A Decisioneering Toolbox for Nuclear Energy System Strategies Assessments: NucInfo / DANESS / NROM

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NUCLEAR-21.NET

Nuclear Energy System Strategies Assessment Toolbox

NESSAT v1

Version 1 – June 2016

NESSAT

NUCLEAR-21.NET

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A.
Introduction

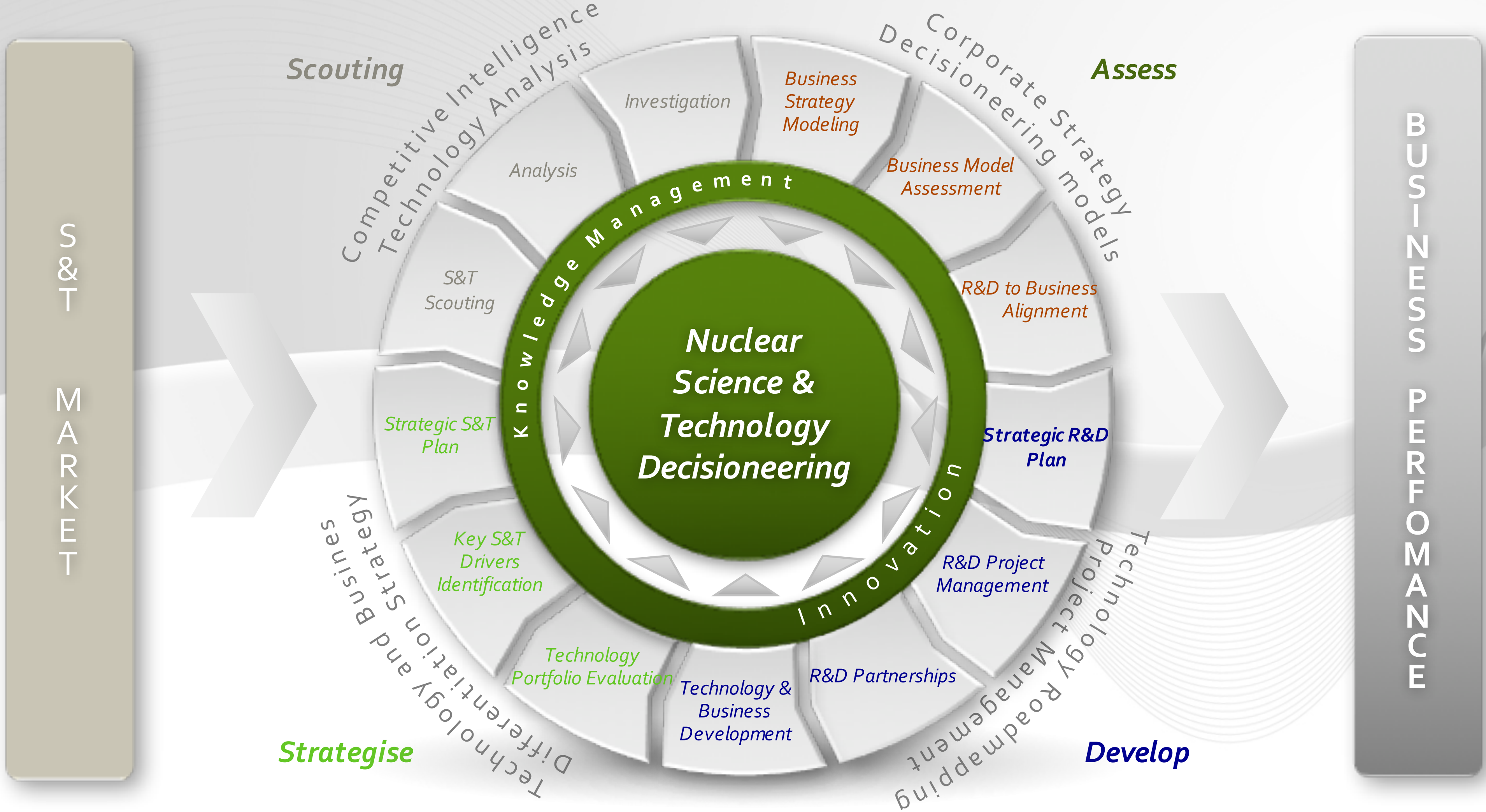
Nuclear-21.Net

We're an international operating expert firm specialised in nuclear science & technology decisioneering services to governments, investors, utilities, industry, R&D-laboratories and waste management agencies worldwide:

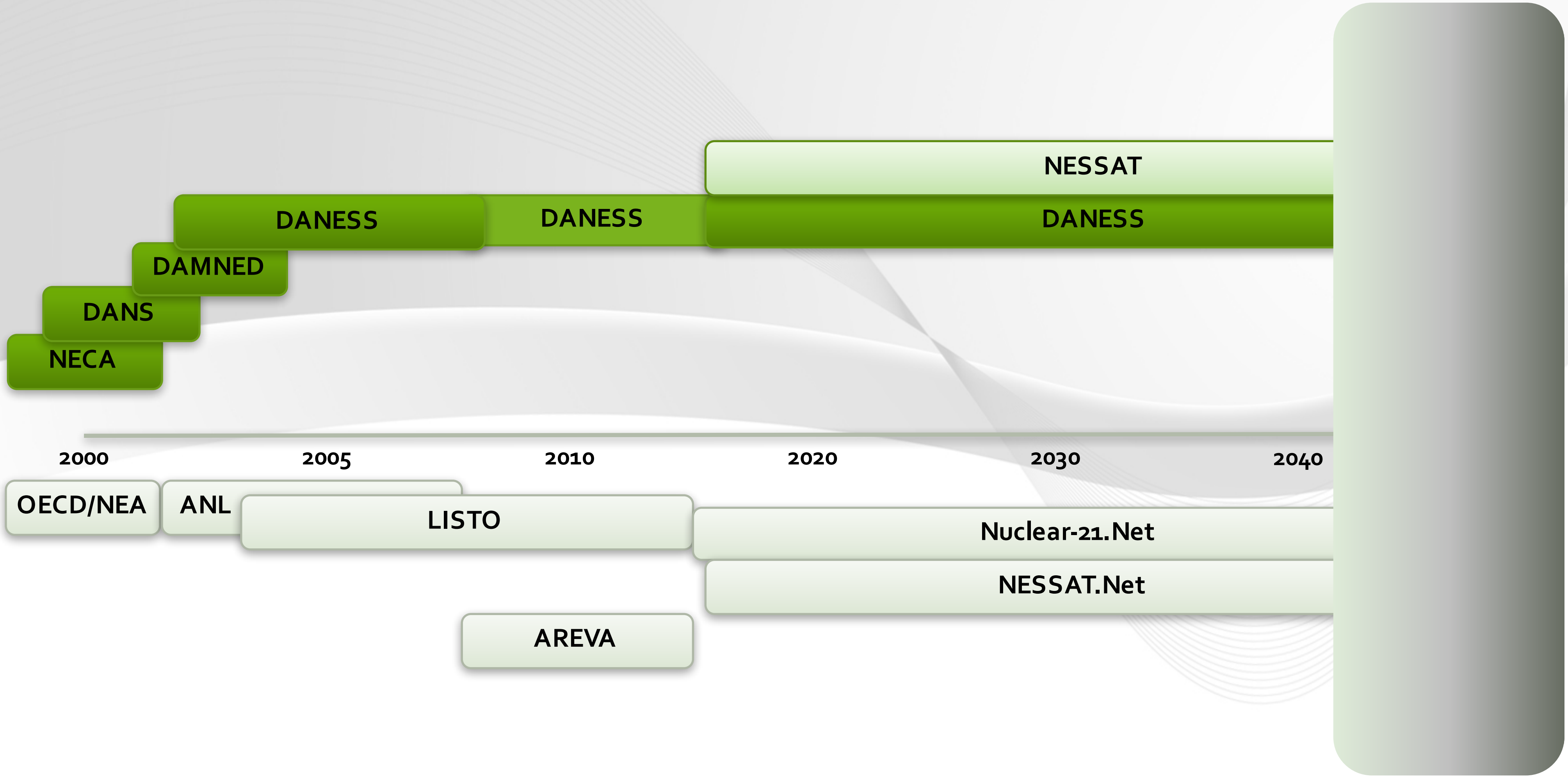
- *Our partners and consultants are among the best independent experts based on extensive international experience in various domains of science and technology, technology-to-business management, engineering and operations*
- *We specifically focus on supporting technology providers and technology seekers in designing, developing and steering profitable business development covering nuclear energy, nuclear medicine, radiation diagnostics and other radiation applications in clean technology development*
- *Our expertise covers the whole decisional process from early consideration to use or develop nuclear science & technology applications up to the investment and business development process as well as the management of such programs internationally. Nuclear energy policies, public policy on nuclear applications including non-proliferation and international safeguards, security as well as safety of our customers' plans and assets are part of our portfolio of activities*
- *We partner with companies, S&T-organisations and experts worldwide fitting your needs and enriching your and our portfolio of expertise and capabilities*

In short, we can help you in developing nuclear science & technology as a critical contributor to sustainable solutions for us all during this 21st century.

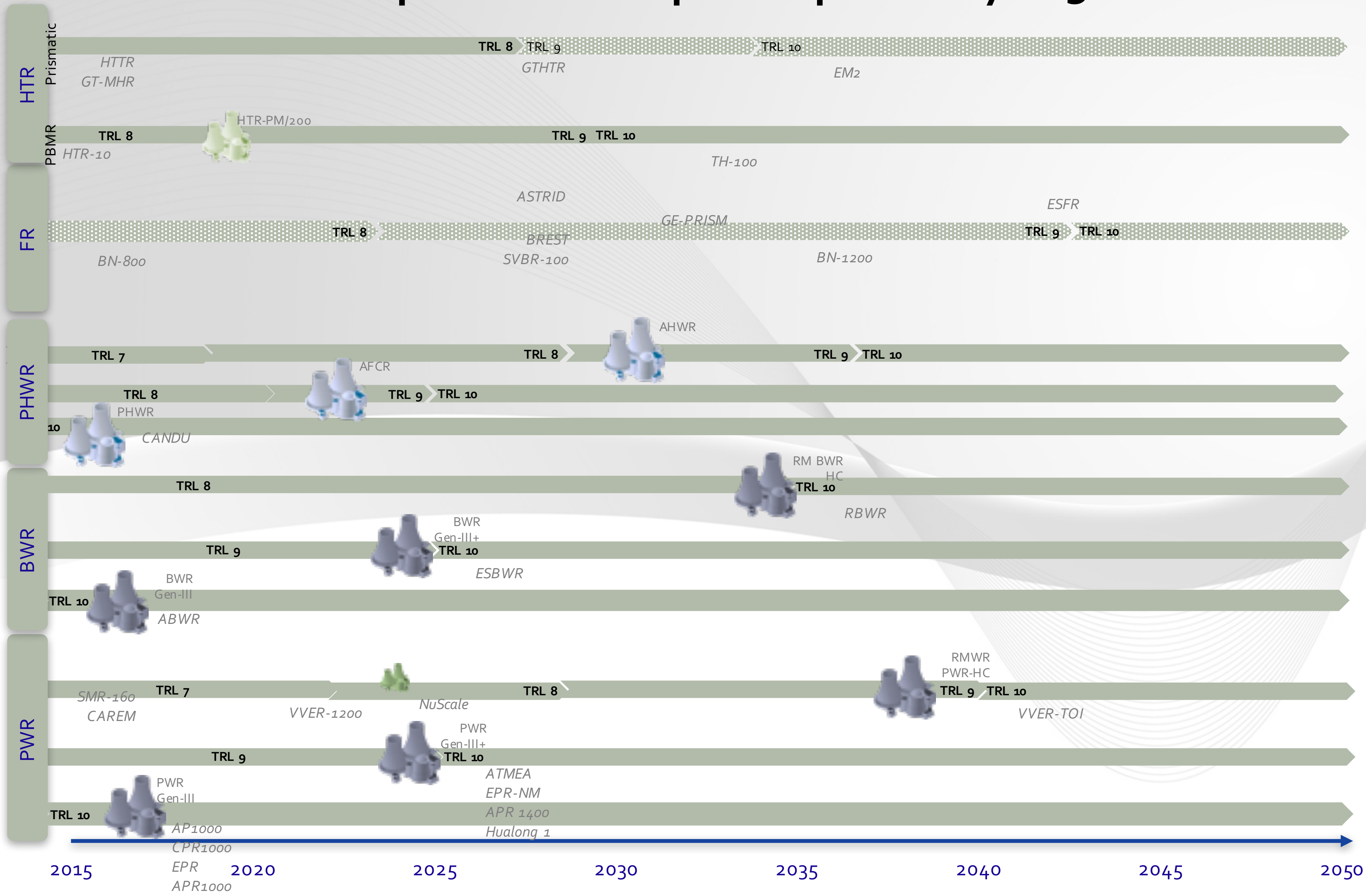
Nuclear-21.Net
An integrated set of expertise and services to optimise technology-to-business decisions



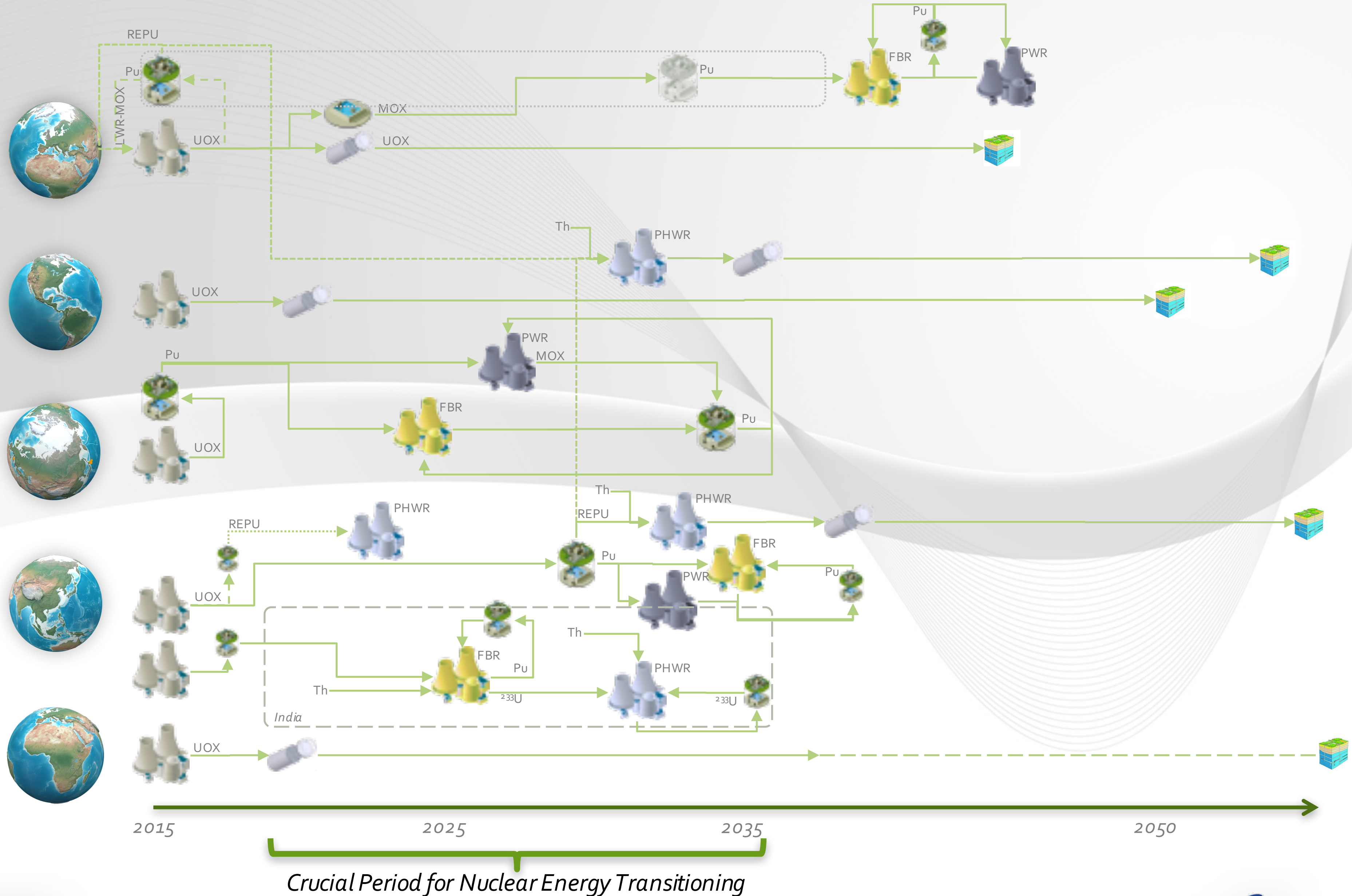
‘My’ past, present and future in “scenario studies”



Overall roadmap for nuclear power plants by 2050

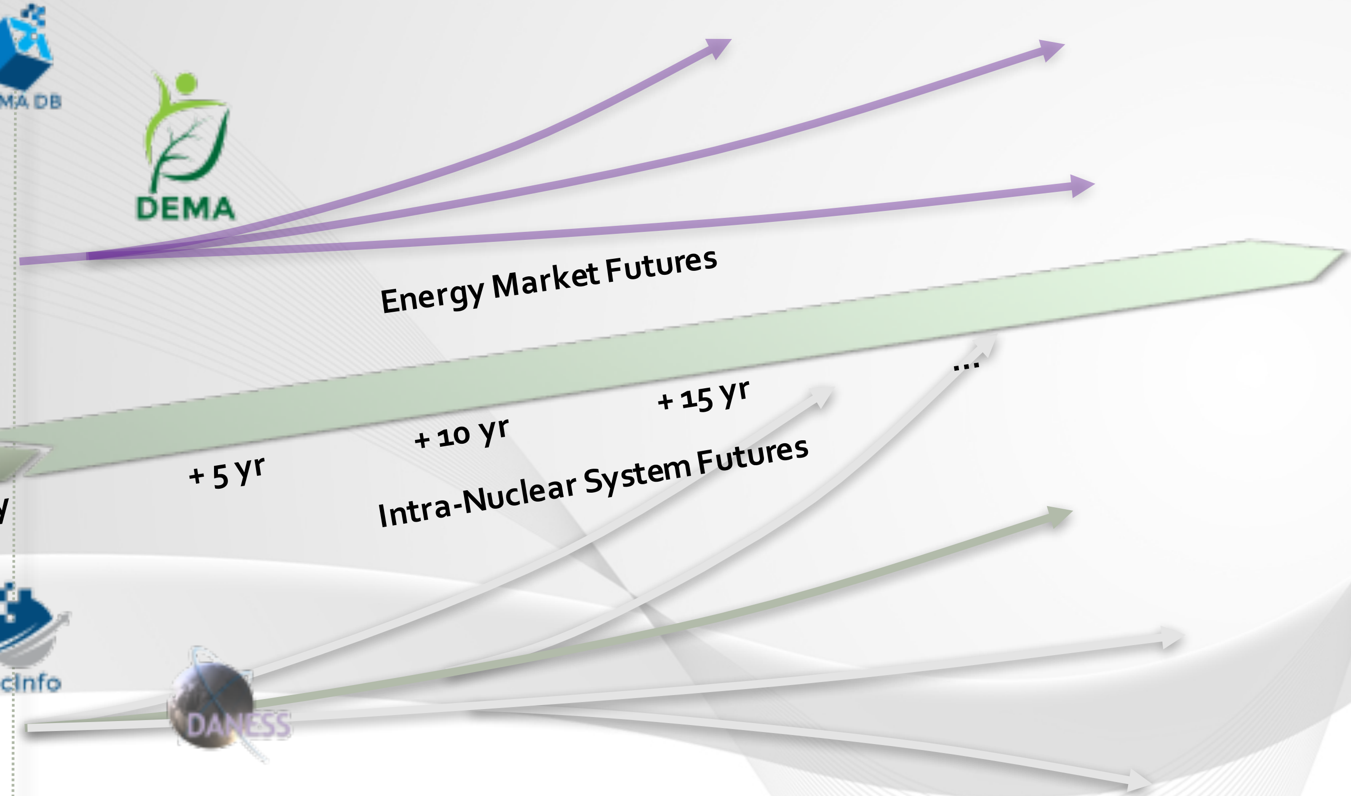


With more diversifying fuel cycle strategies worldwide
Local decisions impacting global business and vice-versa



NESSAT Architecture

Past and Present information on
- Energy market evolution per country
- Technical-economic performance of energy system technologies
- Summary of energy market scenarios per country/region



Past and Present information on
- Nuclear reactor park
- Fuel cycle facilities
- Fuel cycle services
- Mass-flows and inventories
- Economics

per reactor, utility, country, world

Technical-Economic characteristics of present and future nuclear energy technologies and services

DANESS DB

Library of scenarios
- Technology deployments scenarios
- Utility / country scenarios
- User-specific scenarios

FCCM

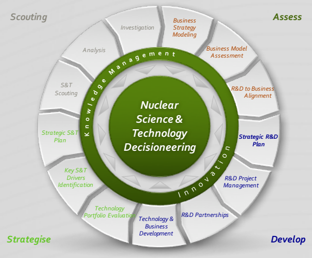
Fuel Cycle Economics
- NPV and levelised costing
- Front-end fuel cycle cost optimisation
- Fuel cycle cost comparison

NROM

Nuclear Real Options Model

Valuing decisional options within uncertain futures
- Reactor investment decisions
- Fuel cycle options
- Cost/risk exposure evaluation

Changing objectives and scope



World Market

Data Validation → Precise Case-description → Clear Case-objectives → Case Simulations → Results Analysis → Decisional Impact → Regular Updating

DEMA DB, DANESS DB, nucInfo

DANESS, DEMA, FCCM

nucInfo, NROM

NESSAT
Nuclear Energy System Strategies Assessment Toolbox

- NESSAT provides
  - ***Up-to-date past, present and future nuclear reactor and fuel cycle information on reactor, utility and/or country level***
  - ***Projection of future deployment scenarios for nuclear reactor park and associated fuel cycle facilities and options***
    - *Technical-economic analysis of nuclear reactor park and/or fuel cycle options*
    - *Library of deployment scenarios from Business-As-Usual to transition scenarios towards more advanced nuclear energy system options*
  - ***Analysis of the technology-to-business potential by***
    - *Market analysis and projected market trends*
    - *Impact analysis of technology innovation*
  - ***Options value assessment allowing to***
    - *Value decisional flexibility in nuclear reactor park and/or fuel cycle options deployment*
    - *Optimise cost and risk exposure by assessing optimal options decision-making*

NESSAT
Description

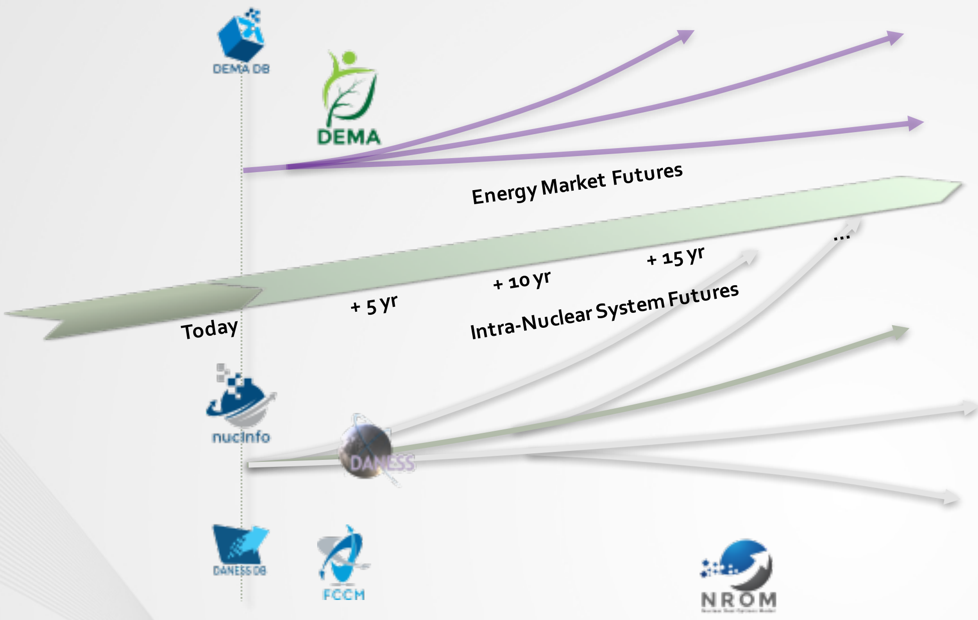
- **NESSAT covers a set of models, databases and interactive visualisation tools allowing to**
  - **Simulate the short to longer-term evolution of nuclear energy systems starting from up-to-date best-available data on past and present in view of:**
    - *Short-term (<10 years) operational decision-making with regard to, f.i.:*
      - Front-end fuel cycle optimisation
      - Used fuel management options evaluation
    - *Medium-term (5 – 15 years) investment decision-making with regard to, f.i.:*
      - Comparative analysis of nuclear power plant investments
    - *Longer-term (>15 years) strategic options decision-making with regard to, f.i.:*
      - Used fuel management options development
      - Synergies between nuclear reactor parks in reducing overall risk reduction in using nuclear energy
      - Technology-to-business assessment
  - **Enrich the decision-making process by projecting decisional impacts in uncertain futures**
    - *Decisions by governments, technology providers, utilities, waste agencies, experts, think tanks*

Meaning of NESSAT logo

- **While the past is known and the future uncertain**
- **NESSAT aims at**
  - Providing technology-to-business clarity in uncertain futures
  - By projecting optimal decisions at optimal decision-moments maximising profitability or minimising cost/risk-exposure for stakeholders
- ***The logo reflects the process of projecting past and present into more certain business strategies despite uncertain futures***

B.

NESSAT Description



B.1.

