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FOR PUBLIC COMMENT

Redesigning the Uranium Resource Pathway

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

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

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Foreword

As the world's population continues to grow and demand quality of life, 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.

Uranium resources are treated largely as a mineral commodity with little recognition of their contribution as a fuel for affordable and low-carbon electricity production. The reality that nuclear energy can reduce or displace carbon emissions is widely recognized. Over 30 countries rely on nuclear energy to meet their energy needs and a number of others plan to join this group. On the other hand, there are countries that have chosen to not pursue nuclear energy because of the risks of incidents or accidents or because of the long-term waste disposal challenges and have announced phase-outs of this energy source.

Uranium resources fuel 437 reactors with a total net capacity of 377 GigaWatt (electric), which represents approximately 10 per cent of global electric generating capacity. This capacity has an availability factor of 90 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, India, Russian Federation, Turkey and United Arab Emirates.

This publication examines uranium as a low-carbon energy material and the application of the United Nations Framework Classification for Resources (UNFC) for planning and implementing 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, 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.

I am pleased to note that this publication is part of ECE's ongoing efforts to focus on responsible production and consumption of all resources. It was prepared by the ECE's Expert Group on Resource Classification. The Expert Group's Working Group on the Application of UNFC to 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.

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and

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Contents

List of Tables

List of Figures

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
CCS	Carbon capture 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
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 emission
HSE	Health, Safety and the 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
ISL	In situ leaching
ISO	International Organization for Standardization
ISR	In situ recovery
JUMCO	Jordan Uranium Mining Company
MEM	Ministry of Energy and Mines
MENA	Middle-East, North Africa
NEA	OECD Nuclear Energy Agency
NGSA	Nigerian Geological Survey Agency, Nigeria
NORM	Naturally occurring radioactive materials
NPPs	Nuclear Power Plants
OECD	Organization for Economic Cooperation and Development
OPEX	Operating costs
PFN	Prompt fission neutron technique
PPM	Parts per million
PWR	Pressurised Water Reactor
ROI	Return on Investment
SDGs	Sustainable Development Goals
SEEA	System of Environmental-Economic Accounting
SGS	Saudi Geological Survey, Saudi Arabia
SLO	Social license to operate
SMRs	Small modular reactors
SMRs	Small- and medium-scale reactors
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
UPSAT	Uranium Production Site Assessment Team
URT	United Republic of Tanzania
USEPA	United States Environmental Protection Agency
WN	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, notably SDG7, not least of which uranium resources as a clean, zero-carbon energy source. Any discourse on the future of the uranium industry outside the context of the 2030 Agenda and the Paris Agreement on Climate Change for a realistic 2°Celsius (C) pathway, and if possible a 1.5°C goal, will not be capturing the full implications of the situation. Therefore, this review is framed by the SDG triad "People – Planet – Prosperity".

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 objectives of providing safe, affordable and accessible energy for all through the selection of a locally or nationally appropriate portfolio of energy technologies and communicating the potential advantages but also with the significant challenges of including uranium in that mix. They also address broader issues 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, namely prioritizing the urgent need to reduce or eliminate the dominant sources of urban air pollution among the factors in energy technology selection.

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."

The report shows how well-suited uranium resources are to create a platform for innovative engagement with the integrated challenge of natural resource management and climate action. 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 material" 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 as a potentially infinite fuel resource matters 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 and Medium-scale Reactors (SMRs) which 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 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.

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[1]. 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)[2]. 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[3] 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)[3] of the Organization for Economic Cooperation and Development (OECD)[4] 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 to 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)[5] [4] and the Paris Agreement on

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[1] For ECE see https://www.unece.org/info/ece-homepage.html
[2] For IAEA see https://www.iaea.org/
[3] 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)
[3] For NEA see https://www.oecd-nea.org/
[4] For OECD see http://www.oecd.org/about/
[5] For the UN SDGs see https://sustainabledevelopment.un.org/?menu=1300

Climate Change[6] [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.

Hence 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 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 SDG13, Climate Action. 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
- Proportionately reduced or very low energy overhead the more the uranium is sourced as a co- or by-product
- Concomitant opportunity for very significant waste reduction the less conventional solid mining is required, with zero waste a possible outcome if the uranium is recovered as a by-product since the primary product incurs in full whatever waste externality there is. The waste balance is net negative at least by the volume of by-product uranium recovered.

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

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

significantly underperforming, and at worst is so flawed 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, zero carbon, energy source.

1.2 Basics

1.2.1 What is uranium?

Uranium is an energy mineral with unique properties, combining radioactivity with a status as a silvery-coloured heavy metal. It has the chemical symbol U and an atomic weight of 92, meaning it takes ninety-second place in the periodic table. Its discovery is credited to a German chemist, Martin Heinrich Klaproth in 1789, who named it after the freshly discovered planet Uranus. 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 of its properties by Marie and Pierre Curie who extracted uranium from ore to conduct their investigations.

Regarding abundance, uranium is all-pervasive in the earth's crust, with a range of estimates from 40 – 100 trillion tonnes may be found on the surface of the earth to a depth of approximately 25km. Some 10 billion tonnes are estimated to be dissolved in the oceans. 99.7 per cent of the naturally occurring uranium is the isotope U238. Typically, the mineral is found in very low concentrations measured in parts per million (ppm). A very small number of deposits are known with much higher concentrations, one of which, containing up to 25 per cent U, is in commercial production using remote, automated recovery technologies.

With respect to risks to people and biota, uranium's toxic properties as a heavy metal are generally of greater significance in an unenriched state than its radioactivity.

1.2.2 Nuclear energy - "atoms for peace."

The potential of uranium as a fuel for nuclear power plants was rapidly developed in the aftermath of World War II, 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 its use as a peaceful, energy resource was promoted as a way of channelling uranium applications away from the military towards economic development reliant on 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 fully commercial power plant using a Pressurised Water Reactor (PWR) was started up by Westinghouse in Rowe Massachusetts, United States of America, in 1960.

1.2.3 How to classify and manage uranium resources?

With the global acceptance of the 2030 Agenda for Sustainable Development, it has become apparent that a new era has been inaugurated. While natural resources are essential for the attainment of most of the Sustainable Development Goals (SDGs), how, when and where

the resources are discovered, produced and consumed have become central to the process of delivering many of the SDGs. In consequence, the United Nations's resource classification and management system, UNFC has become the comprehensive and integrated tool for all resources including uranium that will ensure acceptable balanced and responsible development.

UNFC is a classification system that applies to energy resources of all kinds, including oil and gas, renewable energy, nuclear fuel resources; mineral resources; injection projects for the geological storage; and the anthropogenic resources such as secondary resources recycled from residues and wastes. With regard to uranium, UNFC, as applied within the context of the SDGs, offers the opportunity to redefine the way uranium resources are classified, produced and utilized. 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 on uranium as a zero-carbon fuel that can help realize many of the SDGs and related climate action commitments of the Paris Agreement. Based on this approach, UNFC specifications and guidelines can be used to define an economic and environmentally sound progression pathway for uranium projects.

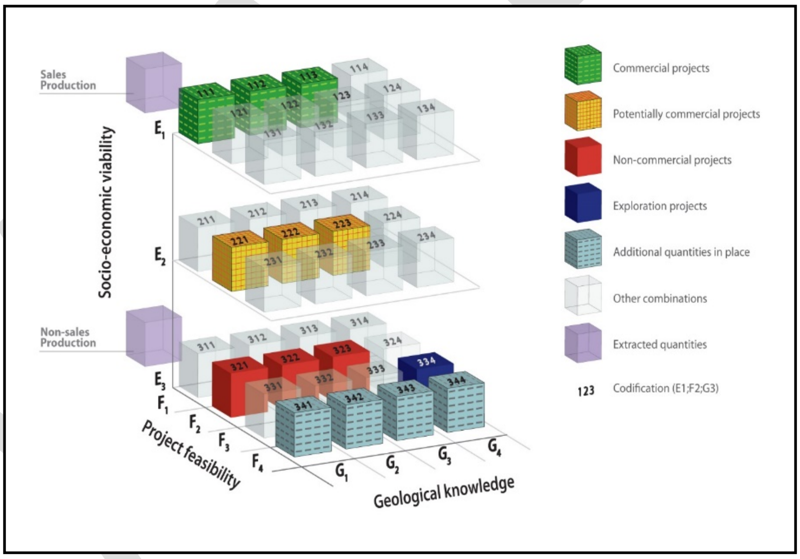


Figure 1. UNFC system based on alpha-numeric codes

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 – Confidence in estimates. Simple definitions at the top-level as principles and detailed instructions as specifications are provided for classification of resources. For uranium, the specifications are provided through the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) and IAEA "Red Book" Bridging Document. Apart from these specification, additional guidelines, with case studies and examples, are provided through the Guidelines for the Application of UNFC to uranium and thorium Projects. Project are then classified according to alpha-numeric codes (Figure 1).

The propose of this classification is not just to satisfy a regulatory reporting need. Proper classification identifies the progression milestone achieved by a project and what is needed to progress the project to a stage where it can start delivering value. 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 further, when it warrants, to place a project on hold. The application of UNFC thus ensures the correct and timely channelling of capital investments to deserving projects. While the bare commerciality of the project is thus satisfied, on other different levels, the social and environmental aspects of a project are also being assessed and clarified.

UNFC is a system that puts the resource base and projects in proper perspective and thus helps policymakers and financial decision makers have the required understanding and knowledge on resource development. 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. At the same level, the general public and other stakeholders are also assured that the social and environmental aspects are being managed and appropriately addressed.

Accordingly, during 2017-2018, UNFC incorporated guidelines for accommodating social and environmental considerations in the process of resource classification and use which enables users of UNFC to capture all related aspects consistently, notably regarding 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.

1.2.3.1 Target mineral

The initial focus of commercial-scale mining has been on the conventional recovery of very low quantities of uranium from open-pit rock deposits. In terms of their relative target of mineral content to "waste" rock (i.e. that part of the mined fraction not required by the miner) these deposits closely resemble gold. In practice, this has meant that some 99 per cent plus of rock turned over in such a "conventional" uranium mine becomes redesignated by the act of mining as "waste" or tailings only because the mine operator has no further use for the rejected material or tailings.

