Moore's law regarding processing power versus processing cost, the entire global economy is tipping away from the material (how to communicate) towards the intangible (what content to communicate and why). Laws and regulations, always slow to follow technology change, will find it even harder to follow, if indeed they can ever catch up.

If a transition to a circular economy can be delivered, which at an estimated 0.5 per cent economic circularity in Europe in 2019 remains a very significant challenge, it will not be enough simply to shuffle the cards in the deck we have in our hands. We may at a minimum need new cards; and maybe we will find the game itself changes, from "cards" to "chess" or a new, different game altogether, as yet unimagined. Whatever the gains made, and however quickly the transition to a circular economy – however defined – it remains at the heart of the fourth industrial revolution. This translates into gains for a new industrial model where efficient flows of materials, energy, labour and knowledge can interact to promote a productive system which is simultaneously new and restorative, disruptive and regenerative. It is now possible to track the flow of materials with ever greater accuracy across their entire life cycles, increasingly requiring a whole "ecosystem" approach rather than one based on an element-by-element, material-by-material basis. The rich information flow required to identify and manage the emerging ecosystem is now increasingly transparent and responsive, accessible to all stakeholders. Thus, it becomes easier for new business models and social norms to emerge. In such a situation, innovative systemic changes can foster a more sustainable world.

One key inflexion point for such a transformation is the lowering of unwanted emissions and resource loads in the energy production and delivery processes. In the new energy resource management models that will emerge – most of all for uranium – all residuals including CO_2 can be turned into assets. For example, carbon capture and storage can be transformed into carbon utilization, based on many useful, innovative applications. Moreover, while new uses of carbon are developed, it can be stored in more stable forms which could be made available to sectors that need it.

Importantly, all stakeholders are prompted to engage in strategies to conserve and regenerate natural capital. Intelligent and regenerative uses of natural capital will ultimately lead to sustainable production and consumption patterns.

3.8 Uranium materials as service

Uranium 4.0 will redefine itself as anything other than just a uranium production operation. Uranium fuels will be just one of the products and services the industry will be offering:

- Uranium fuel for carbon-free energy production
- Other valuable raw materials and mineral based services
- Integrated energy resource services
- Fertilizer supplements and agricultural services
- Renewable energy generation

- Specialized land-uses
- Innovation management service
- Human capacity and capability development service.

Uranium 4.0 is an integrated service industry that also has uranium production as one of the activities. A new business model for the required social and economic outcomes will be the core focus.

3.9 Comprehensive resource recovery

The term "comprehensive extraction" (CX) (redefined here as comprehensive resource recovery (CRR)) has been in use since the early 1990s to describe methodologies that maximize returns from mining and processing especially from low-grade, depleted and other non-commercial ore bodies [44]. While providing an opportunity to recover valuable commodities, this approach satisfies several hitherto unmet requirements of sustainability in mining, of which perhaps zero waste is the most significant. Recovery of uranium as a co-product from "unconventional" resources will be a preferred source for security and sustainability of supply of uranium for nuclear power generation. Uranium recovered in such a manner will have the lowest environmental footprint, as mining and processing are not carried out for the recovery of a single commodity. Environmental concerns in having this uranium as a potential contaminant in product or waste streams are also addressed in such a scenario.

Once, by adopting the policy of comprehensive resource recovery (CRR), the target is opened up of recovering more than one resource of value from a single mining and processing option, a complementary process will be initiated asking the best available recovery technology may be. Mining policies in many countries presently tend to be influenced by policies of sustainability and resource conservation that have favoured the emergence of the comprehensive recovery approach. Comprehensive recovery will seek to maximize the returns from mining by a strategic, long-term approach to resource extraction and processing rather than focusing on a single commodity.

Since 2009, a combination of expectations of rising medium-term demand and sustainability issue has stimulated investigation of a variety of projects, recovery technologies and business models on the part of both governments and commercial entities. The potential to expand the unconventional uranium quantities is strongly tied to the ability to bring it into production. This will depend ever less on market conditions, notably for the commercial recovery of primary commodities, which hitherto have determined the underlying economics of uranium recovery but ever more on energy policy and the social and environmental policy landscape within which energy policy fits. This will increasingly favour, or even require, by-product recovery notably to require hard to recover resources such as uranium and related critical resources e.g. rare earth elements to be recovered comprehensively for strategic and sustainability reasons not for direct commercial return. The intangible goal of capability will trump the tangible goal of stockpiling minerals.

Policy drivers will include the need to enhance the security of uranium supply to the national nuclear fuel cycle or to reap the environmental benefits of recovering uranium from various ores, rather than let it remain in processing residues.

3.10 Energy basin management - comprehensive resource recovery as an ecosystem approach

In many instances, uranium is co-located with other energy resources in so-called energy basins.

Figure 10. **Energy Basin, Kazakhstan**

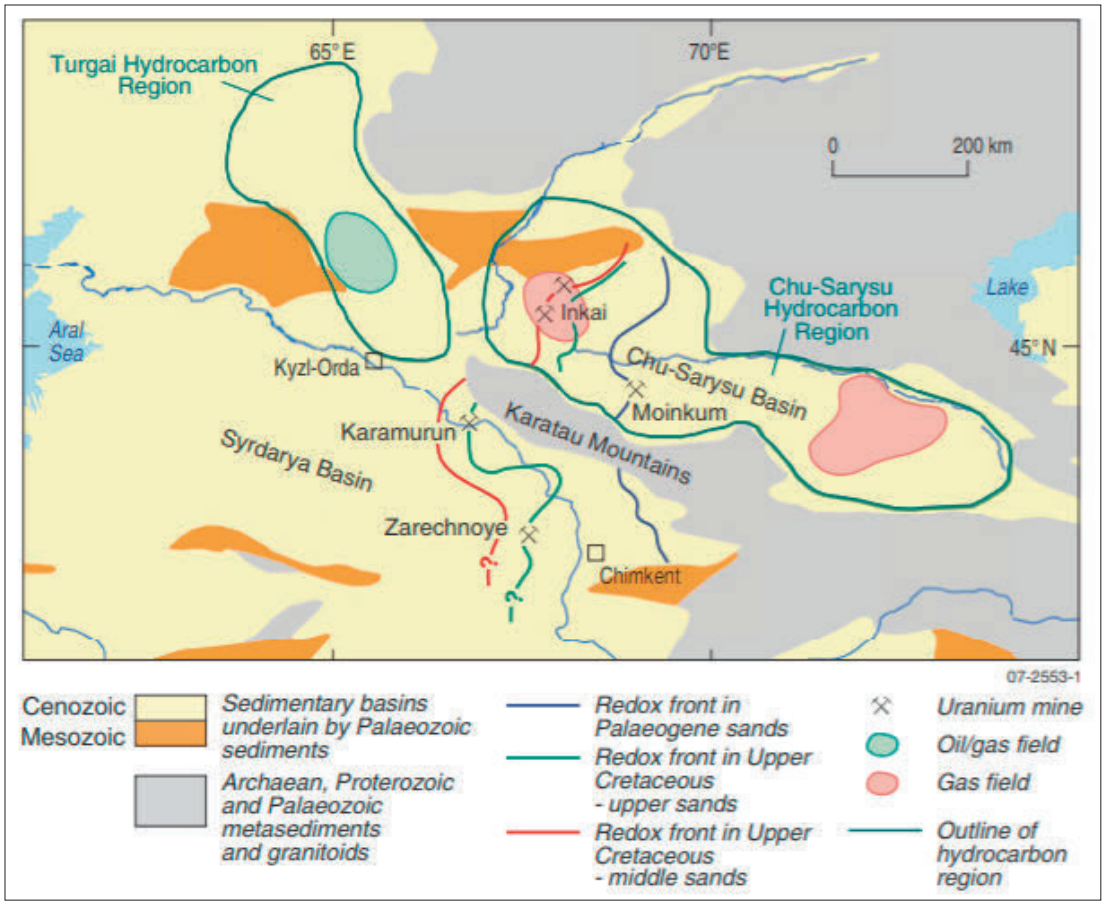
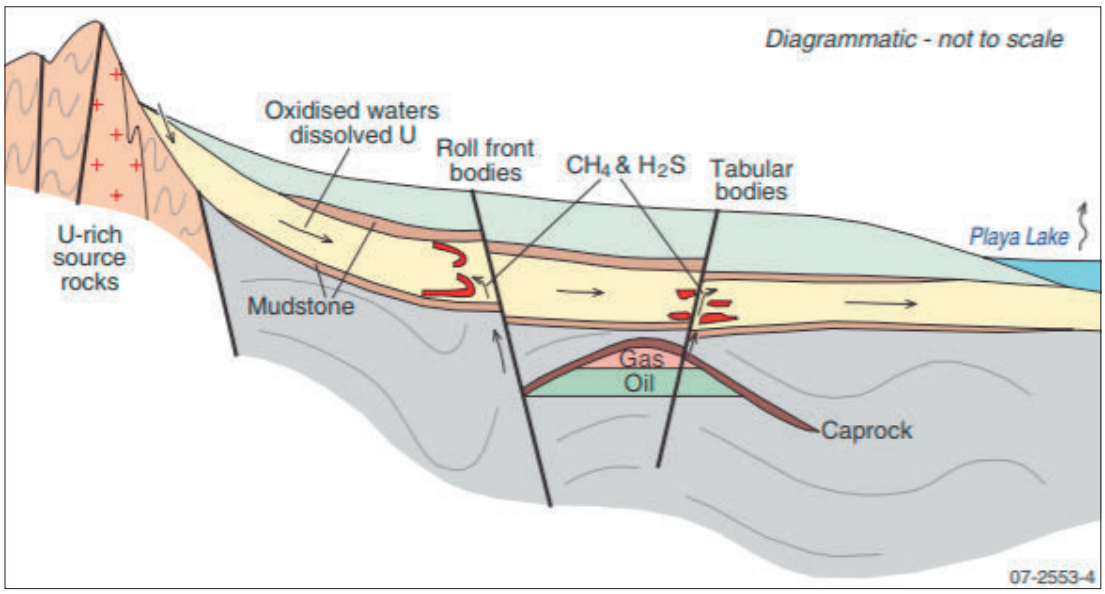