Nuclear Information Database NucInfo

nucInfo

NucInfo

- **NucInfo is an interactive database-driven infographics tool providing information on nuclear energy, i.e.:**
  - Historic data on and evolution of nuclear reactor parks and associated fuel cycle with visualisation per
    - *Geographic region (world, region, country, state/province, reactor site)*
    - *Reactor family (LWR, PHWR, VVER, …) or per reactor generation*
    - *OEM/Operator/Vendor of reactors*
    - *Reactor and fuel facility status (planned, … , decommissioned)*
  - Fuel cycle inventories from mining till waste disposal
    - *Uranium resources per category*
    - *Front-end (DU) and Back-end (Used fuel, HLW, REPU, Pu) inventories*
  - Statistical information on (among others)
    - *Nuclear energy shares per country*
      - Energy mixes and GHG-emissions
    - *Reactors*
      - Historic evolution of Build-to-Operate times
      - Capacity factors
      - Used fuel inventories and fuel types
    - *Fuel Cycle facilities*
      - Used fuel inventories in interim storage

NucInfo main features (1/3)

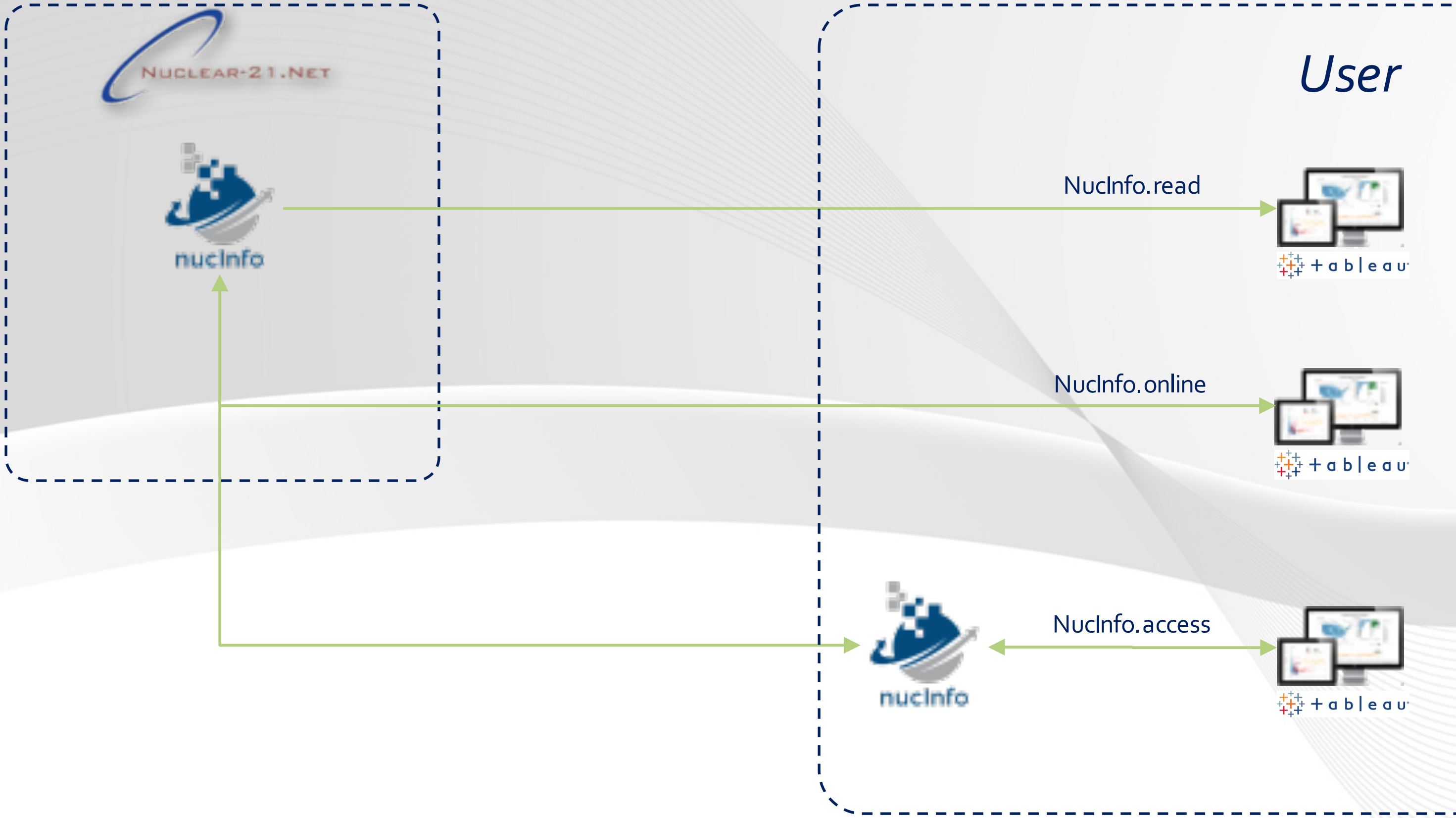
- **All data are interactively visualised in infographs with interactive detailing on world, region, country, province/state, utility, reactor/facility site level**
  - Infographs in webbrowsers, on tablets or as specific application on Windows/IOS/Android (for nucInfo.online and.access)
  - Reactor data
    - *Name, site, geographical data, reactor status (planned … decommissioned), licensing status (original license, license renewal, …)*
    - *IAEA code, Reactor category, reactor type, thermal capacity, gros electric, net electric, average utility factor and capacity factor*
    - *Owner/operator, Architect engineer, NSSS OEM, BOP Engineer*
    - *Effective construction start, grid connection, commercial operation, 1st license renewal, 2nd license renewal, projected shutdown, effective shutdown*
    - *Market (regulated, merchant)*
    - *Economic data (where available)*
    - *Fuel type used, fuel vendor, used fuel at-reactor pool capacity and inventory, dry pad storage capacity and inventory*
  - Nuclear Facility data
    - *Name, site, geographical data*
    - *Owner/operator*
    - *U/Th-mining: reported reserves/resources according Red Book data*
    - *Front-end and Back-end fuel cycle facility capacities and status (planned … decommissioned)*
    - *Effective construction start, commercial operation, projected shutdown, effective shutdown*
    - *Historic evolution of mass-flows and inventories (DU, REPU, separated Pu, used fuel (UOX, MOX), HLW, LLW/ILW, …)*
  - (Nuclear) energy demand scenarios
    - *Nuclear energy demands scenarios on world, regional and (where available) country level based on public data and/or energy scenario studies (among which DEMA)*
  - Where available, historic data available from the early start of nuclear enegy use (i.e. mide 1950's)

NucInfo main features (2/3)

- **Reactor categories, life cycle and licensing status categories in nucInfo**

NPP-Technologies	NPP Life Cycle Status		NPP Licensing Status	
	RS	Reactor Status	LS	License Status
GCR	1	Projected	LI1	License Application
AGR	2	Withdrawn	LI2	License Under Review
PWR	3	Planned	LI3	Initial License Issued
BWR	4	Suspended	LI4	Initial License Expiration
PHWR	5	License Application	LI5	1st License Renewal Application
RBMK	6	Initial License Process	LI6	1st License Renewal Under Review
VVER	7	Licensed	LI7	1st License Renewal Issued
RMLWR	8	Under Construction	LI8	2nd License Renewal Application
SCLWR	9	Constructed	LI9	2nd License Renewal Under Review
AHWR	10	Grid Connection	LI10	2nd License Renewal Issued
VHTR	11	Operational		
PBMR	12	Suspended Operation		
SFR	13	Permanent Shutdown		
GFR	14	Under Decommissioning		
LFR	15	Decommissioned		
TMSR				
FMSR				
ADS				

NucInfo variants



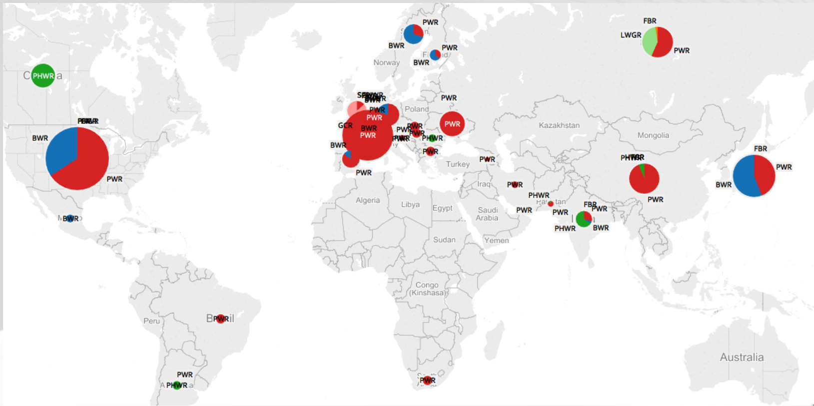
- Read access via web-service or via tablet-application
- No data-access
- No updating or customisation of information

- Full online access via web-service or via tablet-application
- Online up-to-date data-access
- Updating or customisation of information in local database with review service by Nuclear-21.net

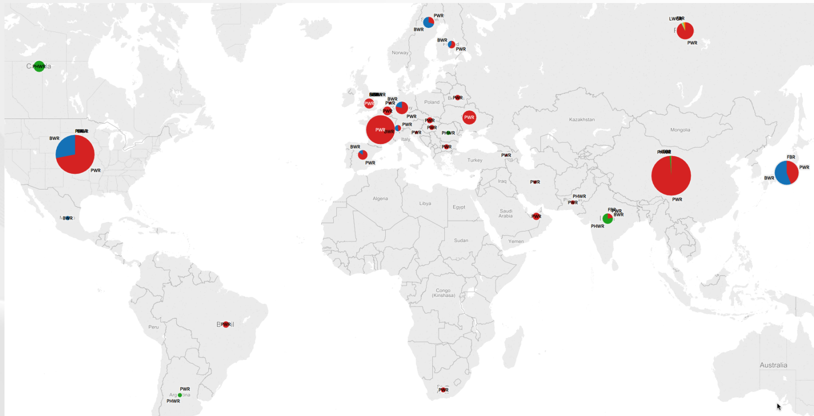
- Full online and local access via web-service or via tablet-application
- Online up-to-date data-access
- Proprietary data-base sections well integrated in infographics environment
- Updating or customisation of information in local database with review service by Nuclear-21.net

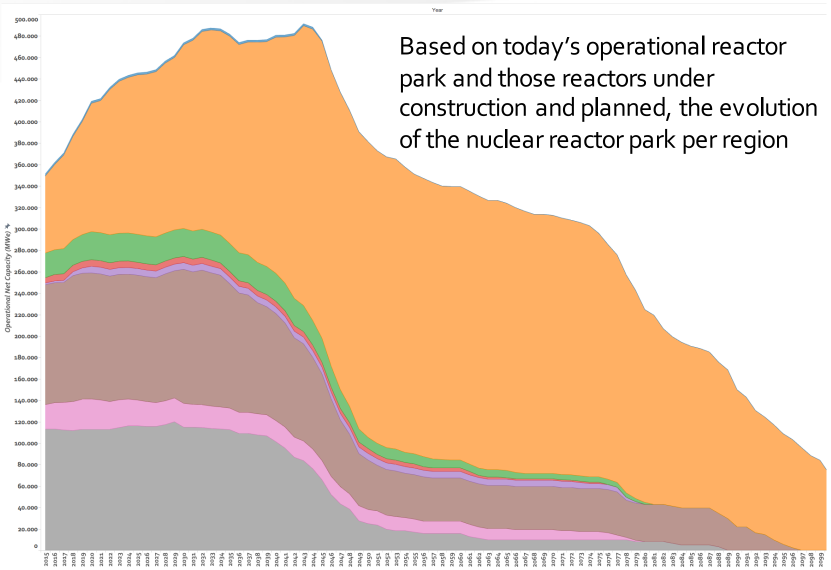
Some snapshots of NucInfo (1/5)

Today's World Nuclear Reactor Park

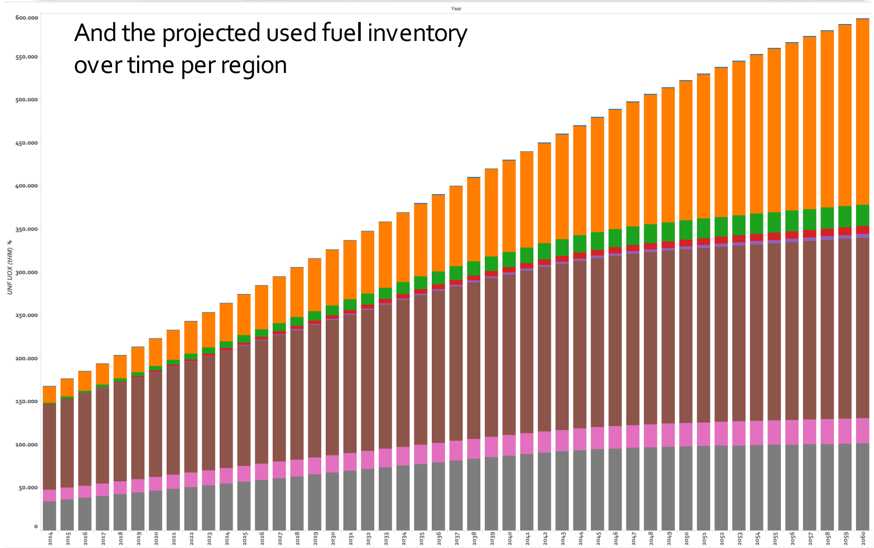


And by 2030 based on today's knowledge





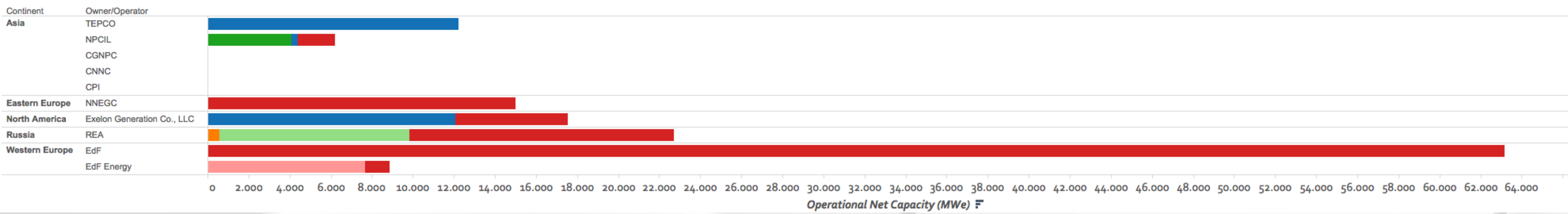
Based on today's operational reactor park and those reactors under construction and planned, the evolution of the nuclear reactor park per region



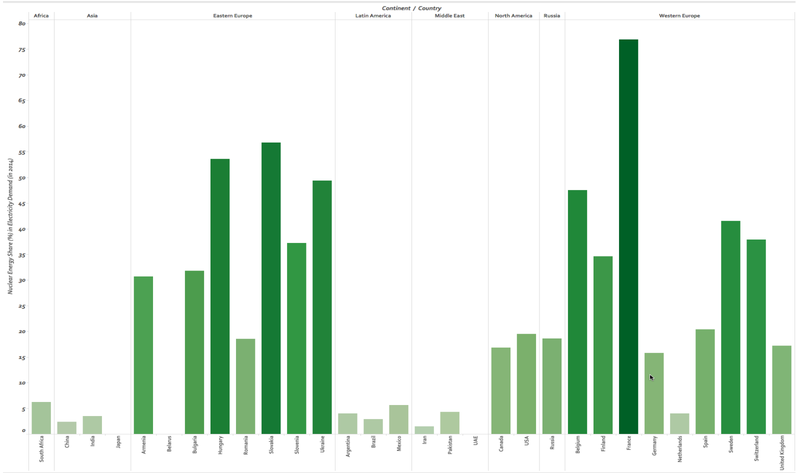
And the projected used fuel inventory over time per region

Some snapshots of NucInfo (2/5)

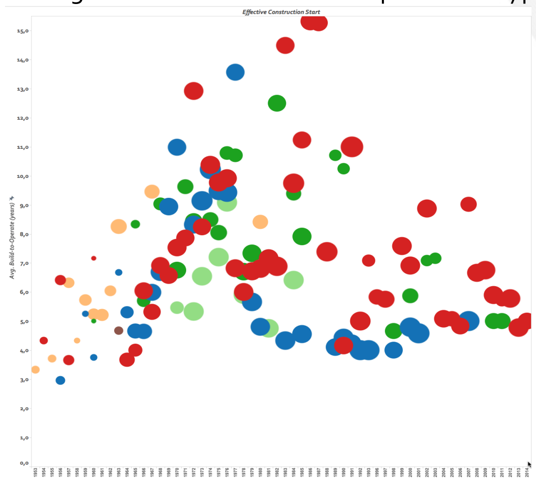
With some statistics as on the larges nuclear utilities per region



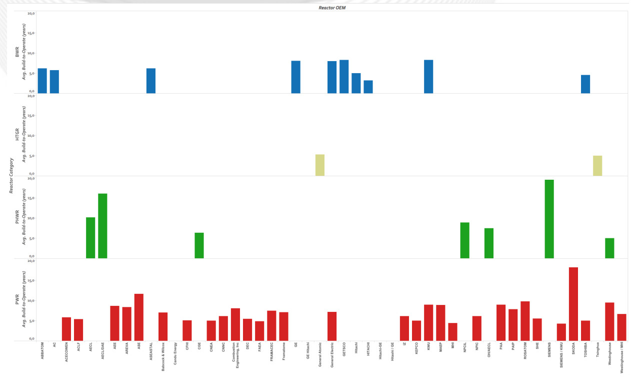
With some macro-statistics such as nuclear share in electricity



Average reactor size over time and per reactor type



Average build-to-operate time per OEM and reactor type

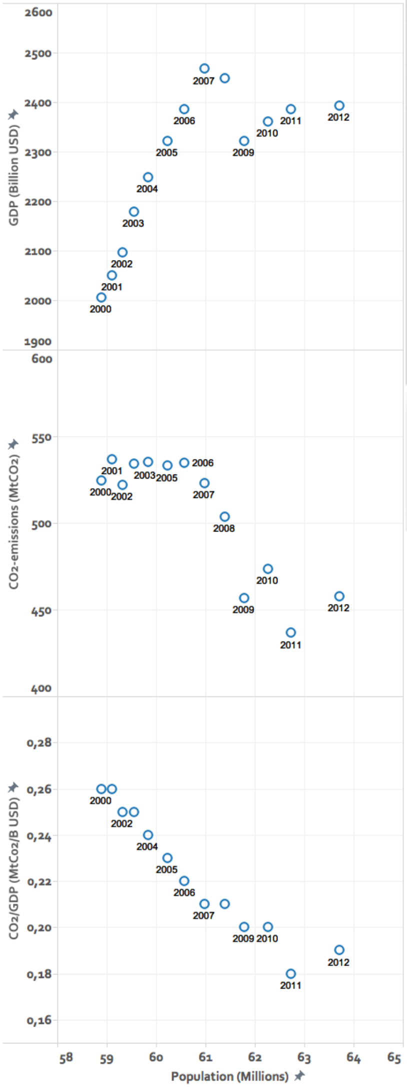


And many other statistics

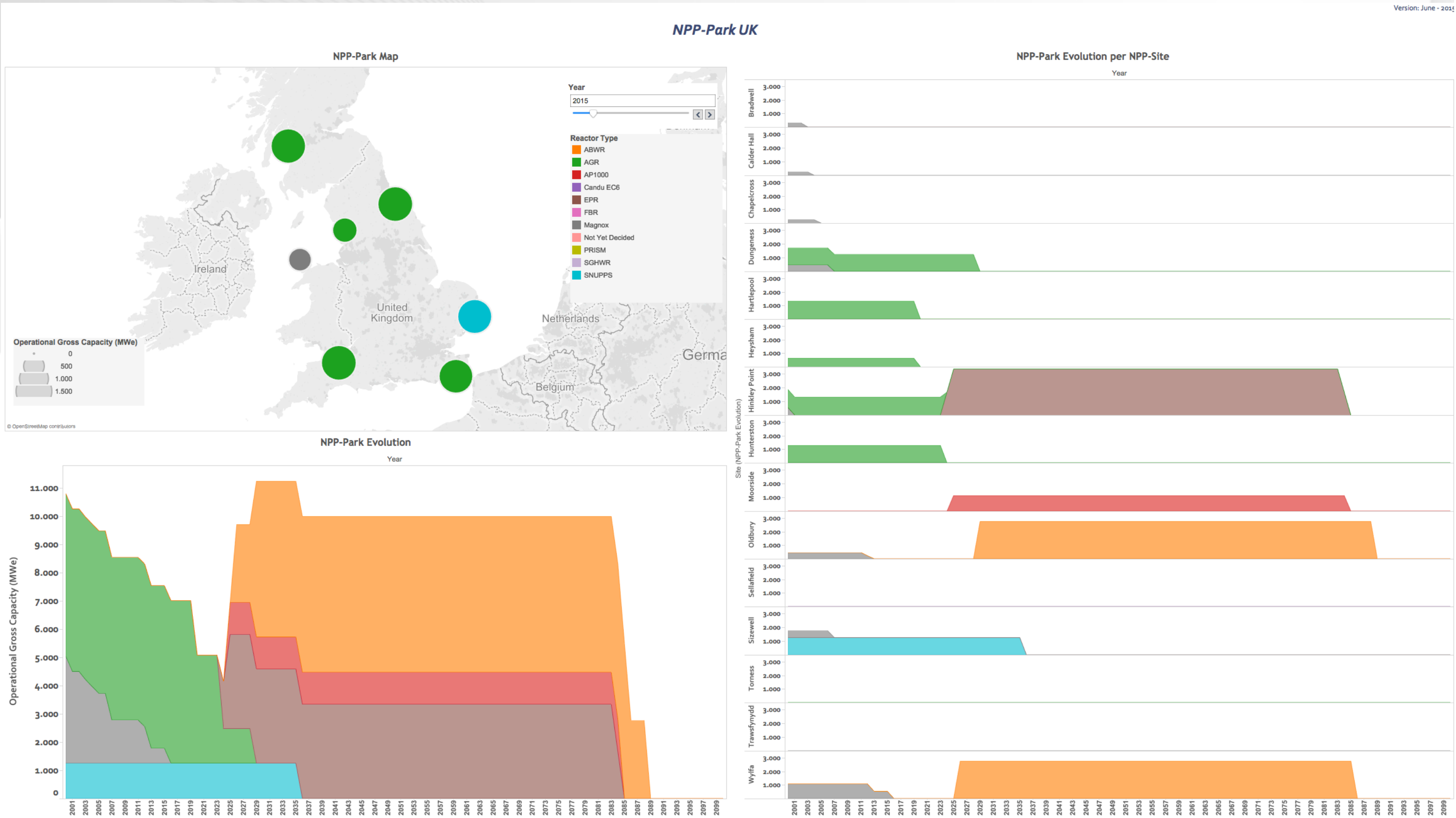
Some snapshots of NucInfo (3/5)

- **A more country-specific infograph-view into NucInfo, f.i. on the UK**

Some macro-statistics on GHG-emission intensity over time



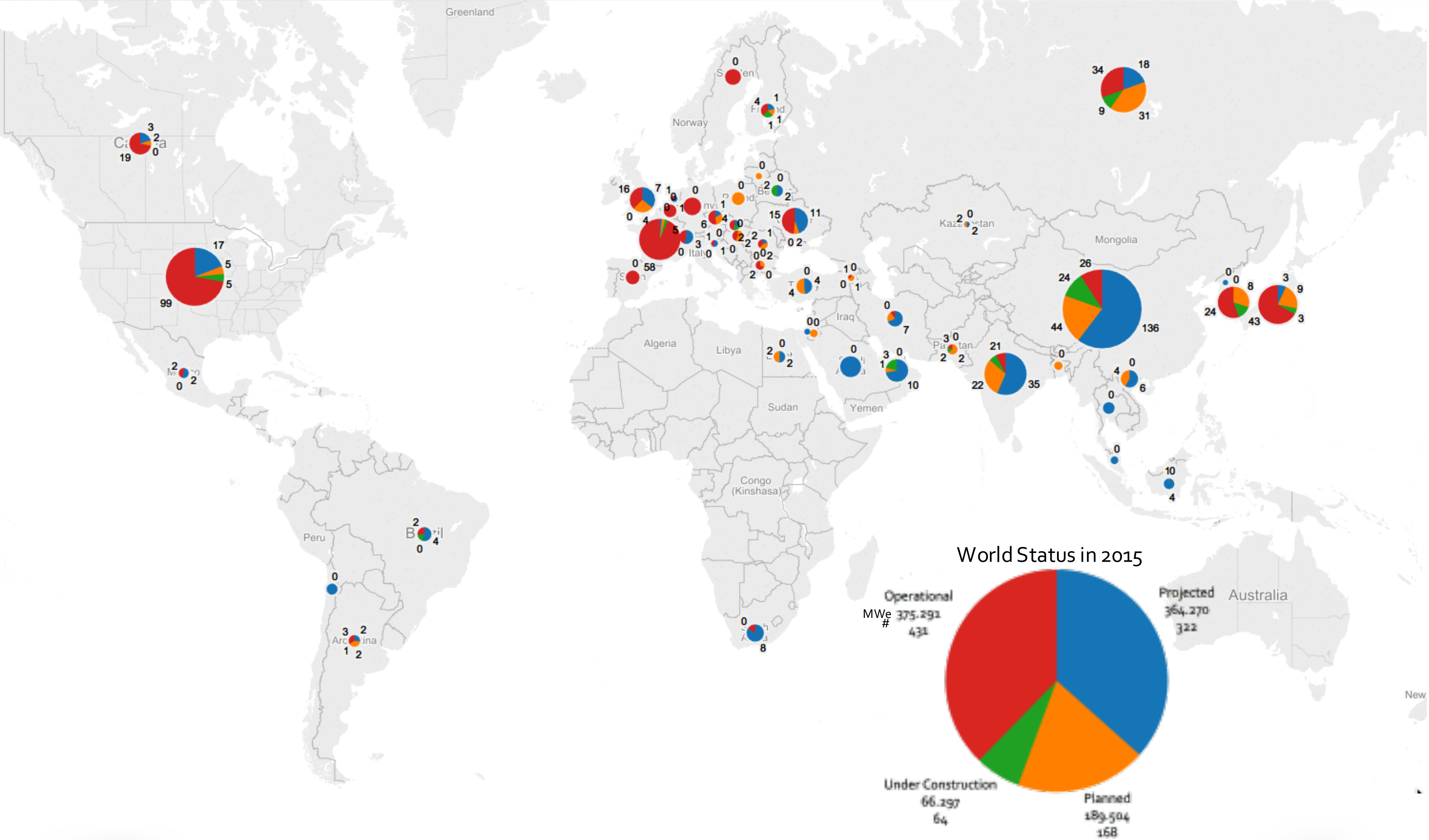
A multi-view on UK's expected reactor park evolution



