DANESS: a system dynamics code for the holistic assessment of nuclear energy system strategies

Luc Van Den Durpel, Dave C. Wade, Abdellatif Yacout
Argonne National Laboratory
Nuclear Engineering Division
9700 S. Cass Avenue
60439 Argonne, Illinois
USA
daness@anl.gov

The role of nuclear energy in future sustainable energy systems is subject of many debates worldwide. The assessment of nuclear energy systems asks for a multi-disciplinary look into the development of nuclear energy according to the sustainability dimensions, i.e. economics, environmental and socio-political.

Modeling the worldwide nuclear reactor park including all supply chain details, i.e. the nuclear fuel cycle, demands for an integrated nuclear energy system model which also includes feedback loops representing physical feedbacks within the system as well as, and most prominently, socio-political feedbacks in the decision-making on the various available deployment pathways for nuclear energy. Despite the availability since the early 1960s of detailed model-codes for nuclear reactors covering physic, supply chain and economic aspects of nuclear energy, development of a truly system dynamics view on nuclear energy development only recently gained worldwide interest.

Argonne National Laboratory (ANL) started in 2000 with the development of such integrated nuclear energy system models based on system dynamics modeling, i.e. resulting in the DANESS-code (Dynamic Analysis of Nuclear Energy System Strategies). This code allows modeling the full mass-flow chain of time-varying mixes of nuclear reactor plants and associated fuel cycle options. Several other sub-models are coupled to the mass-flow kernel calculating heat loads, economics, life cycle inventory, and several other parameters and feedback decision-making loops important in the assessment of nuclear energy futures.

This paper will bring an overview on the role of nuclear fuel cycle centres which have recently regained interest in the light of a perceived growing importance of nuclear energy in the world's energy provision and the inherent proliferation concerns this might entail.

Using the DANESS nuclear energy system dynamics code, ANL performs a comprehensive study on various nuclear energy deployment scenarios in six world-regions and the potential role that regional nuclear fuel cycle centers may play in facilitating such nuclear development while respecting proliferation concerns.

The multi-regional analysis considers various nuclear deployment scenarios for six world-regions (ASI, EUR, FSU, LAM, MAF, NAM) with a nuclear energy demand (covering electricity and hydrogen) in these regions as was projected by IIASA/WEC in 1998. Starting from today's nuclear reactor park in these regions, the various scenarios consider the introduction of LWRs (3rd generation), HTGRs, FRs and STAR-H2 reactors following associated fuel cycle options ranging from once-through to full closure of the nuclear fuel cycle for all transuranic elements.

I. INTRODUCTION

Nuclear energy can play a decisive role in tackling the sustainability questions in delivering massive amounts of energy to world society. Various technology roadmaps and other studies on future energy market development have confirmed this need for nuclear energy in coping with the growing energy demand in a sustainable way. But these studies also indicated that synergies between various nuclear energy technologies should be exploited in making nuclear energy an undeniable energy technology for the future [1].

Multiple nuclear reactor technologies and fuel cycle facility technologies are available or under development with each one of these technologies bringing viable technological solutions to various objectives for nuclear energy in the future, i.e.:

- Various energy products such as electricity, process heat for water desalination and hydrogen production, among others, are to be delivered by light water reactors (LWRs), (Very) high-temperature gas-cooled reactors (V-HTGR), sodium/gas/liquid metal cooled fast reactors (SFR, GFR, LFR) or even molten salt reactors (MSR) in the longer term;
- Minimizing the environmental impact and especially the need for scarce radioactive waste disposal space asks for closure of the nuclear fuel cycle based on reprocessing technologies (aqueous and/or dry) and fabrication of fuels containing higher amounts of transuranics (TRU) for recycling in reactors;
- Fast reactors are needed to make better use of scarce natural resources such as uranium and thorium (despite vast amounts of these resources being available) while also drastically reducing the need for disposal sites for radioactive waste.

While very well-designed technological solutions exist or are developed to address each of these objectives, it has also become clear that only synergistically designed nuclear energy systems composed of various reactor and fuel cycle facility technologies mutually exchanging actinide mass flows may optimize the economic, environmental and socio-political performance of nuclear energy, e.g.:

- *Economics*:
  - Fast reactors (FR) contribute a lot better than LWRs to the reduction of radioactive waste arising but, for the time being, these FRs are economically more expensive than LWRs and can therefore only get introduced in the energy market based on an appropriate combination of financial mechanisms (e.g. subsidies or investment risk reduction practices), niche market applications (e.g. hydrogen), and perfect integration with waste management policies;
  - The energy market is not uniform around the world and therefore asking for a variety of reactor types and fuel cycle services, e.g. small reactors (developing countries and combined electricity/process heat services for cities) versus large reactors (developed countries with very well developed electricity networking infrastructure), regionally indigenous fuel cycle facilities versus fuel cycle services which may favor long-refueling intervals (e.g. LFRs with battery-type whole core cassette refueling of reactors);
- *Environmental*:
  - Reducing further the already small environmental impact from nuclear energy involves reduction of uranium mining and milling operations (by closing the nuclear fuel cycle), reducing transport needs (i.e. co-location of reactors and

    fuel cycle facilities or regional fuel cycle centers), minimizing long-term stewardship of radioactive waste disposal (i.e. closing the fuel cycle), …

- *Socio-political*:
    - V-HTGRs may be very attractive for the medium to long-term future but most of these concepts ask for higher enriched uranium fuels and thus for increased amounts of enrichment capacity which may be a proliferation-issue comparable to reprocessing in the back-end of the fuel cycle.

While a single nuclear energy system (see figure 1) may already involve many trade-offs between, for instance, front-end and back-end considerations, the deployment-space becoming available for multi-regional nuclear energy systems in addressing sustainable development becomes truly numerous (see figure 2).

Figure 1. A simplified view of a nuclear energy system already involves many degrees of freedom to optimize for sustainability.