Public resistance to such forms of very high volume "waste"-generating "extractive" mining procedures, which is far from confined to objection to only uranium mining, has created intense pressure for change. Taken together with high 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 mine, Olympic Dam in Australia, is primarily a vast copper mine which, technically as a reject from copper recovery, yields relatively large quantities of by-product uranium, associated with the copper 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 of the past 20 years, however in the uranium sector have been from mining solid rock either by open pit or underground means, first, to liquid mining in situ using acid or alkaline leaching and more recently (2016 onwards) to in situ recovery using less invasive "bio-leaching" technologies such as carbon dioxide (CO_2) and oxgen (O_2).

The leaching process may require that a mined ore body be reorganised into long, specially engineered "heaps" for uranium recovery (heap-leaching) or, less environmentally invasively, it may apply a process of in situ recovery (ISR), which requires no conventional mining at all. Increasingly in response to rising environmental consciousness bio-leaching technologies are being applied using more benign lixiviants and oxidising agents such as CO_2 and O_2. Assuming the underlying geology of the host deposit is suitable, the target Uranium resource is mobilised and then recovered by the application of either strong acid or strong alkali. Overall, in situ leaching (ISL), also known as in situ recovery (ISR), widely used in Kazakhstan, the world's largest uranium producer, has rapidly become the most significant means of commercial recovery of uranium, accounting for 55 per cent and more of resources recovered worldwide.

1.2.3.2 The rise of ISR and co- or by-product uranium

One of the obvious attractions of ISR, other than cost savings, is the radical reduction in waste volumes generated. Overall, mining industries worldwide are now under public pressure to reduce or eliminate waste, and leading mining nations such as Australia and Canada envision reaching "zero waste" in the coming two decades.

1.2.4 Why recover uranium?

For the 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 offers 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?"

1. Is uranium recovery for use within a planned or actual national nuclear power programme?
2. If so, is this programme aligned with SDG13 on Climate Action and the Paris Agreement?
3. If so, is this in part because of reasons of enhancing public acceptance and/or mitigating social risk and/or national reporting under the United Nations Framework Convention on Climate Change (UNFCCC)?
4. If not, is the objective purely to sell uranium on the open market?
5. 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.

6. 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?
7. 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?[7]
8. If so, are value at the source and local content key national policy objectives?
9. If so, are international standards for these local content policies, e.g. as set out by OECD [6], the broader SDG agenda and the Paris Agreement, being pursued.

1.2.5 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 [7] and Henry Ford [8], 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 needed 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 [8] [9], 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.

[7] For emerging concerns, eg in the United States, 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
[8] 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 the terms of 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 numbers of milestones. For project managers that may be advantageous. For policy and decision makers this may be overcomplicated or just confusing.

So, this document 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.

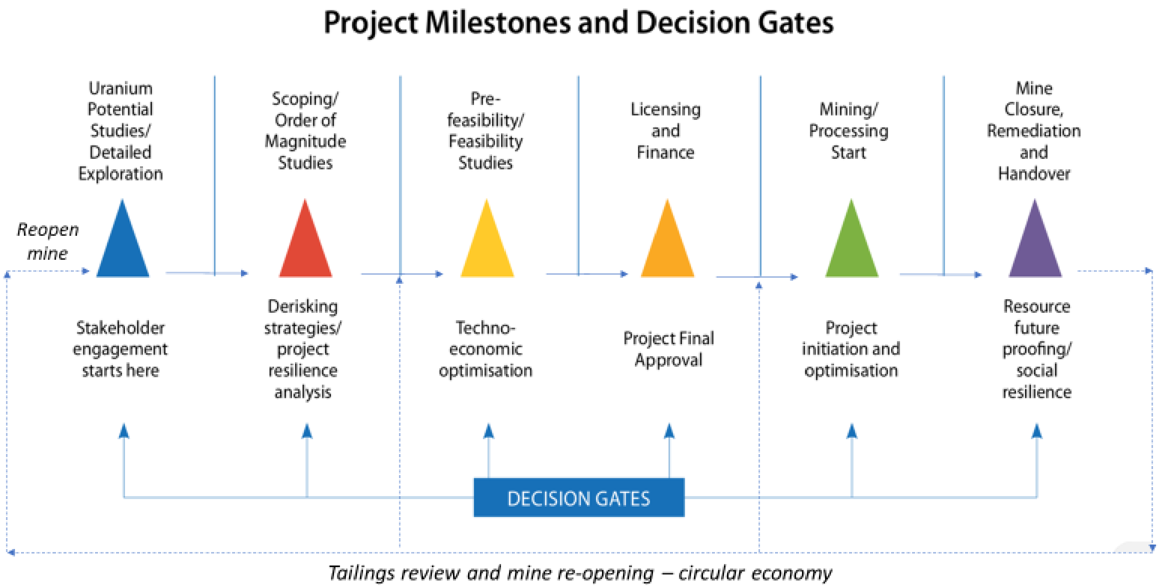


Figure 2. Project milestones, dependencies and decision gates – for decision makers

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 (see 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 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.

So, 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 principally by the development of uranium mining, what happens to that city when uranium mining stops abruptly. Is it resilient? Part of the answer to the question of resilience lies in the change of the life-cycle model from linear to circular, beginning with resource future-proofing on mine "closure" leading to the option to reopen the mine or revisit the tailings when economic and social conditions become propitious to do so.

1.2.6 Critical dependencies

A combination of good practices derived from successful uranium mining projects and related policy documents such as the Africa Mining Vision [10] 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.

1.2.6.1 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?

1.2.6.2 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?

1.2.6.3 Value (add) at the source and local content

Does the country have the capacity/capability to undertake value-add 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?

1.2.6.4 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.

1.2.6.5 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?

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

The tendency in design and operation of nuclear power plants (NPPs) has been to 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 reactor as a power plant. The rapid rise of more localised, renewable sources of power, such as solar panels, has opened up space for alternate, much more widely distributed models of localised energy sources, hitherto neglected partly due to concerns about safeguards. 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 small modular reactors (SMRs) started a new phase of very intensive development[9].

1.3 Climate Action – the new crossroads for nuclear power

In the wake of the Fukushima 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 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"[10] renaissance for nuclear energy or a slow decline to at best a regional market, mostly in Asia.

In 2012, the Global Energy Assessment (GEA) of the International Institute for Applied Systems Analysis (IIASA) had brought together about 500 authors and reviewers across the world to provide comprehensive, science-based perspectives on sustainable energy futures,

[9] 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/

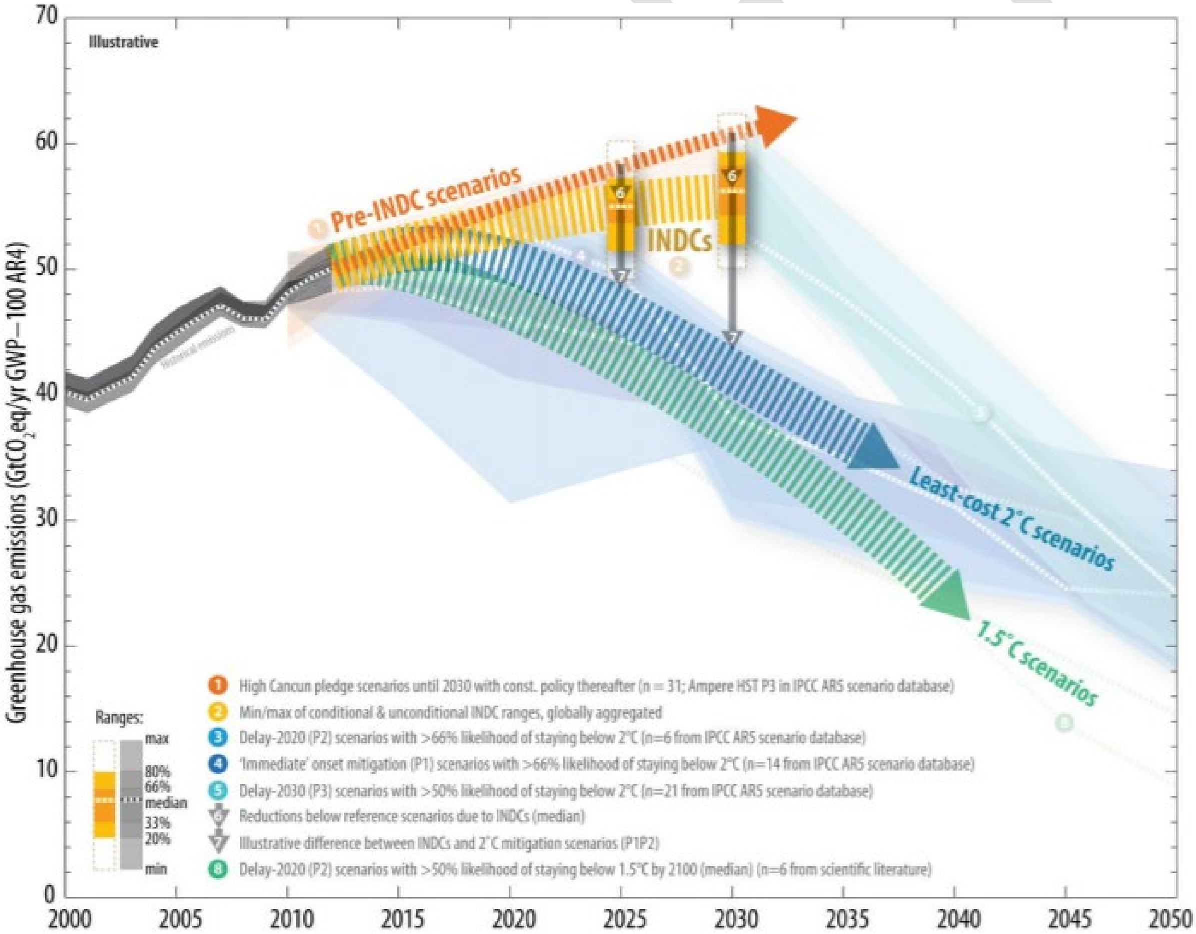
[10] The term "green world" is taken from Jacqui McGill, Uranium a Tale of Two Tails, 28 November 2017, https://www.bhp.com/media-and-insights/prospects/2017/11/uranium-a-tale-of-two-tails

quantitative pathways, and the policies needed so they could be achieved [11] and [12]. GEA pathways, in general, and the six related to SDG 7, portray possible futures with a large share of nuclear energy.