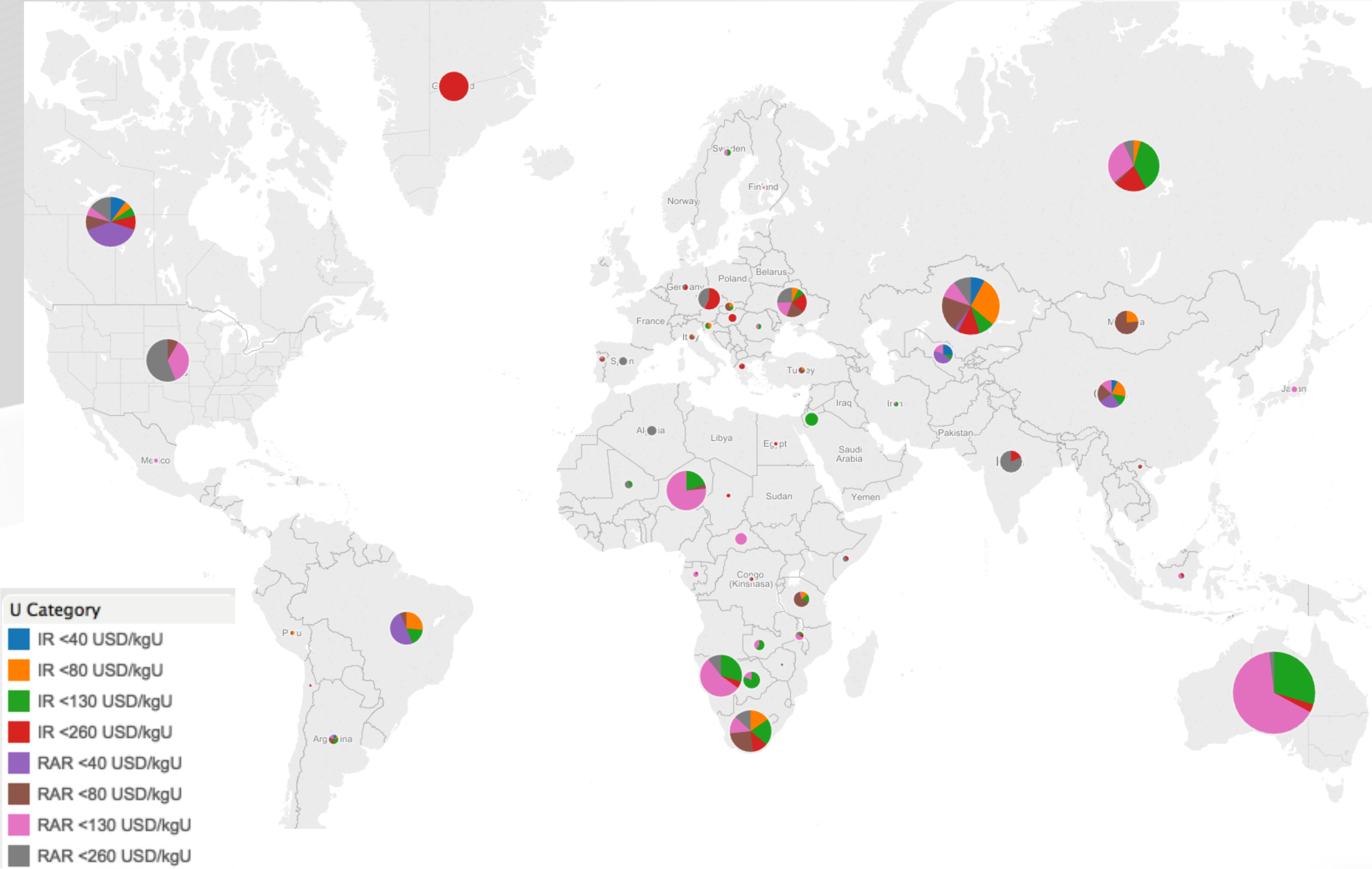
Some snapshots of NucInfo (4/5)

And the expected waste arising in the past and future

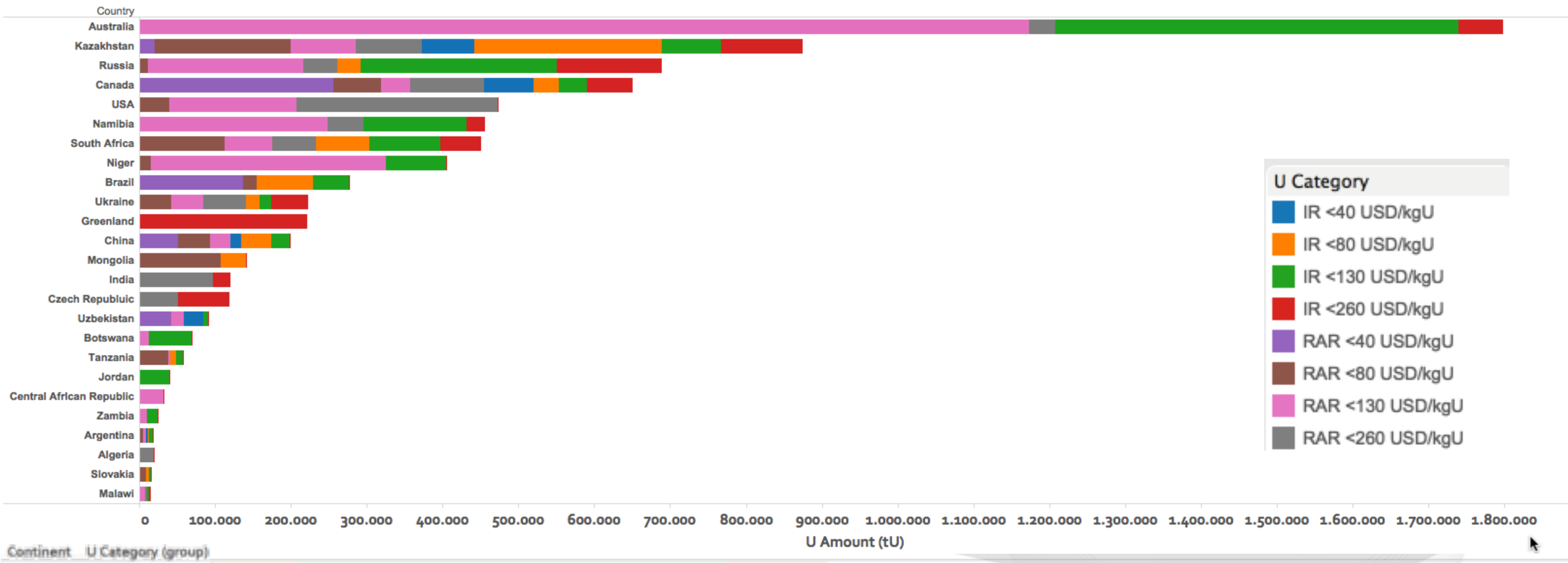
Today's and medium-term projected Nuclear Energy System

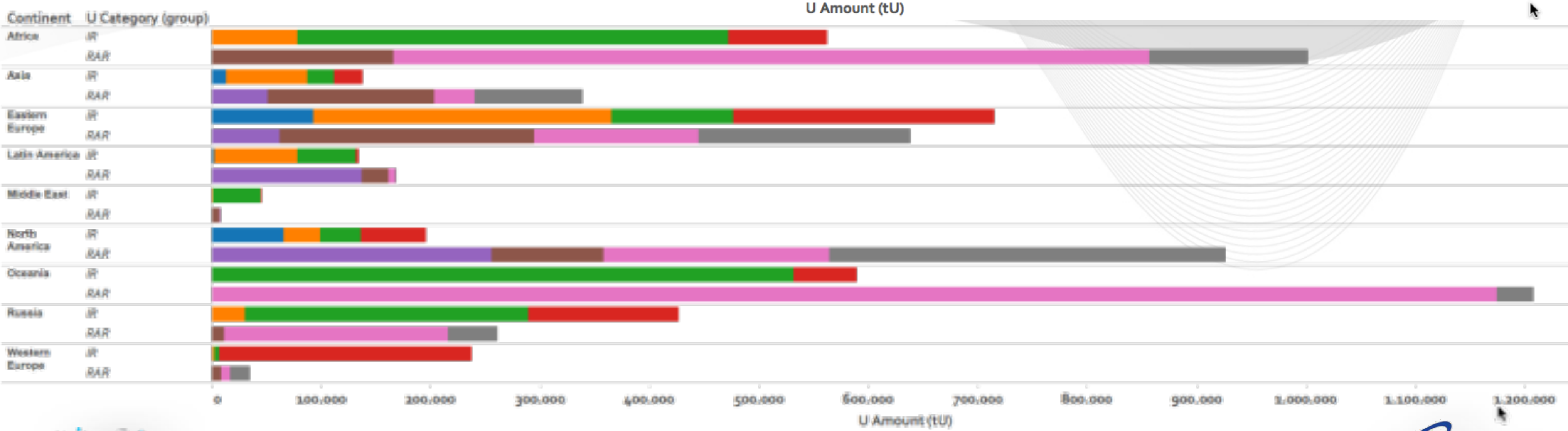


U Resources (RAR and IR) (Red Book 2013)

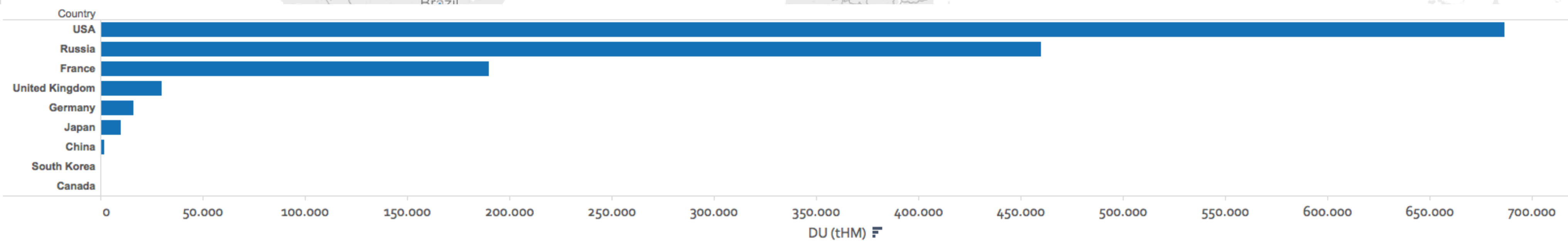


RAR+IR Resources for main producing countries (Red Book 2013)

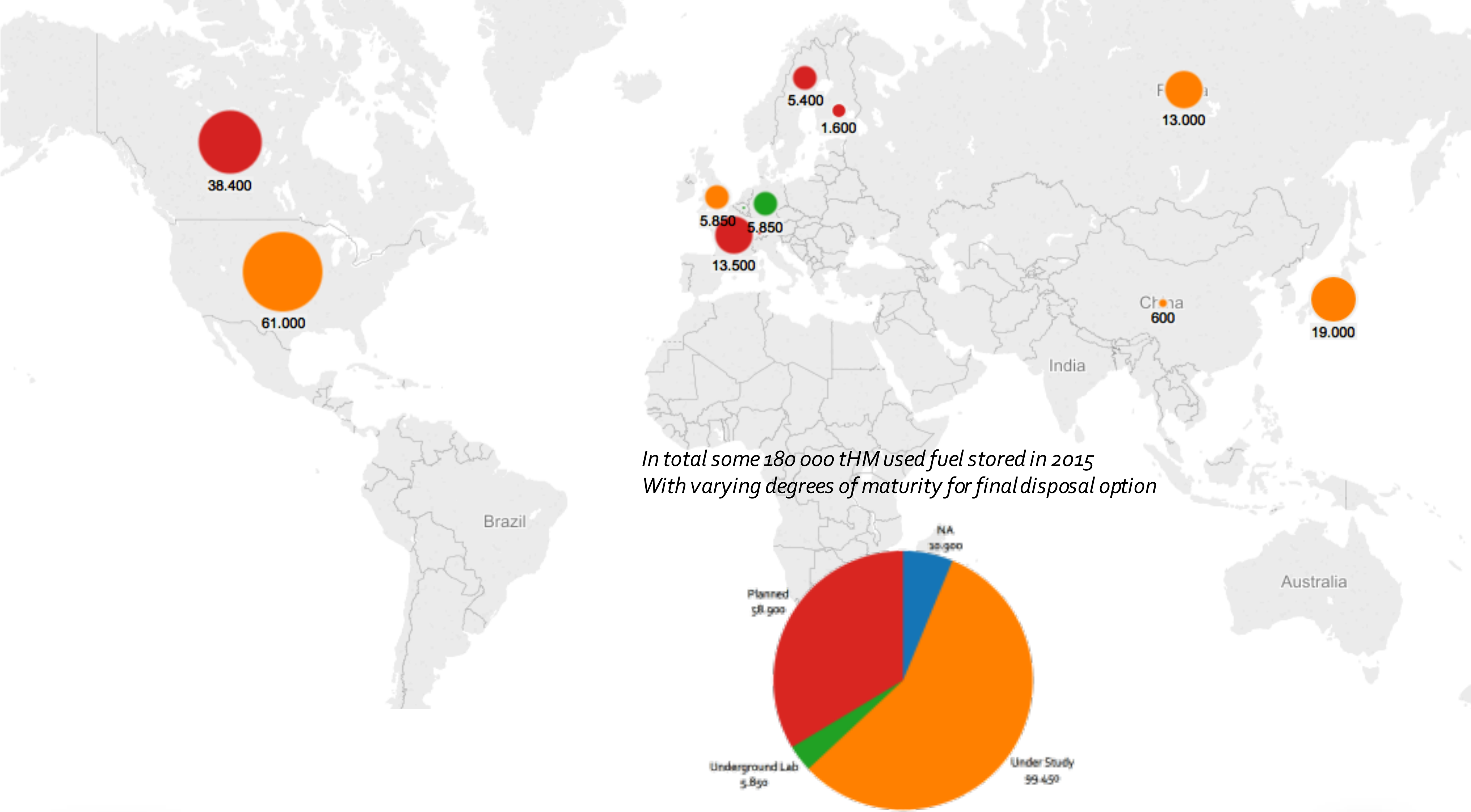




Front-End Inventories … Depleted Uranium

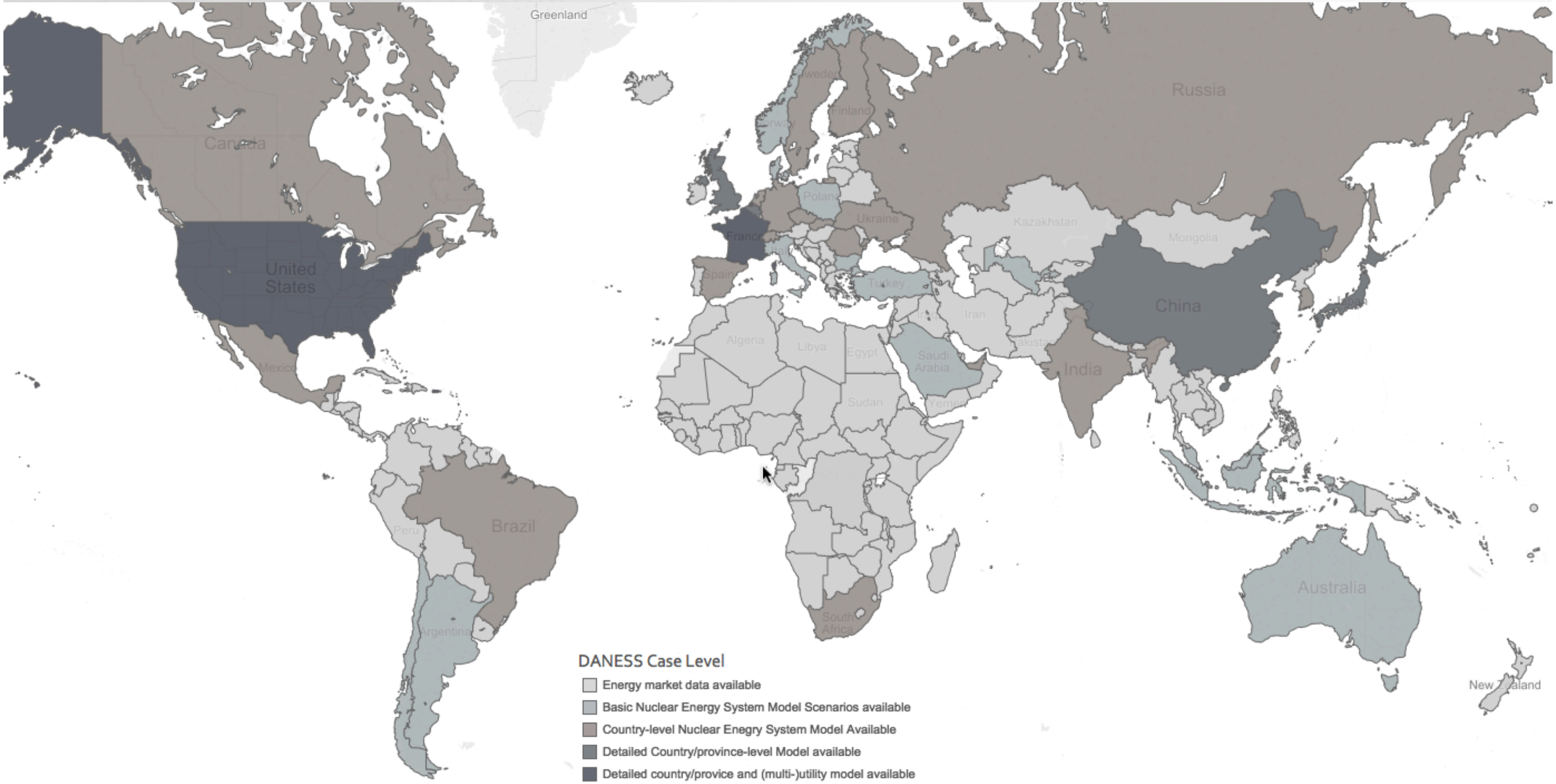


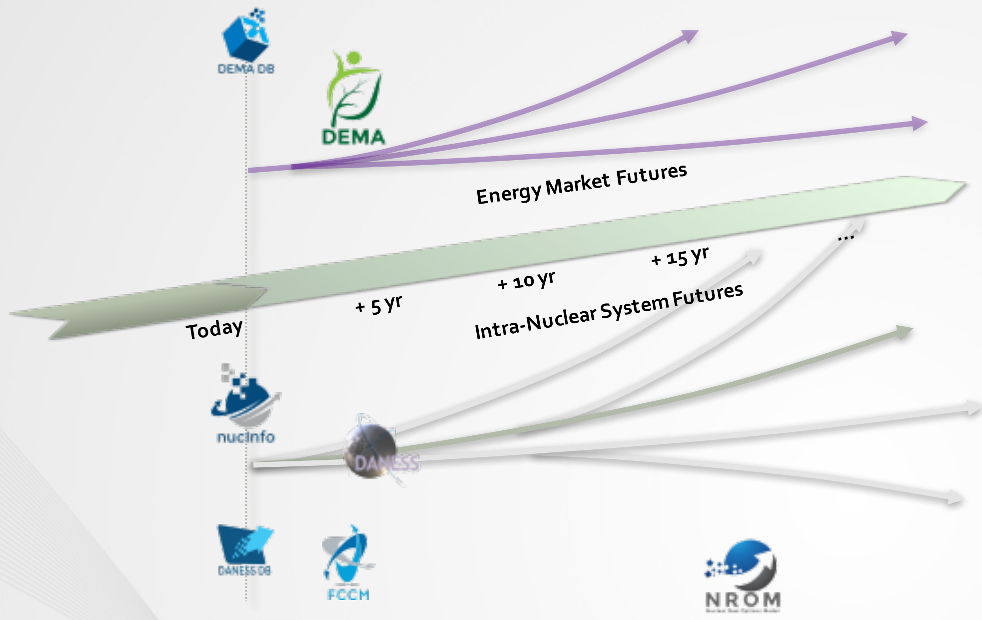
Amount (tHM) of used fuel in 2015



In total some 180 000 tHM used fuel stored in 2015
With varying degrees of maturity for final disposal option

Countries already included in NucInfo and DANESS DB





B.4.

Dynamic Analysis of Nuclear Energy System Strategies

DANESS DANESS DB nucInfo

Why do we need nuclear energy system scenario codes? (1/2)

- **Nuclear energy systems may evolve from one to a time-varying set of nuclear power plants combined to a variety of nuclear fuel cycle options**
  - This is a dynamic system covering multiple decades and any assessment of such systems demands a holistic view on today's decisional impact on tomorrow's performance
  - Multiple (cross-)flows and inventories of material and capacity allocation occur within nuclear energy systems especially in scenarios transitioning towards more sustainability
- **A holistic assessment of nuclear energy systems is required covering the socio-technical-economic dimensions**
  - Given the nature of nuclear energy systems, multi-years or even multi-decades covering simulations are required to assess the whole socio-technical-economic picture of a time-evolving nuclear energy system
  - In deploying nuclear energy systems, the time-dimension is very important as transitions between two stages of a nuclear energy system can be very much conditioned by supply/demand balances for nuclear materials and facility resources
- **With an increasingly worldwide nuclear energy system deployment, assessment of local and worldwide nuclear energy system performance is important seeking overall sustainability while assuring local competitiveness**
  - Ability to simulate one nuclear power plant and its fuel cycle as well as a whole nuclear energy system on world scale with the same tool assures coherence in assessing the local, regional and global performance of nuclear energy systems and exchanges between local and global level
    - *DANESS allows simulation of one reactor, a utility's reactor park, or a country, regional or worldwide nuclear energy system*
- **"Don't forget the short-term questions in preparing for the longer-term"**
  - Nuclear energy system scenario codes need both to address short-term operational challenges as longer-term scenario options as our customers will gain confidence in the performance if such codes if able to address today's priorities as well

Why do we need nuclear energy system scenario codes? (2/2)

- **Nuclear energy systems are complex systems**

Not only from a technical perspective, e.g.:

- Wide spectrum of eigenvalues
- Long Delay lines
- Non-linear systems
- Radioactive decay and transmutation of nuclides/actinides
- Uncertainties
- …

But also from a communication perspective, i.e.:

- *Our audience is diverse*
  - "Nuke-to-Nuke" talks
  - "Nuke-to-NNN"-talks with NNN = politicians, CEOs, investors, financial market, supply chain, operators, public at large, students …
- *Demanding multi-faceted information to be provided 'ideally' matched to the audience and cross-audience trusted*
  - Technical information (inventories, flows, isotopic compositions, waste arising, …)
  - Financial information (investments, LCOE, options value, …)
  - Socio-Political information (jobs, waste arising, resource use, proliferation risk, environmental impact, …)
  - Decisional information (what's the right time to take the right decision?)

"The physics has to be right"

System components, i.e. nuclear reactors and fuel cycle facilities, need to be represented in detail 'at the appropriate level of detail' to ensure trustworthy representation

The model needs to be understandable by different stakeholders

The same model should be providing information to politicians, economists, engineers, researchers and radioactive waste managers … contributing to a truly shared understanding of decision-space

Transparent and verifiable in the modelling and results-analysis

A layered model and especially a stakeholder-matched modelling and results analysis framework which is trusted by domain experts

An economist should have trust in the physics-part … as the engineer should have trust in the economics-part of the model

Qualification of model in decisioneering is critical

Interactive

The complexity of the system asks for scenarios analysis and comparative analysis to understand at full the outcomes of decisions … provide interactivity strengthening the understanding of the model and thus trustworthiness of model

Demanding a model which allows interactivity with scenario results on minutes scale

DANESS

- DANESS
  - **Dynamic Analysis of Nuclear Energy System Strategies**
- **Allows**
  - The modelling of one reactor or facility up to a world time-varying nuclear enegry system composed of various nuclear reactors and associated fuel cycle(s) in 'full' detail, i.e.
    - *Materials flows and inventories including isotopic composition follow-up throughout the nuclear energy system from mining till final waste disposal*
    - *Detailed flowsheets per fuel cycle facility and allowing simulation of up to 20 reactor types and up to 20 fuel types simulated in parallel (with 'unlimited' reactors or fuel batches per reactor or fuel type)*
    - *Dynamic = full account of time-evolution and thus not only equilibrium analysis*
  - Socio-Political-Technical-Economic assessment, i.e. various assessment criteria dimensions are simulated
    - *From material flows/inventories to economics per system component up to waste impact analysis on disposal site as well as material attractiveness levels for proliferation risk assessments*
  - Customisable to customer specific cases using customer proprietary data in addition to the DANESS DB database
    - *Verified executable version of DANESS deliverable according customer requirements*

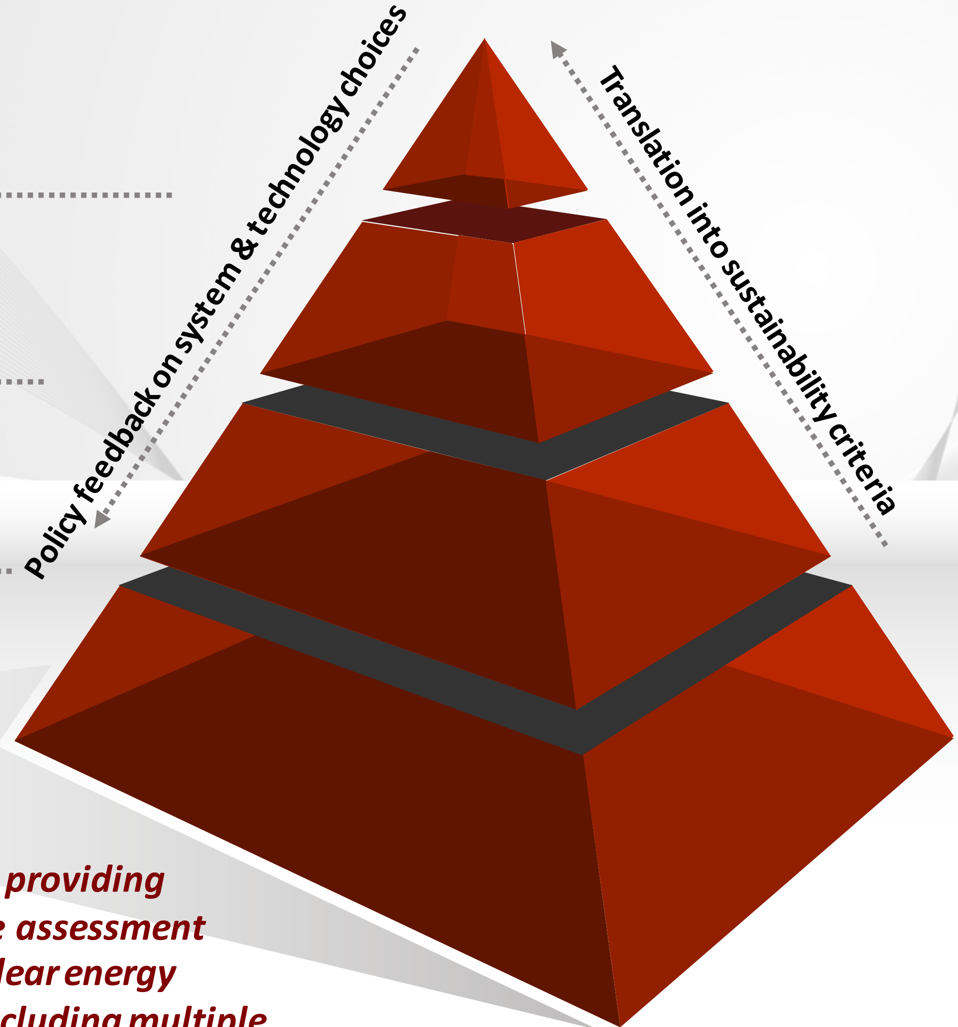
DANESS supports a holistic strategic view on nuclear energy systems strategies through transparency across layers