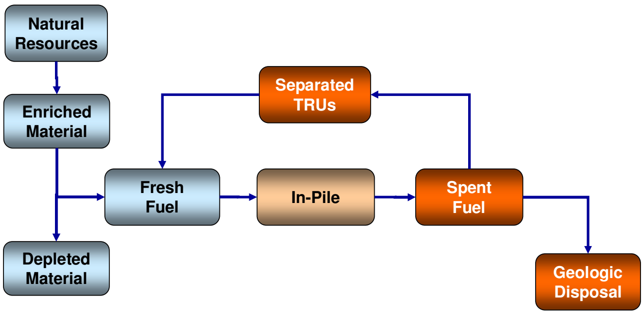
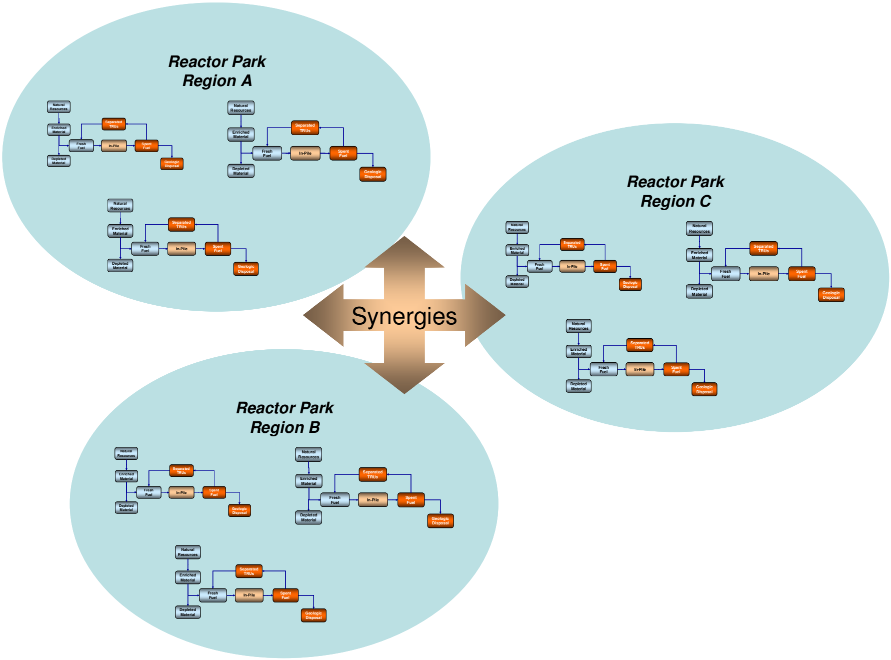


Figure 2. Multi-regional nuclear energy systems have numerous degrees of freedom in optimizing the sustainability character of nuclear energy.



Assessing the role of such synergistic nuclear energy systems in future sustainable energy technology mixes demands a truly multi-disciplinary and multi-dimensional view demanding a complementary set of tools each fulfilling specific parts of such assessment, i.e. macro-economic energy market models, (dynamic) nuclear energy system models, sustainability assessment models, nuclear engineering and reactor physics models, and even many others depending on the scope and level of detail needed in such assessment.

Many of such tools belonging to the nuclear field were developed during the seventies and eighties and only recently, i.e. early 2000s, new initiatives in developing so-called integrated dynamic nuclear energy system models have been launched [2].

It's no surprise why this renewed interest has happened in the recent past. A renewed interest for nuclear energy in an ever growing international energy market demands nuclear energy systems being competitive in various markets around the world, based on internationally proven technology, with international collaborative efforts to keep investment appraisal and the overall sustainability character of nuclear energy optimal. Combined with a new generation of nuclear experts and a more selective financial market, collaboration between partners in R&D and final deployment of nuclear energy systems is a prerequisite to launch new nuclear projects. The public at large as main stakeholder in any development project of that size, also wants to have a transparent understanding of the trade-offs in deploying nuclear energy. Integrated assessment tools, covering not only the purely technical dimension of nuclear energy systems but also the economic trade-offs, the environmental impacts and socio-political aspects shall therefore become a truly important tool in communicating with all the stakeholders involved with nuclear energy development, i.e. from researcher, project manager, decision-maker and, most importantly, society at large.

II. ON THE NEED FOR INTEGRATED NUCLEAR ENERGY SYSTEM DYNAMICS MODELS

Supporting a multi-disciplinary and multi-dimensional view on nuclear energy systems development is a crucial objective for each strategic assessment tool of nuclear energy's future. It is very important to have such integrated nuclear energy system models covering the dynamics of nuclear energy deployment for various reasons, e.g.:

- First, because closing the fuel cycle introduces dynamical mass flow feedback effects, and these become complex indeed when symbiotic flows among reactor types are to be modeled;
- An equilibrium system analysis may give indications on the end-states of any transition between today's and any future nuclear energy system but may not answer questions on how fast the final equilibrium state might be achieved, if achievable at all;
- Temporary separated fissile/fertile material inventories may build up during a transition which may be advantageous, for instance to introduce fast reactors, but may also considered to be avoided for socio-political (i.e. non-proliferation) considerations;
- All components of a nuclear energy system, i.e. reactors and fuel cycle facilities, follow a life-path which inherently introduces delays due to licensing, construction and later-on shut-down and decommissioning of these components. The various life-stages introduce different environmental impacts, economic cost/benefits, and these life-stages may introduce additional delays in the

deployment of nuclear energy systems due to, for instance, temporary fissile/fertile material shortages;
- Phased adaptive management approaches [3] in increasing interest in nuclear waste policies resulting in time-varying inventories of waste in different places and conditions in the fuel cycle.

Truly integrated dynamic nuclear energy system models not only need to take into account these temporal phenomena but also space or regional effects, i.e. transport between fuel cycle facilities and reactors, possible roles for multi-regional nuclear fuel cycle centers or multi-national approaches to waste management [4-6], presence of TRUs in fuel cycle, …

Depending on the level of detail, integrated nuclear energy system models may be categorized as shown in table 1. Various models have been developed in the past and especially in recent years been proposed for further development, e.g. COSI (CEA, France) [7], OSIRIS (NNC, UK) [8], ORION (Nexia, UK) [9], DESAE (, Russia) [10], VISTA (IAEA) [11], DYMOND (ANL, US) [12], DANESS (ANL, US) [13], NFCSim (LANL, US) [14], SINEMA (INL, US) [15], SuperStar (TEPCO, Japan) [16]. Table 1 only flags the functionalities available today in DANESS which shall be described in the next section.

II.1. Material Flow Accounting

A material flow accounting (MFA) part is intended to perform mass flow analysis throughout the whole nuclear energy system, i.e. on reactor level, on fuel cycle facility level, on utility/country/region or world level, or on any other system level defined by the user. The more complex the analyzed nuclear energy system, the more degrees of freedom and interactions between various components of the nuclear energy system may become possible. For instance, multi-regional nuclear energy systems need to account for the mass-flow analysis on an individual reactor basis as well as on grouped regional park basis and any cross-flow of fissile/fertile or other materials between the various regions and reactors. Different regions may also deploy different reactor parks and multiple interactions and decision-making rules come into play, for instance, to decide on which reactors to deploy in which region, the kind of fuels to be used in various reactors and the corresponding fuel cycle facility needs or limitations on such deployment due to shortage of fissile/fertile material, …

Decision feedback-loops can be implemented deciding on fuel cycle facility deployment, reactor park deployment, reactor core composition, forecasted fissile/fertile material availability, and others and thus driving the trade-offs to be made in the material flow accounting simulation.