Figure 11. **A "typical" sedimentary energy basin – uranium and co-located resources**



In addition to uranium, such basins host resources including petroleum, gas, coal, phosphate rocks, rare earth elements and renewable energy resources. Examples include the huge energy basins of Kazakhstan (Figures 10 and 11) [45] and Texas, United States. Likewise, the Gondawana (Karoo, Parana) basins in Asia, Australia, Africa and South America show co-location of uranium with coal and petroleum. Applying comprehensive resource recovery (CRR) principles to Uranium 4.0 will lead to the progressive integration of the management and production of all resources in an energy basin in a manner which promotes recovery efficiencies and carbon neutrality. The application of UNFC makes integrated and whole basin management a manageable proposition and one that is SDG compliant.

3.11 Small footprint and efficiency

Mining, in general, is traditionally associated with a large open cut or underground operations resulting in huge, very deep excavations and mountains of waste i.e. overburden and tailings (Figures 7, 9 and 12). To reverse or prevent such an outcome, uranium production has shifted to ISR where possible, which does not require the solid mining of ore nor the creation of tailings dams or piles. Hence tailings or mining wastes are also not produced in the process. ISR is, however currently feasible only from specific permeable sandstone-type deposits confined by the impermeable bottom and top layers.

Small footprint operations could also be possible for transforming open cut and underground operations. Mining and recovery of uranium and other minerals of value in open cut operations could proceed by distributed small cells migrating progressively over the deposit rather than as a single chasm-sized pit. Such an approach is more feasible in surficial deposits, but with innovative mine design it is feasible for any deposit type.

Figure 12. **Uranium tailings, Tajikistan**

Figure credit: Nuclear and Radiation Safety Agency of the Academy of Sciences, Tajikistan

3.12 Zero waste and zero harm

In line with the principles of the waste hierarchy which are increasingly embedded in national and international law, the driving environmental expectation is now that at the end of the whole mining and processing cycle there should be zero waste.[40] Applying this constraint constitutes a very significant challenge to the traditional mining and processing narrative, which is typically focused on a single mineral, such as uranium or gold. Very commonly in both industries the volume of tailings, spoil or residues that may be generated in pursuit of the target mineral can by volume be vastly out of proportion to the target mineral itself.

A uranium mine, for example, with a cut-off grade of 300 ppm will have to process 1 million tonnes of rock to recover 300 tonnes of uranium. Addressing this issue is now seen as an urgent priority in leading mining nations such as Canada and Australia, but equally so in countries long affected by unremediated tailings, see Figures 7 and 12.

3.12.1 Canada

A zero-waste initiative has been started in Canada by the Canada Mining Innovation Council (CMIC) to bring a staged, concerted approach to the desired zero waste solution[46]. The problem statement is as follows:

> *"Base metal mines typically recover less than 1% of the volume of rock extracted. Most gold deposits recover less than 0.001%. Typical cut off grades for uranium means that 1 million tonnes of rock mined yields 200-300 tonnes of uranium ore. The result is the extraction of huge volumes of rock that end up either in mine waste piles or tailings ponds. Both represent a major part of production cost and of the mine footprint that must be managed for their potential environmental after mine closure."*

The Canadian mining industry's greatest challenge then is how to more efficiently extract the desired commodity through the minimal displacement of the host rock, and more effectively managing mine tailings that continue to be produced. CMIC clearly understand that a change as profound as zero waste can only be achieved by mobilising all stakeholders – industry, academia and governments. The CMIC technical groups are addressing some cross-disciplinary and linked initiatives leading towards reducing the mining footprint. The groups have identified targets and are developing innovation priorities that will lead to significant reductions in mining waste in the next 5 years and move towards net-zero waste in mining and mineral processing in 10-20 years.

These end points would be staged through the more efficient definition of new ore discoveries, more effective *in situ* mining methods to minimize waste rock production, closed system processing to reduce water and energy waste, and refinement of mine tailings towards a benign, saleable product. Rather than having each of these innovation paths developed separately, the CMIC Zero Waste initiative is developing industry-academic-government consortia through both parallel and sequential linkages. These inter-disciplinary and inter-sectoral consortia will minimize overlap and focus joint efforts on the mutually understood endpoint of zero mine waste.

The programme will make Canada a leader in sustainable mining practices, a leader in the development and adoption of new technologies and a leader in exporting new mining technologies. Stepwise achievements in meeting a zero mine-waste endpoint will produce significant economic benefits, high-paying jobs and the sustainable development of remote, northern communities.

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[40] See CMIC, Zero Waste http://cmic-ccim.org/our-approach

3.12.2 Australia

The case for a comparable approach for Australia has been set out by W. John Rankin. In terms of the problem statements, he observes:

> *"The total quantity of directly produced wastes decreases along the value chain from mining to manufacturing to recycling. The largest quantities of solid and liquid wastes are produced during mining and beneficiation, while the major quantities of gaseous wastes are produced during high-temperature chemical processing, particularly smelting of metals and cement manufacture."*

Wastes from mining and beneficiation have the largest potential environmental impact on land and water, and chemical processing wastes have the largest potential impact on the atmosphere[47]. In terms of the strategic response required, the steps are very similar to those envisaged by CMIC, notably that *"Company behaviour has moved in recent decades from complying with regulations to corporate social responsibility. In the next decades, it will need to move progressively to 'closing the loop' strategies to reduce the quantities of wastes dramatically. The drivers for change have moved from being almost exclusively profit to include regulations, stakeholders and increasingly to changing social values. In parallel, the materials cycle focus has shifted from a narrow focus on products towards including co-products. Increasingly, the focus will shift to the entire materials cycle and, ultimately, to the entire economy."*

What zero waste is, and how it is best defined remains hotly debated. Some argue that the terms should be expressed as "zero waste", i.e. in quotation marks, while others believe that the boundary condition should be absolute. Zero waste means zero waste. Whichever definition of zero waste ultimately prevails, the power of the concept derives from the fact that the desired downstream outcome from any mining process is that it should not be possible after the mining and processing life cycle has ended to detect any negative legacy from it. In other words, the notion that the operator can simply resort to permanent disposal (abandonment) of all unwanted materials (tailings, residue, over-burden etc.) as has previously been practised is now no longer acceptable.

3.12.3 The role of the social licence to operate in zero waste and zero harm

Both Rankin and CMIC see that there is a deep connection between the pursuit of zero waste and the sustainability of the SLO. In respect of the internal SLO, granted in effect by the operator to itself, Rankin is clear that the zero-waste requirement for future operations from a company-internal perspective is far from being addressed:

> *"Companies often perceive themselves as in the business of making a particular commodity (alumina, iron ore, steel, aluminum, gold, etc.). All other materials created in making their product are seen as wastes to be disposed of as cheaply as possible. Changing the culture of a company so that it perceives the resource in its entirety as its greatest asset is a challenge which no minerals company has yet come near to tackling."*

CMIC is under no illusion as to the difficulty of the challenge, but is equally clear what the prize is, a robust basis on which to achieve a long-term SLO, driven by the premise of zero waste:

> *"Solving this challenge will result in Canada's mining industry increasing revenues, reducing long-term liability, and enhancing an international reputation for responsible mineral extraction, with resultantly increased community buy-in and an improved, more durable social licence to operate."*

3.13 Focus on key outcomes, led by zero waste

Uranium mining in common with all other mining is increasingly seen as a value-destructive, environmentally and socially degrading "extractive" activity. Major problems have arisen in the 50 plus years of the history of commercial uranium mining, mostly from large volumes of radioactive legacy wastes that have long even potentially indefinite negative externalities as their unwanted 'gift' to future generations. This outcome alone defines uranium mining historically as having failed the inter-generational test of sustainability. Therefore, the future uranium production industry to address the "why" agenda successfully will have to radically redefine its "how" objectives as well, starting with how to competently and responsibly manage or eliminate uranium mining wastes.

In that context, "zero waste" and "comprehensive resource recovery" are co-dependent. Where CRR is a necessary condition for social acceptance, but also investor confidence, zero waste, or at least a realistic prospect of progressively and measurably reaching that point in say a 30-50-year time horizon, is the only "sufficient" outcome that will keep intergeneration acceptance alive. Hence, secondary uranium sourcing will become increasingly important, but in proportion uranium mining will still be needed requiring innovative approaches to meet heightened standards of social responsibility and ecological impact.

Reliable data and effective policy interventions can only be developed in a defined framework and require the improved collaboration of all involved actors in a more transparent system approach. Several actors have to work together to implement sustainable solutions at the country, company and financial decision levels. It will always be helpful if all the actors speak a shared language in resource management.