4. Policy layer

3. Assessment layer

2. Nuclear Energy Systems layer

1. Component layer



Only by addressing these layers in one coherent model, providing appropriate degree of detail in each layer according the assessment focus, assures best practice assessment of dynamic nuclear energy systems being it for one NPP or a world-park of NPPs including multiple nuclear fuel cycle strategies

Physics layer being the kernel of DANESS defining overall capabilities

- ***Physics Layer***

  The Physics layer incorporates all capabilities, some as optional and/or proprietary modules, allowing to simulate the mass-flows and inventories throughout the whole nuclear energy system, i.e.:

  - *Mass-flows and inventories throughout nuclear energy system including*
    - *Isotopic decay of nuclear materials throughout nuclear energy system, i.e.*
      - *Front-end and back-end fuel cycle, separated materials, used fuel in at-reactor and interim storage, waste streams, …*
    - *111 nuclides (actinides, fission and activation products) and 2 lumped fission product groups*
      - *Nuclide-list optimised for >95% of the DANESS user cases, optionally customised isotopes list*
  - *Nuclear Power Plant in-core fuel use*
    - *All NPP-types in DANESS are generic and parametrisable in order to represent a specific NPP-type*
    - *In-core fuel management for each NPP-type includes:*
      - *Standard: yearly averaged fuel management based on tabled values*
      - *Optional modules:*
        - *Initial load towards equilibrium fuel load*
        - *Fuel management transition, e.g. UOX to MOX*
        - *In-core burn-up models:*
          - *Database of fresh and used fuel compositions*
          - *Analytical interpolation model for LWR-UOX, LWR-MOX and FR-MOX as function of BU*
          - *U and Pu reactivity-equivalence model(s) LWR-MOX, FR-MOX*
          - *1D Burn-up model for LWR and FR using JEF 3.1.1 cross-section data*
  - *Fuel cycle facilities*
    - *Zero-order mass-flow representation, i.e. annual mass throughput characterisation*
    - *Optional modules:*
      - *Fuel cycle facility specific flowsheet models (e.g. enrichment, reprocessing, fabrication, repository, …)*

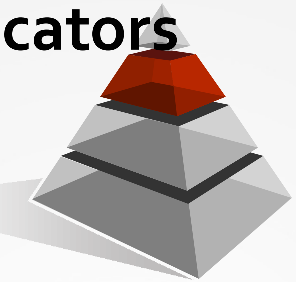
Nuclear energy systems layer providing flexibility in scenario deployments

- ***Nuclear Energy Systems Layer***

The nuclear energy systems layer allows to combine various components, i.e. NPPs, fuels and fuel cycle facilities, in time-varying combinations to simulate a whole nuclear energy system from "cradle-to-grave", i.e.:

- Nuclear Power Plant park and fuel cycle facility capacity deployment scenarios
  - *Defined by user prescribing a specific deployment scenario*
  - *Partially or fully defined by*
    - *User-defined nuclear energy demand scenarios with*
      - *Partially or fully objective-based deployment decision-making by DANESS, e.g.*
        - *Lowest LCOE*
        - *Lowest separated fissile material inventory in fuel cycle*
        - *Lowest U_{nat}-use*
    - *Fuel cycle facility deployment fully or partially user-defined*
      - *Capacity expansion model based on assurance of fuel cycle services*
- *Nuclear power plant and fuel cycle facility histories from licensing through construction, operation and finally shut-down and decommissioning*
  - *Allows for*
    - *economic analysis throughout life cycle*
    - *(environmental) life-cycle inventory analysis*
    - *fuel cycle capacity extension decision-making*
- *Time-varying nuclear energy system scenarios, i.e.:*
  - *Time-varying combinations of nuclear power plant types with fuel types*
    - *E.g. LWR-UOX to LWR-MOX transition*
  - *Time-varying combinations of fuel types with fuel cycle facilities*
    - *E.g. LWR-UOX from PUREX to UREX reprocessing*

Assessment layer translates physics into criteria and indicators for policy analysis



Assessment Layer

The assessment layer translates the detailed physics and nuclear energy systems layer information into criteria and indicators and visualises the results of the scenario simulations. It is an important interface between the previous two layers and the policy layer:

- Assessment models based on internationally recognised sustainability assessment methodologies, i.e.:
    - *INPRO Nuclear Energy System Assessment Methodology*
    - *Generation-IV International Forum Assessment Methodology*
    - *User-defined or specific assessment models developed by DANESS-users*
- Objective-function modules allowing to introduce specific objectives in nuclear energy system deployment, e.g.
    - *Lowest cost of energy generation (LCOE-objective)*
    - *Lowest U_{nat}-use*
    - *Low separated fissile material working inventory in fuel cycle*
    - *Minimal waste repository footprint*
    - *…*
- Visualisation of the scenario results
    - *By default visualisation of results within DANESS graphical output and with transfer into automated visualisation template in MS-Excel*
    - *Optional modules*
        - *Interface for Sankey-diagram visualisation of mass-flows and inventories*

Policy layer defines the nuclear energy system strategy overall

- ***Policy Layer***

The policy layer allows the user to define the overall nuclear energy system scenario strategy by:

- Defining the priorities in nuclear energy system' deployment, i.e.:
  - *Defining the use or not of decisional feedback-loops into DANESS*
  - *Introducing objective functions pre-programmed in modules in assessment layer*
  - *Weighting of criteria and indicators in assessment layer*

- Defining the nuclear power park deployment scenario and the major material flows throughout the nuclear energy system, e.g.
  - *Reprocessing of used fuel or long-term interim storage or direct disposal*
  - *Separated fissile material allocation*
  - *Conditions for introduction of new nuclear power plant types*

DANESS Architecture

Macro-Economic Energy Market Models

Nuclear Energy Demand Scenarios

Nuclear Energy system Strategy

Sustainability Objectives

IAEA INPRO/NESA Methodology

GIF Assessment Methodology

Energy Cost model

Nuclear Fuel Cycle Cost model

U-price model

LCI model

Non-Proliferation Model(s)

NPP-Park Deployment Strategy

New NPP Investment Decision model

NPP History model

NPP Investment & Cash-flow model

NPP Technology Development model

Nuclear Fuel Cycle Facility Investment Decision model

Facility History model

Facility Investment & Cash-flow model

Facility Technology Development model

Nuclear Fuel Cycle Option model(s)

Fissile Material Availability Forecast model

Objective decisional feedback models

Reactor Models

Fuel Burn-up model(s)

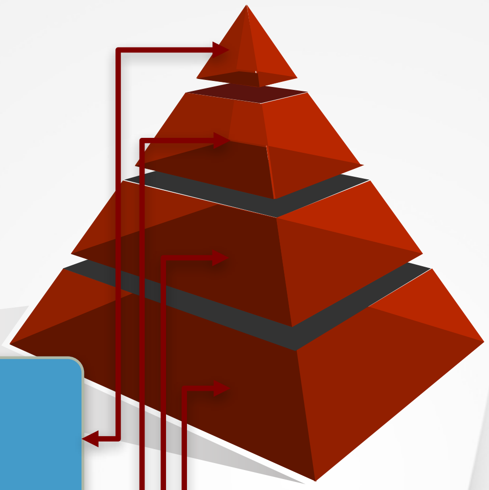
Nuclear Fuel Cycle Mass-flow model

Specific Fuel Cycle Facility model(s)

Isotopics model

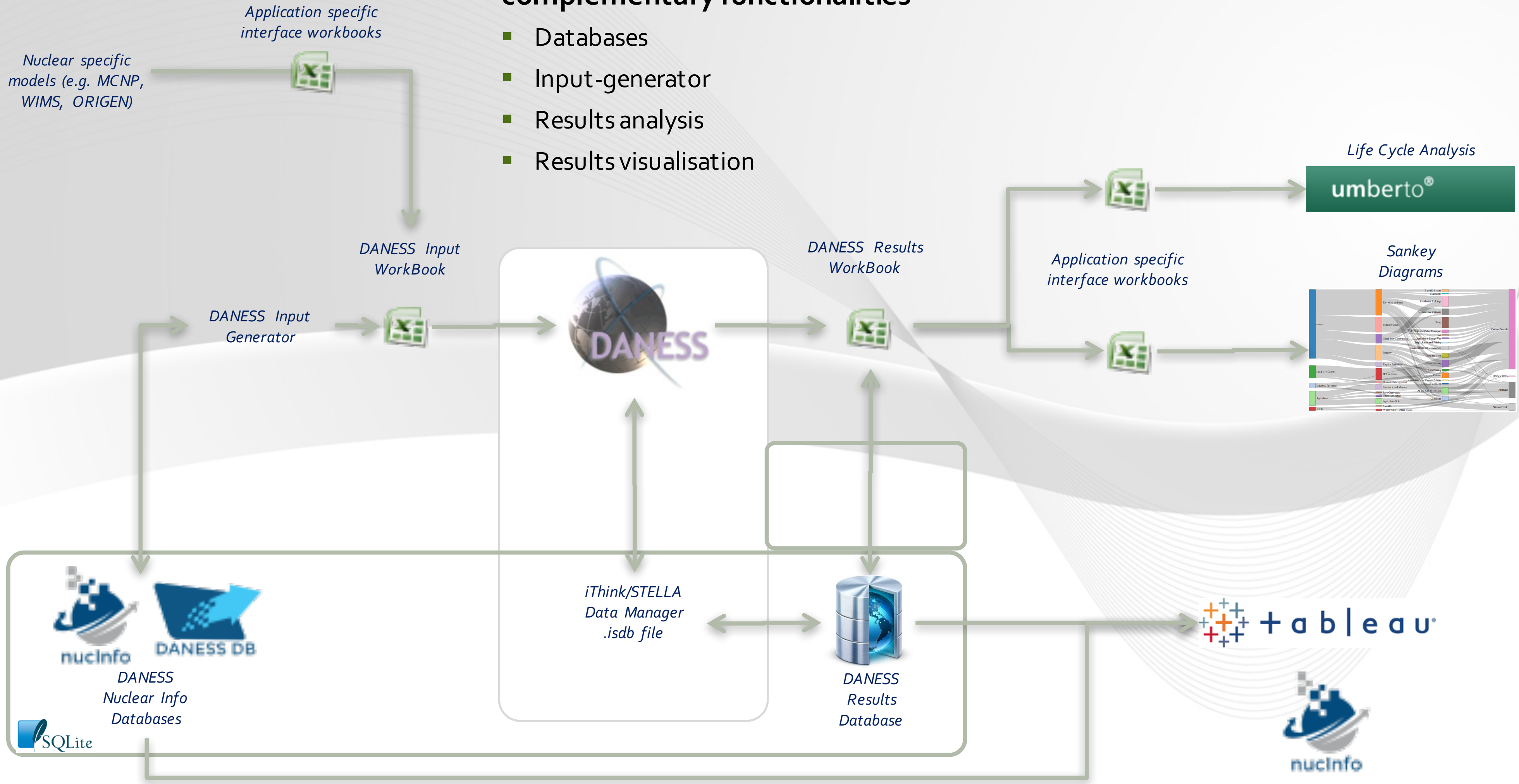
Waste management model

Radiological model

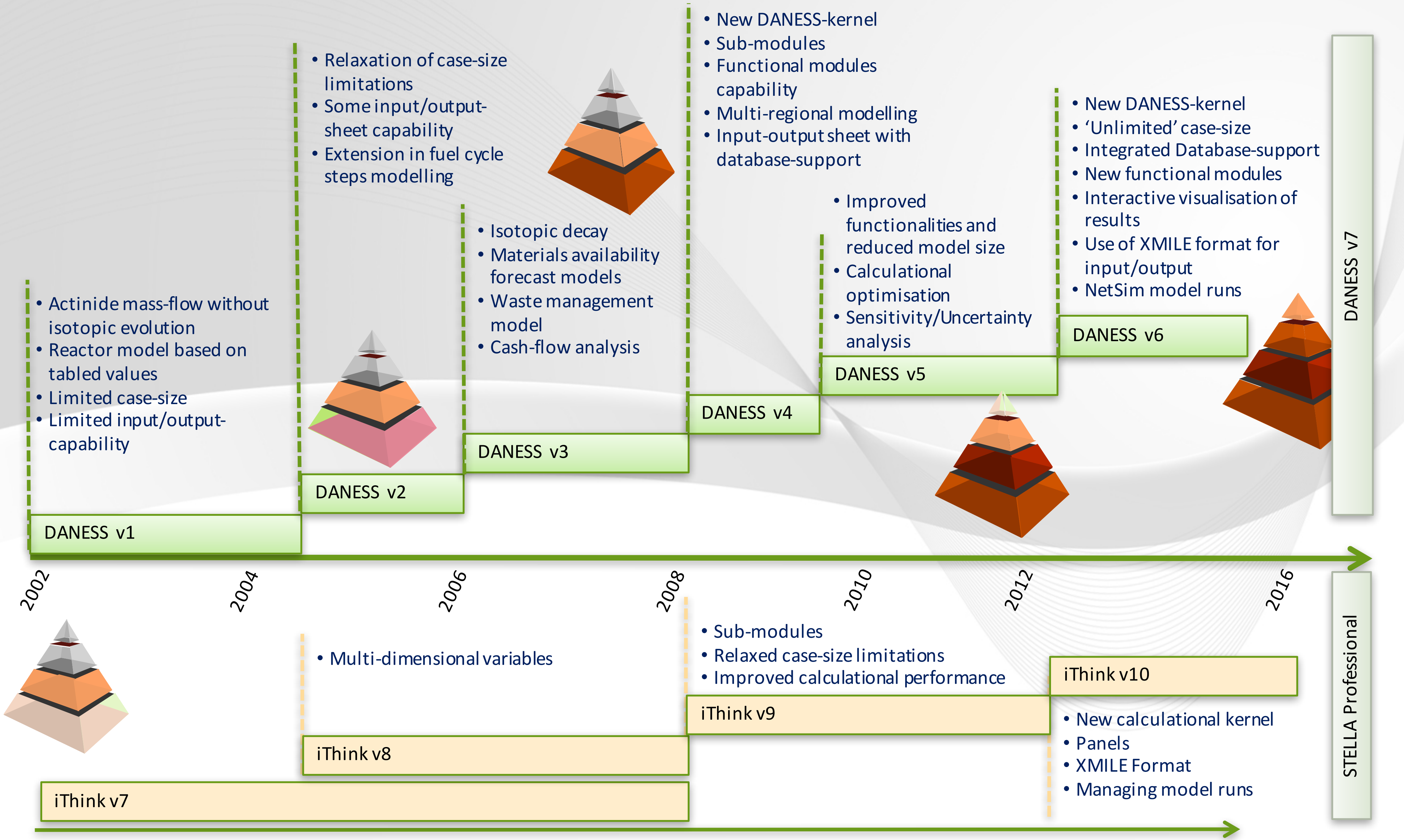


DANESS Toolbox

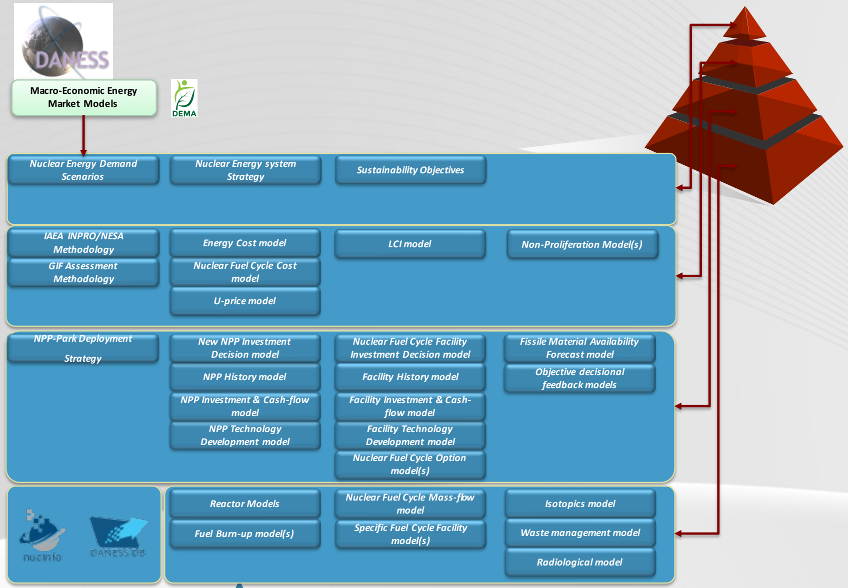
- **The DANESS Toolbox covers complementary functionalities**
  - Databases
  - Input-generator
  - Results analysis
  - Results visualisation



Chronology of major DANESS-releases

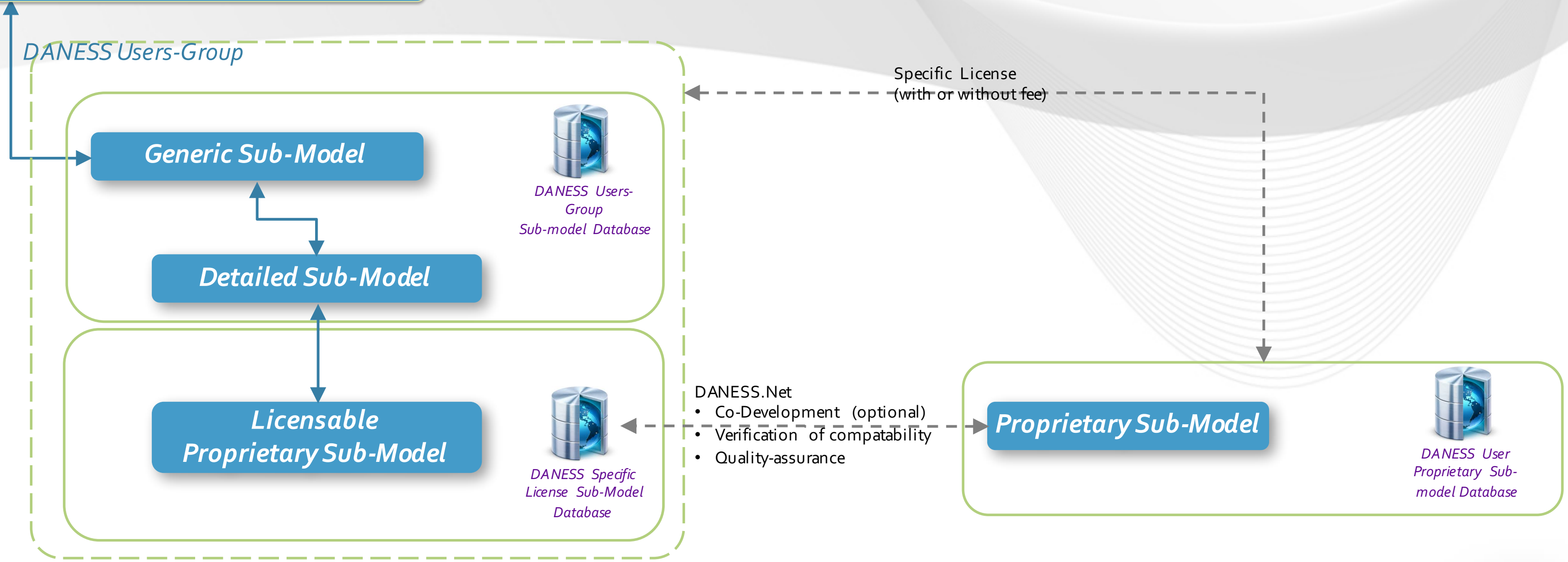


DANESS Modular sub-model approach



DANESS is composed of various sub-models:

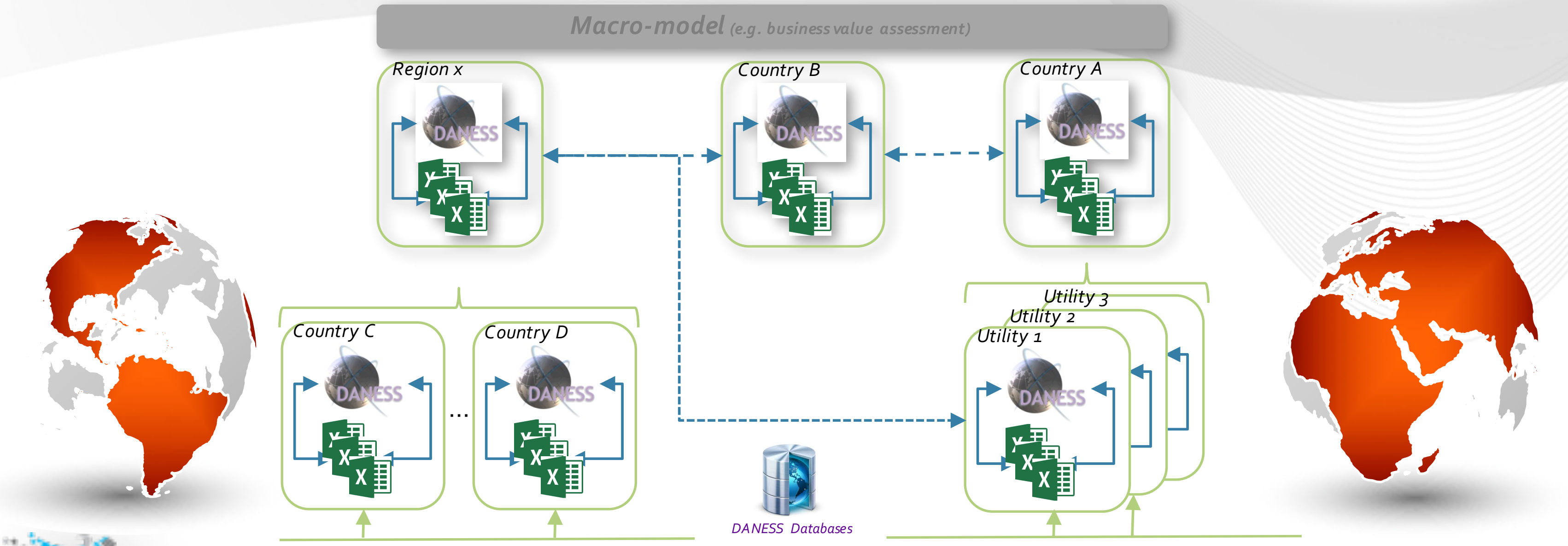
- Each of which is versioned and validated;
- Some of the sub-models
  - Are available as "generic" sub-models in DANESS for all DANESS-users use;
  - Some of the "generic" sub-models can replaced by:
    - More detailed sub-models allowing more detailed NES-assessment studies
    - DANESS-User *proprietary* sub-models which may be provided to DANESS User-Group as specific licensed (with or without fee) sub-models



Multi-regional/customer NES-model

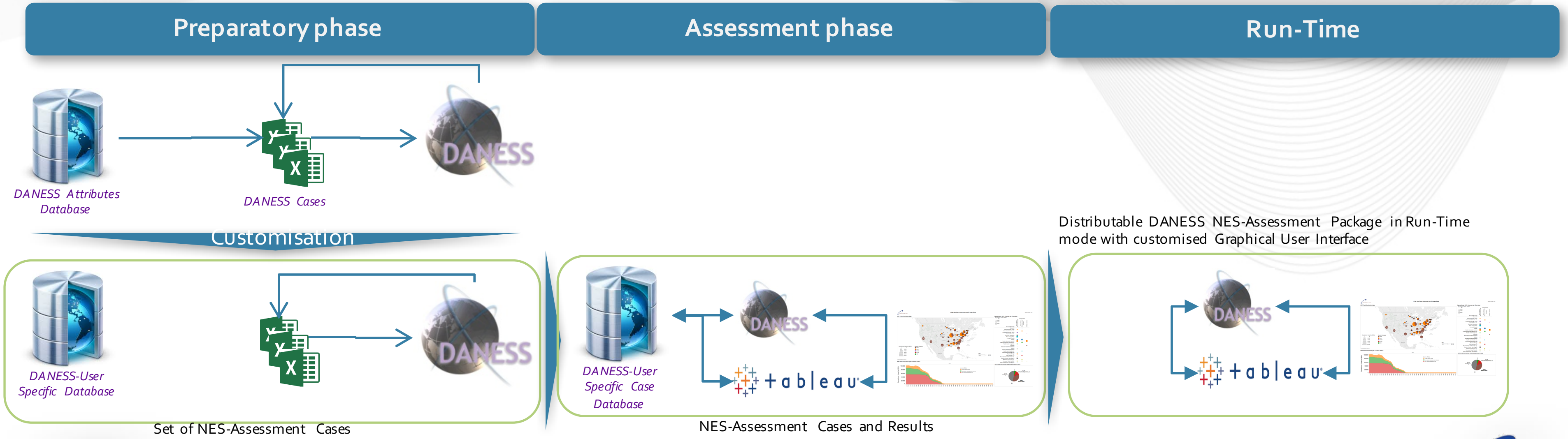
- **DANESS can be used in different modes, i.e.:**
  - From one reactor to multiple reactors and associated fuel cycles
  - On world, regional, country, utility, reactor-site or reactor-specific level

  - Based on a transparent parameterisable DANESS-case MS-Excel inputsheet, all DANESS-cases can be combined into one large/combined DANESS-case or run in parallel
- **DANESS allows modular use, i.e.:**
  - Modularity by allowing 'generic' DANESS-Cases be further detailed into 'Proprietary' DANESS-Cases
    - *E.g. 'Generic' publicly available DANESS-Case supported by a non-public 'Proprietary' more detailed DANESS-Case*
  - Country/Utility specific cases can be combined together into multi-regional/customer cases to investigate synergies between individual NES



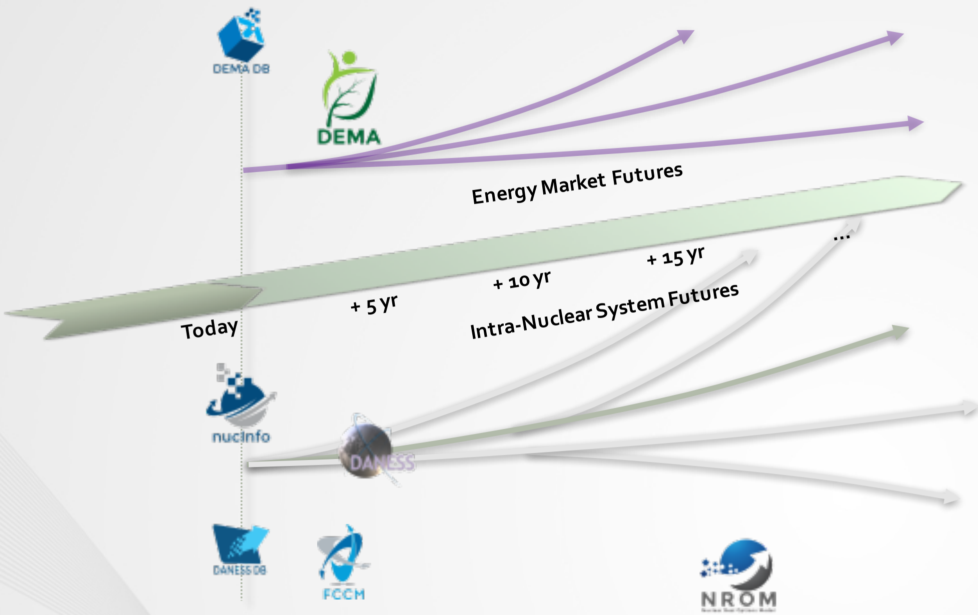
Typical DANESS-use process

- **A Preparatory phase consists of**
  - Collecting the NES-data and defining the hypotheses for NES-assessment study
    - *Typically based on DANESS Attributes Database available to licensed DANESS-Users*
  - Testing and Customising the NES-assessment model
    - *Setting-up of customised NES-cases and associated (proprietary) DANESS-User Database (optional)*
- **Assessment Phase consists of:**
  - Running multiple "what-if"-scenarios to test the validity of the NES-model with regard to various hypotheses
  - Down-selection of validated NES-assessment cases and integration in (proprietary) User-specific Case Database
  - Visualisation of NES-Assessment Results
- **An Optional phase consists of providing a Run-Time customised version of DANESS preconfigured for a set of NES-cases**
  - Allows the use of DANESS by less-skilled DANESS users or to use as distributable demonstration/assessment package to customers



Benchmarking / verification

- **Benchmarking**
  - Simulation code
    - *Participation in various exercises involving COSI, ORION, DYMOND, VISION, NFCSIM, Tirelire-Strategy, COSAC*
      - Most dating back to <2009
      - Some comparisons undertaken during 2015-2016
  - Real data systems verification
    - *Country/utility specific 'images' simulating past and present of NPP and fuel cycle*
    - *Detailed verification of irradiation histories and fuel cycle service requirements for two utilities as part of choosing between interim SF storage options*



B.5.