Isotopic compositions are to be traced in order to allow for reactor core management (criticality and burn-up calculations, …) in the MFA-calculations as well as to calculate doses, decay heats and neutron-source strengths to be used in the calculation of repository needs, impact on fuel cycle facilities and environment, etc.

Most codes today limit themselves to an MFA for a single or regional reactor park in equilibrium and transient conditions including, in varying details, the additional functionalities mentioned before.

The output of such MFA-codes is a detailed mass-flow analysis including the temporal and geographical evolution of the different mass-flows and inventories and the calculation of mass-flow indicators used in sustainability assessment, e.g. resource use, waste arising, TRU-inventory, …

II.2. Sustainability Assessment

While the MFA-part is the kernel of any integrated nuclear energy system assessment model, the translation of this MFA into sustainability dimension indicators and criteria is a very important aspect rendering these integrated assessment models very relevant to nuclear energy policy making.

II.2.1. Economics

Levelized energy generation costs per reactor and per region, in case of multi-regional analysis, are important indicators for any economic sustainability assessment. The decomposition of these levelized costs into capital, operation&maintenance and fuel cycle costs is important information as input to macro-economic energy market penetration models such as MARKAL [17], ENPEP [18], MESSAGE [19] and others. The need for investment in the nuclear fuel cycle is also an important indicator on the financial attractiveness of certain nuclear energy system options and, when considering for instance multi-regional fuel cycle centers, in assessing the economic value of certain options in deploying nuclear energy systems.

While levelized energy generation costs are useful information on a reactor, region or multi-region level, a more detailed cash-flow analysis is needed especially for fuel cycle facilities in order to analyze the investment attractiveness for each facility and thus indicating the attractiveness and impediments in deploying certain fuel cycle options which may seriously impact nuclear energy system deployment potential.

Learning curve effects might be needed to fully take into account the future market potential for reactors and fuel cycle facilities due to decreasing costs, losses, capital needs due to the gain in experience in licensing, constructing, operating and decommissioning these facilities.

II.2.2. Environmental

Each of the nuclear energy system components, being it reactors or fuel cycle facilities, is accompanied by the use of resources and the emission of so-called stressors which will finally result into an environmental or health impact. Life Cycle Inventory (LCI) models track the level of resource use and stressors over time for each of the components of a nuclear energy system. A Life Cycle Analysis (LCA) model then tracks the consequences of this resource use and stressors while an Impact Assessment (IA) focuses on the analysis of the impacts on environment and health but also on economic and socio-political criteria.

Most LCI/LCA-models consider a time-aggregated representation of today's reactors and fuel cycle facility technologies and therefore cannot fully grasp the time evolution of resource use and environmental stressor levels which might give important differences between various nuclear energy system options despite that a time-aggregated and regionally aggregated LCI/LCA would not show major differences. For instance, differences in dose to workers, transport needs, reduction in mining of uranium for closed fuel cycles and therefore difference in timing when such activities are needed shall result in differences in environmental stressor levels and impacts.

II.2.3. Socio-political

Socio-political issues address, among others, non-proliferation and physical protection aspects, work intensiveness, institutional and ethical questions, and other mostly non-quantifiable indicators that are, however, of very high importance for stakeholders.

Table 1. Categorization of integrated dynamic nuclear energy system analysis functionalities.
ANL's DANESS capabilities are flagged by ✓, those to be released soon as (✓).

Scope	*Equilibrium Analysis*		*Transient Analysis*	
	Single Reactor	*Reactor Park*	*Regional Reactor Park*	*Multi-Regional Reactor Park*
Material Flow Accounting				
Natural U/Th use	✓	✓	✓	(✓)
Front-end capacity needs & use	✓	✓	✓	(✓)
Reactor core loading	✓	✓	✓	(✓)
Back-end capacity needs & use	✓	✓	✓	(✓)
Separated material inventories	✓	✓	✓	(✓)
Disposal needs	✓	✓	✓	(✓)
Related functionalities				
Isotopic composition	✓			
Decay heat	✓			
Reactor core management				
Equilibrium core loading	✓			
Economics				
Levelized generation cost	✓	✓	✓	✓
Investment needs	✓	✓	✓	✓
Cash-flow analysis	✓	✓	✓	
Market penetration	✓	✓	✓	✓
Related functionalities				
Learning curve effects	✓	✓	✓	✓
Environmental				
Life Cycle Inventory	(✓)	(✓)		
Life Cycle Analysis				
Impact analysis				
Socio-political				
Proliferation risk				
Other functionalities				
Uncertainty/sensitivity analysis	✓			
Interfacing with other codes				
Decision feedback loops	✓			

II.3. System Dynamics

In developing integrated nuclear energy systems models, ANL has viewed it important to keep in mind the following objectives from a user's perspective, i.e.:

- *Transparency of the model*, i.e. the final user, being it a researcher or an energy policy advisor, needs to be assured that the underlying systems model behaves as in the real world and communicates the results of systems simulations in a format according standardized sustainability criteria;
- *Appropriate level of detail* to guarantee correct results while this level of detail surely depends on the specific case being analyzed;
- *Scalability*, i.e. the architecture of the model should allow small as well a very complex, e.g. multi-regional systems, be analyzed using a standard methodology;
- *Interactivity*, i.e. part of the systems simulation aims at allowing iterative intervention capability to the user so he can investigate on the possible synergies in deploying nuclear energy systems as well as to show the trade-offs to be made in advancing nuclear energy systems deployment;
- *Connectivity,* i.e. such dynamic nuclear energy system models are complementary to other models addressing, for instance, macro-economic energy market aspects. Connectivity, preferably on-line, with this other codes is very important.

System dynamics [20] tools have been especially developed to support these kind of systems thinking approaches on complex problems incorporating technical, economic, environmental and social feedback mechanisms. Especially the capability of system dynamics models to cover the temporal and geographical information of the simulated systems is an important advantage coupled to the ease of simulation based on commercial software packages, almost all responding to the above mentioned objectives to develop such nuclear energy systems models.

ANL has currently chosen IThink to develop the DYMOND and DANESS models but is also the capability to extend DYMOND and DANESS to agent-based models.

III. ANL'S MODELS, DYMOND & DANESS

Argonne National Laboratory started developing dynamic nuclear energy system models in the context of the Generation-IV Roadmap Fuel Cycle Cross-Cut Group activities [1] and the Advanced Fuel Cycle Initiative [21]. Today, two models are available, i.e. DYMOND being a US-specific model and DANESS which is a more elaborate nuclear energy system model. A brief description shall be given of both.