As of the end of October 2016, 163 Intended Nationally Determined Contributions (INDCs) were submitted from 190 countries. However, only ten countries (Argentina, Belarus, China, India, Islamic Republic of Iran, Japan, Jordan, Niger, Turkey and the United Arab Emirates) have indicated that nuclear energy will play a role in their INDCs [13]. Initial INDCs fall well short of meeting the Paris Agreement targets [14]. 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 the IAEA [15]. The future of nuclear energy will depend on how many of these countries will introduce nuclear energy in the next two or three decades.

Figure 3

Comparison of Global emission in 2025 and 2030 resulting from the implementation of intended nationally determined contributions 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.

While energy efficiency and emission reductions through 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 (see 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, CCS, shale gas, investing in high-efficiency low-emission (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 [17].

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[11] [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 tones should come from Bioenergy Carbon Capture and Storage (BECCS), which will require land twice the area of India. Currently only four CCS projects of 1 million tonnes CO_2 per year (or less) capacity are operational. To meet the required CCS targets, there should be 15,000 of such projects by 2050. However, the outlook remains bleak in some regions 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"[12].

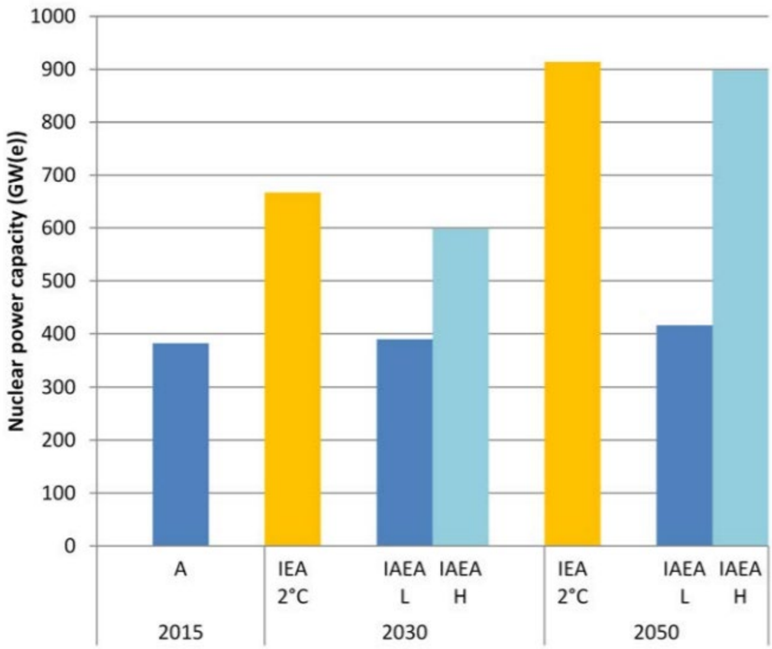
As seen in Figure 4, International Energy Agency (IEA) 2°C scenarios will require significantly more from nuclear power than the "High scenarios nuclear capacities by 2030 and 2050" projected by IAEA [22]. A higher target for nuclear is also called for in other scenarios [23]. Though nuclear energy has been prominently considered in many of the 2°C scenarios, there are no specific targets set in the 2030 Agenda.

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 need 1,000

[11] For the IAEA training course (9-18 July 2018, UN HQ New York) on SDG7 delivery see https://www.iaea.org/newscenter/news/at-un-forum-iaea-highlights-its-energy-planning-tools-and-nuclear-science-for-development
[12] Carbon capture, utilisation and storage - https://ec.europa.eu/jrc/en/research-topic/carbon-capture-utilisation-and-storage

GWe of new nuclear capacity by 2050[13] and require a level playing field in energy markets. Such a level playing field supposes optimized existing low-carbon energy; harmonized regulatory processes to provide a consistent, efficient and predictable nuclear licensing regime; and creating an effective safety paradigm focusing on genuine public wellbeing, where the health, environmental and safety benefits of nuclear energy are set out.

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



Natural gas, uranium (and thorium) and hydrogen may be more effective global foundational fuels for the twenty-first century [24]. Nuclear fission is a reliable, high-capacity, high-load mode of electricity generation, which makes it an ideal 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 the better, more efficient, and inherently more reliable and safe designs that have been under development for more than twenty-five years, including a greatly enhanced role for small- and medium-scale reactors (SMRs).

1.3.1 The impact on non-technical factors

The main impact of the Fukushima event on the looming choice as to which of these two 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 event exposed a generational

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

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 event crystallised.

The failure of nuclear electricity to reach its full potential has not been due to any fundamental technical problems or economic considerations. Instead, the decisive factors have been a faulty perception of risk [25]. The sixty years with nuclear power have seen thirty-one deaths in the 1986 Chernobyl disaster together with a few thousand early deaths from cancer above the 100,000 natural cancer deaths in the exposed population. The other two famous accidents, at Three Mile Island in 1979 and Fukushima in 2011, killed no one. Compared with nuclear power, natural gas kills 38 times as many people per kilowatt-hour of electricity generated, biomass 63 times as many, petroleum 243 times as many, and coal 387 times as many—perhaps a million deaths a year. As with oil tankers, cars, planes, buildings, and factories, engineers have learned from the accidents and near-misses and have progressively squeezed more safety out of nuclear reactors, reducing the risks of accidents and contamination far below those of fossil fuels [26].

1.3.2 A failed uranium narrative

To those sceptical of or opposed to nuclear power, the“atoms for peace” had been a strategy in the aftermath of World War II to mask “unacceptable” continuation of the military objectives of uranium use with the “acceptable” alibi function of nuclear energy generation. The two parts of the story had never happily coexisted since the bombs were dropped on Hiroshima and Nagasaki and now the narratives have completely fractured. For the sceptics and the opponents, the increasing prominence given to medical uses of nuclear technologies only deepened the suspicion that there was either an attempt to distract from or evade the issue, or that the whole truth was not being told. What the Fukushima event in retrospect brought to a head was that the post-war nuclear energy narrative of “atoms for peace” had failed to convince public opinion that nuclear power deserved its place at the peaceful, clean energy suppliers table. Was this a failure of a uranium narrative or an inherent flaw in uranium itself? Was it a failure to make the case as to how uranium should be recovered and used?

This narrative failure, as evidenced by significant statements from uranium industry opinion leaders such as BHP, is at the heart of the crisis the nuclear industry in general and the uranium industry, in particular, is currently facing. At best, the sector is experiencing extremely adverse conditions and at worst, terminal decline, a state BHP describes as a “tale of two tails”.

> Our belief is that the long run future of uranium is more likely to be in either the “left hand tail of the distribution” (i.e. a low case world where nuclear generation dwindles in importance) or the “right hand tail of the distribution” (i.e. a green world where nuclear generation increases in importance), than a traditional distribution

scenario (i.e. the average of tomorrow will look similar to the average of the past). Hence, the uranium story is a "tale of two tails"[14].

Against that background, the existential question this document cannot but ask is whether the "tale" the sector has to tell has a future audience or not. In blunt terms, has uranium as an energy resource had its day because the problem to which it provided a solution – defending nuclear technology by reference to it's peaceful rather than its destructive applications - has now been solved by rejecting the "how" case for both? Alternatively, is the failure that of the broken narrative itself and that the real issue is getting the right "why" narrative in place to justify the use of uranium as a key component of a "green-world" energy strategy and policy, as suggested by BHP.

Taking as its point of departure the stark alternatives facing the uranium industry, between atrophying demand and green growth, this publication considers the role that the United Nations Framework Classification for Resources (UNFC) can play in setting out and comparing the cases for both scenarios. In UNFC terms, the choice will be determined by whether or not, in the particular context of achieving SDG7, Clean Affordable Energy and SDG13 Climate Action, uranium resources are understood as of critical significance to a successful, policy-driven change towards "clean" energy provision by systematically reducing global dependency on electricity generated from carbon sources.

If uranium does not find its stable place in this "decoupling" transition, the alternative is that it remains a niche business within a commodity minerals market with a highly uncertain and volatile future. If uranium can reinvent its raison d'être within the framework set by "clean", and "green world" energy provision it will signal an underlying pivot from the post WWII "push" approach (uranium is ok as long as we focus on peaceful applications) to a 2030 Agenda "pull" narrative (uranium is fundamental to sustainable energy provision)[[27]]. In this pull narrative, the compelling reason to stay with uranium is not based on atoms for peace but on placing uranium use as an energy source at the heart of a "decoupled" climate action. The central reason should be to mitigate the highly damaging consequences, notably in major cities, to public and environmental health and safety from dangerous levels of dependency on carbon energy sources, notably coal and wood, whether commercial or artisanal.

In that policy context, UNFC may take its place as a high-level decision support tool for evaluating, planning and implementing future "green world" uranium projects as part of a wider sustainable "green world" energy provision. Hence, while the assumed readership of this publication includes technical experts, it is written expressly to assist the senior policy and decision makers first to analyse and then to decide why, and if so how, uranium resources might play a role within their respective energy resource narratives.

1.3.3 The case for uranium: Risk-benefit or risk-risk?

Put another way, the post-World War II "push" narrative proposing uranium as a peaceful and beneficial application of a potentially lethal and destructive resource was based on a

[14] See Jacqui McGill, Asset President, Olympic Dam, November 28 2017, https://www.bhp.com/media-and-insights/prospects/2017/11/uranium-a-tale-of-two-tails

"risk-benefit" equilibrium in which the "risks" of nuclear destruction were counter-balanced by the "benefits" of nuclear energy. What has not been offered to date is a "risk-risk" "pull" narrative based on a dispassionate analysis of what in the policy landscape set by the Sustainable Development Goals and the Paris Agreement on climate change are the risks entailed in *not* retaining nuclear power. If uranium fuel loses its place at the heart of delivering the climate action objectives, what is lost and what is gained in comparison with the risks and benefits of alternative solutions?