DANESS DB

DANESS DB

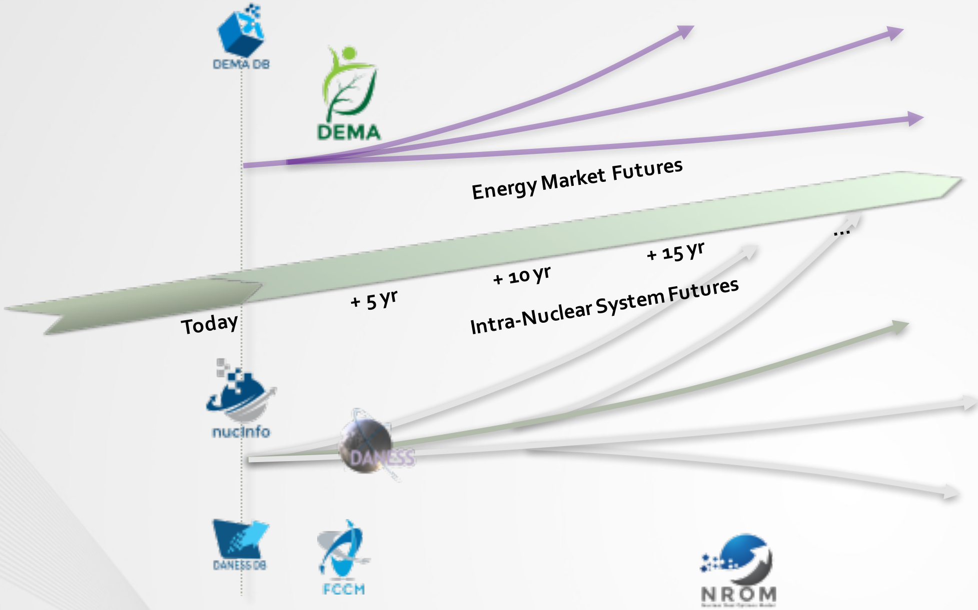
DANESS DB overview (1/2)

- **The DANESS DB Database relates specifically to technical-economic data for reactors, fuels and fuel cycle facilities**
  - Where nucInfo covers the data for the existing nuclear energy system including the historic data and today's inventories and capacities
  - DANESS DB covers the technical-economic data for reactors, fuels and fuel cycle facilities to be considered in nuclear energy system scenario studies

- **DANESS DB features**
  - Per reactor type:
    - *Thermal power, gross and net electric power, average capacity factor*
    - *Licensing and construction time-period*
    - *Expected commercial/industrial availability/deployment*
    - *Investment cost, O&M cost, decommissioning cost*
      - Assumed cost profile during licensing and construction period (typical cost profiles pre-configured)
    - *Core management*
      - Fuel type(s) used
      - Initial fuel type loading and anticipated equilibrium fuel core loading
      - Parametrisation of in-core burn-up model
    - *Learning curve coefficients for investment and O&M costs*
    - *Number of FTE (engineers, technical)*
    - *LLW/ILW Waste arising per MWe and per MWhe*

DANESS DB overview (2/2)

- Per fuel cycle facility type
  - *Unit capacity, maximal annual deployable capacity*
  - *Average capacity factor*
  - *Expected commercial/industrial availability/deployment*
  - *Investment cost, O&M cost, decommissioning cost*
    - Assumed cost profile during licensing and construction period (typical cost profiles pre-configured)
  - *Learning curve coefficients for investment and O&M costs*
  - *Number of FTE (engineers, technical)*
  - *LLW/ILW Waste arising per unit throughput*
  - *Losses in process*
    - U, Pu, MA, TRU, FP, ... losses
  - *Transfer function(s)*
    - Applicable sub-model for more detailed fuel cycle facility description
- Per fuel type
  - *Fuel category (oxide, carbide, nitride, metal)*
  - *Average and peak BU*
  - *(Typical) Initial composition (may change during simulations depending on core-management model used)*
    - Composition with 111 isotopes in tabled format
  - *(Typical) used fuel composition (may change during simulations depending on core-management model used)*
    - Composition with 111 isotopes in tabled format
  - *Materials composition*
    - HM, structural material
    - Mass per assembly
  - *Assembly size*
  - *Transport container compatibility*



B.6.

Fuel Cycle Costing Model FCCM

FCCM

FCCM
Objectives

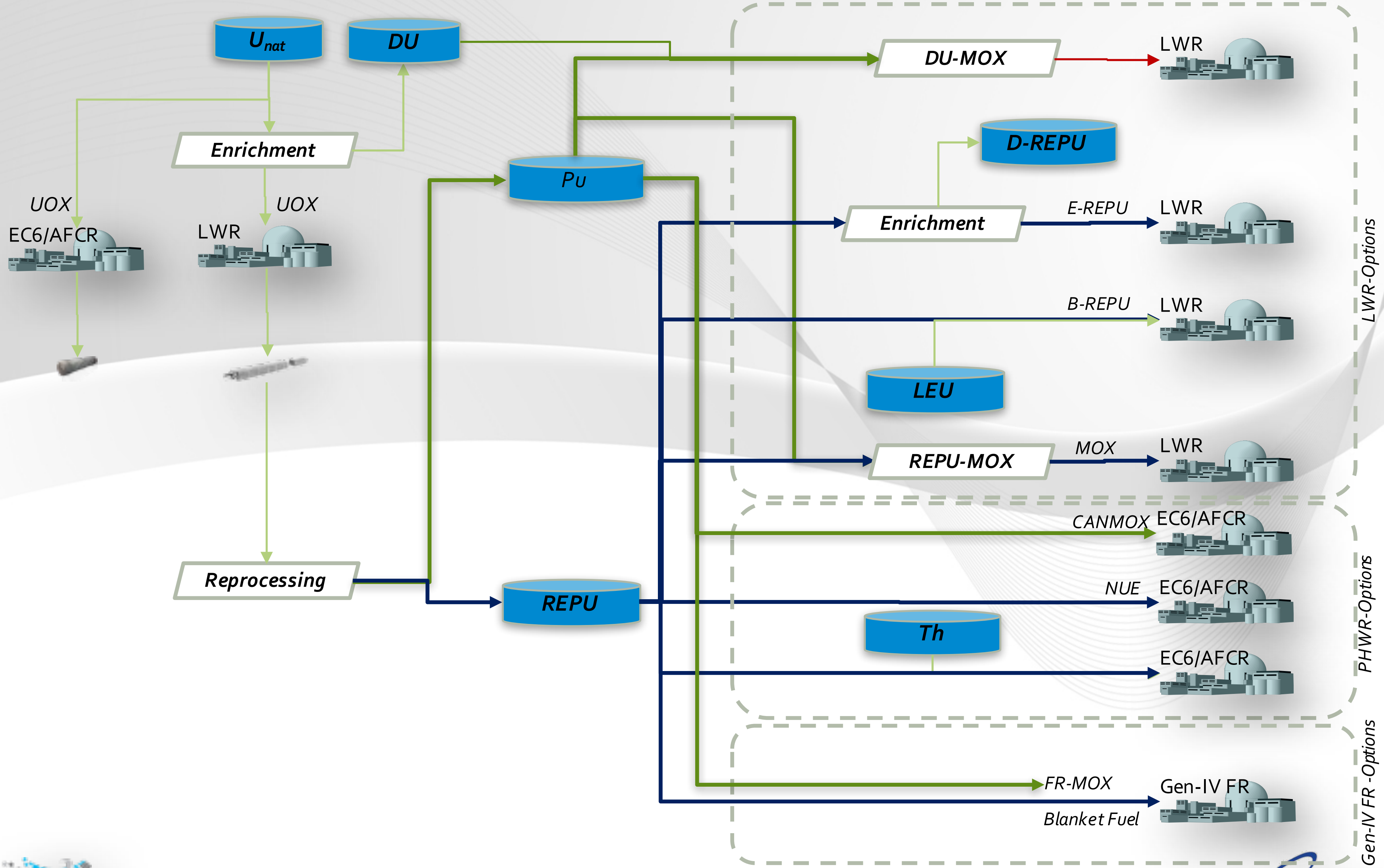
- **FCCM aims at providing the user a toolbox based on MS-Excel and @Risk-modules for:**
  - Net-Present Value and Levelised Costing of equilibrium fuel cycle options
    - *Covering LWR, PHWR, FR and HTR fuel cycles and including recycling scenarios of fissile materials across reactors' fuel cycles*
    - *With annual price inflation and discounting per fuel cycle service*
    - *With associated database(s) of fuel cycle service costs based on*
      - International literature as embedded in the DANESS DB
      - Customer-specific data embedded in a separate database file
  - Uncertainty analysis based on database-defined uncertainty distributions on fuel cycle service costs
  - Fuel cycle cost optimisation
    - *Front-End fuel cycle*
      - Optimal tails assay
    - *Back-end fuel cycle*
      - Optimisation of interim storage options
      - UNF-type and size of reprocessing campaigns and MOX fraction to be recycled
      - REPU-recycling scenarios in LWRs and PHWRs

Brief Description FCCM v3.1

- **The fuel cycle costs are calculated from natural materials mining till final disposal of radioactive waste**
- **The fuel cycle costs are calculated**
  - In equilibrium conditions, i.e. no start-up core-management nor time-evolving fuel cycle modifications considered
  - Fifteen different fuels can be analysed for LWR, PHWR and FR based nuclear energy systems
  - 10 nuclear energy systems are considered (see slide 6) with recycling of separated materials between these reactors and corresponding fuels
- **For each fuel cycle service, a unit cost and associated annual cost inflation can be provided with a duration and/or lead/lag-time with respect to moment of fuel loading into reactor core (for front-end services) and with respect to discharge of used fuel (for back-end fuel cycle services)**
- **Both Nominal Cost of Fuel cycle (COFC) as Levelised Cost of Fuel Cycle (LCOFC) are calculated**
  - Levelised LCOFC used discount rates which can be specified per fuel cycle service, e.g.
    - *Short-term fuel cycle services can be discounted at industrial rates*
    - *Long-term fuel cycle services, e.g. disposal, can be discounted at intergenerational rates*

Fuel types
LWR-UOX
E-REPU-OX
E-REPU'-OX
B-REPU-OX
B-REPU'-OX
PHWR-UOX
PHWR-REPU-OX
PHWR-REPU'-OX
PHWR-CANMOX
PHWR-U/Th-OX
PHWR-Pu/Th-OX
LWR-MOX
LWR-MOX'
FR-MOX
FR UOX Blanket

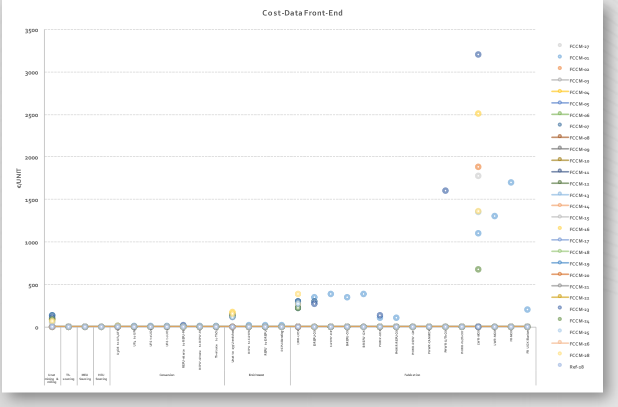
Fuel cycle options within v3.1 (1/2)

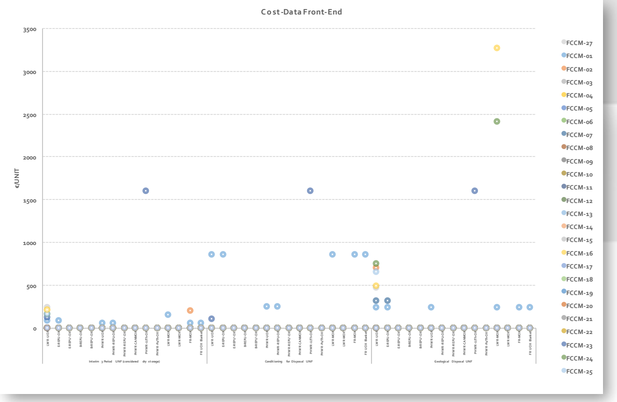


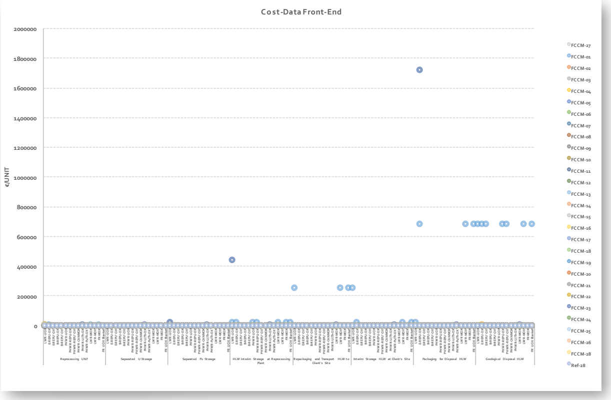
Cost-Data References

- **A continuously updated reference data-base (part of DANESS DB) is maintained and interfaced with FCCM**
  - Includes technical-economic studies performed by industry, universities, consultants, utilities and international organisations (IAEA, OECD-NEA)
  - Translation of reference data into FCCM-compatible cost-data file performed six-monthly by Nuclear-21.Net
  - Cost-Data reference base
    - *Includes 27 references in version 3.1*
    - *Reference documents are available for download via NESSAT-portal (ProjectPlace-based)*
    - *Can include user-specific proprietary data*
- **FCCM includes comparative graphs of cost-data**
  - Allowing intercomparison of cost-data across references
  - Defining uncertainty distribution parameters for FCCM, DANESS and NROM/NFCOM-assessments

Intercomparison of cost-data across references

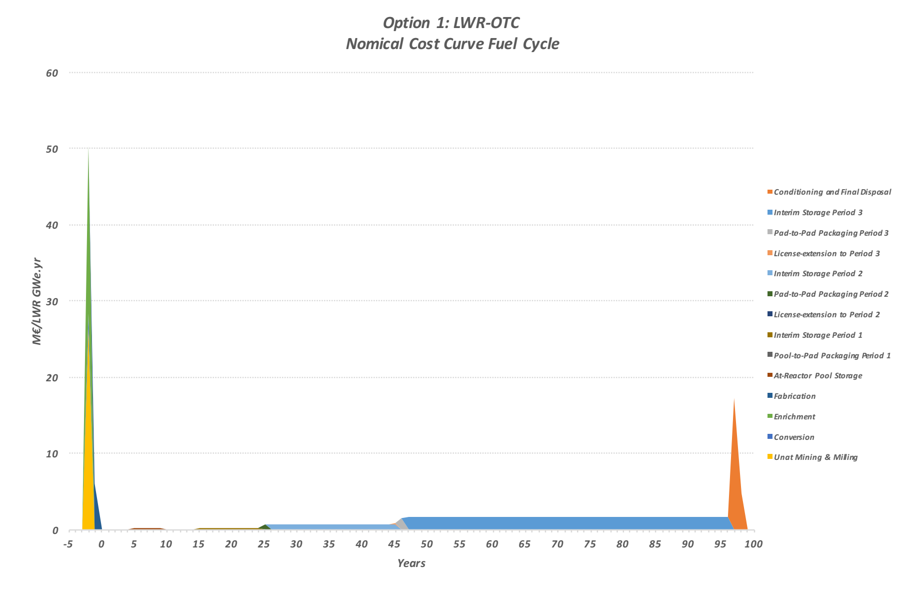


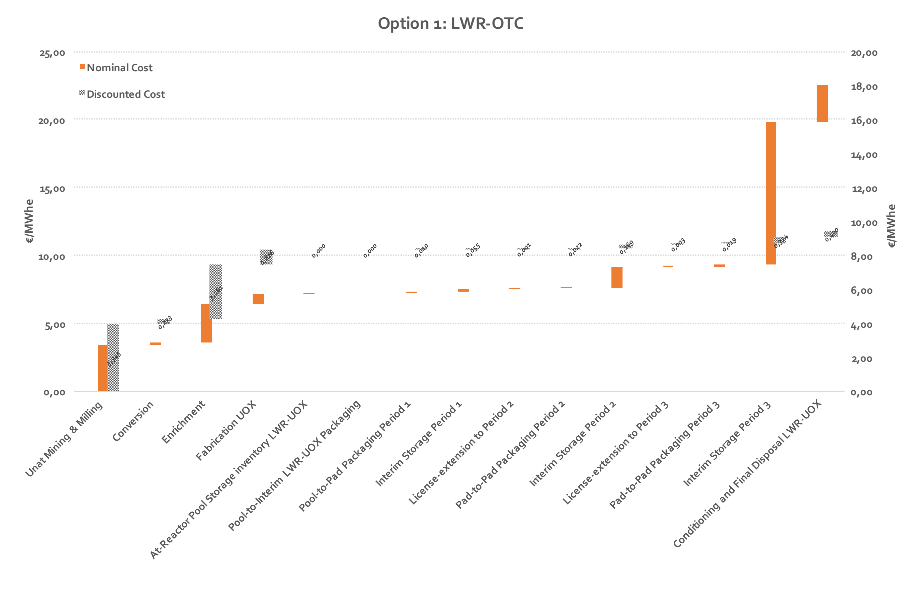




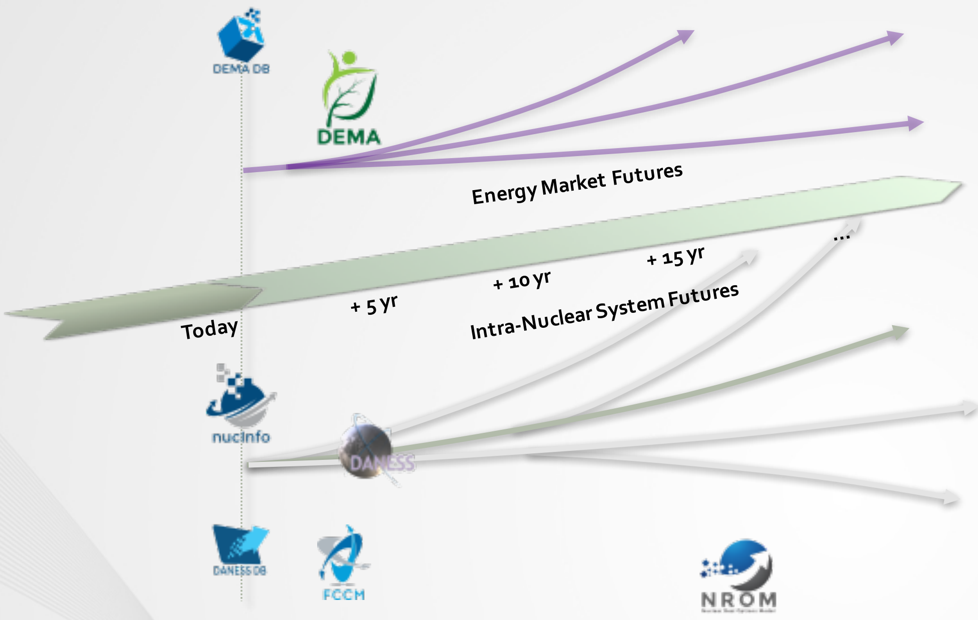
- **Cost-data from different references are intercompared**
  - Using cost-data reference date (e.g. 2015) where Nuclear-21.Net ensures documented constant/actual-money transfer
- **Complementary cost-data are proposed by Nuclear-21.Net based on expert judgement**
  - Cost-data are entered into the NucInfo-DB based on expert judgement and ensuring to include data in correctly comparable data-variables (e.g. fuel specific)
- **As none of the references includes all nuclear fuel cycle services, sets of coherent cost-data are proposed and documented**
  - These Nuclear-21.Net proposed technical-economic data-sets are provided to FCCM/NROM licensed customers
  - Six-monthly updated
- **Distributions or uncertainties for cost-data can be derived**
  - Uncertainties used in real options NROM/NFCOM-model

Example
Option 1 LWR-OTC





- **For each of the FCCM fuel cycle options, two cost curves are graphed**
  - Nominal cost evolution per GWe.yr
    - *This cost curved being translated into NROM/NFCOM-model cost curve files*
  - Nominal and discounted fuel cycle cost per Mwhe
    - *Used for comparative NPV/(L)COFC-analysis in standard DANESS economic fuel cycle decision-model*



B.7.

Nuclear Real Options Model

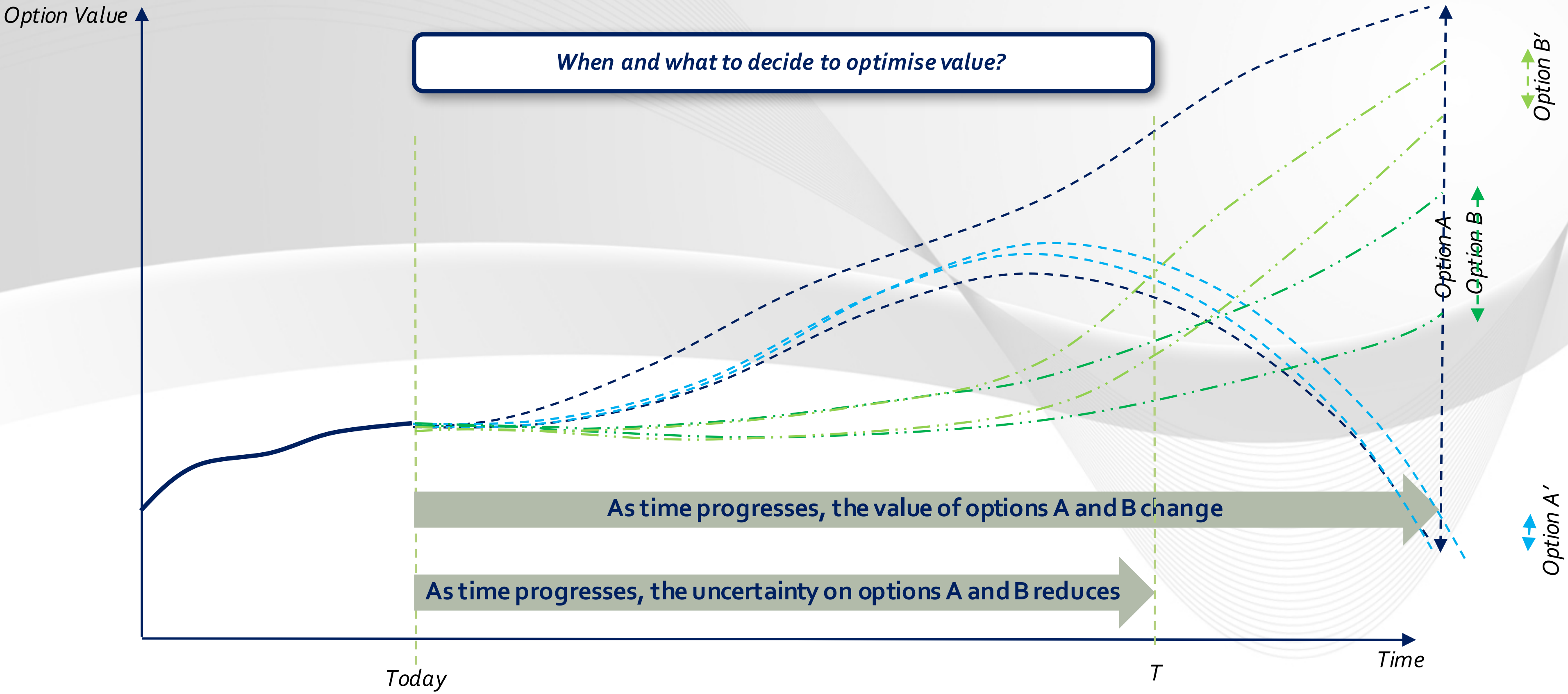
NROM
Nuclear Real Options Model

Nuclear Real Options Model (NROM) Positioning

- **Where**
  - NucInfo provides information on past and present
  - DANESS projects scenarios into the future
  - FCCM calculates at each moment the NPV/(L)COFC of nuclear energy system options
- **Though, none provide the answer to**
  - ***"When is it optimal to decide upon (a) nuclear energy system option(s)?"***
    - *Given uncertainty in future (nuclear) energy market and in intra-nuclear options performance*
    - *Given compounded option value spanning multiples decades*
    - *Given changing socio-political and technical-economic context for intra-nuclear system options*
    - *Given the long technology-to-business periods required*
- **NROM is a set of real options methodology based models addressing above question for**
  - NROM/NPOM
    - *Nuclear Power Investment Option Model*
  - NROM/NFCOM
    - *Nuclear Fuel Cycle Option Model*