III.1. DYMOND, i.e. Dynamic Model of Nuclear Development [12]

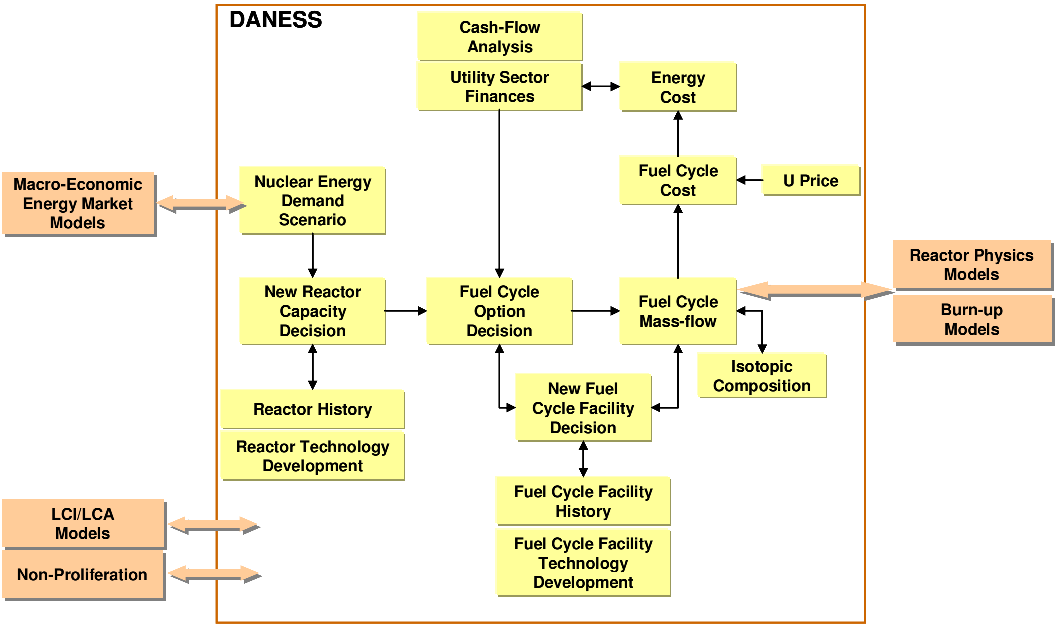
DYMOND was developed during the Generation-IV Roadmap exercise and is currently used to model the US-specific reactor park. It's not intended as a general nuclear energy system model for use by other countries or regions around the world. Specific AFCI-related fuel cycle options are pre-set in DYMOND and only the mass-flow analysis is performed by DYMOND. No economic or environmental and socio-political aspects are considered by this code.

III.2. DANESS, i.e. Dynamic Analysis of Nuclear Energy System Strategies [13]

DANESS is the more elaborate dynamic system analysis code which is developed according the objectives described in the previous sections, i.e. able to cover the range from single reactor equilibrium cases up to the most advanced multi-regional systems transient analysis while also looking into the material flow accounting and, at the user's option, all sustainability assessment dimensions. The general architecture of the DANESS-model is shown in figure 3.

DANESS is capable to handle the full detailed material flow accounting part as well as the full economic analysis of nuclear energy systems by considering the levelized energy costing, detailed cash-flow analysis on reactor and fuel cycle facility level, intra-nuclear market competitiveness analysis while allowing each of the cost components experiencing cost escalation, learning curve effects and discounting. The user selects the degree of complexity and need not use features at no interest to him. The energy products to be delivered by the nuclear energy systems is derived from other macro-economic energy market codes where DANESS is intended to allow on-line interaction with such codes.

Figure 3. Architecture of DANESS.



The MFA uses reactor, fuel and fuel cycle characteristics contained in a database and where these attributes are based on more detailed reactor physics and burn-up calculations. There is today no direct link between DANESS and such codes but a simplified criticality and burnup engine is considered in future versions in order to interpolate between the tabled fuel compositions. Isotopic compositional changes in the fuel cycle, i.e. out-of-pile, are traced in order to correctly represent the material balances and especially the dose, neutron-strength and especially decay heat as the latter is an important parameter to assess the repository space needs. Of importance is the capability to perform uncertainty and sensitivity analysis, using Monte Carlo techniques, on all parameters in DANES.S

Each reactor and fuel cycle facility follows a life-path allowing to track the cash-flow for each component of a nuclear energy system but also to analyze the environmental stressors related to these components and to give information on the temporal and geographical distribution of these stressors.

The non-proliferation aspect and other difficult to quantify socio-political aspects are currently under consideration. DANESS is designed such that any future model specific to these aspects may be integrated and coupled to the MFA-part in DANESS allowing consistent comparison between various scenarios using one transparent MFA-model.

IV. A MULTI-REGIONAL NUCLEAR ENERGY SYSTEM STUDY

Energy is crucial for economic development. Energy services also help to fulfill basic needs such as food and shelter and contribute to social development by improving education and public health. Energy has therefore deep and broad relationships with each of the three pillars of sustainable development – the economy, the environment and social welfare.

The growing demand for energy worldwide has, however, been increasingly associated in the recent two decades with environmental detriments among which the emission of greenhouse gases has been the most prominent one. The 'Limits to Growth'-question raised by the Club of Rome in the 1970s [22], has recently spurred renewed attention due to increasing energy prices, a perceived shortage of (liquid) fossil energy resources and their increasingly deemed unfavorable geo-political distribution. Last but not least, the environmental possible impact of these fossil-based energy conversion technologies with climatic consequences for the future is a growing worldwide concern.

Nuclear energy has been an important energy technology since the middle of the last century and is increasingly seen as an important option to be put in this balance of growth and environment. While nuclear energy was initially seen as a prominent means to prosperity (i.e. 'Too cheap to meter!'), it has become a flagship of socio-political concern in the latter part of the 20th century and is even so today in some countries. While nuclear energy is predominately an environmental friendly energy technology, there remains the issue of highly radioactive waste management as a politically perceived problem despite the availability of scientific and technological solutions being developed. Among them is recycle as a waste management strategy.

It is becoming increasingly clear that the future energy market in different parts of the world will need nuclear energy systems tailored to the local or regional market needs. Wide-spread use of nuclear energy services has to take account of the socio-political concerns relating to the spread of nuclear technological knowledge, the need for international transport of nuclear materials, the issue of waste management, the need for fuel cycle facility investments around the world and demand growth rates which are region-dependent.