Empirically, the "pull" option has now offered itself as almost inevitable. The slow-down in some energy markets and the reversal in others of developing nuclear energy supply to meet rapidly growing demand, especially in the most populous emerging economies, has left a large and very costly gap in energy supply which highly polluting utilization of coal and oil has effectively in a largely uncontrolled way. The outcome is a pollution crisis in many of the world's largest cities with devastating consequences for public health whether measured in terms of life-expectancy or more specifically in the health status of the most vulnerable, young children, their mothers and the elderly. These consequences are both visible and measurable. They affect hundreds of millions of people directly and the planet as a whole indirectly.

Uranium is undoubtedly not the only option to reverse this public health crisis, nor is it a silver bullet. However, merely to abandon it because of a past generational communications failure is not an acceptable course of action, no matter how demanding the process will be of rewriting the uranium "tale" in a way that it engages and satisfies the majority audience in the coming generations.

1.3.4 A new uranium narrative

Against that background, and fully conscious of the enormity of the real issue – defining and agreeing practicable options for climate action with a likely prospect of a successful outcome – the primary purpose of this document is to rewrite the uranium tale in such a way that the compelling reasons to continue to use it can be heard. To make that case – to "tell that tale" – it proposes that UNFC can be used as a vehicle for structuring its narrative into a coherent "beginning, middle and end", where managing the sustainable and secure progression of uranium as a critical nuclear fuel resource, results in an essential, transparently measurable and significant contribution to resolving the climate change crisis.

This means tracking uranium resource progress from exploration and discovery to production and eventual closure (Figure 1), 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). 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 take precedence.

1.4 Purpose – UNFC and uranium resources in alignment with 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 SDG7 on affordable, clean energy, SDG13 on climate action, and the Paris Agreement.

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 "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. However, whatever the setting, to deliver a low- or zero-carbon energy system preference successfully in energy generation, technology must go to an optimum mix of options based on high efficiency-low emission (HELE) technologies in fossil fuel use, carbon capture and storage (CCS), renewable energy, nuclear energy and energy efficiency.

Among the clean, "green" energy options, uranium has a uniquely 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 or phosphates, and (b) land use is a key determining factor premised on the scarcity of available land in an energy-intensive urban or peri-urban environment. Positioning uranium resources within the new global policy landscape rather than as competitors for mineral project investment funding enables this report to define 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 nuclear accident in Japan[15] 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 German 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, rather than undertake costly upgrades, have announced shutdowns.

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

Uranium supply and demand were thought to be in balance as recently as 2013[16]. Since then the situation has changed into a state of significant oversupply[17]. Uranium prices in 2016, for example, were in the range of US$42 - US$75/kg U, the lowest since 2004 [28]. 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[18]. 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[19].

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

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 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 resource 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 the 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 which, rather than any technical resource-recovery considerations, will weigh most powerfully with the decision makers. What makes the decision itself intrinsically harder to make is that the risk/risk analysis required is not pitting

[16] 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
[17] 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
[18] 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
[19] See World Nuclear News, Kazakhstan to cut uranium production, http://www.world-nuclear-news.org/UF-Kazakhstan-to-cut-uranium-production-0412177.html

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 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 to enter the nuclear fuel cycle. The careful 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 to the adoption of a 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 give particular emphasis to the fact 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 such outcomes 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 by-product uranium resources, well exemplify such opportunities.

1.7 Social acceptance

The so-called “social licence to operate” [29], which has been under considerable and growing strain for many years in the minerals sector as a whole, 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 productions 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 resources are defined, managed and utilized. Redefining the uranium resource pathway hence becomes not just the rational economic option based on clean energy (tale 1), but also a matter of creating a paradigmatically new narrative for the uranium industry as a crucial, indefinitely sustainable energy resource (tale 2). 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). 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. Perhaps such a narrative can be grounded uranium and nuclear power as essential to the energy decarbonization agenda, which itself is critically urgent to curb and roll back the destructive pollution in modern mega-cities from carbon fuels whether for cooking and heating or for motor vehicles. This has to be coupled with the need for innovation and localisation in providing affordable and accessible energy solutions by small and medium scale reactors (SMRs) integrated within an optimal energy mix.

1.8 The special case: Uranium, UNFC and 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.

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 has not been identified for the first time in 2015. Already with the publication in 2009 of the Africa Mining Vision (AMV)[20] [10] the critical dependencies for success were identified as investment in

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

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, the 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 indefinitely 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 not by "atoms for peace".

2. Current State

Sustainable development is fundamentally linked to shared access to strategic and critical raw materials, among them uranium, which of all energy resources is the one which most exhibits the attribute of indefinite sustainability. That attribute is perhaps 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 very critical aspect of the nuclear fuel cycle. The currently defined 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 of oversupply and inventories, resulting in continuing pricing pressures. 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 is currently assessed and managed?

The total identified uranium resources (reasonably assured and inferred) as of 1 January 2015 amounted to 10,188,700 tonnes of uranium metal (tU) in the <USD 260/kgU category [30]. Total undiscovered uranium resources (prognosticated resources and speculative resources) as of 1 January 2015 amounted to 7,422,700 tU.

Significant quantities of uranium are found in many "unconventional" resources (Table 1) [31] and Figure 3. 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 U, or the means of extraction. 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 coal-lignite, and copper. How useful the “conventional” vs “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 (1) in the case of what is after all the world’s largest uranium mine, Olympic Dam, which is (a) primarily a copper 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 by-product exceeds the nuisance cost of recovering it; and (2) 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.

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

Country	**Phosphate rocks**	**Non-ferrous ores**	**Monazite**	**Carbonatite**	**Black schist/ shales, lignite**
Brazil	84 500	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			25 900		
Jordan	60 000				
Kazakhstan	29 000				
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	140 000 – 330 000	1 800			
Venezuela	42 000				
Viet Nam					500

Table 2 shows the quantities of unconventional uranium reported in UDEPO as of 2018 [32]. 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 [33].

In particular, 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 [34]. 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 [35].

Table 2. Unconventional uranium resources as in 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 "bio" leaching "organic" methods with 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 driven 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 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 from a long period when it was dependent on imports from third countries. This has broader geopolitical and economic consequences.

First, energy prices in some, but not all, markets are likely to remain relatively low over the long-term future. 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 and challenges. As the footprint of operations becomes smaller, capital and operational expenditures can be reciprocally smaller. New technologies and their resultant efficiencies may reduce or eliminate some jobs, a matter of social concern. However, such losses may be compensated 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 gains will have significant 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 can be moved in production. However, focusing 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. The exploration expenditures have been drastically reduced in recent years, and there has been a move away from greenfield to brownfield exploration, such as the plan to reopen the Salamanca Uranium Mine in Spain[21].

Against that background, there is increasing the 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 have to 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. That

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

is, by digital means, both empirical and probabilistic, future mines can be designed and tested online rather than in the ground. This 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 lead being taken by well-led engineering/EPC contracting companies such as FINE, China.

2.2.2 Demand side

As of 1 January 2016, for a total of 437 commercial nuclear reactors that are connected to the grid with a net generating capacity of 377 GWe, it is estimated that about 56 585 tU are required annually [31]. This amounts to an average requirement of 150 tU/GWe/year. In the low case scenario mentioned above this will relate to a demand decline to 51 750 tU by 2030, 49,800 tU by 2040 and raising back to 57 300 tU by 2050. According to this scenario, uranium demand will slightly decease in near and medium term and will be at current levels at long term. If the high case 83 100 tU by 2030, 107 550 tU by 2040 and 131 100 tU will be required. As IAEA projections reflect, this an ambitious estimate.

Demand for uranium has been further depressed by nuclear utilities deciding to keep lower inventories. Before Fukushima, the general practice 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.

Improving efficiency in uranium utilization in the fuel cycle itself has similarly reduced uranium demand, along with contributory 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 150tU/year. Such increases in uranium use efficiency mirror broader resource efficiency gains in the so-called “4.0” industrial economy.

Global uranium mine production has been on a steadily decreasing trend, down by 4 per cent since 2013 alone [31]. Overall, world uranium production decreased by 4.1 per cent, from 58 411 tU in 2012 to 55 975 tU as of 1 January 2015. 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 about 24,575 tU in 2016 but then reduced output by 10 per cent in 2017 and a further 20 per cent reduction by 2018[22,23].

In situ leaching (ISL) production continued to dominate uranium production, accounting for 51 per cent of world production as of 1 January 2015. Underground mining (27 per cent),

[22] 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

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

open-pit mining (14 per cent) and co-product and by-product recovery from copper and gold operations (7 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 continue to grow.

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. 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 (see 1.3.2). This has reduced uranium demand and requirements, further depressed prices and slowed the pace of mine production and investment in new uranium project development.

This decline has significantly impacted the likely contribution of conventional and the unconventional resources in the future uranium supply scenarios. Large commercially funded uranium production facilities will be likely to survive only if sufficient long-term contracts are available. With interest in small, modular, less capital-intensive reactor fleets strengthening[24], 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 medium-scale reactors as change agents?

If demand for small and medium reactors (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 a large NPPs. It makes more sense to consider the lifetime uranium fuel requirement for a small reactor, rather than its annual reactor. For example, a CAREM 25 MWe reactor will require 600 tU for its 40-year lifetime. 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 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 a security of fuel supply perspective, apparently the whole life-cycle model is preferable.

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

In-situ recovery (ISR) has now become the dominant uranium recovery method (see Figure 5).