3.13.1 UNFC and the Why questions

Within a CRR/zero waste policy and technology envelope, UNFC provides three levels of support for sustainable resource management executive decision-making. This support comes in the three-tiered form of:

- Principles
- Specifications
- Guidelines.

While UNFC principles can be used as the basis for addressing all the management and decision-making modes (both how and why), the derived specifications and applicable guidelines should be used progressively. Principles will apply primarily to making "why" decisions, while guidelines are used in "how decisions". The inflexion point between how and why lies in the specifications, which because of their increasing attention to social and environmental as well as economic and technical factors are coming into better equilibrium with their new role in SDG delivery.

For example, codes applicable for public disclosure (why questions) if used inappropriately for early-stage policy formulation or competitively sensitive company business process innovation might easily have a wholly negative outcome while codes aimed at showing technology transparency (e.g. as technology selection affects the change of state of a deposit from resources to reserves or vice versa) may be the basis on which an enduring SLO is acquired from key stakeholders.

3.13.2 From outputs to outcomes

While UNFC has pre-SDGs weighted heavily to outputs (a clue lies in its alphanumeric classification system, where E1, F1, G1, expresses the highest and most cost-efficient management status a resource may have), post-SDGs the delivered outcomes of these cost-efficiencies are being recognised as necessary modifying factors in what "cost-efficient" actually means and from whose perspective that metric is assessed. At stake is the rectification of what is perhaps the biggest deficit of the output driven model, the inequitable distribution of the benefits that such outputs have enabled.

A successful transition from a present output-centred to a future equilibrium of output- and outcome-centred performance indicators in the uranium mining narrative requires the delivery of some highly disruptive and innovative outcomes for the mining narrative to define a future state of sustainable sufficiency. The output measures which have dominated the traditional uranium mining narrative do not suddenly disappear. However, the significance of these output measures, and what is done to evaluate and enhance them in the interests of achieving sustainability in mining, has to be moderated by policies of:

1. Zero waste (0W)
2. Social licence to operate (SLO)
3. Comprehensive resource recovery (CRR).

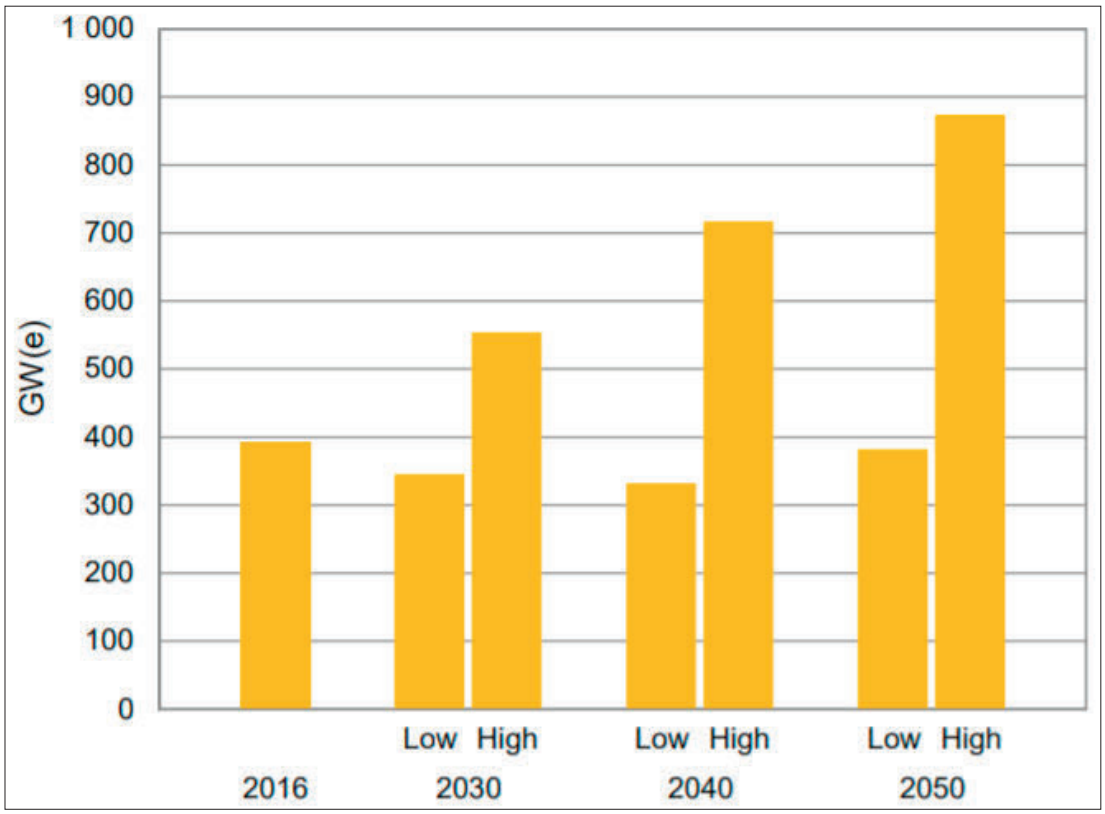
Taken together, these all contribute to the superordinate outcome of sustainability, where sustainability is understood to yield socio-economic and environmental resilience through the comprehensive use of sustainable mining and processing practice.

4. The Changing nuclear energy landscape

4.1 Current state

As of May 2019, there are 452 operational nuclear power reactors in the world with a total net installed power capacity of 399 GWe, generating some 2563 TWh. An additional 54 units with a total capacity of 55.36 GWe are under construction.[41] IAEA provides projections for the nuclear capacity to 2050 every year, and these estimates have been lowered each year since 2011. In 2017, IAEA estimated in the low case (Figure 13) the world nuclear electrical generating capacity to gradually decline to 345 GWe by 2030 and 332 GWe by 2040 and then rebound to 382 GWe by 2050. In the high case, it is projected to increase to 554 GWe by 2030, 717 GWe by 2040 and to 874 GWe by 2050 [48].

Figure 13. **World Nuclear Electrical Generating Capacity to 2050 [56]**



Source: IAEA

The low case represents expectations about the future, assuming that current market, technology and resource trends continue and there are few additional changes in explicit laws, policies and regulations affecting nuclear power. The low case explicitly represents a 'conservative' set of projections. The high case projections are much more ambitious but are still plausible and technically feasible. The high case assumes that current rates of economic and electricity consumption growth will continue, particularly in the Eastern Asia region. Country policies toward climate change are also considered in the high case.

[41] See IAEA Power Reactor Information System https://pris.iaea.org/PRIS/home.aspx. Accessed 20 May 2019

4.2 Changing market forces and financing models

Questions are often raised on the competitiveness of nuclear energy. Nuclear reactors require significant upfront investments, which may require up to 40 years to be repaid[49]. Financial institutions have become understandably averse to such long-term risk and commonly require governments to act as guarantors. With governments unable or unwilling to provide such guarantees, the future of investment in nuclear energy remains uncertain.

A variety of potential financing models have been developed to address some of these uncertainties, particularly those market risks to which project developers — and providers of finance — may be exposed to during the build, operating and decommissioning phases of a plant's life cycle. These risks, which may lead to a plant being unable to sell the power it produces at an adequate price to maintain profitability, may be perceived as particularly severe in liberalized electricity markets. Mitigation of such risks may be achieved through arrangements — potentially backed by the government of the country hosting the plant — to buy some or all of the power produced by a plant at a guaranteed fixed price. Such arrangements have been central to developing projects such as Akkuyu (Turkey), Hinkley Point C (United Kingdom), and Olkiluoto and Hanhikivi (Finland).

4.3 Changing design and technologies – the rise of the Small Modular Reactor

Of perhaps the greatest significance to the future of nuclear energy production is the advances being made in the design, technology development but also adaptability of small and medium-sized modular reactors (SMRs). This newer generation of modular reactors are designed to generate up to 300 MWe but to be built in a unitary manner, akin to Lego blocks, such that increased capacity can be added through time. Constructed and equipped with factory-fabricated systems and components and being transportable as modules to the operating sites as demand arises, SMRs aim for the economies of scale achieved by serial production but with shorter construction schedules for each module installed and much lower CAPEX entry thresholds.

SMRs hence offer flexible power generation for a wider range of users and applications, including replacing ageing fossil fuel-fired power plants. There are approximately 50 SMR designs and concepts worldwide, some of which are thought to be near-term deployable. Countries such as Argentina, Canada, China, Russian Federation and United Kingdom with existing nuclear power programmes are conducting SMR research and development, and some newcomer countries are considering investing in SMR development programmes of their own.

The three SMR types that are in advanced stages of construction in Argentina (CAREM), China (HTR-PM) and the Russian Federation (KLT40) are scheduled to begin commercial operation between around 2020. The first commercial fleet of SMRs is expected to operate in the timeframe of 2025–2030.

This trend has not stopped parallel investment in the feasibility studies for innovative nuclear technologies where the emphasis is on the technology itself rather than the generating capacity. In early 2017, China and Saudi Arabia signed a cooperation agreement for a joint study on the feasibility of constructing high-temperature gas-cooled reactors (HTGRs)[42] and investment at the national level continues.

[42] See World Nuclear News Feasibility study for Saudi Arabian HTGR project, http://www.world-nuclear-news.org/NN-Feasibility-study-for-Saudi-Arabian-HTGR-project-1703174.html

However, the nuclear energy landscape is under strong commercial pressure to change shape as very large nuclear projects experience increasing difficulty raising finance. Rolls-Royce, leading a consortium of British companies to design small modular reactors, requested more than £200 million from the United Kingdom Government in 2019 to accelerate the development of SMR technologies with much lower CAPEX requirements.[43] Rolls Royce a year earlier announced a technical feasibility study for SMR deployment in Jordan,[44] illustrating (a) that such initiatives almost inevitably require government engagement, and (b) that interest in more affordable modular solutions is worldwide and not just in countries with an existing nuclear energy installed base.