IV.1. Regional Nuclear energy Demand

The world's primary energy demand is projected to increase by a factor of 1.5 to 3 by the year 2050 [23]. This growth in energy demand will not be distributed evenly and is essentially the result of the combined effect of increasing population and changes in energy consumption per capita in the different regions. In 1998, the World Energy Council (WEC) together with the International Institute for Applied Systems Analysis (IIASA) published the 'Global Energy Perspectives' report which still is considered as one of the most authoritative reports on future energy demand projections [23]. Figure 4 shows the projected nuclear energy demand for the six-regions according to the six energy demand scenarios defined in that publication and used in ANL's multi-regional analysis. These six-regions are NAM (North America), LAM (Latin and Central America), WEU (Western European Union), FSU (Former Soviet Union and Eurasia), MEF (Middle East and Africa, i.e. sum of MEA and AFR) and ASI (Asia).

Figure 5 shows the annual demand for new reactors in the different world regions for energy demand scenarios B and C2 respectively. (i.e., the time derivatives of the curves in Fig. 4)

This annual demand, expressed in energy-equivalent (TWhe/yr), corresponds to the amount of reactors that should become operational in that specific year in order to keep up with the nuclear energy demand in that region.

The future market for new reactors is clearly different for different regions according to figures 4 and 5. The WEC/IIASA-scenarios allow summarizing the following trends:

- The market for new deployments of nuclear reactors in today's industrialized countries (i.e. NAM, WEU) is important until mid-century but becomes less important later-on. This is especially the case in energy demand scenario C2;
- The NAM and WEU are essentially replacement markets during the period until mid-century;
- The FSU-market extends over a longer time-period due to a slower but steadily growing energy demand;
- The main markets for new nuclear reactors, in energy demand scenario B and C2, are the ASI and MEF regions. The latter region is projected to have a later market launch for nuclear reactors after mid-century;
- The LAM-region is a rather slow growing market for new nuclear reactors in energy demand scenario B and is hardly relevant in energy demand scenario C2.

The main question that the ANL-study is analyzing is how the different regional nuclear energy system deployment scenarios may be meshed together by use of various nuclear technology options such that the sustainability character of nuclear energy worldwide is maximized?

Figure 6 gives a graphic summary of the outcome of various nuclear technology roadmap studies from the past few years. This so-called three-dimensional representation shows the kind of 'deployment-space' for nuclear energy which recognizes differences in regional or market environment (the so-called client categories), energy products to be delivered in these markets, and finally the sustainability character of nuclear through the use of symbiotic actinide mass cross flows between reactors and fuel cycle facilities.

Client Categories dimension

Nuclear energy demand projections shown above have already indicated the differences between various regions with respect to future growth in demand. Next to these energy demand projection differences, other energy market and business differences between the developed, transitioning and developing regions in the world with respect to the nuclear energy system deployment conditions should be mentioned as summarized in table 2.

These differences will be important for the nuclear reactor deployment options available and the achievable symbiosis between the regions, e.g. preferential use of LWRs in developed regions, but potential preference for fuel leasing options combined with so-called 'battery' type small reactors with long refueling intervals, e.g. lead-cooled small fast reactors such as STAR-H2 [24] supported by regional centers in developing regions.

Figure 4. Nuclear energy demand scenarios for electricity services in six world regions according the six energy demand scenarios defined by the WEC/IIASA report of 1998.

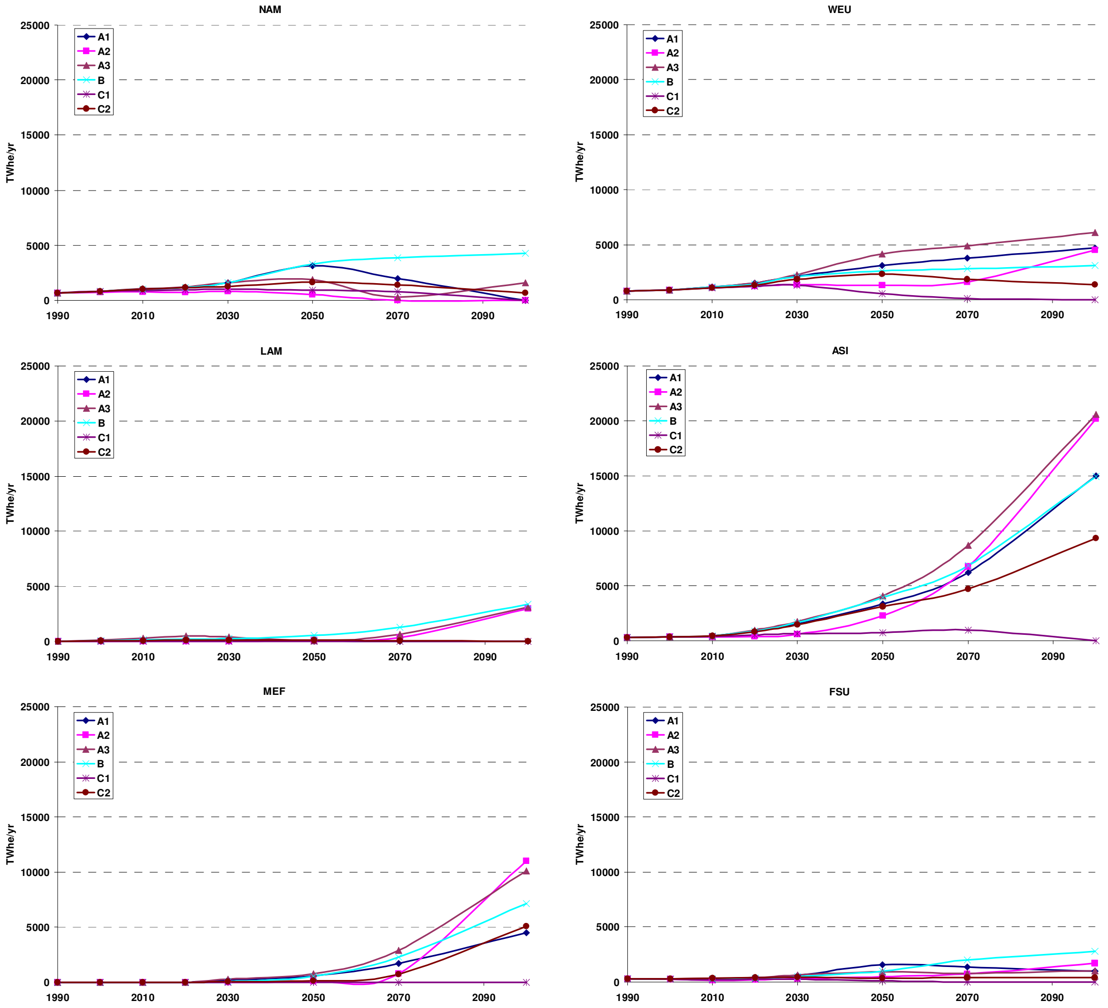


*Figure 5*Amount of new reactors needed per year for the six world regions and for energy demand scenarios B and C2.
(Expressed in TWhe/yr to be delivered by these new reactor plants)