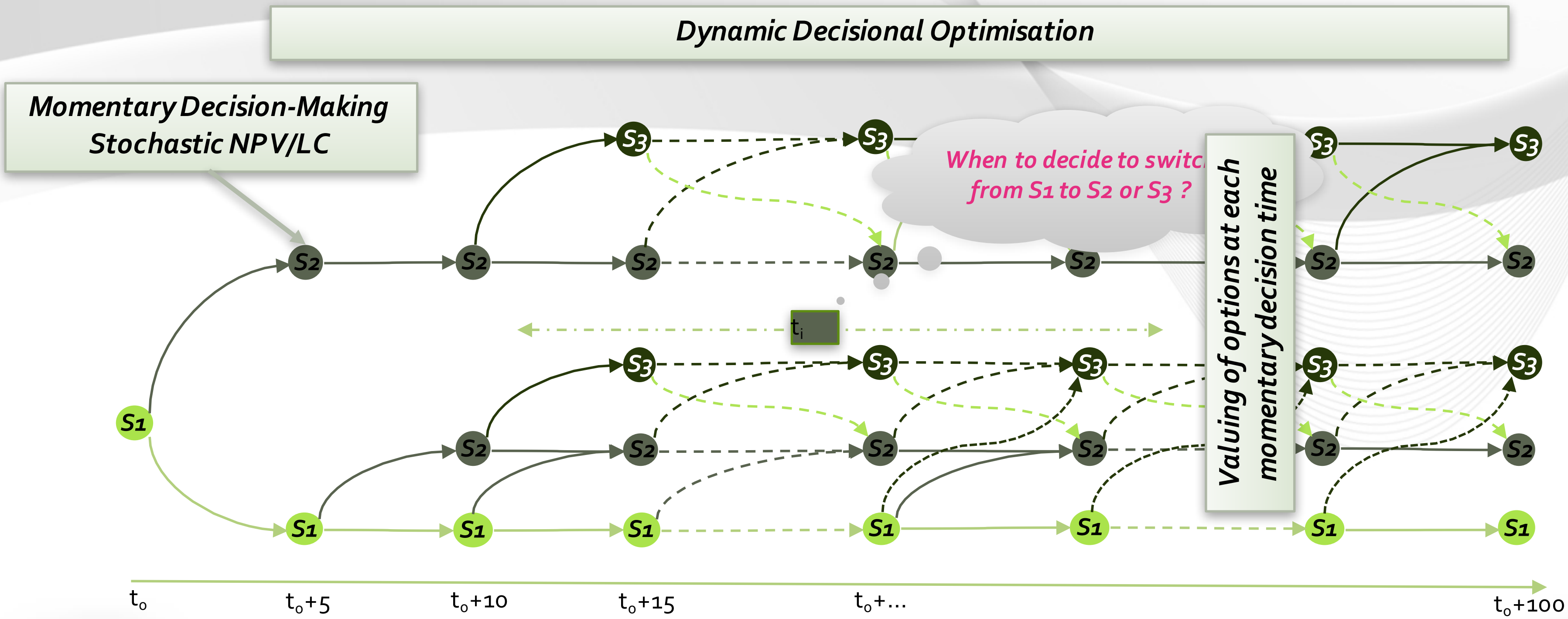
Real Options valuing

- **Real options valuing is a technique to value the decisional flexibility today in view of uncertain futures or options upon which future decisions need to be taken**



NROM Description

- **NROM is composed of three sub-components making up one real options valuing methodology**
  - *Momentary decision-making mostly based on Stochastic net present value and levelised cost analysis at each decisional moment*
  - *Real Options decision tree valuation*
  - *Dynamic decisional optimisation*



NROM/NPOM

- **Nuclear Power Options Model uses the NROM-methodology addressing questions relating to:**
  - Economic competitiveness for nuclear power plants (NPP) in volatile energy markets, including sub-questions such as
    - *Option value for Small Modular Reactors versus large unit-size NPPs*
    - *Value of load-following for NPPs*
    - *Process-heat and electricity generation optimisation within differing demand dynamics*
    - *Technology-development valuing, e.g. appropriate level of R&D for new NPP technologies*
    - *Risk-adjusted financing schemes for new nuclear power plants*
      - Alternative financing schemes such as sub-ordinate debt financing

  - Each of the specific questions is translated into decision-process objective functions adequately describing the various aspects of the question
    - *Supported by continuously update data-sets, ideally including experience-based data-sets, addressing both technical as financial parameters of objective function(s)*

NROM/NFCOM

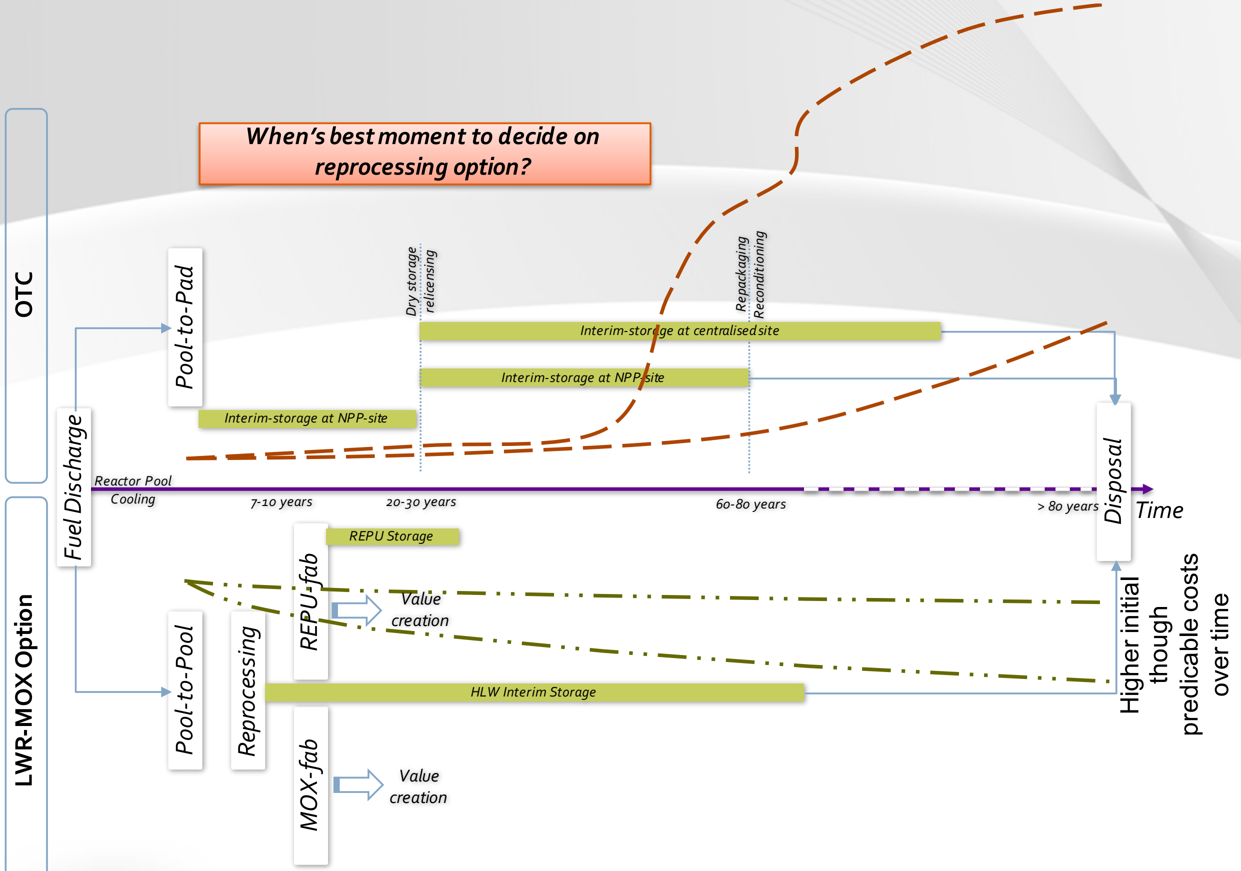
- **Nuclear fuel cycles include varying degrees of uncertain futures within specific fuel cycle services**
  - Switching costs between fuel cycles may be very important and take time, mostly at least a decade to transition between fuel cycle options
- **Nuclear Fuel Cycle Options Model is based on the NROM-methodology and allows to assess the decisional flexibility value in:**
  - Choosing between fuel cycle options both from short-term operational perspective as for more strategic longer-term options
    - *Optimal enrichment tails assay*
    - *Pool versus dry interim storage of used fuel for a portfolio (on NPP or utility or country level) of used fuel*
    - *Once-through with direct disposal of UOX or mono-Pu recycling as MOX in LWRs*
    - *Value of FRs in advanced fuel cycles*
  - The decisional flexibility value being assessed from the perspective of a utility, fuel cycle service company, R&D-organisation or government organisation addressing, f.i.:
    - *Cost/risk exposure for utility with respect to used fuel management options*
    - *Risk-adjusted level of investment in new fuel cycle options and associated services*
    - *Timely deployment at optimal cost/risk-exposure of newt fuel cycle technologies and options*
    - *Optimal fuel cycle service pricing for profitable business continuation*
    - *…*

Example of NROM/NFCOM Application

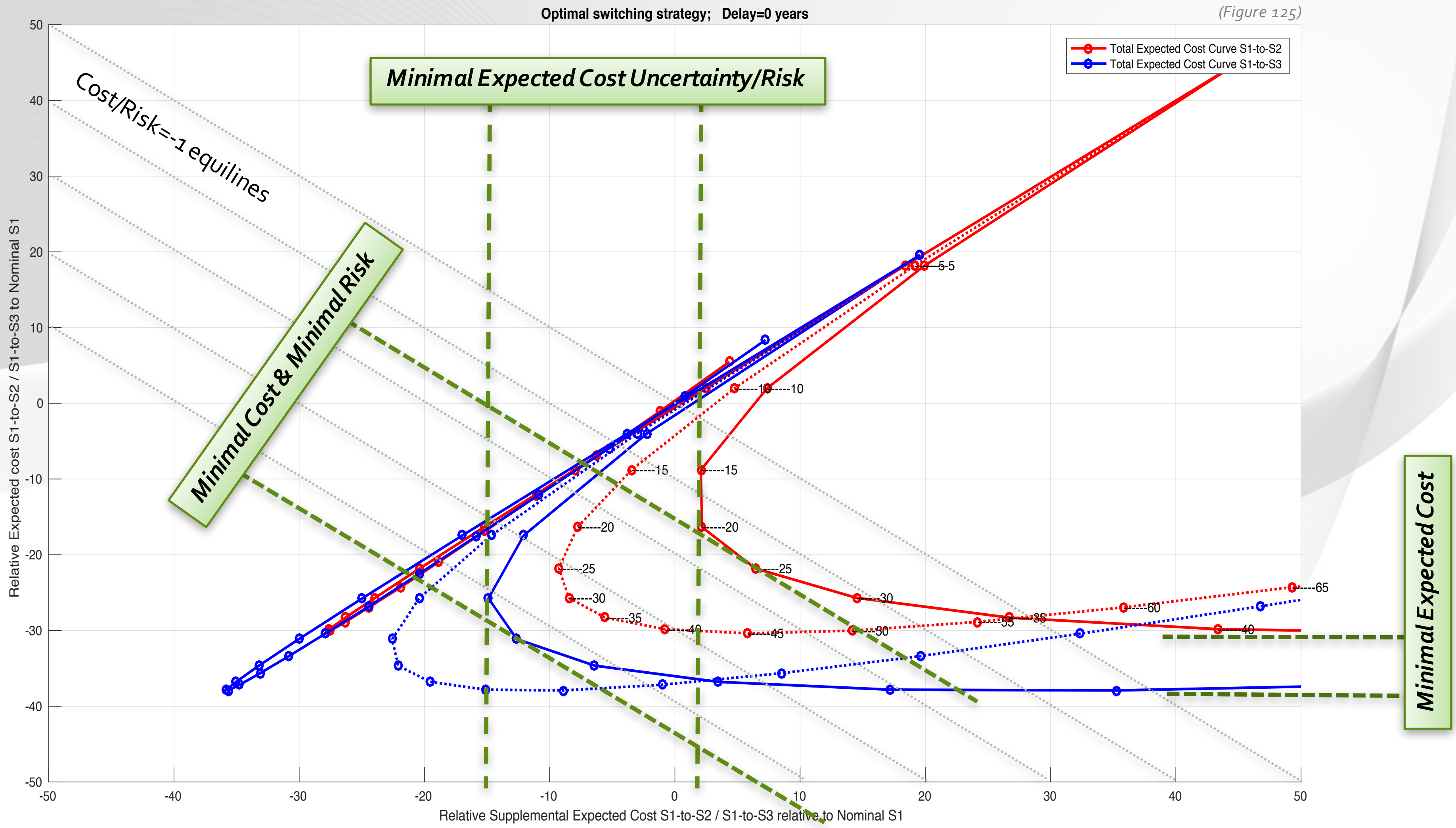
Used Fuel Management Flexibility

Used Fuel Management choices
How and when to decide to cost/risk minimisation options?

- **How to value the trade-off from OTC towards other fuel cycle options, e.g. LWR-MOX and/or FR-MOX options?**
  - Classic NPV-analysis doesn't capture the decisioneering dynamics nor the correct financial decisional framework
  - Under which conditions as function of decisional time becomes the LWR-MOX (with or without FR-MOX compound option) attractive?
  - What are the switching points for the option LWR-MOX and/or FR-MOX?



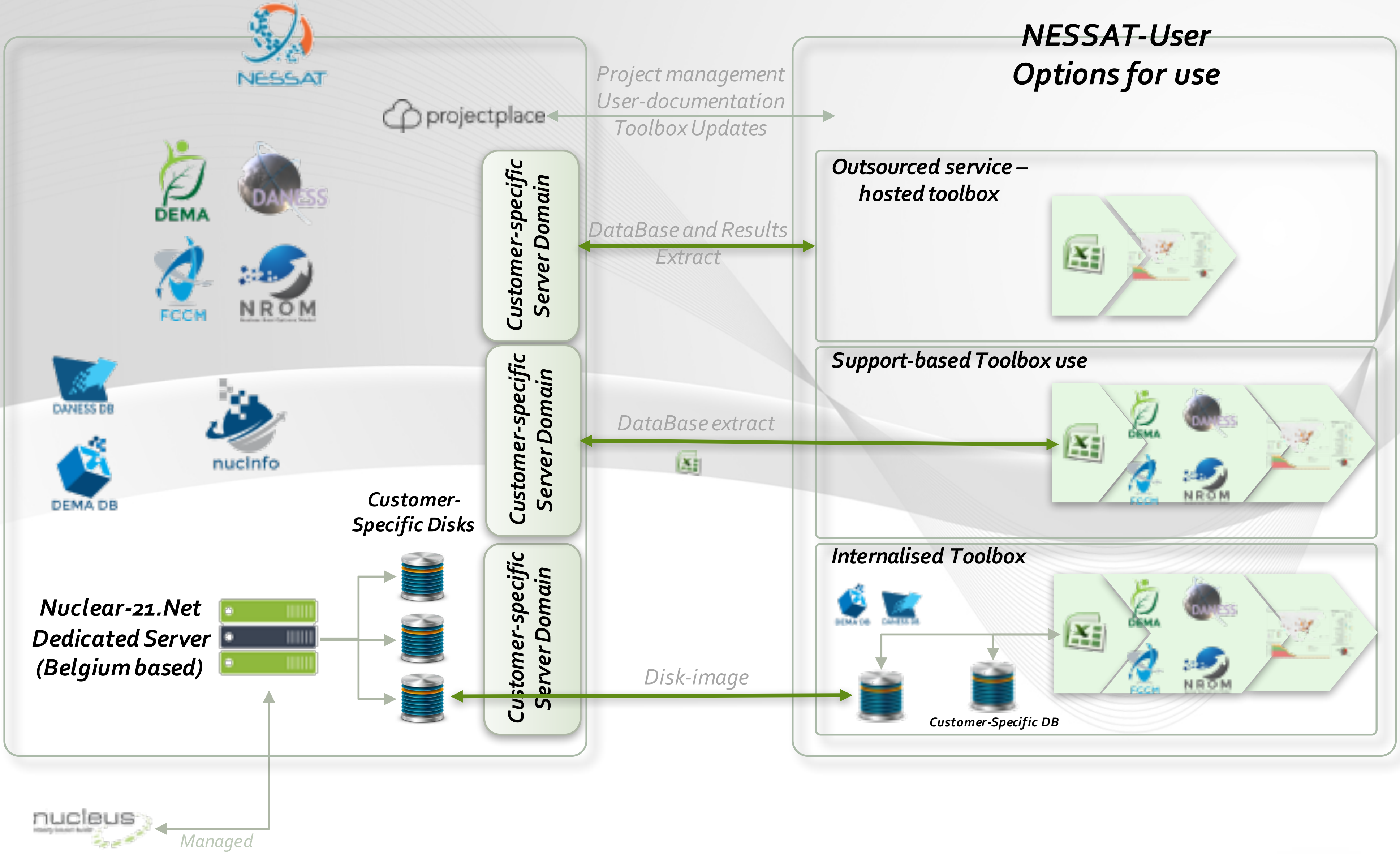
Cost/Risk-exposure evaluation for utilities and SF-fund managers



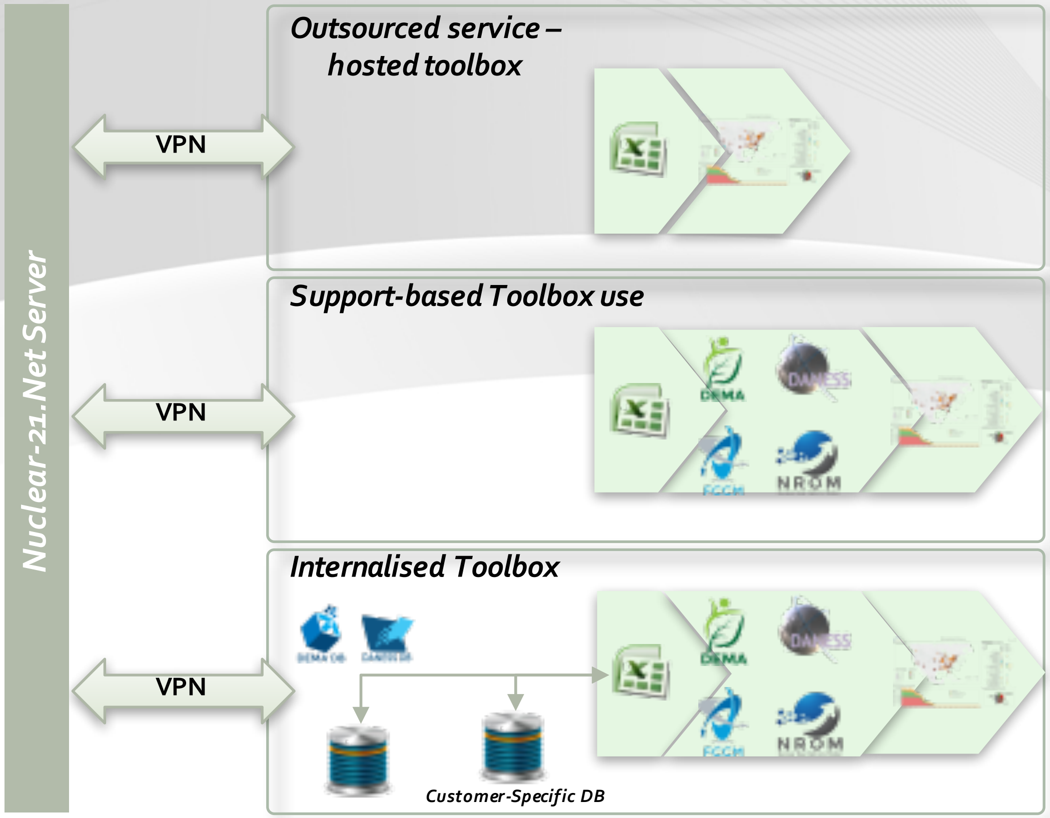
C.

Licensing Options
IT Requirements

NESSAT
Overall licensing architecture



IT-requirements per license-option



Basic requirements

- Operating System
  - Microsoft® Windows® 8, 7, Vista, Server 2012, Server 2008
  - OSX 10.9 or later
- MS-Excel (version 2013 or later)

Three options to visualise NESSAT Toolbox Results

- *Tableau Online access*
  - Access to Results visualisation on Nuclear-21.Net server via web-interface
- *Tableau Desktop*
  - Local Tableau version to edit, modify and visualise results
- *Tableau Reader*
  - Local Tableau version to read and visualise results

In addition

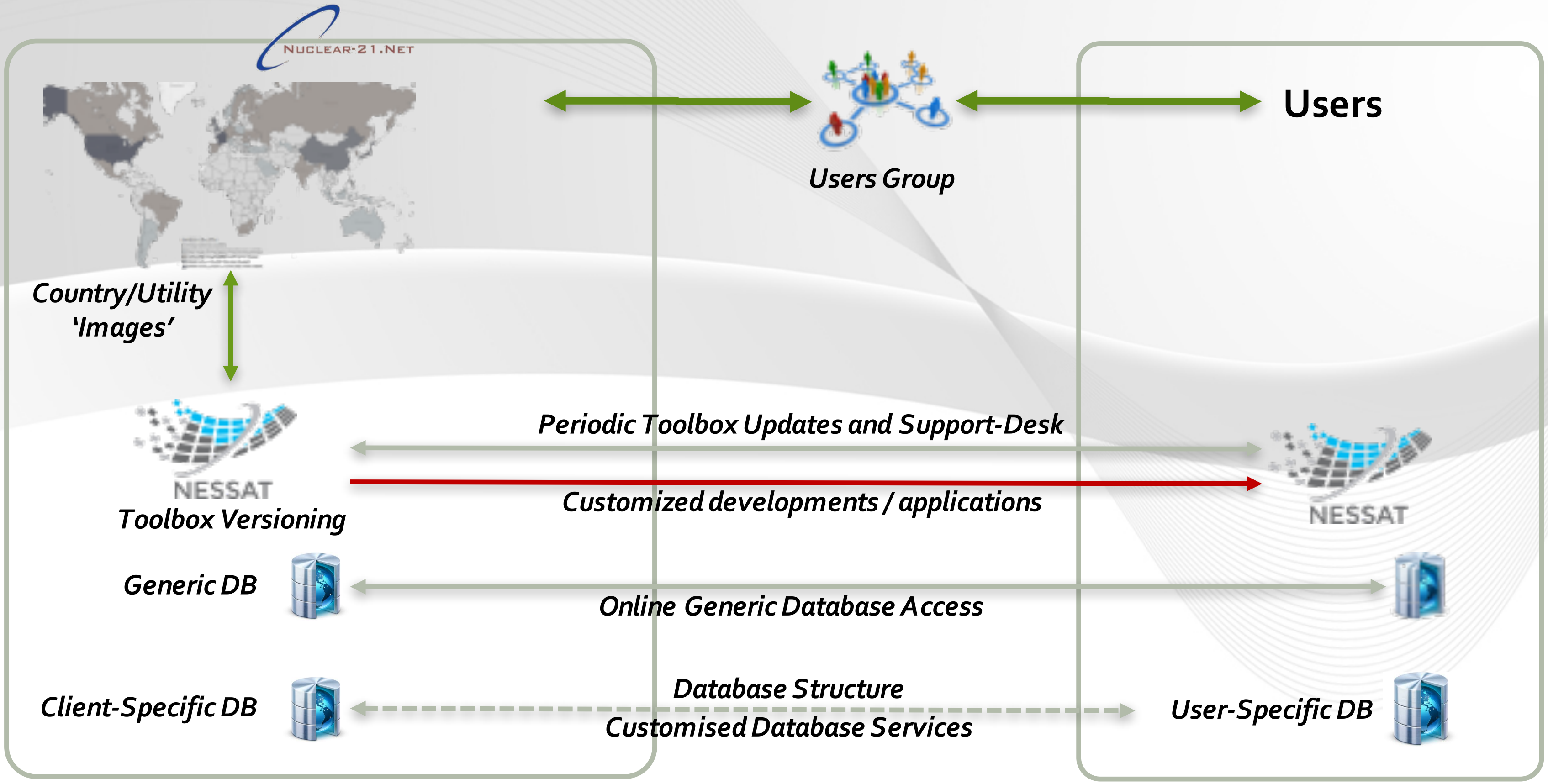
- *STELLA Professional*
- Optional when customised development considered
  - *MatLab (R2016a or later)*
  - *@Risk*

In addition

- *SQLite*

NESSAT Users Group

- **A NESSAT Users Group is being set-up and officialised from January '17 on**
  - First NESSAT Users Group Workshop in May 2017