In parallel, there has been a surge in interest in breaking down the traditional barriers between energy types which have typically set one against another in a kind of sustainable energy beauty context, a lead being taken in exploring the potential for hybrid solutions between nuclear and renewables, notably solar and wind. "It may be speculated that integrating nuclear energy and renewable energy into a single hybrid energy system, coupled through informatics linkages would enable [both energy provision] types to overcome the[ir respective] demerits present when they operate individual[ly]"[50]. In a similar vein, national governments are investigating the economic potential of such hybrid solutions[51].

4.4 Innovation

Innovation is a critical dependency identified by the Paris Agreement for meeting the 2°C goal. It is also key to achieving a change in energy strategy in conformity with the objectives of SDGs 7 and 9. Innovative nuclear power technologies, including evolutionary hybrid designs with renewables, SMRs and advanced fuel cycles can all contribute to reducing GHG emissions and merging the role of nuclear power with other green, clean energy sources to supply process heat to industry, or to produce desalinated water for cities in dry climates.

[43] See Financial Times Jan 27, 2019. https://www.ft.com/content/1bbfefb0-20bf-11e9-b2f7-97e4dbd3580d

[44] See World Nuclear News, Rolls-Royce to conduct SMR study for Jordan, http://www.world-nuclear-news.org/NN-Rolls-Royce-to-conduct-SMR-study-for-Jordan-09111702.html

5. Redesigning the uranium resource pathway – Push to Pull?

Some of the fundamental change drivers facing the uranium sector and causing the need for a redesign of our approach to and narrative of developing uranium resources for energy generation have their roots in its first uses for that purpose in the late 1950s. The question "why" this was done – to substitute for or merely to disguise military objectives - has never been fully and satisfactorily answered. Hence, uncertainty as to how to justify nuclear energy production i.e. what precisely is the intention, or perhaps the policy, or perhaps or desired outcome when investing in, exploring for and recovering uranium resources to fuel nuclear reactors remains unresolved.

Other more recent change-drivers reflect the profound rethink being conducted regarding what is meant by "sustainable energy" provision, from both supply-side and demand-side perspectives, in a world increasingly committed to a secure, stable and "smart", lower or zero-carbon footprint for energy generation. With regard to energy security, the primary focus in respect of uranium is its guaranteed availability *per se*, not its price. This unique attribute should positively affect the uranium industry if it is seen as an essential service provider rather than as a commodity merchant.

This is causing not just an energy-market specific rethink. The energy market as part of the economy as a whole is challenged to make good use of rapid advances in digital technologies as part of a wider industrial ecosystem reset towards model 4.0. For example, the re-emergence of artificial intelligence places a new emphasis on communications and control systems in energy provision, not just generation technologies, leading to the reframing of energy markets in terms of energy as service rather than energy as a commodity.

If the principle of primacy in energy provision is now to be driven by climate action and biodiversity, it is energy density and impact on land use that will decide the composition of the most appropriate matrix within the context of national and regional decision-making. In terms of energy density, with its evident advantages in terms of low-footprint land use, uranium used as nuclear fuel can be a direct contributor to mitigating the crisis in global biodiversity flagged by the UN in May 2019 [6].

5.1 Pathway redesign

Hence the pathway redesign for progressing uranium resources from in-ground to fuel rod must address both uranium-specific and more general natural resource management concerns, as follows:

5.1.1 Uranium specific

- Against the background of the non-peaceful use of uranium in WWII, widespread public concern about the safety and security of nuclear power in general and uranium as a fuel source in particular associated frequently with public misunderstanding about the nature of uranium itself as a ubiquitous element of the earth's crust must be addressed transparently and robustly, including all necessary provisions for safeguards, security and safety.
- This concern has caused varying, and now increasing, degrees of disruption to the SLO on which, as with any other sustainable mining and processing activity, uranium production depends; the uranium SLO must be renegotiated.

- Changing approaches to uranium mining worldwide, driven by a powerful combination of environmental and economic factors focused on the twin objectives of resource efficiency and zero waste need to be carefully and patiently explained.
- In particular, the history of uranium tailings generation and management has left numerous unresolved and extremely costly legacies (Central Asia, Czech Republic, Germany, China). Pioneering projects to turn these legacies into "mines" both to recover the remaining uranium resources they contain and then return the land previously used for tailings disposal to economically productive use must be used as reference projects to reset the public understanding of the costs and benefits of managing uranium resources in a circular economic rather than linear-economic manner.
- The broad-based transition in uranium recovery from "solid" mining of so-called conventional resources (typically ore-bearing rocks) in which uranium is the primary or even sole target towards "liquid" mining by techniques such as ISL and heap leaching using either acid or alkali as leaching agents, and increasingly by less invasive means such as bio-leaching with CO_2 and O_2 must be further pursued, with particular emphasis on ending the practice of deep open pit mining.
- Growing attention to the option of recovering uranium as a co-product (not just a by-product) of recovering other mineral resources (such as phosphorous and copper) in the form of an integrated flowsheet best exemplified by the Santa Quiteria Project in Brazil (see Figure 16).
- The contributions greater use of uranium as an energy resource can make to protecting and enhancing public health in rapidly growing, heavily polluted cities, and to mitigating and then reversing the potentially catastrophic decline in global biodiversity must be given their due weight in future policy determinations on sustainable energy.

5.1.2 General mining and processing sector – core principles

There is a need for a fundamentally new narrative for the mining and processing industries based on the following core SDG principles:

- "Integrated and balanced" management of all natural resources.
- Comprehensive resource recovery (CRR) and zero waste.
- Equilibrium of environmental-economic objectives in project design, execution and financing.
- Associated "all-in sustaining cost" approach to project financing, inclusive of co- and by-products.
- Resource use efficiency (entailing revision to/modification of both supply and demand behaviours).
- Fair/ equitable distribution of benefits
  - Transparent governance
  - Constructive regulation/ elimination of negative externality
  - The partnership between operator, regulator and investor (grounded in a Nash-Stackelberg Equilibrium45 which can be characterised as "Constructive Regulation" [52]).

[45] In the Nash-Stackelberg investment equilibrium model, suited in particular to "platform" investments which typically are undertaken or underwritten by government, the first entrant into that market determines the conditions under which other investors come in. Hence it is cooperative no competitive in nature where value release is typically through equity participation rather than taxes, royalties or rents. However, care should be taken to avoid taking undue advantage of market imperfections by such mechanisms.

Applying these principles has two fundamental consequences for the redesign of the uranium resource pathway, both of which were anticipated in the Bridging Document [1] and Case Studies undertaken by the Task Force. These are:

1. Redefining the role of uranium as a critical energy resource within the new paradigm of sustainable energy as adopted by ECE.
2. Aligning the outcome of the redesigned resource pathway to resetting the boundaries and linkages of the sustainable energy system within which uranium is deployed.

5.1.3 Key challenges

Perhaps the two biggest challenges, therefore, for the uranium industry are:

1. To redefine the global policy framework within which uranium resources are managed as a unique resource rather than a commodity to focus on energy security, affordability, accessibility and sustainability within the framework of the Paris Agreement, and
2. To reinvent the resource recovery process based on how best to harness these digital opportunities to regain control over the resource management timeline rather than to enhance exploration and recovery technologies and hence reduce costs.
3. The point of convergence between these two objectives is that both represent "pull" factors that are not inherently based on the mineralogy but on purpose behind our wish to recover the uranium resources in the first place.

5.2 The birth of nuclear power – the "push."

The "push" for uranium resources has historically been driven by two complementary objectives, military and energy. This duality has both complicated the market and been the cause of much of the "in principle" objection to uranium as an energy resource because of the understandable fear that its military application could always prevail, however strict and well managed the safeguards against abuse.

The rapid development of nuclear power technology was a perhaps understandable socio-economic response to an outcome of the consequences of nuclear technology being applied to munitions at the end of WWII. In that sense, the introduction of nuclear power was driven by a combined policy and technology "push". Based on its availability and suitability for a peaceful purpose, the momentum of its early years as a military strategy was diverted in part at least into energy. However, in terms of its public narrative the existential challenge now faced by the uranium sector in meeting the concerns listed above derives in no small measure from the fact that (a) it was born out of the same fundamental R&D effort that was assigned to the Manhattan Project, and (b) military uses remained a fundamental application for nuclear technology in parallel.

The first nuclear reactor to generate electricity (3 September 1948) and power a light bulb was the X-10 Graphite Reactor housed at Oak Ridge, Tennessee, United States. The world's first nuclear power station to generate electricity for a power grid started operations at Obninsk, Russia, on 27 June 1954. The world's first full-scale nuclear power plant, Calder Hall, UK, started operations on 17 October 1956. Illustrating the ambiguous narrative, Calder Hall was also intended to produce plutonium and hence had a double peaceful/non-peaceful mission reinforcing public concern about the underlying intentions of having a nuclear industry. The first full-scale NPP devoted exclusively to electricity generation was at Shippingport, Pennsylvania, United States. This was connected to the grid on 18 December 1957.