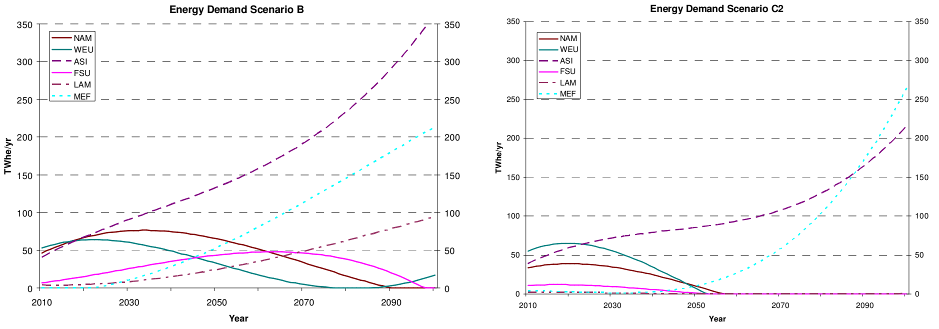
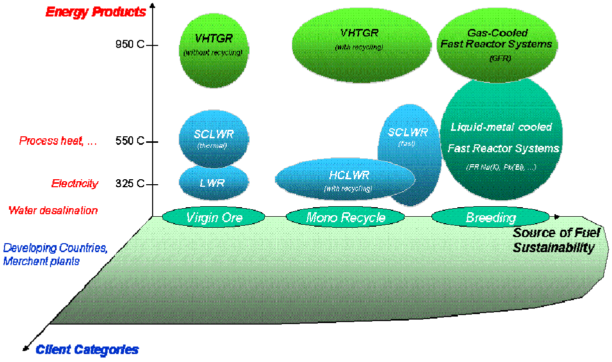


Figure 6. The three-dimensional grid for future nuclear energy system deployment.



Energy products dimension

While nuclear energy has been generating essentially electricity in the past, an increasing demand for process heat applications, including water desalination and hydrogen production, is considered worldwide. These kind of applications generally need smaller heat sources than the typical Gen-II and III kind of 2 500 MWth or more nuclear power plants. Plant sizes in the range of 100 to 500 MWth for so-called small reactors and 500 – 1000 MWth for medium sized reactors seem to be more appropriate for these kinds of applications. Especially the siting of nuclear power plants becomes in these cases very important, i.e. closer to local customers, nearby industrial sites (e.g. petrochemical industry for process heat and hydrogen), nearby cities for district heating and water desalination, etc.

This energy product dimension hints for certain optimal combined reactor and fuel cycle concepts that might become achievable in symbiotic multi-regional nuclear energy systems, e.g.:

- Small reactors located nearby final customers, i.e. cities and industrial sites, should be ‘plug-and-play’ type, i.e. needing minimal auxiliary facilities for fuel management and at-reactor storage of spent fuel, very short licensing and especially construction times asking for some modular construction design, reduced technological knowledge needed to operate reactor, … This hints towards the use of small, passively safe long core lifetime reactors using fuel leasing contracts with fuel cycle companies delivering the fuel as a whole core cassette and quick removal of spent fuel cassettes towards (regional) fuel cycle centers.
- Medium size reactors might be more appropriate for larger industrial sites or cities needing comparable services as for the small reactors but where additional fuel cycle related functionalities can be integrated, i.e. burning of actinides or even breeding of fissile material intended to feed other (small) reactors.
- Large reactors are typically adequate for those regions with an existing well-functioning electricity network and where the delivery of process heat is secondary. These plants, if based on fast spectrum reactor technology, may also fulfill fuel cycle functions in burning or breeding fissile materials but would do so as a kind of ‘fuel cycle regulator’ of the (worldwide) fissile material working inventory.

Table 2. Differences between world regions for nuclear energy system deployment.

	Developed Regions *NAM, WEU, parts of ASI*	***Transitioning Regions*** *FSU*	***Developing Regions*** *LAM, MEF, Major part of ASI*
Current Industrial Situation			
Industrial Infrastructure	Robust	Significant	Lacking
Labor Market	Skilled, Expensive	Skilled, Less expensive	Less skilled, inexpensive
Access to Capital	Robust	Constrained	Constrained
Energy Market organization			
Liberalized/deregulated	Yes	No	No
Investors energy market	Private	Private/Government	Government/Private
Investment criterion	Shareholders value creation	Cost-of-ownership	Capital requirements
Nuclear Power Plants			
Nuclear deployment	Initially high, replacement market, later-on small	Small, but steadily growing	Small but fast growing
Nuclear technology generation	Gen-II and III, gradual introduction of Gen-IV in a replacement market	Gen-II and III, Some Gen-IV introduction as part of regional fuel cycle service centre	Gen-III and Gen-IV
Emplaced grid and favored plant size	Large	Small to Large	Small
Energy services	Electricity Hydrogen	Electricity Process Heat Water Desalination	Electricity Process Heat Water Desalination Hydrogen
Fuel cycle Infrastructure			
SNF-inventory already existing and in the pipeline, i.e. current fissile material working inventory	Large	Small	Very small
Current access to indigenous enrichment and fuel fab facilities	Yes	Yes	No
Current access to indigenous reprocessing and "hot" fuel fab facilities	Yes – for MOX as waste management time delay	Some	No
Typical reactors to be deployed in region	LWR, SFR	LWR, SFR	LWR, STAR-H2

(Resource and Waste) Sustainability dimension

While there is probably plenty of natural uranium available worldwide to cover the worldwide nuclear energy system deployment as described above, the real issue will be to have this natural uranium available at reasonably low cost and on time, i.e. equilibrating the supply demand equation at all times. While nuclear energy is relatively insensitive to natural resource price fluctuations, the rather poor use of this natural uranium in today's once-through and mono recycling fuel cycle options makes that there are costs in the front- and back-end and especially the waste management parts of the fuel cycle which may be reduced or even eliminated when more resource-effective fuel cycle options are deployed.