Typical Examples

China: detailed assessment

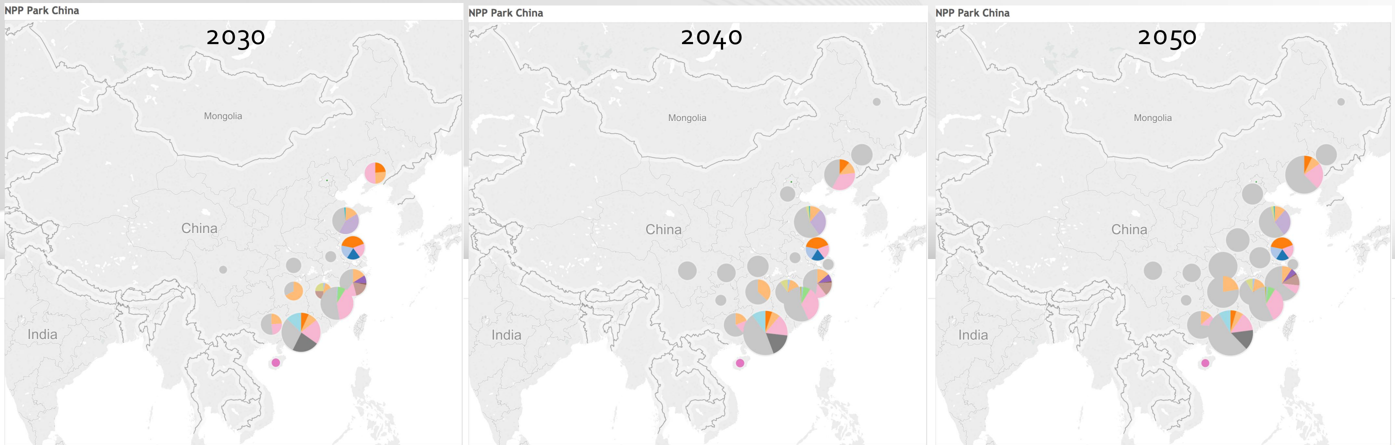
China NES

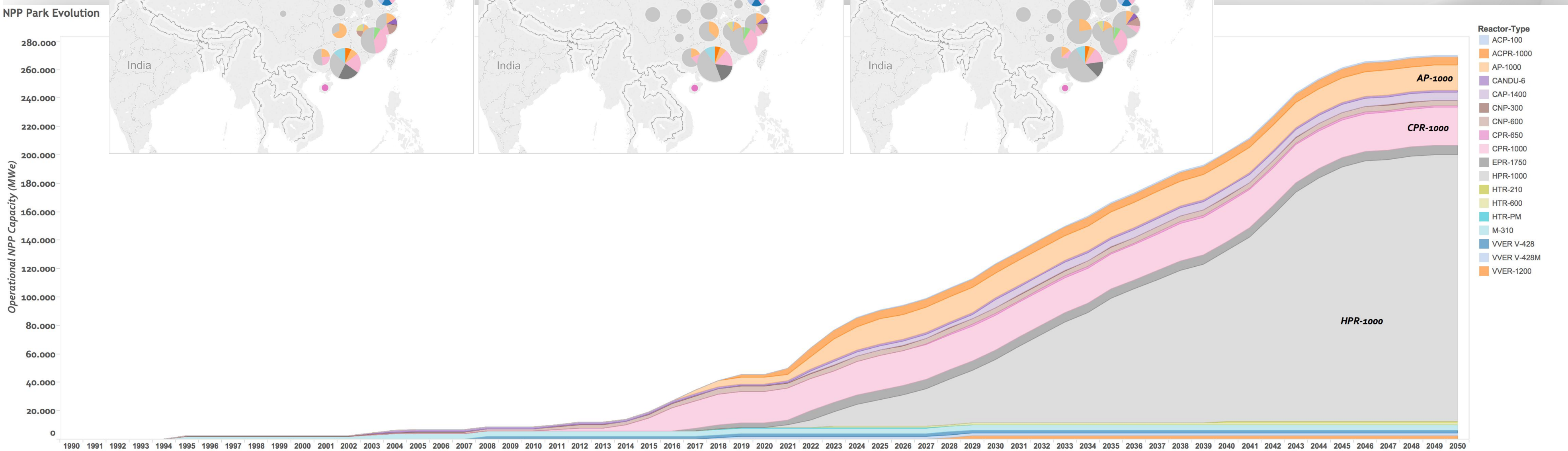
China is geared towards a rapid and large deployment of nuclear energy including the closure of the nuclear fuel cycle

- The 'reference' option according multiple presentations by Chinese representatives is to deploy a LWR+FR fuel cycle, i.e. LWR-UOX with subsequent multi-recycling of Pu in FRs;
- R&D is ongoing, including demo facilities, on HTGR, MSR, and ADS
  - Covering the U/Pu fuel cycle as well as some R&D on Th-use
- Shorter-term options
  - Demonstration of U/Pu-cycle in LWR+FR cycle
  - REPU-recycling in PHWRs with, from mid/late-2020's on, REPU-Th use
- China's strategy of deploying « as fast as possible » FRs for fuel cycle sustainability requires rapid deployment of FR-maturity and fuel cycle capacities
  - Alternative option may be to recycle in LWR-MOX
- The China NES study assesses the different options for China's NES 'locally' as well as globally

Anticipated NPP-Park deployment by mid-century

- **Anticipated rapid growth of NPP-park from 2016 on (some post-Fukushima slow-down) with increasing introduction of domestic NPP-technology (HPR-1000 'Hualong')**
  - Deployment based on plans announced till end 2015 with NPP-orders reported till 2035
  - NPP-Park = "pre-2035 NPP-Orders" park deployment
- **Increasing deployment of NPP-Park into mainland China**



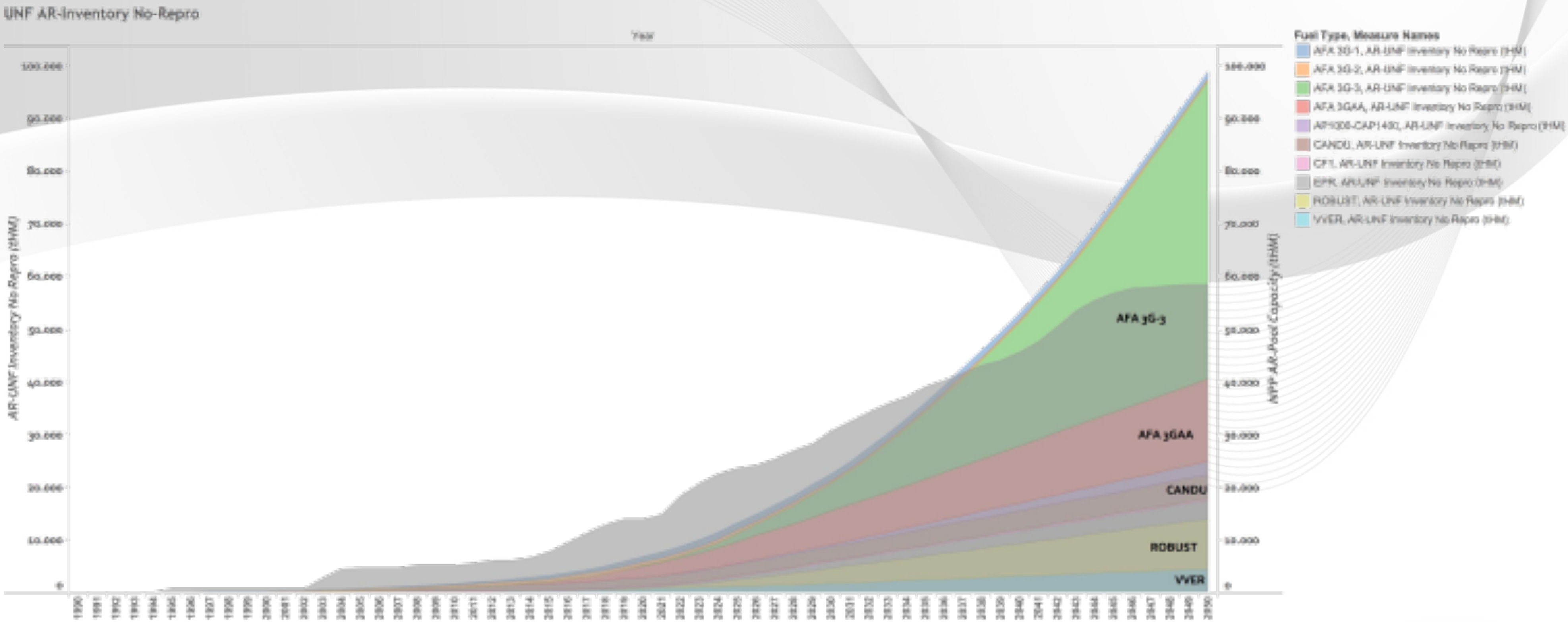


NESSAT

NUCLEAR-21.NET

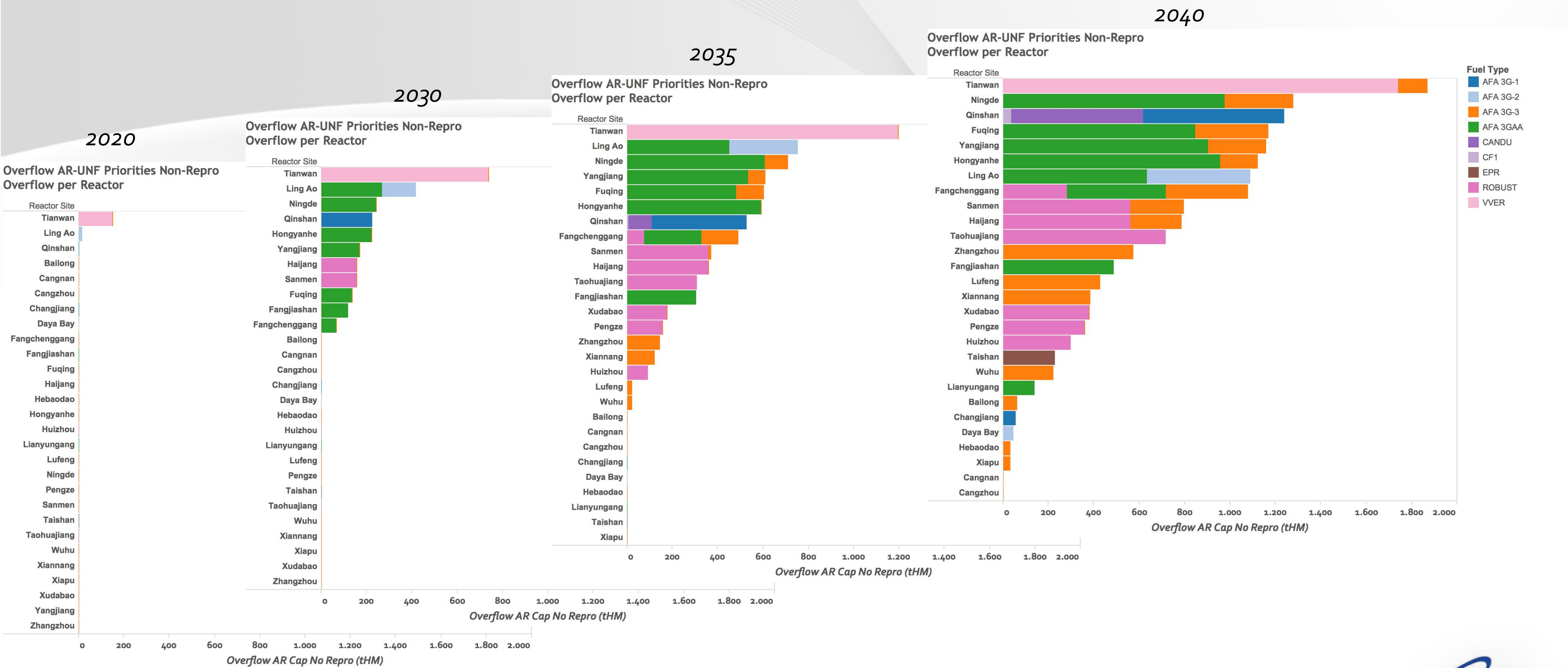
OTC Cumulative UNF inventory

- **Cumulative UNF indicates an “overall” saturation of the At-Reactor UNF-pools by the year 2036**
  - “Overall” = assuming unlimited intra- and inter-site transfer of UNF to optimise At-Reactor pool use
    - *Takes into account the transfer of AFA 3G-2 UNF to DIWOPU/CWSF and to Ling Ao Dry Storage facilities*



Overflow of At-Reactor Pools per fuel type

- **Analysis per NPP and reactor-site indicates the "UNF Overflow" and urgency to evacuate such UNF**
  - "UNF Overflow" = amount (tHM) of UNF beyond the net At-Reactor Pool capacity taking into account the licensed pool capacity and full core discharge margin
  - These overflows of At-Reactor Pools defining the priorities in evacuation towards Reprocessing UNF-pools



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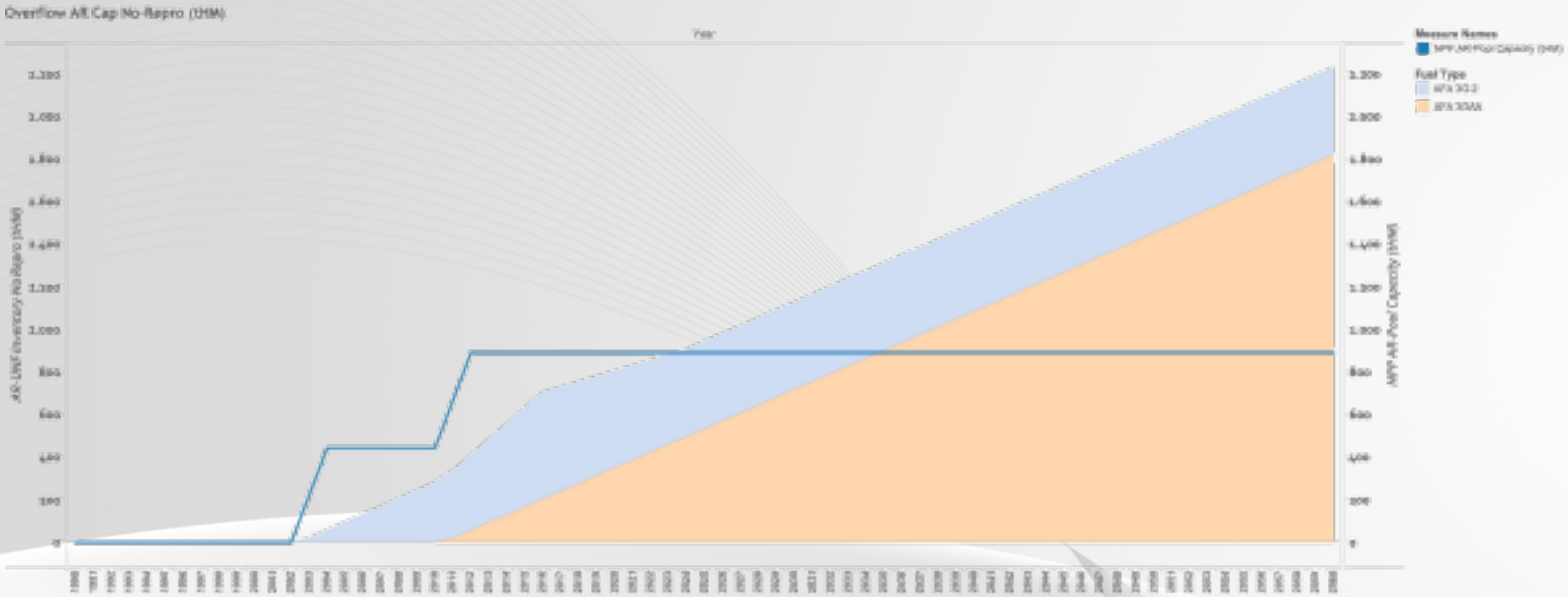
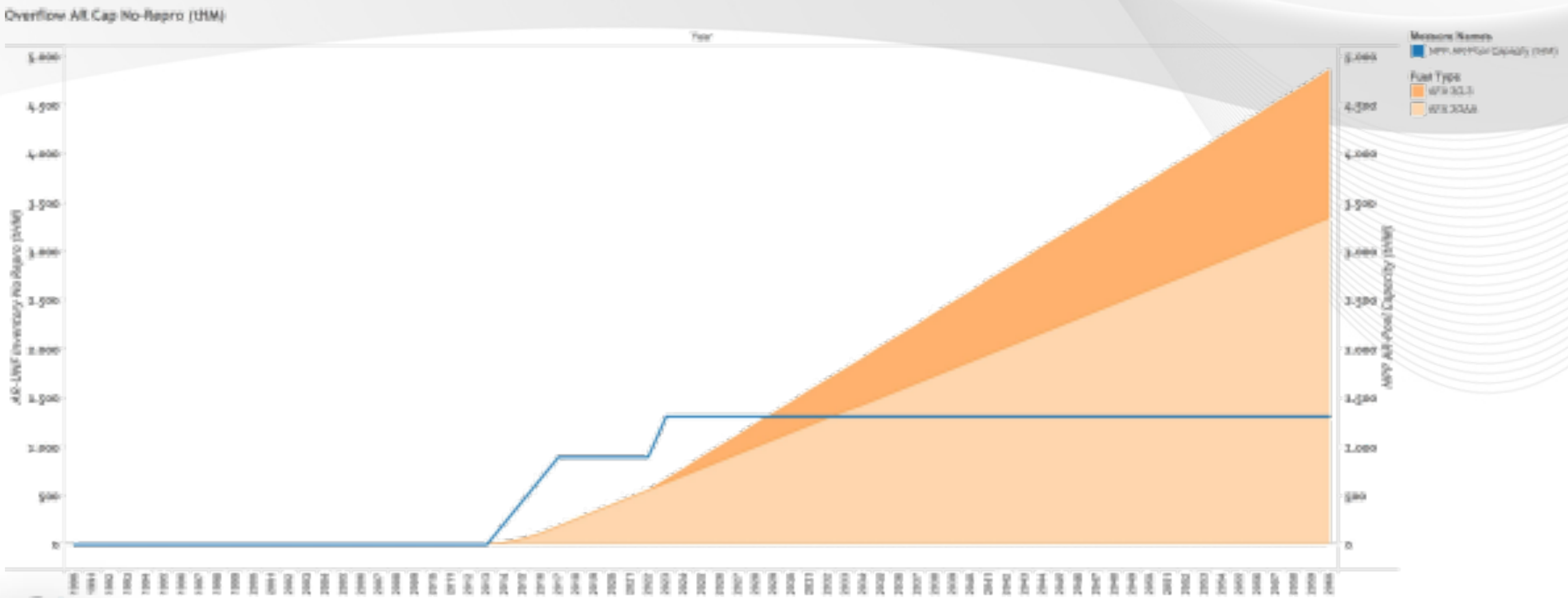
Examples of our assessment detail
Ling Ao and Ningde UNF-inventory versus AR-Pool Capacity





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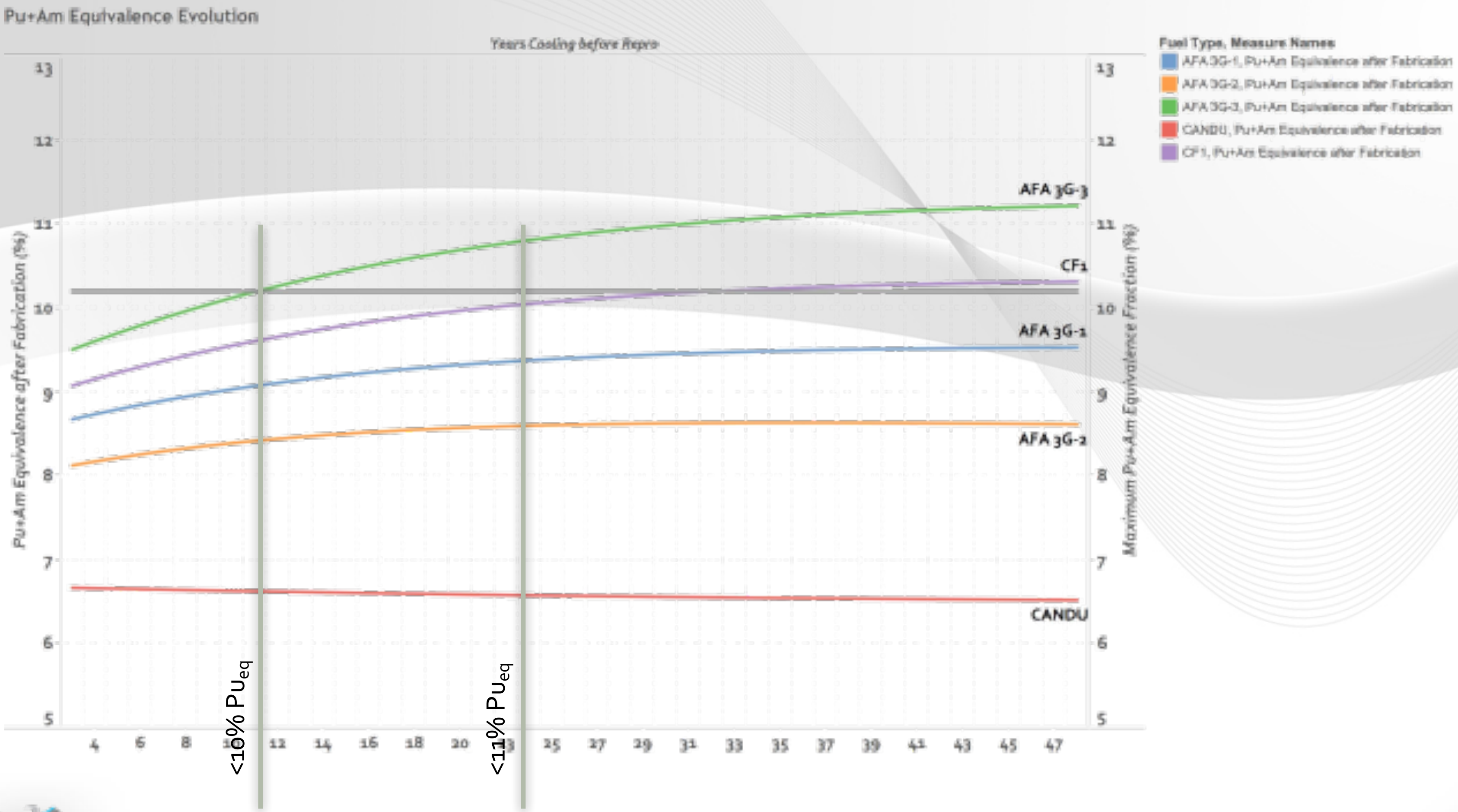
Recyclability of the Pu
from CF1/AFA 3G-1/AFA 3G-2/AFA 3G-3 fuels (2/2)

- **Verification of 'recyclability' of Pu in LWRs**
  - Pu+Am equivalence calculations per fuel batch and depending on reprocessing logistics



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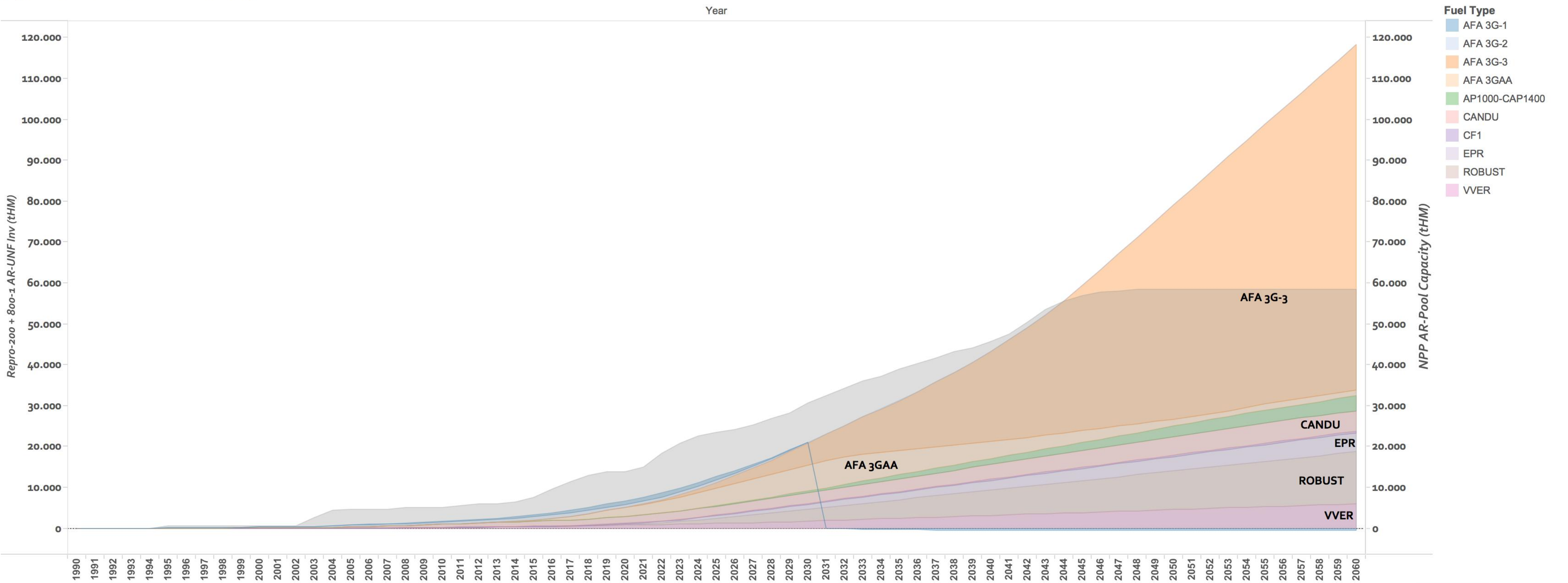
UNF Evolution
Repro-200-0 + Repro-800-1 reprocessing plants (1/3)

- **The deployment of the first 2 reprocessing plants allows to alleviate the urgent "overall" UNF-evacuation need to > 2040**
  - Assuming perfect intra- and inter-site UNF transfer
  - Though, individual NPP-site at-reactor pools remain to have UNF evacuation needs before 2040 despite Repro-800-1 deployment

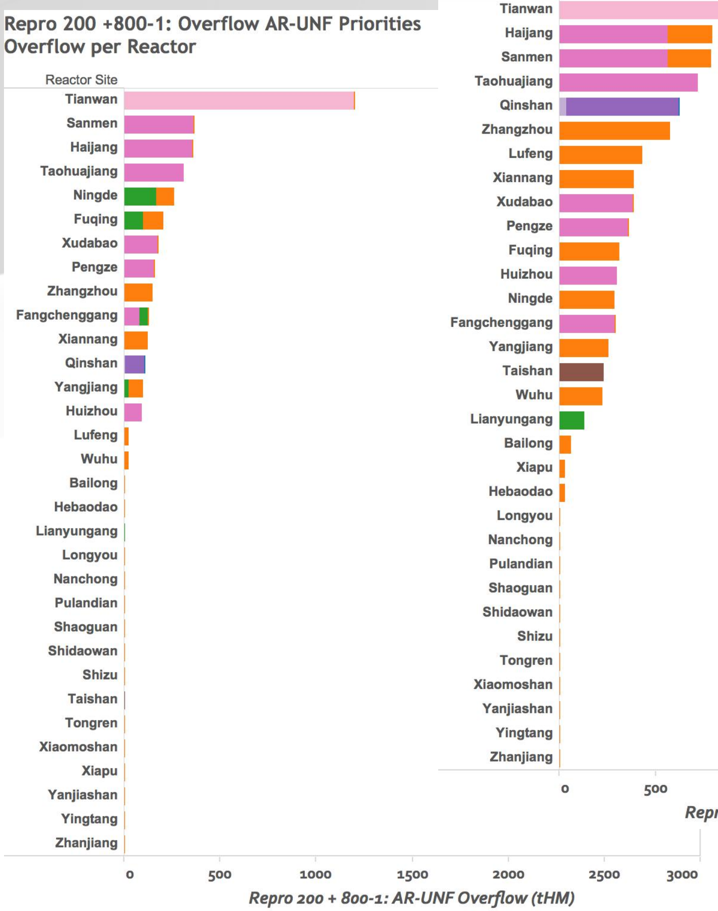
Repro 200 + 800-1: AR-UNF Inventory



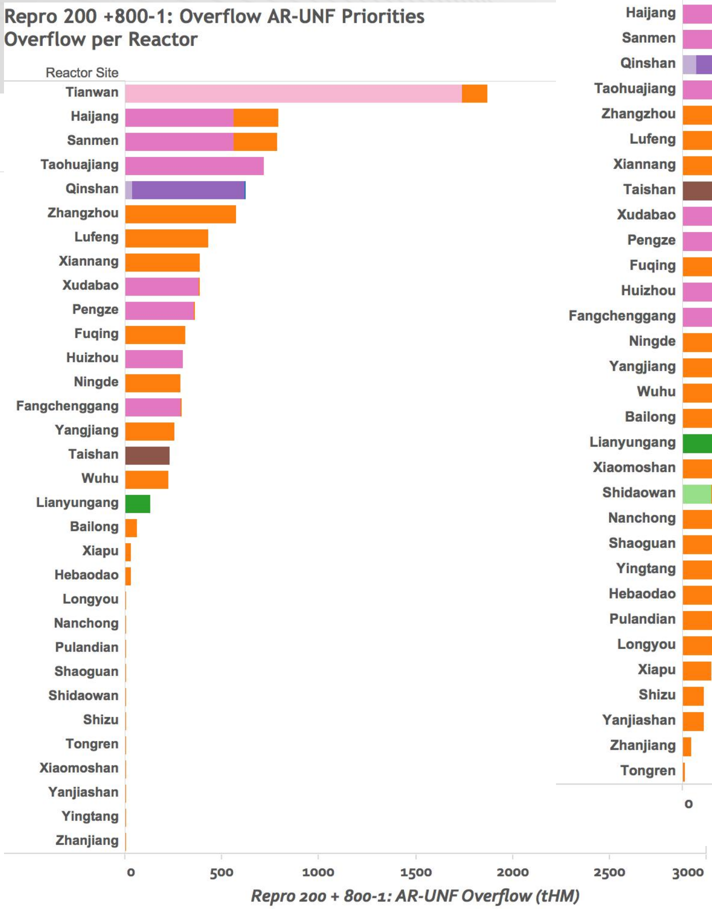
UNF Evolution
Repro-200-0 + Repro-800-1 reprocessing plants (2/3)