[24] See for example the UK investment announced December 2017 https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

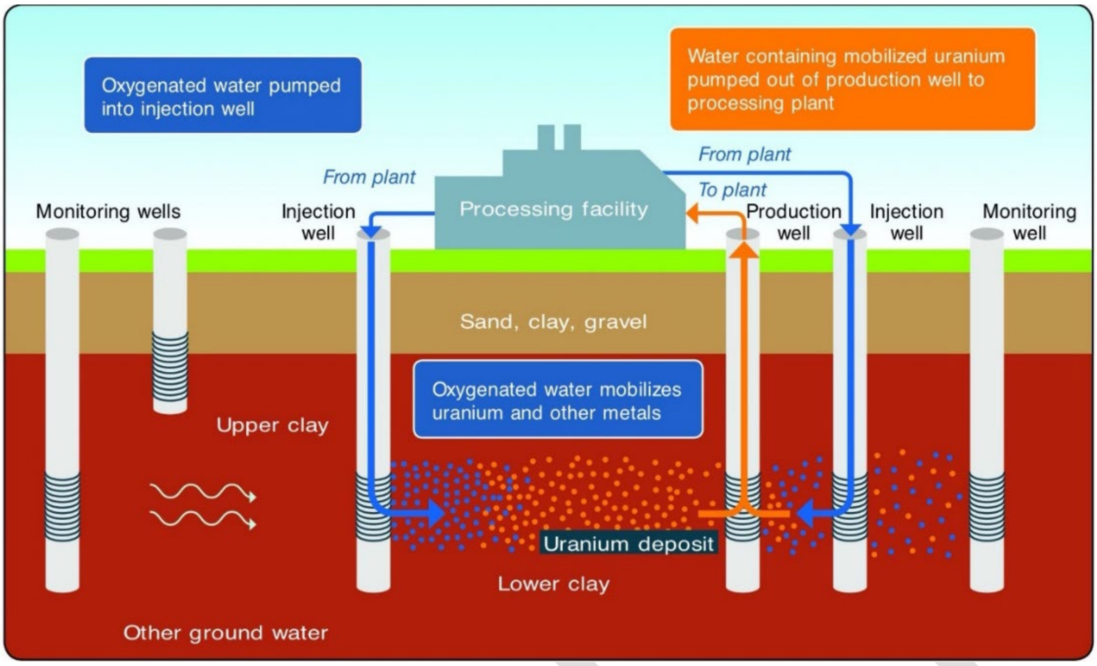


Figure 5. The uranium ISR process – US Environmental Protection Agency model

Initially the ISR case has been driven by an environmental imperative to eliminate all the very long-term and extremely costly 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) and Central Asia (Figure 11), or from open-pit/underground mines such as Ronneburg, run by Wismut GmbH in Germany [36] (Figure 7).

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

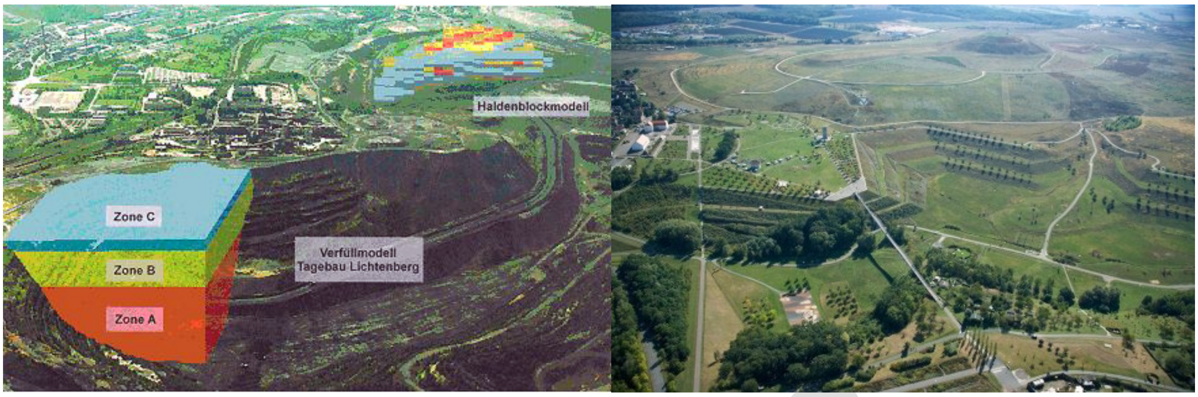


Figure 7. Uranium mine remediation and restoration, Ronneburg, Wismut GmbH, Germany

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, Příbram (Figure 9).

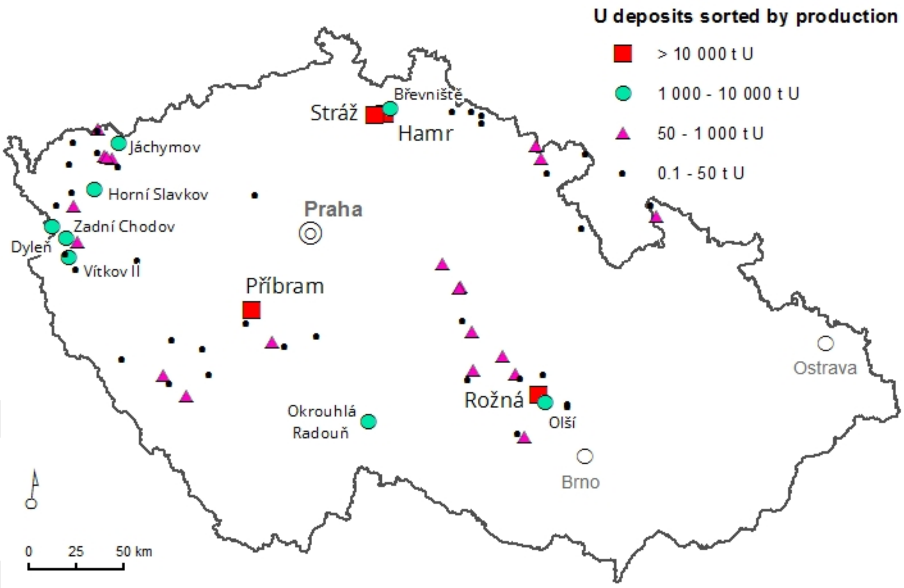


Figure 8. Uranium deposits by production volume, Czech Republic

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

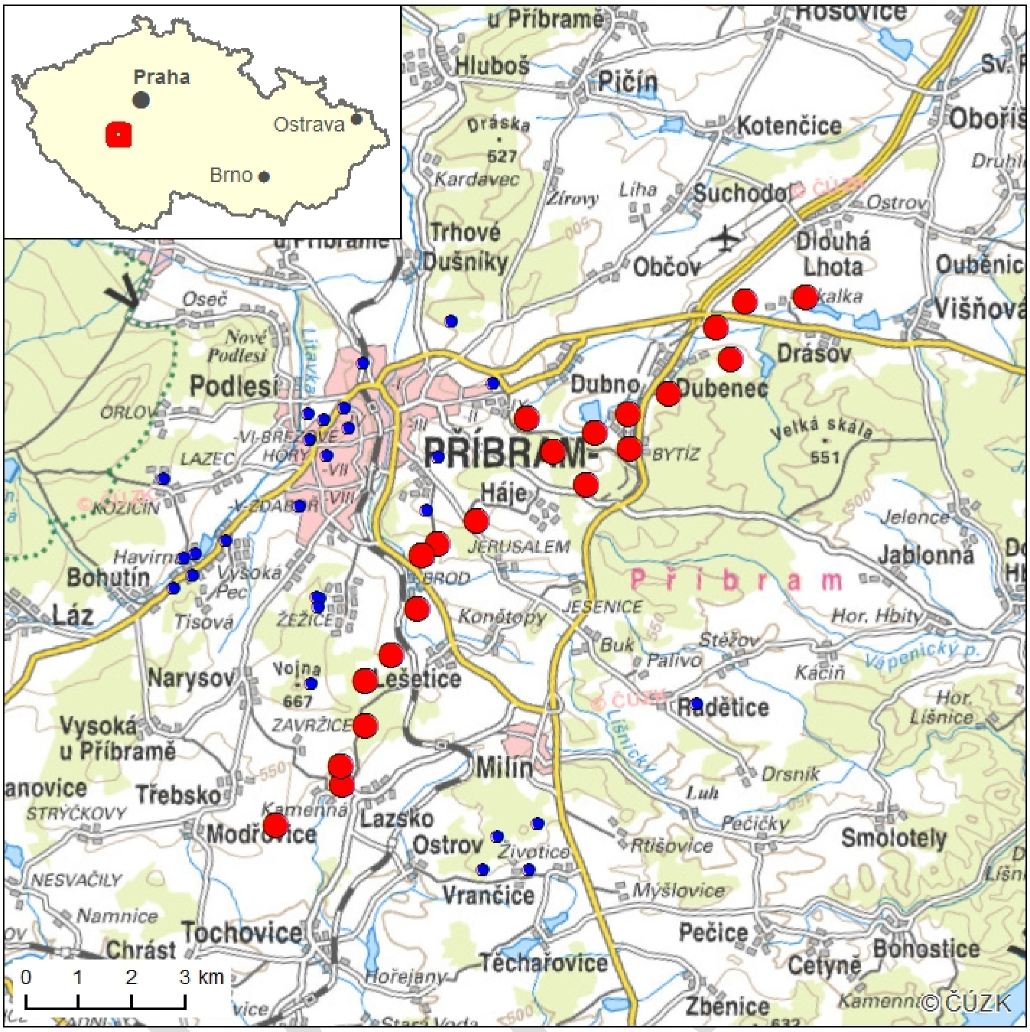


Figure 9. Uranium mine tailings (red dots) and other mineral tailings (blue dots) Příbram, Czech Republic

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.

2.3.1 ISR/ISL Technology

In-situ Recovery (ISR) or In-situ Leaching (ISL) is a generic ore recovery technology suitable in the case of uranium recovery for application to sandstone-hosted deposits below the water table in weakly lithified or non-consolidated sands [37]. 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).

By 2017, ISR accounted for 50.8 per cent of the world replacing the more conventional method of underground mining (Table 3). 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.

Table 3. World uranium production by technology (2014)

Uranium production method	Per cent of global Uranium production (%)
ISR/ISL	50.8
Underground	27.3
Open-pit	14.0
Co-product/by-product recovery	7.3
Heap Leaching	0.5
Other methods	0.1

2.3.2 Geology and mineralisation

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.