As acknowledged by IAEA itself: "The IAEA was created in 1957 in response to the deep fears and expectations generated by the discoveries and diverse uses of nuclear technology". These fears have never been thoroughly addressed. The redesign of the uranium resource pathway must include that task of engagement with and allaying of stakeholders' fears if it is to meet social acceptance.

5.3 The end of push?

The growth of nuclear energy from the late 1950s gave rise to the so-called Red Book [53], a joint NEA and IAEA publication. First published in 1965, the Red Book has developed to become the standard reference work for managing uranium resources worldwide, contributed to by more than 100 countries. The original purpose of the Red Book was simple – to provide a tool for governments investing in nuclear power for ensuring the security of supply into the nuclear fuel cycle, based primarily on classifying available resources by comparative cost of recovery. With the emergence of a spot market for uranium as a commodity, this simple purpose became confused, and with it, uranium's status within the mineral sector economy became increasingly ambiguous. Is it just a mineral commodity to be treated like any other commodity and hence subject to all the vagaries of the open market? Alternatively, is it better understood as a unique platform asset for the sustainable energy economy whose role is defined by security, accessibility and affordability of base-load supply, but not by its tradable value? In their current form, many of the uranium discourses have no real answer to this question. Perhaps it is time both to reform the underlying purpose of such discourses to meet the new "pull" objectives for uranium as an energy resource but also to inventory the secure and sustainable supply of uranium fuel as a unique energy resource now critical to Climate Action and preservation of biodiversity.

This question of how to manage uranium is not simply one for the nuclear industry to answer. Many countries, identified by IAEA as candidate states, are considering either the adoption of nuclear power or the recovery of national uranium resources or both. The case for both is centred on an increasing awareness at policy and decision maker level that nuclear power is much more likely to gain public acceptance if (i) the fuel resources on which it depends derive from national resources and hence constitute a key part of the "local content" dividend which communities and countries rightly expect from any mining and processing activity but in particular from uranium, (ii) this contributes directly to INDCs, and (iii) this helps mitigate the conflicts over land use for food and energy production which are causing a biodiversity crisis.

This very clear trend has been recognised by the two countries currently most highly invested in developing their NPP capacity, China and India. Given that both suffer from a degree of scarcity in national uranium supply, both are heavily dependent on sourcing uranium from third countries. In consequence, both have supply chains which have suffered considerably from the turbulent nature of the mineral sector "super-cycle" which in the case of uranium shows no immediate sign of ending. Hence a new approach is required, one which China has framed by its Belt and Road Initiative which is now premised on partnership and cooperation in the supply chain with third countries, the nature of which significantly transcends the narrow focus of sourcing yellowcake.

Hence the change of emphasis from push to pull requires a change to the historical emphasis on recovering uranium as a means of "pushing" nuclear power to basing the case for nuclear within our collective response to delivering SDG 13, "climate action", a case in which SDG 13 "pulls" the case for uranium as an indefinitely sustainable energy resource necessarily with it. SDG 13 makes clear that it is not enough to focus on energy security without considering how that security is met and its consequences for climate change. In that sense, the need to deploy uranium as a green energy resource and substitute for carbon fuel sources, notably for base-load provision, is the primary "pull" factor powering demand for uranium resources.

This makes uranium a "critical raw material", based on supply risks and strategic requirements for clean energy, an attribute which puts in question as to whether or not uranium should in future be managed as a tradable commodity. Perhaps the current market situation is best understood as a failure of the commodity path uranium took from the 1970s onwards? If so, the need to redesign the uranium resource pathway (a) within a new "pull" Climate Action policy framework, and (b) using the full extent of the opportunities offered it by the digital revolution becomes paramount.

5.4 The Transition to Pull – Uranium fuel resources and climate change, a convergent approach

As predicted by Moore's "Law" that expects processing capability to double in power and halve in price every 18-24 months for the foreseeable future, the digital revolution (industry 4G/4.0) has opened up revolutionary opportunities for mining and processing industries to digitise the whole resource management life cycle. But it has also laid bare a clear risk, given the current capital intensity of the sector's projects and its history of resistance to change, compounded by the very long time it now takes to progress from the identification of a resource until the start of commercial-scale recovery (Figure 14), that if its use of such technologies does not change an asymptotic gap will open up between what the sector, in theory, could do and what in practice it actually does.

Nor does this stop at the policy level. What is needed is a ground-up reappraisal of what is meant by uranium as a resource in the first place. In the so-called "conventional" model of resource recovery, uranium is treated like any other commoditised mineral as a single target resource. In recovering uranium from a mine, any other materials found in that deposit are typically rejected as "wastes". The problem this causes is obvious: unless the project economics can be justified wholly and solely on the return on investment that can be derived from uranium, the project fails. Not only does this seriously distort the economic proposition, it also adversely impacts the exploration and resource classification process as a whole. Because one-dimensional single resource metrics are applied, notably the uranium cut-off grade, many deposits which could be approached in line with the SDG objectives of "balanced and integrated" resource management are simply ignored or overlooked.

A potentially game-changing example of how an innovative approach can transform this practice while addressing the critical food-energy nexus at the heart of the land-use conflict is offered by the Santa Quiteria uranium and phosphate project in Brazil (Figure 15) which integrates the production of yellowcake and phosphate fertilisers in a single flowsheet.

This integration necessarily impacts the project's business model, which rests on a strategic partnership between the phosphate company originally Galvani, now Yara, and the government. In the business and wider Nash equilibrium sense, "push" and "pull" factors are in good equilibrium.

Figure 14. **Uranium project lead times from discovery to commercial production [53]**

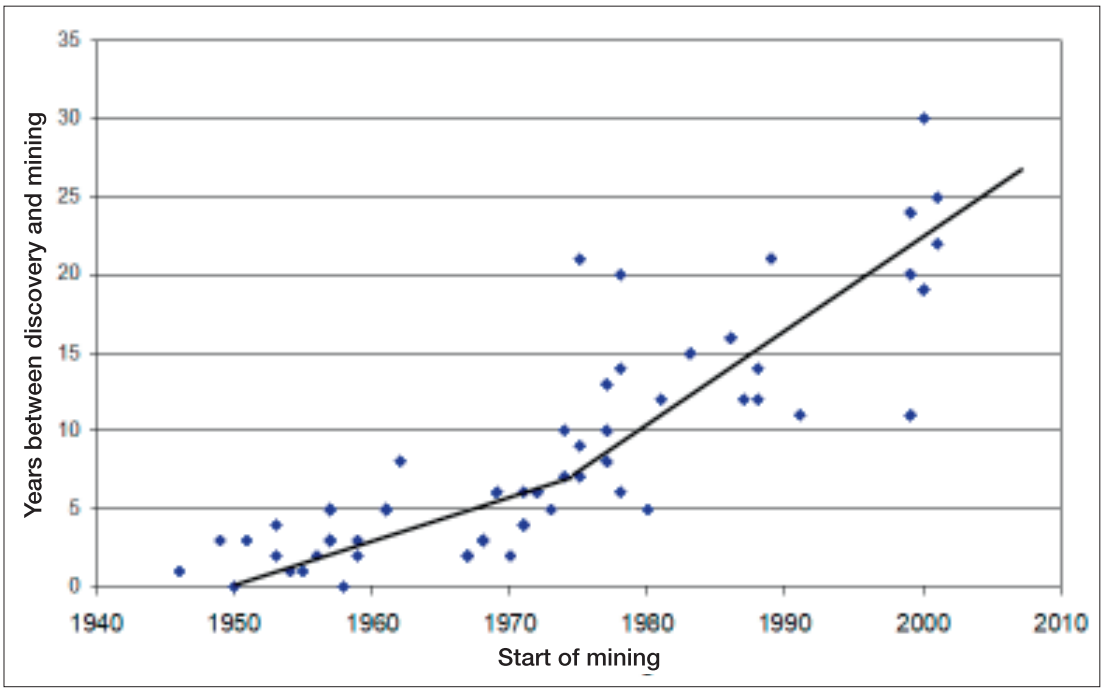
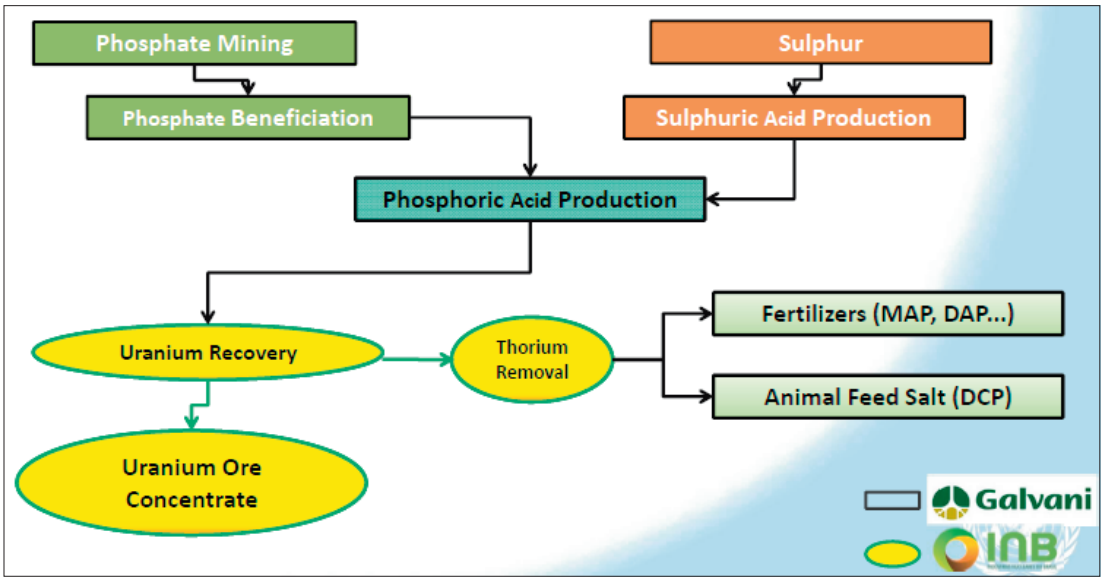


Figure 15. **The Integrated flowsheet (UxP), for two energetic minerals, Santa Quiteria example – co-production of diammonium phosphate fertiliser (DAP) and yellow-cake**



5.5 The new world of "pull"

A ground-up reconstruction of the uranium resource recovery narrative, with particular attention to ethics and communications, notably with stakeholders, is now opening up as a deliverable outcome, one in which agreed and transparently shared terminology and definitions are of the essence – "nomen est omen" – because without such agreement and transparency the notion of "informed consent" which underpins the SLO is not achievable.