- UNF evacuation needs from at-reactor pools
- Repro-800-2 required from 2040 on

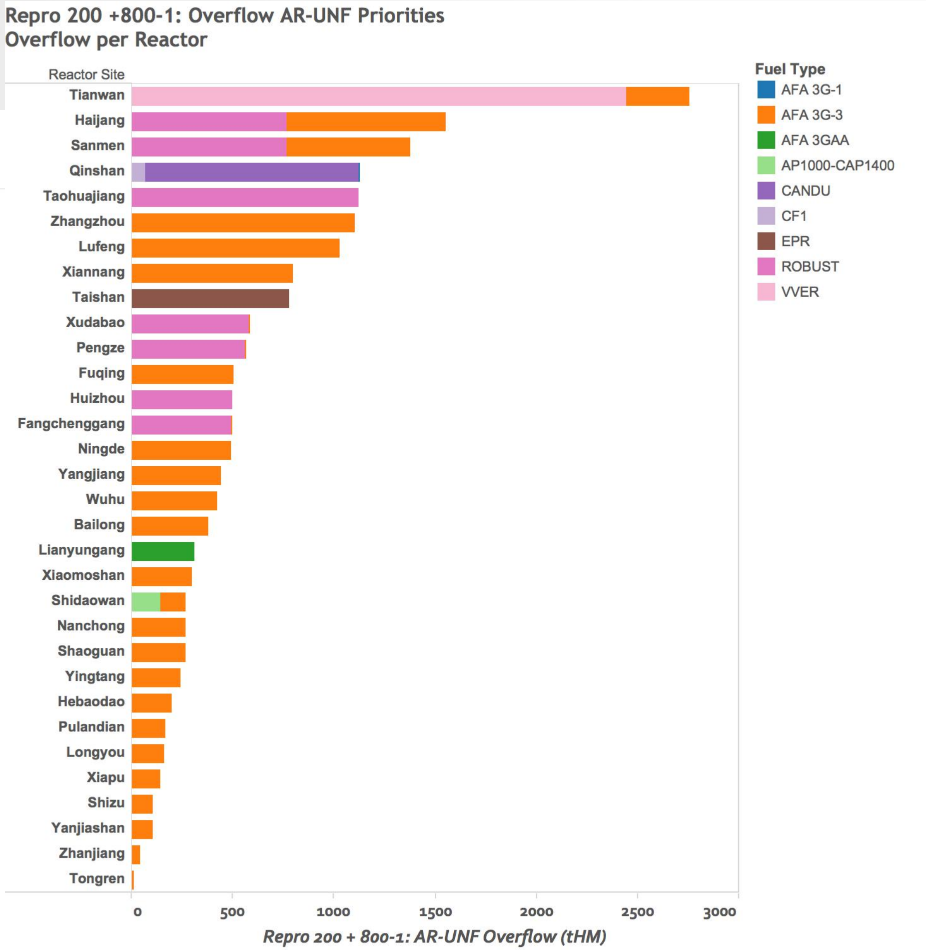
2035



2040



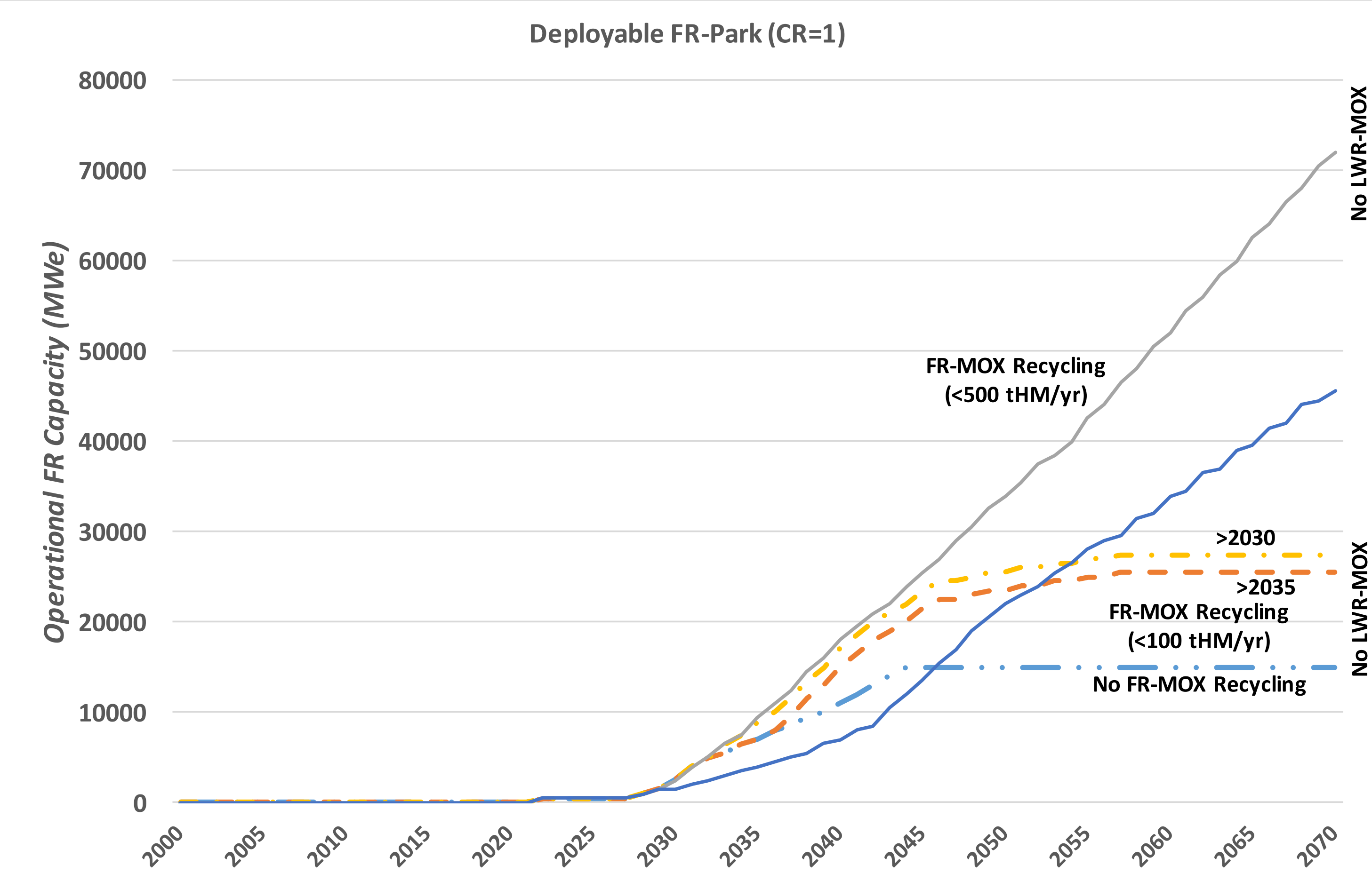
2045



Realistics MOX-ification of CRP-1000's to < 17.5% allows reservation of Pu for FR-deployment

- Assuming MOX-ification up to 17.5% of existing CPR-1000's
- 50% of the separated Pu from Repro-800-1/2 can be reserved to FR-deployment (in addition to Repro-200-0 Pu-flow)

- Higher FR-deployment possible by limiting MOX in CPR-1000's to lower values according reactor core management (limitations)
- And/or to increase FR's CR>1



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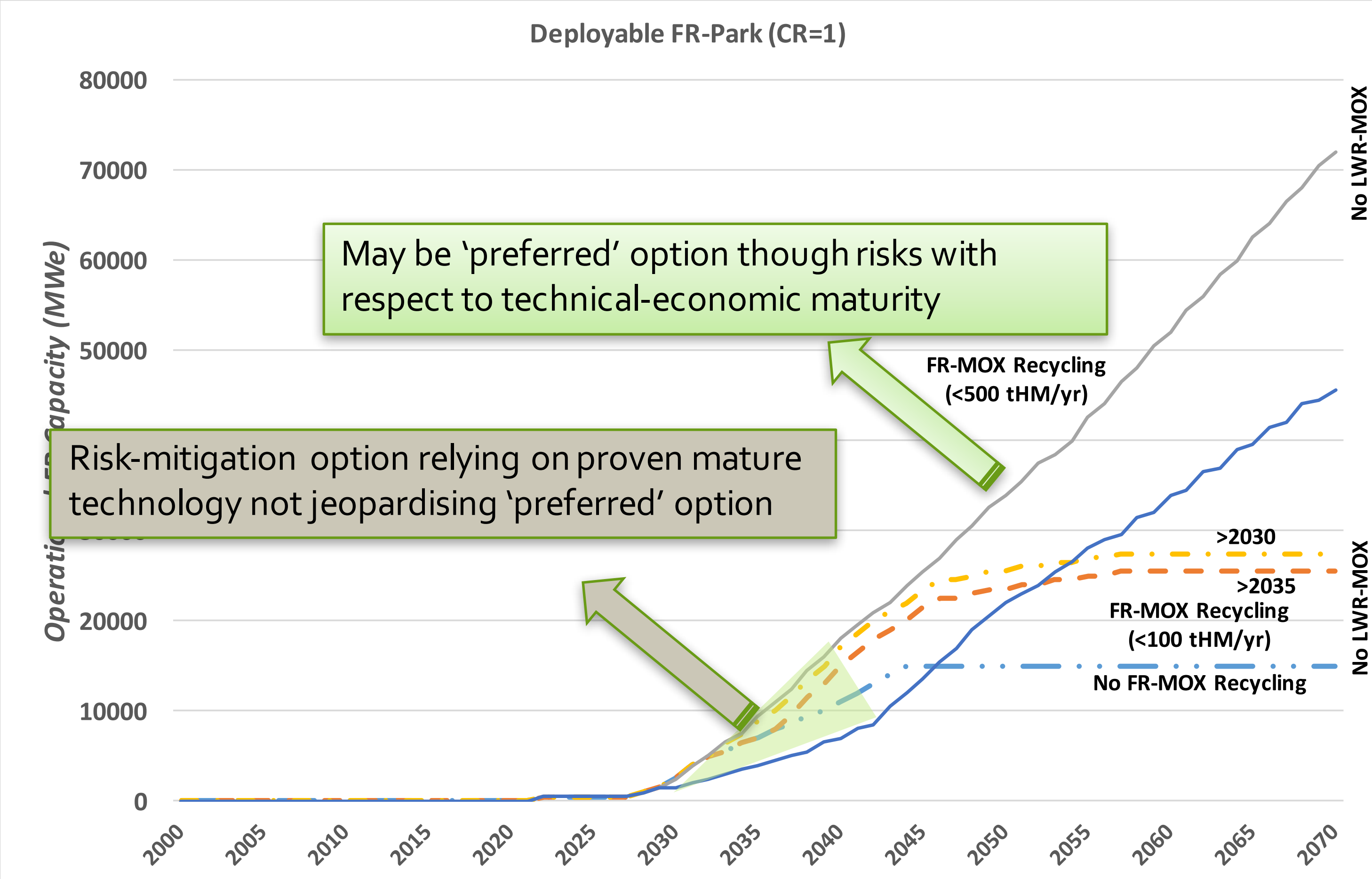
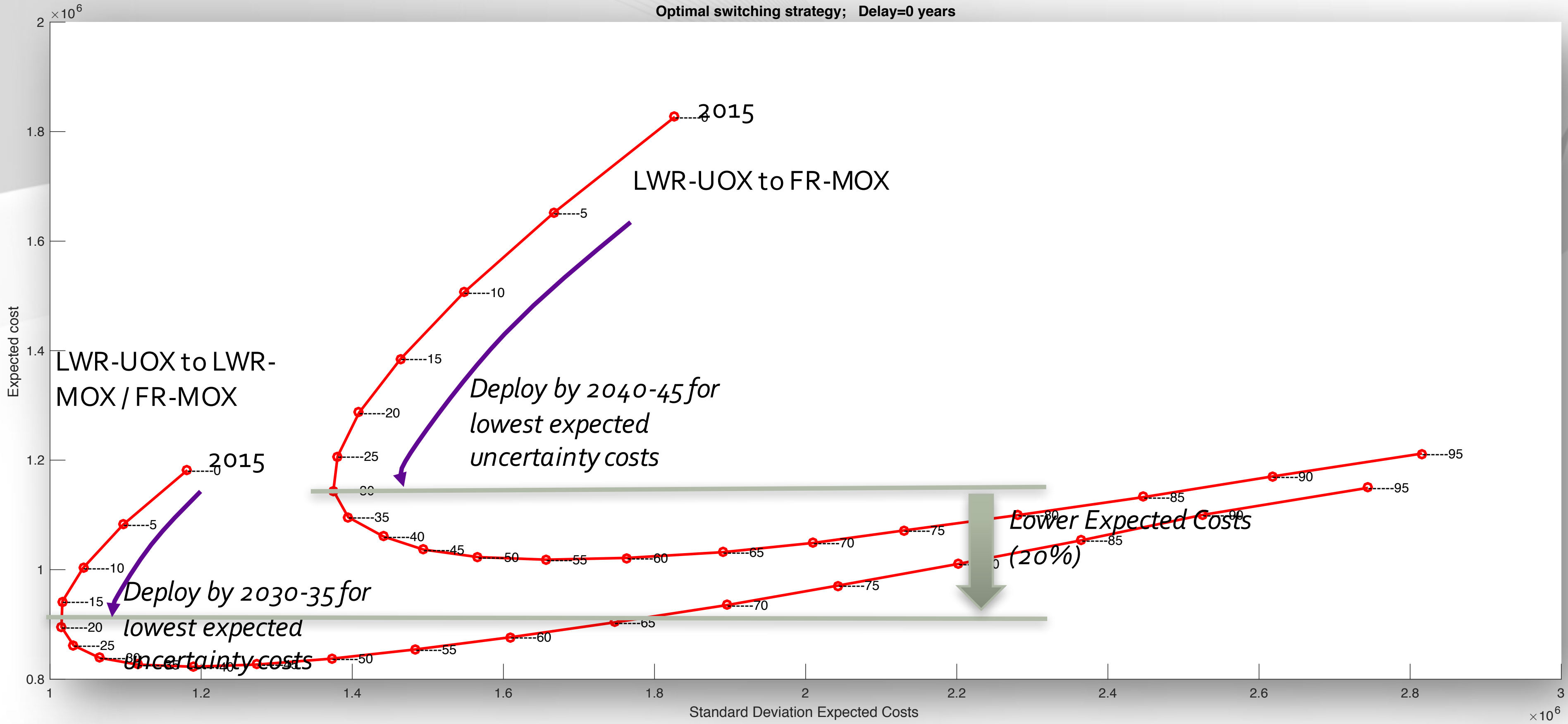
Decisional framework?
How to cope with uncertainty in these scenarios?
Illustration with Chinese NES scenarios LWR-MOX / FR-MOX



Expected Costs and uncertainties for two options
Illustrative results based on generic cost data

- **Expected costs and uncertainties for UNF-management, LWR-MOX deployment and FR-MOX deployment**
- **Evolution of U_{nat}-prices, technical-economic risks with respect to FR-MOX**



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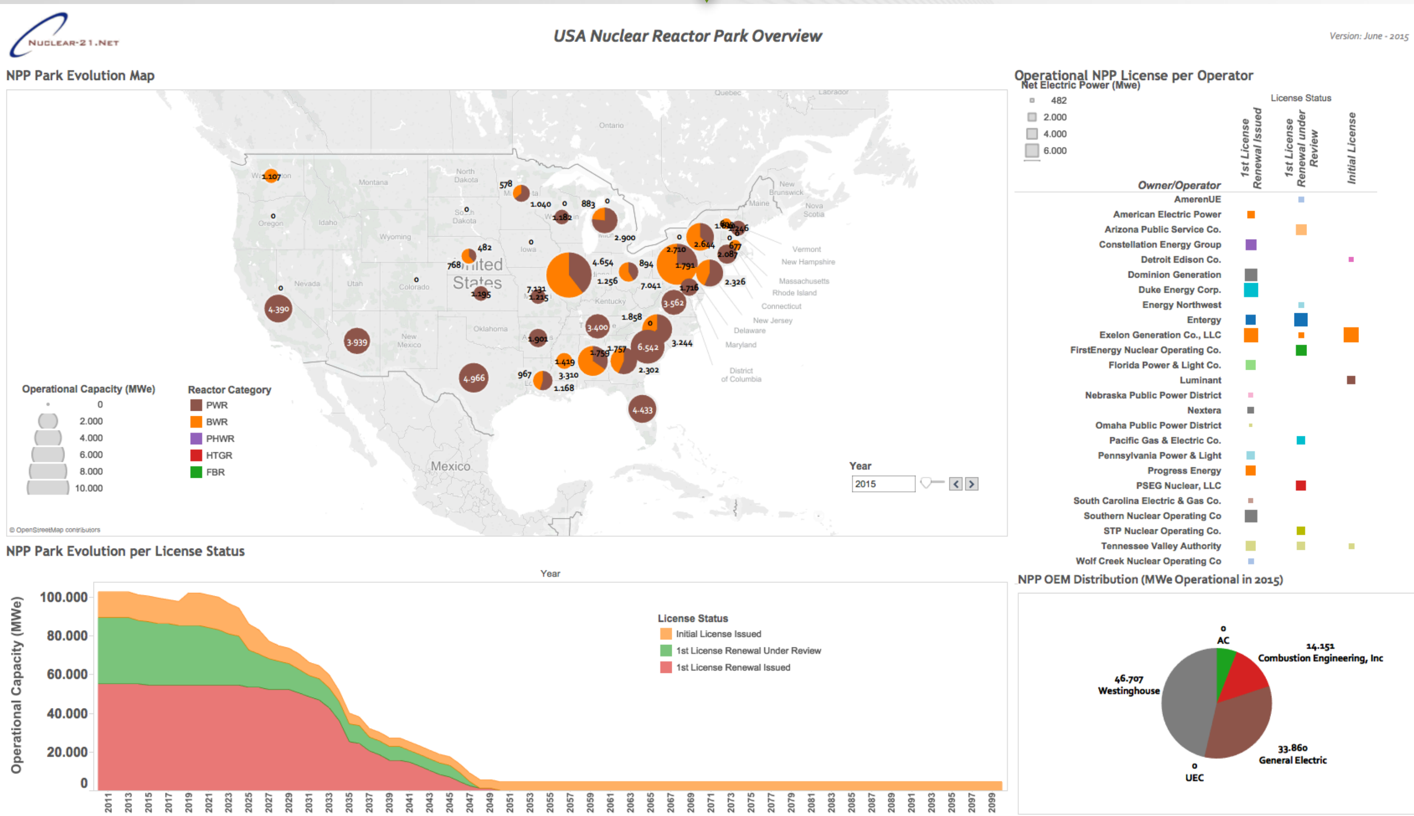
USA Example

Typical Example 1 (1/2)
United States Nuclear Energy System

DANESS Attributes Database

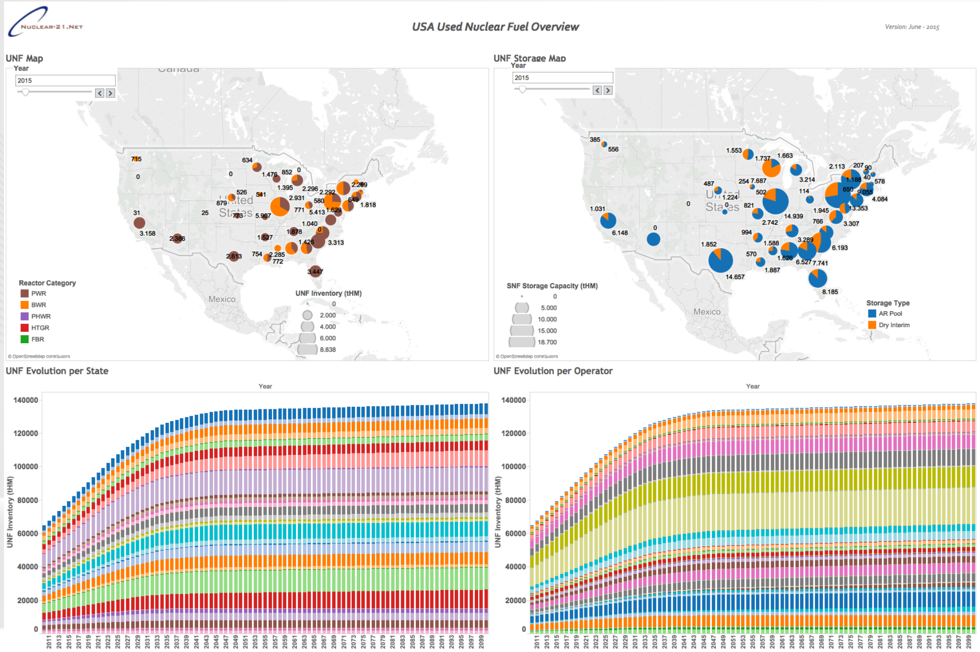


DANESS Input WorkBook

STELLA Professional iThink 10.1

Scenario analysis by nuclear energy system evolution simulation

Typical Example 1 (2/2)
United States Nuclear Energy System



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DANESS

Scenario analysis by nuclear energy system evolution simulation

DANESS Results Database of isdb files

+ a b | e a u

- Online Webserver
- Private Webserver
- Reader

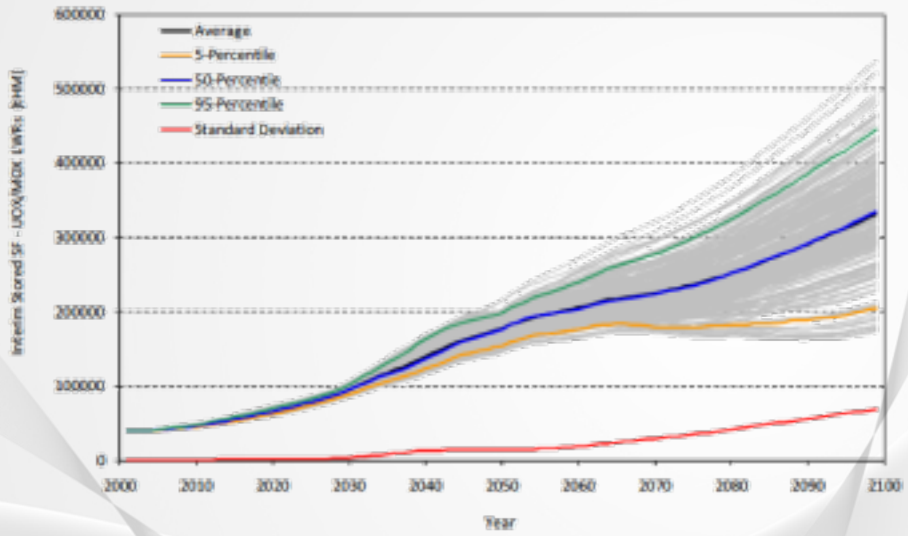
DANESS Results Workbook

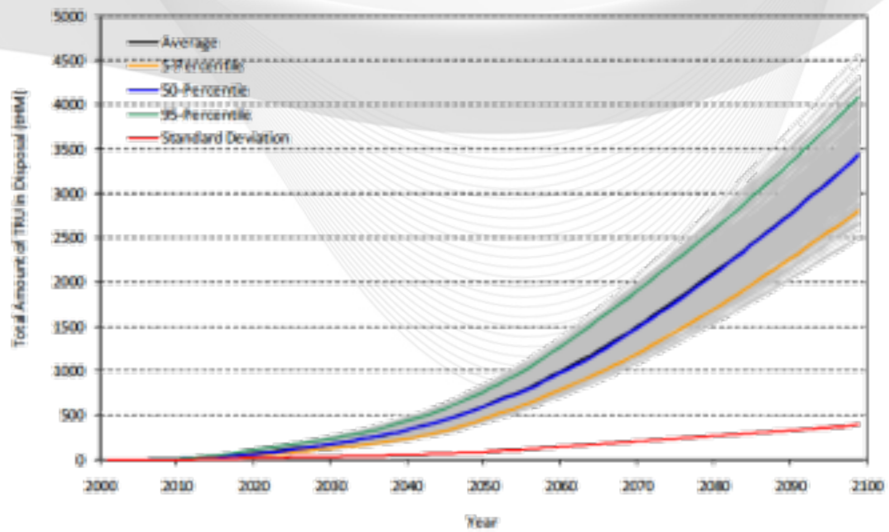
nucInfo

Uncertainty analysis

- **Sampling of input-variables according documented distributions**
  - Impact on key system variables/criteria

  - Example:
    - *Input-variables sampled*
      - NPP-Park competitiveness
      - BU-variations in UOX
      - Load factor variations
      - Reprocessing yields
    - *Impact on*
      - SF inventory
      - TRU inventory in disposal site





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