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.

2.3.3 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 [38]. 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.

2.3.4 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 AI-driven mining techniques evolve, so predictive/ probabilistic resource modelling will rapidly improve.

2.3.5 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 [37]. The conversion of uranium resources to uranium reserves by applying the modifying factors is somewhat more complex. Modifying factors for conversion 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.

2.3.6 Uranium recovery

The *in situ* recovery (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), and 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).

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 [37]:

(1) Uranium ore grade, the geometry of the ore body, and the type of mineralization. The accuracy of the ore grade estimate is to 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) Determine the hydrogeological confinement of the mineralized horizon.
(4) Determine the permeability of the mineralized horizon.
(5) Carefully characterize 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) Determine the groundwater flow.
(7) Determine aquifer salinity.
(8) Determine 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% 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.

2.3.7 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 ~17 days (with a range of 7 - 66 days). A wellfield lifecycle 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.

2.3.8 Case study: Beverley and Four Mile mine, Australia

Among the most modern ISR uranium production centres are the Beverley and Four Mile mines in South Australia[25]. These combined have an average recovery rate of about 65% at 0.26% U_3O_8 ore grade (including combined losses due to ISR mining and hydrometallurgical processing [31]. The in-situ uranium recovery process used comprises the following steps [39]:

(a) The aquifer groundwater in the confined sandstone units is pumped to the surface.
(b) A small amount of sulfuric acid and oxidant is added to the recovered water.
(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.

3.0 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 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 the preeminent energy resource regarding fulfilling the requirements of the new point of environmental-economic equilibrium on which sustainable development depends. This can be characterized as uranium 4.0 or 4G [40]. Presenting the advantages regarding climate action, public health and energy security is the concomitant narrative challenge which moving to uranium 4.0 (U4G) entails.

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[25] 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

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 extracting uranium into a speculative uranium commodity market to securing the supply of U 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 Uranium 4.0 pathway could charted will be necessary [41]. The redesign of uranium industry does not happen in a vacuum, but with building upon on the lessons learned and adopting what is available from changes supplied by wider gains made in industry 4.0 in general.

Fundamental cornerstones of the Uranium 4.0 industry will address in equal and co-dependent manner the social, environmental and economic aspects of an operation, in the course of which an equitable distribution of benefits to all stakeholders, beginning with local communities dependent on, or perhaps displaced by, the mine, is a fundamental assumption for social acceptance. Commitment to 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 [42], 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" [43]. Based on this principle, the criteria for Uranium 4.0 are well defined as:

(i) Beneficial
(ii) Responsible and
(iii) Sustainable [44].

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 [45]. However, each “End of Life” step will 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 [46]. 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 [47]. 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 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 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 any disruptive technology 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 a number of 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 bio-diversity 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. However, Uranium 4.0 operation will 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 in 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 have 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, European Union places more attention on strategic considerations and new, more sustainable paradigms. The EU has made €80 billion funding available to innovation through the "Horizon 2020" programme in the period 2014-2020, and some further €100 billion Euros will be available for the 7-year period of 2021-2027 through the proposed "Horizon Europe" programme[26]. As shown by the size of investment in these programmes, research and innovation are central to the EU's energy strategy[27].

Unlimited production and consumption patterns are being substituted with alternate approaches that hinge on a "circular economy"[28] and increasing efficiencies. Such methods often lead to complex value chains that are not often either unfamiliar or hard to understand or manage. For instance, balancing policy objectives such as zero waste, the recovery and reuse of secondary resources (comprehensive recovery), security of supply for critical/key raw materials, and optimal land use are 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 today spent 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 could be presented to non-specialists and educators; while professionals are also trained in the rudimentary tools of the trade in communicating science. SLO is now not seen as an isolated process, but something that needs to be

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

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

[28] 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.

integrated with the projects themselves, as well as to company business process and government resource management.

"Policy needs data", is the usual refrain, especially when it concerns a complex issue such as mining, but to churn information out of data much more is 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. Raw material communities are now being fostered in Europe, where date to information to knowledge transitions can happen effectively.

3.6.2 Asia

In Asia uranium raw material scarcity contrasts with growing demand. Nuclear growth in China or 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 targets stable growth, employment and non-fluctuating revenues, the market swings make even the best-laid plans go awry. The companies also see issues in regulatory multiplicity and break down of communications at times between the governments, investors and companies. This becomes acuter as transformations are sweeping through all levels which sees a need to break out of traditional mechanisms and 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 for diverging government and company views is on how reserves and resources are assessed, the difference mostly resting on how much material that is recoverable vs non-recoverable. The state gives importance to mineral conservation; hence the government's estimates of a resource base is always higher than the companies' estimates. A better understanding of the shared concerns in maximizing resource recovery always leads to a good relationship[29].

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 long. 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 a 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 has pointed out at the scale of revenue loss in Africa caused by this weakness, which if plugged could make Africa effectively non-aid dependent.

[29] 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 Regional and inter-regional collaboration

All regions now place high attention to multiple issues peculiar to their regions and their unique solutions. The European Union, 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 some of the issues through regional and inter-regional collaboration. It is well recognized that many of challenges are not with the remit of individual countries to address and collective efforts bear fruits.

Collaboration and transparency are prerequisites of standardization, which is where UNFC may apply. Using UNFC in mineral resource management is now recognized as valuable by European Commission, African Union Commission[30] and by major resource producing and consuming countries such as Russia, China and India. UNFC provides the necessary framework for sustainable mineral resource management to avoid multiple issues as above 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

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 [48]. 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 [49]. However, the degree to which the uranium tale needs reconstruction to take advantage of the new conditions within which it can be told might argue that for some existing resources the only alternative is to imagine they are entirely new, a process that 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

[30] See 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

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 of for-profit companies in particular around intangibles rather than tangibles might argue 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 the table. However, it understates the role of innovation to an asset that revolutionary devices such as the smartphone derive their impact simply from rearranging various, often neglected, members of the periodic table in such a way that our phones are now equally cameras, navigation instruments and multimedia communication instruments. In that sense, thanks to the astonishing gains delivered by Moore's law regarding processing power vs processing cost, the entire global economy is tipping away from the material (how to communicate) towards the intangible (what 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 as now increasingly imagined, and at an estimated 0.5% economic circularity, for example in Europe in 2018 this remains a very big if, 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 game as yet unimagined. Whatever the gains made, and however quickly, the transition to a circular economy – however defined - underlies 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-cycle, increasingly regarding a whole "eco-system" approach rather than on an element by element, material by material basis. The rich information flow required to identify and manage the emerging eco-system 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. However, this is its motivation, rather 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 [50]. 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 by-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 such as 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 the 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.

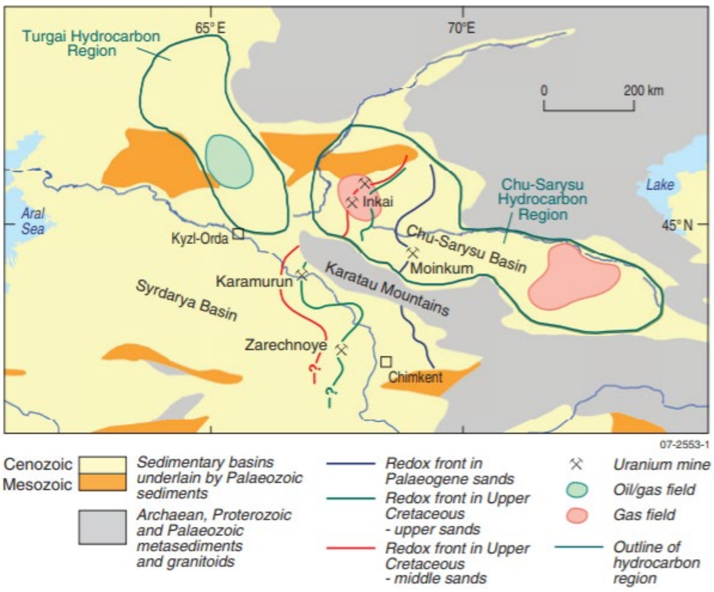

Figure 10 – Energy Basin, Kazakhstan

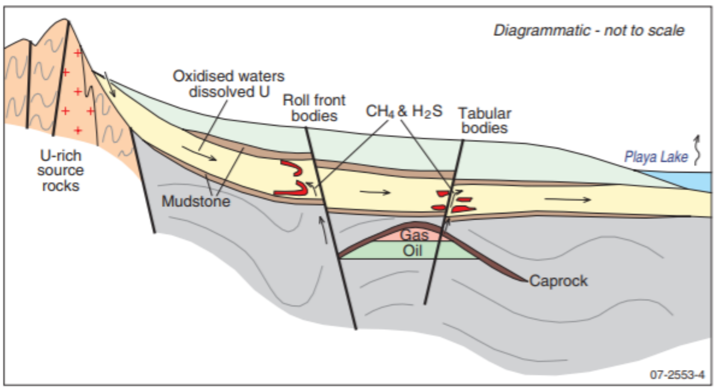

Figure 11. A “typical” energy basin – Uranium and co-located resources

The resources in addition to uranium such basins host include petroleum, gas, coal, phosphate rocks, rare-earth elements and renewable energy resources. Examples include the huge energy basins of Kazakhstan (Figure 10 [51] and Texas, USA (Figure 11). 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 such integrated, whole basin management a manageable proposition, 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. To reverse or prevent such an outcome uranium production has shifted to ISR, 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 operation could also be possible for transforming open cut and underground operations. Mining and recovery of uranium and other minerals of value 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

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[31]. 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, or 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 300ppm, 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, in countries long affected by unremediated tailings, see Figure 6 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 [52]. 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 host rock, and more effectively managing mine tailings that continue to be produced. The CMIC clearly understand that a change as profound as zero waste can only be achieved by mobilising all stakeholders – industry, academia and government. 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-

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

disciplinary and inter-sectoral consortia will minimize overlap and focus joint efforts on the mutually understood endpoint of zero mine waste.