Some trends which are supporting this transition include:

- Higher bar entry into the field overall. (To support the high bar, UNFC must set tough, decision gate resource progression criteria for transit up and down the E, F, and G axes, notably E, mirroring the Uranium Production Site Assessment Team (UPSAT) milestones model).
- Use of state-of-the-art exploration and resource classification and estimation tools (Uranium 4G).
- Retain competent persons but in new requisite competencies.
- Digital mining in detail – the ability to develop full life cycle simulations of mines, all inputs and outputs.
- Intangibles now the new constants in projects; tangibles notably the control and characterisation technologies will evolve extremely fast. Project design must develop the capability to adapt to this speed of change. A new balance between CAPEX and OPEX – more to OPEX. Reduce capital intensity through process innovation. (e.g. ISL itself).

6. UNFC and sustainable energy management

UNFC is not just a classification scheme for resources present in the ground or could be mined. It provides a model for considering all aspects of how a resource project could be viable in future. The examination of energy production pathways, therefore, will take three directions of enquiry:

- Socioeconomics
- Technological maturity
- Uncertainties.

All possible factors that could influence uranium production and supply are therefore seen and analysed through the prism of UNFC. The white colour of the energy production landscape then splits into a spectrum of issues, in line with the colour-differentiated approach of UNFC.

6.1 Resource management

Considerable confusion exists while treating data, information and knowledge on energy projects. A major source of confusion is how to identify and agree on what are the necessary and sufficient functions of 4.0 resource management. It will be desirable to remove this confusion by investment in:

- Competency-based training derived from 4.0 competency analysis
- Policy formulation and implementation
- Government policy and resource management based on “constructive regulation.”
- Company business process innovation and internal management
- Financial reporting and public disclosure.

All the above functions are quite distinct from each other. Each function has its specific objectives, directions and implementation details.

6.2 Advantages of using UNFC for uranium resource progression and management

Implementing UNFC at a country or company level for resource progression and management has many advantages. It may also bring with it an amplifier effect in making uranium production more innovative and competitive, increasing efficiency and productivity.

At the country level, sustainable development of nuclear energy is fundamentally linked to easy and free access to uranium resources. Potential bottlenecks must be considered along with the entire supply chain, addressing mined uranium, semi-finished as well as finished products. Mitigation measures, such as the transition away from uranium as a commodity to ensure a secure, more sustainable future supply, need to be taken today.

For a company, successful uranium resource management requires not only relevant information on the resource base, adequate framework conditions set by governments and society and enterprising capacity or the integrative dynamic capabilities in the public, private and financial sectors.

A country may require a push in three directions to ensure raw material supply:

1. Increase primary uranium production
2. Maximize benefits from secondary resources
3. Ensure global access to uranium resources.

While all three are well understood, the current peculiar position of many countries being resource-poor due to many factors, including increasing competition for land use, e.g. between agricultural versus mining or resource recovery purposes should not be ignored. What needs underscoring is the strong advantage industry today has in terms of innovation and access to smart technologies, with applications well beyond mining and resource management, which could be used to converge the interests of sectors of the community with traditionally diverse objectives in regard to land use to a point where a new environmental-economic point of equilibrium (a new "win/win" point) can be found satisfying both their interests.

The UNFC toolkit, expanded as indicated in Section 6.2 can be applied to achieve this new point of equilibrium, thus leading to:

- A differentiated consultation and decision-making process regarding the uses of resources based on a clear and meaningful distinction between:
  - (i) Answering "why" questions and "how" questions;
  - (ii) promoting balanced tangible and intangible asset growth;
  - (iii) delivering an equitable distribution of benefits to all key stakeholders as verified by transparent governance and accountability.
- More inclusive, outcomes-driven policymaking and planning in which input and outputs are in balance with both incomes (prosperity) and outcomes (SDG delivery) more generally
- A well-accepted, cost-efficient uranium industry contributing both directly and indirectly to the delivery of clean, indefinitely sustainable, affordable energy with wide-ranging benefits to the public and environment, health and safety.
- Increase discernment and understanding in financial capital allocation, spurring both traditional financial institutions (stock-exchanges, banks) but also disruptive investors to higher levels of participation
- A reduced sectoral environmental burden from natural resource management, including reduced carbon footprint, lower GHG and related emissions and a positive not negative public perception of the value-add of the sector to the SDGs.
- A balanced portfolio of SDG compliant resource-management activities including primary resource conservation through optimised secondary resource management and use, waste minimization and recovery from tailings and residues, focus on co- and by-products in an integrated CRR strategy.
- Increase collaboration with other countries and regions that use UNFC sharing knowledge, capabilities and success stories.

6.3 UNFC and managing the national security of supplies

UNFC, and in future UNRMS, are tools that allow countries to manage their total resource base at the national level in a consistent, coherent and transparent manner. Long-term policy and strategic planning framework of a country may be based on UNFC data, which is disaggregated at a project level.

For many prospective users of UNFC, notably in the emerging and developing economies which have high expectations of the role the natural resource sector, especially minerals, will have in promoting sustained economic growth, realistic assumptions about the total resource base and its economically affordable supply over the medium- to long-term (say the next 25 years) can provide a well-considered basis for growing the domestic mining industry in a country, attracting the right mix of national and external investors (the Nash-Stackelberg equilibrium approach) and implementing an appropriate local content policy, aligned to OECD guidelines [8]. Within such a structure, companies, whether government or privately held, can use the same data for more nearer term planning, incorporating a blend of tested and new technologies and flexible business models.

If there is an existing but suspended history of uranium mining the potential for reopening "closed" mines can be explored, for example the Salamanca mine in Spain. While affordability, even market competitiveness may be a consideration, the secure availability of uranium resources from the national endowment may be the primordial consideration, tied as that is likely to be to the prospect of better social acceptance if that uranium comes from domestic, not overseas resources.

UNFC-based classification and management assures a high quality of information, derived transparently from capturing raw data into a UNFC format, which can form the basis for needs as diverse as stock-exchange reporting by mature companies to access to finance for new projects or innovative business solutions. Countries seeking to base resource management policies and project selections on social and environmental factors as well as traditional market measures such as internal rate of return or net present value metrics can use UNFC for this purpose. From a cross-border or regional perspective, if UNFC is applied globally, it can enable easy "like for like" communications grounded in coherent and consistent data, across the world. In the uranium sector, traditionally hedged with uncertainties and ambiguities, this would facilitate transparent uranium resource "diplomacy", for example between suppliers and customers, to ensure equitable and free access both to uranium as a fuel source, but also to state of the capabilities as to how to manufacture, use and safely repurpose or dispose of that fuel source at end of life, leading to indefinitely sustainable nuclear energy generation as a critical resource for sustainable development.

6.4 UNFC and secondary supplies

The growing interest in sustainable resource supply has created a need to assess the future availability of secondary raw materials of all kinds. It not only includes uranium that could be recycled from spent fuel but also uranium that could be potentially be recovered from mining and processing residues, as is in advanced planning in the Czech Republic (Figures 6 and 9).

The potential for secondary raw material production is enormous, but still in its infancy. UNFC has opened up this task under the rubric of "anthropogenic" resources which has placed the topic high on the working agenda for UNFC in the coming work cycles of the ECE Expert Group on Resource Management. Many countries have a rich history of mining with many mines idled or closed due to fluctuations in the resource life cycle. While some of these mines can be future-proofed and potentially be reopened notably when new exploration techniques and recovery technologies such as remote mining change the economics, much is still to be learned about how to manage such closed and closing mines to ensure that the resources they still contain can be used in the future. A few such operations have left behind substantial legacies, for examples as tailings, which are a potential source of secondary raw materials, i.e. not a "waste dump" but a "future mine".

A third option is to revisit the hitherto reported "uneconomic" or "marginally economic" deposits and see how new technologies and business models could be applied to produce raw materials in a non-commercial but socio-economically productive manner. Foremost among such models are ones which focus on the development of transferable skills and capabilities but whose economics also depend on including co- and by-products, and equally tailings and residues, in their scope not just the linear pursuit of a single target resource. Existing mineral resource classification and reporting systems were not designed with such approaches in mind. Hence, it is possible to see several mining operations where significant volumes of valuable materials such as rare earths are discarded as "wastes" simply because the operator or the investor does not recognize their place in the mining plan or wider business model.