The nuclear energy scenarios considered in this paper are based on a set of reactors responding to the above described diversity of needs in the deployment-space, i.e. light water reactors (LWRs), high-temperature gas-cooled reactors (HTGRs) and sodium-cooled fast reactors (SFRs) in developed and transitioning regions, LWRs and STAR-H2s in developing regions with the STAR-H2 using fuel cycle services delivered by the other regions.

IV.2. World Nuclear Energy System Scenarios

The multi-regional nuclear energy system deployment scenarios were simulated using ANL's DANESS-code [25-26]. Each region had its own model of growth in demand and reactor type preferences – with cross-flow of fissile/fertile materials between the six regions. In this paper, the region by region results are aggregated over the six-regions, and presented as representing the world as a whole.

This paper will only report results for the IIASA/WEC energy demand scenario B (see Fig. 4). Reactor and fuel attributes were representative for typical LWR, HTGR, SFR and STARH2 reactor designs [27-28].

The full multi-regional analysis considers in total about 24 different multi-regional cases but only a sub-set is reported here.

The scenarios considered in this paper all are compared to a Base Case, i.e. the existing nuclear reactor park today in each-region with continuation of, for instance, partial MOX-loading in some LWRs and continuing today's reactor market composition, i.e. comparable to the E1-scenario (see below) without HTGR-introduction and with 95% LWRs and 5% CANDUs.The following evolutionary scenarios were studied first:

- *Open and Partially closed fuel cycles:*
    - *E1*: Continuation of today's nuclear reactor park (with some reactors using MOX) and a new park consisting of 5% CANDU, 70% LWRs using UOX only and 25% HTGRs;
    - *E2*: Continuation of today's nuclear reactor park (with some reactors using MOX) and a new park consisting of 5% CANDU, 70% LWRs using UOX and MOX, and 25% HTGRs. The core-load for the new LWRs and the number of LWRs being MOX-ed corresponds to a continuation of today's 'market share' of MOX, i.e. on average for the new LWR-park being 3.3% MOX in the park (which is, of course, low as it is today);
    - *E3*: Continuation of today's nuclear reactor park (with some reactors using MOX) and a new park consisting of 5% CANDU, 55% LWRs using UOX and 3.3% MOX, and 40% HTGRs. Core loads for LWRs again as defined in previous case;
    - *E4*: Continuation of today's nuclear reactor park (with some reactors using MOX) and a new park consisting of 5% CANDU, 55% LWRs using UOX and MOX, and 40% HTGRs. The core-load for the new LWRs and the number of LWRs being MOX-ed is now increased such that 10% of the fuel-load in new LWRs becomes MOX, i.e. asking for additional reprocessing capacity as well.
- *Then, transition towards fully closed fuel cycles were studied:*
    - *C1*: based on the Base Case scenario with 95% LWRs using 3.3% MOX-core loadings and 5% SFRs. New LWRs only use UOX. Appropriate metal fuel fabrication and dry reprocessing capacities are deployed according to the reactor park's needs.

- *C2*: reactor park deployment based on 5% CANDUs, 75% LWRs only using UOX and 20% SFRs. The SFRs may only be introduced after the year 2030.
- *C3*: reactor park based on 5% CANDUs, 60% LWRs using only UOX, 5% SFRs and 30% STARH2s. The SFRs and STARH2s may only be introduced after the year 2025 and 2030 respectively. In addition, the allocation of separated Pu from the different reprocessed fuels to other fuels is set as follows:
  - From UOX40 reprocessing:
    - Until the year 2025, 100% of the separated Pu for use in MOX (used in existing LWRs)
    - After the year 2025, separated Pu reserved for SFR.
  - From UOX50 reprocessing:
    - 20% of separated Pu goes to SFR-fuel fabrication
    - 80% being reserved and used for STARH2 fuel fabrication
  - From SFR fuel reprocessing:
    - 30% of the separated Pu being re-used in SFRs;
    - 70% being reserved and used in STARH2s.
  - From STARH2 reprocessing:
    - Separated Pu is being re-used in STARH2s.

IV.2.1 Legacy of today's nuclear reactor park, i.e. a so-called nuclear phase-out scenario

All scenarios started from today's nuclear reactor park. A first scenario consists of assuming that no new reactors are build, assuming an average 50 years technical lifetime for these reactors, allowing to verify the legacy of spent fuel, high-level waste and transuranics (TRUs) that today's world reactor park would leave for the future. This assumes continuation of today's practices, i.e. reprocessing and Pu-mono recycling in some LWRs, until the end of their technical lifetime where the current aqueous reprocessing capacity is considered to end by the year 2012, i.e. 'sudden' stop of the full 2 600 tHM/yr commercial reprocessing capacity available today. This is, of course, a very hypothetical assumption as the whole phase-out scenario is hypothetical as well. A more realistic and optimized scenario might be envisaged reducing the separated Pu-stocks to zero by the end of the MOX-use.

The total amount of spent fuel evolves from some 220 000 tHM spent fuel in the year 2000 to about 450 000 tHM by the end of the phase-out. The amount of high-level waste produced during the period 2000 till end of phase-out amounts to some 1 360 tHM HLW.

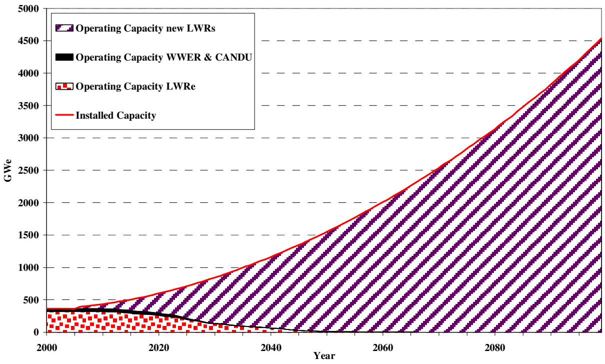
IV.2.2 Business-as-usual scenario BAU

The continuation of today's nuclear reactor park where some of the reactors are partially MOX-loaded, i.e. approximately 10% of the reactor park accepting MOX-fuel with 1/3-MOX core loading and where some 20% of the discharged LWR-UOX fuel is reprocessed, is shown in figure 7.

The "Base Case" scenario assumes market growth based on ('Operating Capacity LWRe', i.e. the 'e' stands for existing LWRs). In this case, only LWRs are deployed as shown by 'Operating Capacity new LWRs'.

The total amount of SF, despite some reprocessing, to be managed by end of century becomes about 3 million tHM, i.e. the equivalent of 27 equivalent Yucca Mountain geological repositories (based on technical YM-capacity of 112 000 tHM). The amount of HLW to be managed is around 50 000 tHM in addition to this SF. The total amount of TRUs out of reactor reaches 47 000 tHM by end of century, most of it stored in SF as the amount of reprocessing and MOX-use was balanced such that the separated Pu-inventory remained to a bare minimum (from a 220 tHM separated Pu stock in the year 2000).