The program 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. Step-wise achievements in meeting a zero mine-waste endpoint will produce significant economic benefits, high paying jobs and the sustainable development of remote, northern communities.

3.12.2 Australia

The case for a comparable approach has been set out for by W. John Rankin for Australia. 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 [53]. In terms of the strategic response required the steps are very similar to those envisaged by CMIC:

> 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; and 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, aluminium, 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+ 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 tackle aspects 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 the financial decision levels. It will always be helpful if all the actors will be speaking 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 been 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: socio-economic and environmental resilience through the comprehensive use of sustainable mining and processing practice.

4.0 Changing nuclear energy landscape

4.1 Current state

Currently, there are 448 operational nuclear power reactors in the world (at the end of 2016), with a total net installed power capacity of 391 GW(e). An additional 61 units with a

total capacity of 61 GW(e) are under construction. IAEA provides projections for nuclear capacity to 2050 every year, and these estimates are being lowered every year since 2011. In 2017, the IAEA estimates in the low case (Figure 13), the world nuclear electrical generating capacity to gradually decline to 345 GW(e) by 2030 and 332 GW(e) by 2040 and then rebound to 382 GW(e) by 2050. In the high case it is projected to increase to 554 GW(e) by 2030, 717 GW(e) by 2040 and to 874 GW(e) by 2050.

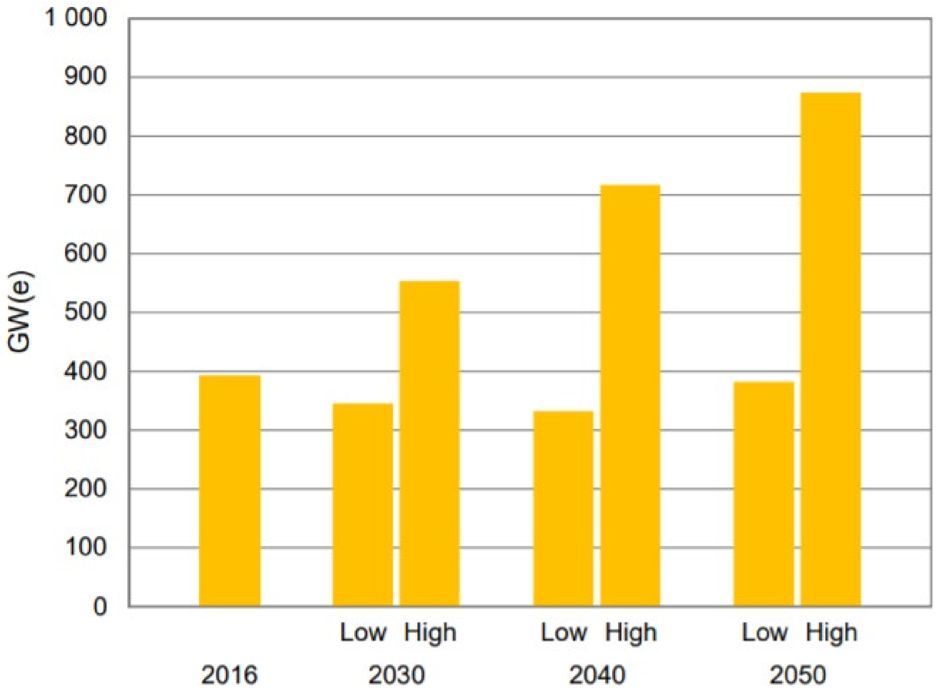

Figure 13. World Nuclear Electrical Generating Capacity to 2050

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.

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 paid back [54]. Financial institutions are becoming averse to this long-term risk and are asking governments to provide guarantees. With governments unable or less willing to provide such guarantees, the future of 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 operating phase 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, 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 or modular reactors (SMRs). This newer generation of modular reactors are designed to generate up to 300 MW(e). Equipped with factory fabricated systems and components and being transportable as modules to the sites as demand arises, SMRs aim for the economy of serial production with short construction schedules and much lower CAPEX entry thresholds.

They offer flexible power generation for a wider range of users and applications, including replacing ageing fossil power plants. There are about 50 SMR designs and concepts worldwide, some of which are said to be near-term deployable, and several countries with existing nuclear power programmes as well as newcomer countries are conducting SMR research and development. The three SMR types that are in advanced stages of construction in Argentina (CAREM), China (HTR-PM)3 and the Russian Federation (KLT40) are scheduled to begin commercial operation between 2018 and 2020. The first commercial fleet of SMRs is expected to operate in the time frame of 2025–2030.

Many recent development points to the interesting turn the nuclear energy landscape is talking. Rolls-Royce, leading a consortium of British companies to design small modular reactors, recently announced a technical feasibility study in Jordan[32]. China and Saudi Arabia have signed a cooperation agreement for a joint study on the feasibility of constructing high-temperature gas-cooled reactors (HTGRs)[33].

4.4 Innovation

Innovation was named in the Paris Agreement as key to meeting the 2°C goal. It is also key to SDG9. Innovative nuclear power technologies, including evolutionary designs, small and medium-sized or modular reactors (SMRs) and advanced fuel cycles could more effectively contribute to reducing greenhouse gas emissions and extending the role of nuclear power into new applications. For example, nuclear power can further reduce carbon emissions by

[32] 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

[33] 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

supplying process heat to industrial processes, and it can also be used to produce desalinated water for cities in dry climates.

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 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 our intention, or perhaps our policy, or perhaps or desired outcome when we invest 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 and supply-side and demand-side perspectives, in a world increasingly committed to a "smart", lower or zero-carbon footprint for energy generation. This is not just an energy-market specific rethink. The energy market like the economy as a whole is also challenged to rapid advances in digital technologies and the re-emergence of artificial intelligence which taken together place 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 commodity. Uranium perhaps of all energy sources will benefit most from this reframing process. Relative to all the other energy sourcing options, the relative cost of uranium as a fuel for the nuclear power is significantly lower than the equivalent costs for coal, oil, gas or even wood. Hence the primary focus of fuel security as applied to uranium is its guaranteed availability per se, not its price. This unique attribute cannot but positively affect the uranium industry if seen as an essential service provider rather than as a commodity merchant.

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 World War Two widespread public anxiety 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 in the earth's crust, must be addressed transparently and robustly, including all necessary provisions for safeguards, security and safety
- This anxiety has caused varying, and now increasing, degrees of disruption to the "social licence to operate" (SLO) on which, as with any other sustainable mining and processing activity, uranium production depends; the uranium SLO must be renegotiated

- Associated decisions by some major economies to end their national nuclear power programmes and transition fully to renewable energy sources must be reviewed, as is happening already in less developed economies such as Nigeria and Philippines
- 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 in-situ leaching (ISL) and heap leaching using either acids or alkalis 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 P and Cu) in the form of an integrated flow-sheet best exemplified by the Santa Quiteria project Brazil (see Figure 15).

5.1.2 General mining and processing sector – core principles

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

- "Integrated and balanced"(SDGs) 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, 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 (Nash-Stackelberg Equilibrium[34])

[34] 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

Applying these principles has two fundamental consequences for the redesign of the uranium resource pathway, both of which were anticipated in the Bridging Document 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 UNECE
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.

UNFC (as revised) can be used as a resource progression tool to address these tasks within the changed policy context now in place for determining how to meet sustainable energy needs.

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.

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

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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.

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 (September 3, 1948) and power a light bulb was the X-10 Graphite Reactor housed at Oak Ridge, Tennessee, USA. The world's first nuclear power station to generate electricity for a power grid started operations at Obninsk June 27, 1954. The world's first full-scale nuclear power plant, Calder Hall, UK started operations October 17, 1956. However, illustrating the ambiguous narrative, Calder Hall was also intended to produce plutonium, hence had a double peaceful/non-peaceful mission reflecting or perhaps reinforcing the 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. This was connected to the grid on December 18, 1957.

As acknowledged by the 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 rise of nuclear energy from the late 1950s gave both to and is to an extent mirrored in the so-called Red Book [30, 31], the joint publication of the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD) and the IAEA. First published in 1965, it 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’s 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. However, 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.

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 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 U. 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 us to change 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 the means by which 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 material", 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) 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 SDG objectives of "balanced and integrated" resource management are simply ignored or overlooked.

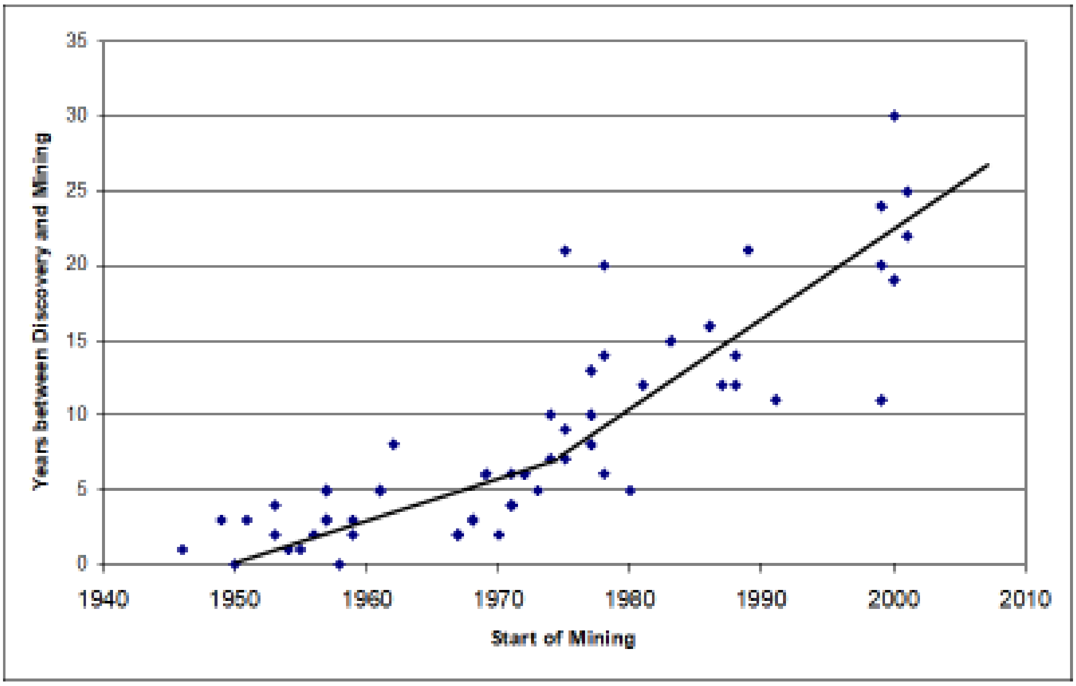

Figure 14. Uranium project lead times from discovery to commercial production [55]

A potentially game-changing example of how an innovative approach can transform this practice is offered by the Santa Quiteria co-product project in Brazil (Figure 15) which integrates the production of yellowcake and of phosphate fertilisers in a single flowsheet.