UNRMS is a planned new management tool, which puts a balanced approach in focus, and thus could help investors, regulators, governments and industry require a common and comprehensive understanding for assessing the availability of resources from both natural and anthropogenic sources, on the project, country and global levels. In contrast to primary resources, classification and reporting of secondary/anthropogenic resources is currently not established and guided by standardized and globally accepted frameworks.

6.5 UNFC and financial reporting

UNFC can be the basis for a public reporting code that can be used by companies to report their mineral assets to stock exchanges and banks. Stock exchanges currently use various codes developed around the world to report mineral resources. While these codes may serve the current purposes in those countries, it could be debatable whether the new mineral industry based on aspects enumerated above could find such codes entirely suitable.

For example, anthropogenic resources or minerals that exist (or are recovered) as fluids such as lithium and potash are not covered by such codes. Social and environmental considerations do not even find a mention in many such codes. It will be desirable to have a comprehensive public reporting code for all raw materials, including uranium that will be acceptable to all stock-exchanges and financial institutions.

6.6 Helping new entrants into the uranium sector – example UPSAT

At the request of the Government of the United Republic of Tanzania (URT), IAEA and URT jointly organized a special mission to the Mkuju River uranium project, 27 May to 5 June 2013. It was led by the project counterparts the Ministry of Energy and Mines (MEM) and the Tanzania Atomic Energy Commission (TAEC), under the rubric Uranium Production Site Assessment Team (UPSAT).[46] The UPSAT mission took place with the active cooperation and consent of the operator Uranium One [Mantra Resources].

The UPSAT Terms of Reference (ToR) focused on five discrete but inter-dependent aspects of the Mkuju River project and its associated key dependencies:

1. Regulatory system
2. Sustainable uranium production life cycle
3. Health, Safety and Environment (HSE)
4. Social licensing
5. Capacity-building.

[46] For an UPSAT update (2018) see IAEA https://www.iaea.org/newscenter/news/uram-2018-five-years-on-tanzanias-progress-in-uranium-exploration

At the IAEA workshop held in Arusha, Tanzania, January-February 2018, representatives of TAEC provided a detailed update, five years on, concerning both the direct outcomes of the UPSAT mission and the follow-on benefits it had stimulated at TAEC Headquarters and more broadly in the country. Of significance is the fact that even though the Mkuju River project as of 2018 had no immediate prospect of starting at a commercial scale, the benefits to the country flowing directly and indirectly from UPSAT are in abundant evidence.

6.6.1 Operational Milestones and Workflow

The founding premise of the UPSAT mission was that to manage and communicate workflow, and related critical dependencies, clearly to decision makers and stakeholders it was necessary to normalise the project into a small number of "meta" milestones which in the aggregate set out the complete project life cycle. These milestones, while applicable to uranium, with little modification can apply to many resource management and recovery projects. Hence the knowledge and skills learned to better support Mkuju River could be readily transferred to other projects for recovering different resources, whether mineral or not. The milestones are shown in Figure 16 and comprise:

The issuance of a special permit to mine.

(i) Construction start.

(ii) Mining and milling start.

(iii) First yellowcake shipment.

(iv) Mine closure, decommissioning and rehabilitation.

(v) Handback to URT by the operator and return of the site to within the boundaries of the UNESCO protected Selous Game Reserve.

Figure 16. **Project operational milestones**

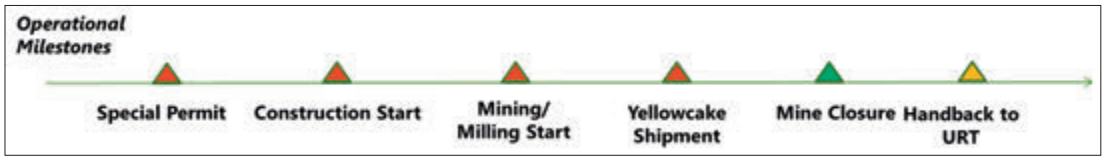
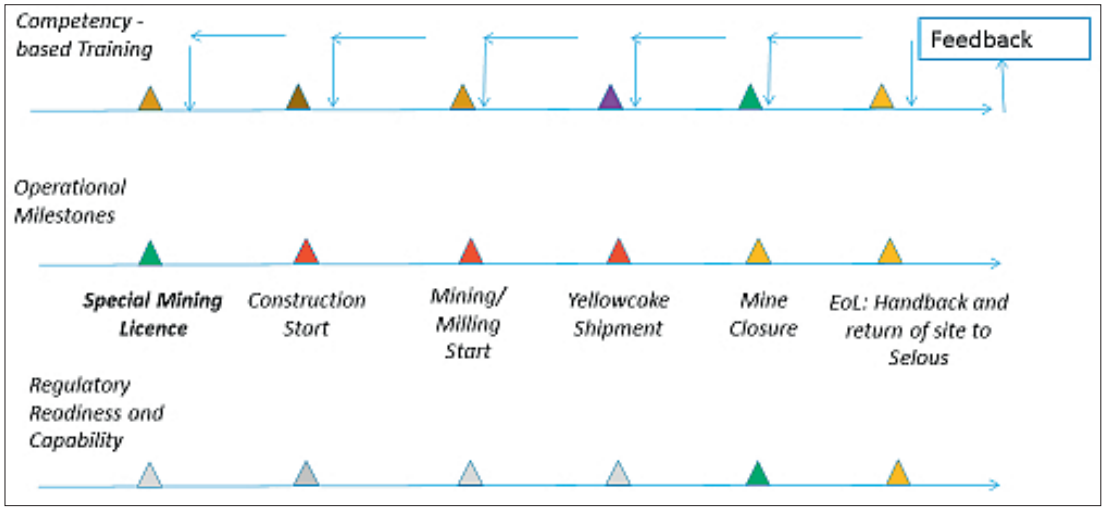


Figure credit: Denis Mwalongo, Tanzanian Atomic Energy Commission

Figure 17. **Integrated competency-based training aligned with operator regulatory needs**



Having adopted the objective of clear and transparent communications between all parties, it was also recognised that operational success was co-dependent with regulatory preparedness, readiness and capability. It was hence directly (a) in the interest of the operator to align its activities with its own internal competency-based training schemes to train up the local workforce to operate the project, in line with national "local content" policies, and (b) to achieve alignment by both operator and regulator to these milestones, thus assisting the regulator directly or indirectly in developing its capabilities to regulate effectively and fairly. How this alignment process translated into practice can be seen in Figure 17.

6.6.2 Competency-based Training

A programme of cross-cutting competency-based training was the outcome of this agreement, and as can be seen in Figure 17, this was designed to be implemented in complete alignment with the milestones by operators and regulators alike. Moreover, while both stakeholders were encouraged to work to a single, agreed "map" of the project life cycle, as neither operator nor regulator was endowed with an unlimited resource of either personnel or finance, the emphasis was on the next immediate milestone regarding where to prioritize the allocation of resources.

6.6.3 Infrastructure, capability strengthening and regulatory preparedness

Against that background of alignment of interests, and as a direct result of the success of UPSAT towards the end of the UPSAT mission a meeting was called between the UPSAT team and a team from the Joint Research Centre (JRC) of the European Commission visiting URT to review the proposed extension of URT mineral development activities into the uranium sector. The outcome was very positive and the JRC team subsequently agreed to sponsor a follow-on project whose objective was to strengthen URT capabilities in the nuclear and radiation safety including occupational health and environmental aspects related to uranium mining activities. The project focused on infrastructure improvement, support to the Nuclear Regulatory Authority for licensing and regulatory oversight activities and training of staff.

Four sub-projects centred on the following specific objectives:

1. Enhancing the legal and regulatory framework related to uranium mining and milling and associated transport;
2. Supporting the Tanzanian government for the use of the Dar Es Salaam seaport for uranium transport and export;
3. Regional outreach on uranium regulatory framework and nuclear/radiation safety education and training; and
4. Strengthening the technical capabilities of TAEC.

In parallel with this significant expression of support from outside URT, the government of URT itself, influenced by the underlying principles of UPSAT as well as its uranium-specific recommendations, also made substantial new monies available to TAEC for strengthening its service and regulatory offering to both uranium-specific and wider NORM industry capabilities and services.

Much of the outcome of this investment has been intangible in nature, with skills and capabilities developing in a significant measure both technically and administratively. However, as can be seen in Figure 18, the tangible asset contribution regarding laboratories, equipment, staff and specialist storage facilities, e.g. for spent gauges, is highly impressive. Hence in a very short five-year cycle, TAEC has developed from a nascent national resource into a flourishing national and regional centre of excellence.

Figure 18. **Infrastructure and capabilities – new facilities in advanced construction with new equipment at Tanzania Atomic Energy Commission (TAEC) Arusha, August 2018**

6.6.4 Integrated Workflow – Project Dashboard with KPIs

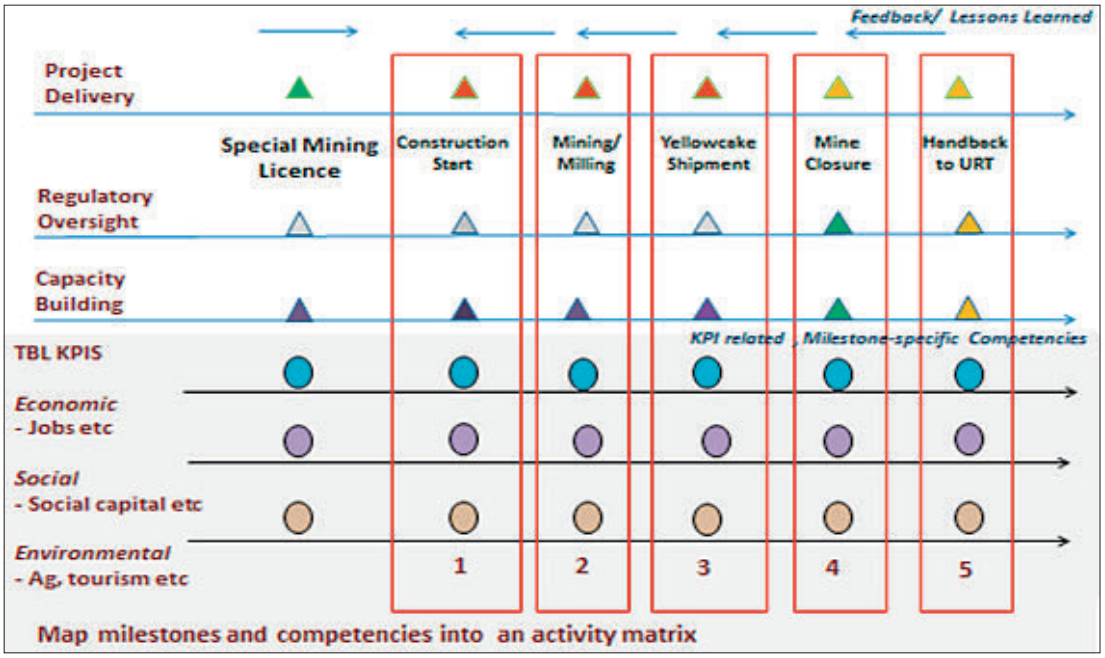
The objective of a milestones-based dashboard (Figure 19) is to facilitate communications between operators, regulators technical advisers and government decision-makers. As it became apparent that the UPSAT mission and its follow-on activities were delivering the desired results, it became possible to add a set of Key Performance Indicators (KPIs) to the milestones model, reflecting the three axes of the so-called "Triple Bottom Line" (TBL) project return on investment model. These axes are economic, social and environmental, and for TBL to be achieved, each has equal significance as the other.

For each TBL axis, some sub-objectives (a measure of return) were identified, each of which could be used as a performance indicator (Figure 19). Of these for economic return "local content" in the form of job creation both in construction and operation, but also wider infrastructure development (communications, roads, hospital, schools, public and occupational health) was seen as key, including stimulus for small and medium enterprises to join the supply chain. From a social perspective, social capital in the form of education and vocational training, stakeholder engagement and the social licence, combined with equitable distribution of benefits was identified as a critical dependency, together with a commitment with minimized or zero waste.

So, when at the end of life, the Mjuku River project site was returned to within the boundaries of the Selous National Park it would be hard or impossible to tell there had been a mine at all. From an environmental perspective, the responsible development of the regional infrastructure around the Selous Game Reserve would (i) facilitate the long-term growth of ecotourism with revenues from such sources, (ii) help preserve and foster wild-life, notably endangered species, control and prevent poaching and illicit trade, whether in ivory or bushmeat, and (iii) promote and sustain biodiversity. These and other objectives were subsequently mapped to a project dashboard which while directly applicable to the Mkuju River project could be applied with modest changes to any other major resource project, especially one such as Mkuju River with a regional development ambition associated with it.

From a project performance and outcome point of view, the essence is that the key components are aligned not just across project delivery (operations), and oversight (regulations) underpinned milestone by milestone by competency-based capacity building. Where alignment is not yet reached or capabilities, have still to be fully put in place the conditions are not met for a decision gate to be passed, and hence the decision maker exercises a stop or hold approach.

Figure 19. **The integrated project performance dashboard**



6.7 Resource efficiency management

More widely, some trends towards comprehensive measures to enhance resource efficiency in uranium and associated mining projects can be identified, based on the following objectives and desired outcomes:

1. Effective management performance monitoring systems at mines *[big, smart data]*.
2. Prioritisation of operational excellence through asset performance including waste elimination.
3. Innovation, both company internal and through partnership strategies with the supply and value chain.
4. *Develop integrated ecosystem resource management and recovery capability.*
5. *Zero waste (0W) and comprehensive resource recovery (CRR) equilibrium waste/ resource (= environmental-economic equilibrium).*

6.8 End of Waste and resource future-proofing – regenerating legacy uranium production sites

Since the beginning of commercial-scale uranium mining in the 1950s many legacy uranium mining sites, notably tailings and waste dumps, have become a long-term threat to environment and society. Even after spending huge funds to remediate the sites, the efforts tend to break down quickly with time. An alternative will be to regenerate the sites as productive projects that can:

- Promote small-scale mining and mineral based industries such as value-added agro-chemicals.
- Reprocess the legacy mining waste to recover all valuable materials.
- Use legacy mining wastes as soil supplements or to produce artificial soils or similar products leading to “zero wastes”.

- Address water contamination if any by converting contaminated water into liquid fertilizers and other allied products.
- Use the sites for renewable energy (solar, wind or small hydro) co-production and integrate this with the local energy system.

Such legacy sites will be increasingly characterized using the UNFC model and all the resources that could be produced from the site accurately estimated and valued. This will provide detailed information and support to the business case for re-developing such sites as productive sites for economic, social and environmental returns.

The advantages of using the UNFC methodology to regenerate such sites will be:

- A complete inventory of all available resources and accurate valuation.
- Funds that are used for costly and often underperforming remediation activities could be channelled to resource development activities.
- "Zero waste" and site restoration during production will make remediation unnecessary in future.
- Renewable energy production available to support the site regeneration and local energy system.
- Useful mineral-based products including fertilizers, soil amendments and artificial soils.
- Local economy reinvigoration through entrepreneurial opportunities, jobs and social security.
- Local environment restored to acceptable states.

7. Conclusions

This report attempts to analyse the current uranium industry landscape through the prism of UNFC and sees how a new direction could be provided to uranium production. There were shortcomings in the performance of the uranium industry in the past, which has created legacy issues in many countries. For this reason, some countries have chosen to not pursue nuclear energy or uranium production. However, other countries have decided to pursue nuclear energy and uranium production. Uranium 4.0 could provide an alternative pathway, bypassing some of the mistakes of the past, for countries that have decided to pursue nuclear energy and uranium production.

While the energy markets are adapting to requirements of the new world order based on the Paris Agreement and the SDGs, the role of nuclear energy remains crucial. However, due to steadfast adherence to old business models, the nuclear industry's growth remains challenging. At best, nuclear electricity generation capacity will remain at the current levels well into 2050. Uranium demand likewise will not increase in the near or medium-term.

While the nuclear electricity sector has an opportunity to penetrate new markets with SMRs and with Generation IV technologies that are being designed to be more acceptable to the public and financiers, it must fit into an Energy-as-a-Service model. Uranium-as-a-Service should integrate into this new model. This will require changing the narrative driver from "commodity project" to "energy policy" to pivot the uranium "tale" from a "push" to a "pull" story where the policy landscape demands the inclusion of uranium in the set of energy resource options available to decision and policymakers facing multiple challenges: climate action; a public health crisis in the form of dangerous high levels of urban pollution and a related sub-urban, peri-urban and rural crisis of deforestation; the massive loss of fertile topsoil and desertification caused not by climate change but by bad farming and forestry practices and wider natural resource management, notably use of water resources; and, the potential catastrophic loss of biodiversity resulting from land use conflicts related to energy and food security.

Rapid changes that are sweeping through the global economy, especially with regard to sustainable energy resources, their availability, production and marketing have made uranium resource management urgent but at the same time challenging and more complex than ever. Resolving this complexity and achieving long-term, public acceptance will require changing the view that uranium is just a tradeable commodity competing with other energy commodities such as coal, oil and gas, to be extracted rapidly on a project-by-project basis and sold to the highest bidder in the market. This is not only economically untenable but also socially unacceptable. The necessary and sufficient conditions for successful engagement in the uranium sector are no longer confined to or even led by the mineral itself. Much else is at stake.

By applying these objectives and values as the primary modifiers for how to apply UNFC's three-fold classification criteria, namely the socio-economics (E); the technical feasibility (F); and the inherent characterisation of the in-ground resources, including related uncertainties (G), it becomes possible to redesign and map a redesigned, "balanced and integrated" pathway for the future sustainable recovery and use of uranium as a contributor to two of the most compelling and existential challenges of our time, climate action and the conservation of biodiversity while still meeting the food, energy and wider prosperity needs of the peoples of our planet.

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Redesigning the Uranium Resource Pathway

Application of the United Nations Framework Classification for Resources for Planning and Implementing Sustainable Uranium Projects

The adoption of the Sustainable Development Goals (SDGs) has made it essential to have a ground-up review of all resources indispensable for the successful delivery of all goals, notably for SDG 7 on access to affordable, reliable, sustainable and modern energy for all and SDG 13 on climate action. The energy and climate-related goals have a bearing on uranium resources, one of the clean, low-carbon energy sources.

This report shows how uranium resources could create a platform for innovative engagement with the integrated challenge of natural resource management and climate action. The United Nations Framework Classification for Resources (UNFC), the comprehensive resource management scheme, provides the necessary tools and conditions for the redesign of the uranium resource pathway.

This report argues that the conventional model of uranium as a mineral commodity needs to give way to a new model of uranium as a "critical energy material' for meeting the global sustainability objectives on energy and climate action.

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