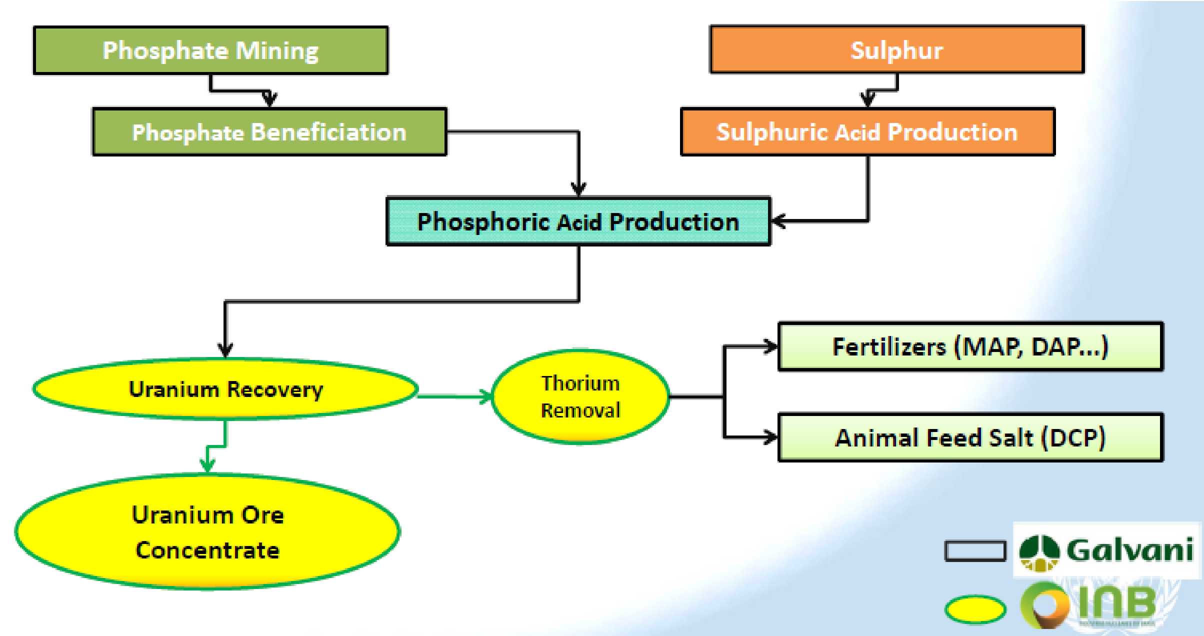

Figure 15. The Integrated flow-sheet (UxP), Santa Quiteria example – DAP and yellow-cake

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

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 social licence to operate 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 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 now 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 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 in 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 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.

6.2.1 UNFC – from Tool to Tool-kit

UNFC, as it evolves into a toolkit, puts 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 resource-driven tool is transforming into a more comprehensive tool-kit, with at least five main categories:

- **Resource centred** (life-cycle resource management, primary & 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 this tool-kit 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.

6.3 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 vs 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 (i.) Based on a clear and meaningful distinction between (i.) Answering “why” questions and “how” questions; (ii.) Equally promoting 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 policy-making 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 competitive contributing both directly and indirectly to the delivery of clean, indefinitely sustainable, affordable energy with wide-ranging benefits to the public and environmental 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 sustainable development goals.
- 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.

6.4 UNFC and managing the national security of supplies

UNFC is a tool that allows countries to manage their total resource base at the national level. 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 [6]. 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, as 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 incoherent 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.

6.5 UNFC and secondary supplies

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 5, 7 and 8).

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 agenda high on the working agenda for UNFC in the coming work cycles. 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 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 futureproof the resources they still contain. 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 a number of 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.

UNFC is a 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.

6.6 UNFC and financial reporting

UNFC can be the basis for a public reporting code, which is used by companies to report their mineral assets to stock exchanges and banks. Stock exchanges use various codes developed around the world to report mineral resources currently. 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 recovered) as fluids such as lithium and potash are not covered by such codes. Social and environmental consideration 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.

6.7. 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 (TAEC) Commission, under the rubric Uranium Production Site

Assessment Team (UPSAT)[35]. 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 5 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.

At the INT meeting held in Arusha Jan-Feb 2018, representatives of TAEC provided a detailed update, five years on, concerning both on the direct outcomes of the UPSAT mission and the follow-on benefits it had stimulated both at TAEC HQ and in wider URT.[56] 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 URT flowing directly and indirectly from UPSAT are in abundant evidence.

6.7.1. 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, awhile 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 1. The issuance of a special permit to mine; 2. Construction start. 3. Mining and Milling start. 4. First yellowcake shipment, 5. Mine closure, decommissioning and rehabilitation; 6. Handback to URT by the operator and return of site to within the boundaries of the UNESCO protected Selous game reserve.

Figure. 16. Project operational milestones

Having adopted the objective of clear and transparent communications between all parties it was also recognised that operational success was co-dependent with regulatory

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

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 below (Figure 17).

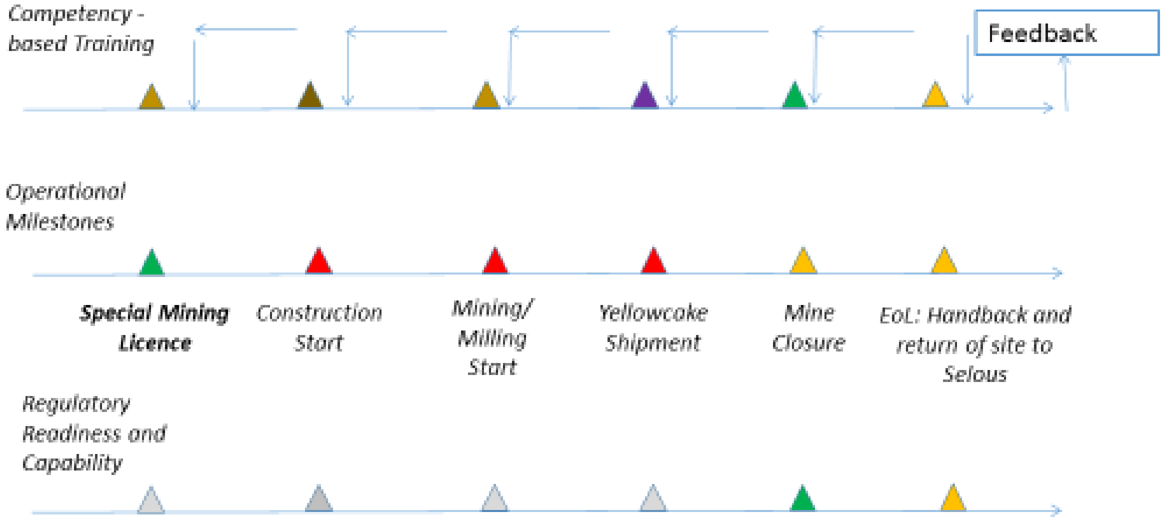

Figure 17. Integrated competency-based training aligned with operator regulatory needs

6.7.2 Competency-based Training

A programme of cross-cutting competency-based training was the outcome of this agreement, and as can be seen in Figure 15, 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 unlimited resource of either personnel or finance, the emphasis was on the next-immediate milestone regarding where to prioritize the allocation of resources.

6.7.3 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 of the European Commission visiting URT to review the proposed extension of URT mineral development activities into the uranium sector. The outcome as very positive and the EU 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. Support to 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;
4. Strengthening the technical capabilities of the Tanzanian Atomic Energy Commission (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, skills and capabilities developing in significant measure both technically and administratively. However, as can be seen in Figure 16 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 5-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

6.7.4 Integrated Workflow – Project Dashboard with KPIs

The objective of a milestones-based “dashboard” (see 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 to the milestones model, reflecting the 3 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 eco-tourism while 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 Mkuju River 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.

Figure 19. The integrated project performance dashboard

Of the essence from a project performance and outcome point of view 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.

6.8 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 eco-system resource management and recovery capability*
5. *Zero waste (0W) and comprehensive resource recovery (CRR) equilibrium waste/ resource (= environmental-economic equilibrium).*

6.9 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 it with the local energy system.

Such legacy sites will be increasingly characterized using 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 the UNFC methodology to regenerate such sites will be:

A complete inventory of all available resources and its accurate valuation

- Funds that 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 to support the site regeneration and local energy system
- Useful mineral based products include fertilizers, soil amendments and artificial soils

- Local economy reinvigoration by entrepreneurial opportunities, jobs and social security
- Local environment restores 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. While the energy markets are adapting to requirements of the new world order based on the Paris Agreement and the Sustainable Development Goals, the role of nuclear energy remains crucial. However, due to steadfast adherence to old business models, the nuclear industry's growth remains challenged. 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 future and will remain more or less flat.

While the nuclear electricity sector has an opportunity to penetrate new markets with small modular reactors (SMRs) and with Generation IV technologies which will be more acceptable to the public and financiers, it has to 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 the challenge of 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.

Rapid changes that are sweeping through the global economy, especially in relation to sustainable energy resources, their availability, production and marketing have made uranium resource management more and use more urgent but at the same time more challenging and complex than ever. Resolving this complexity and achieving long-term, public acceptance will require the view that uranium 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 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.

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