Figure 7. Reactor park evolution for a BAU-scenario using LWRs loaded with UOX and MOX.



As a variant, the impact of increasing the UOX average burn-up from 50 GWd/tHM to 60 GWd/tHM, i.e. assuming all new LWRs using 60 GWd/tHM, results in a reduction of at most 600 000 tHM of spent UOX-fuel to be handled by end of century, i.e. approximately 20% reduction as expected from the 20% burn-up increase.

IV.23c Open and partially closed fuel cycle based on evolutionary reactor designs

The evolutionary (E-series) scenarios (described above) introduce HTGR's. Having an increasing part of the nuclear reactor park being occupied by HTGR's rather than LWR's, and thus not asking for reprocessing of UOX and use of MOX, allows reducing the reprocessing capacity deployment. The E-scenarios use aqueous reprocessing capacity deployments attempting to balance as well as possible the separation of Pu and use of Pu in MOX in LWRs, i.e. keeping the separated Pu-stock to a bare minimum. A comparison of the reprocessing deployment for the three evolutionary cases specified above is given in figure 8. The reprocessing capacity needs were defined such that the TRU-needs were fulfilled for the requested nuclear reactor park deployment while not unnecessary separated TRU-stocks were piling-up neither reprocessing capacity sitting idle (i.e. lower than 75% average capacity factor). The significant increase in reprocessing required for E4 is noteworthy.

The evolution of the reactor parks for these evolutionary scenarios E1 to E4 is shown in figure 9. Comparison of front-end and back-end needs for the E1 to E4 scenarios is given in Table 4 for the years 2050 and 2100. As the HTGR-fuel considered in this paper is only 80 GWd/THM operating in a once-through mode, and as the initial enrichment is 8.1% compared to 4.2% for UOX-fuel at 50 GWd/tHM, these scenarios are rather neutral with respect to enrichment needs with a slight reduction in natural uranium needs and some 10% reduction in DU-arising in the front-end. The ore requirements by century's end are around 50 million tonnes. The higher burnup of the HTGR-fuel results in a reduced mass spent fuel inventory (and also HLW-inventory from UOX-reprocessing) compared to the all-LWR scenarios in the business-as-usual case.

Figure 8. Aqueous reprocessing capacity needs

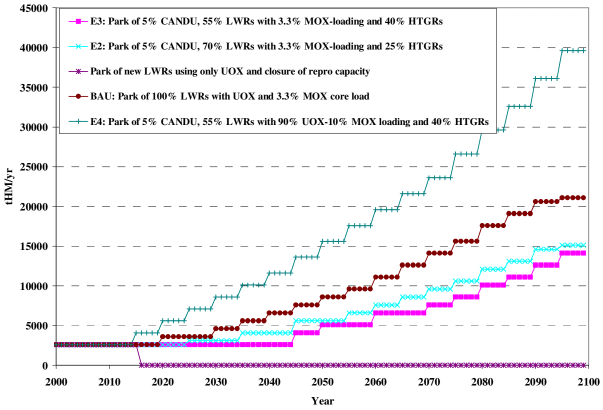
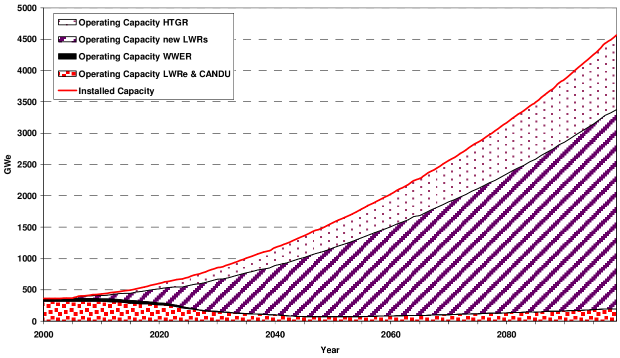
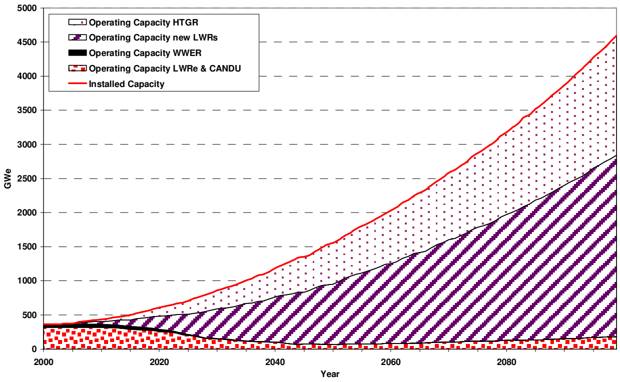


Figure 9. Reactor park evolution for the E1, E2, E3 and E4 scenarios respectively

a) E1 & E2 scenarios



b) E3 & E4 scenarios



It has to be remarked that the calculations performed with DANESS are based on transient analysis where the early deployment of the reactor parks is not exactly equal due to the decision-making feedback loops in DANESS deciding on which reactors to be developed based on fuel cycle facility and thus fissile/fertile and fuel availability. Depending on specific case-settings, the error-margin on the different mass-flow parameters for the scenarios due to these decision feedback loops in the simulations is estimated on average 5%.

Table 4. Comparison of business-as-usual and some evolutionary nuclear energy system scenarios E1 and E2 based on LWRs and HTGRs and the C-scenarios based on LWRs, SFRs and STAR-H2s.

	BAU		*E1*		*E3*		*C1*		*C2*		*C3*	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
U_{nat} used since 2000(1000 tHM)	12 790	52 850	12 250	50 500	12 200	50 200	12 350	50 850	11 880	46 750	10 700	35 100
DU Stock (1000 tHM)	10 850	45 200	9 640	40 590	10 075	40 520	10 375	44 450	9 870	37 480	9 200	29 300
SWU needs (tSWU/yr)	316	910	294	907	295	906	317	902	270	800	218	520
Fabrication (tHM/yr)												
UOX	33 000	97 000	23 400	68 500	20 570	58 300	33 500	95 500	33 200	97 400	25 900	63 200
MOX	1 100	3 300	920	2 500	690	1 970	3	-	3	-	4	-
Particle	-	-	-	-	3 100	11 100	3 000	11 640	11 200	41 500	5 300	7 150
Repro Capacity need (tHM/yr)	8 600	21 100	5 600	15 100	5 100	14 100	22 300	49 500	28 100	81 700	21 700	42 800
SF inventory (1000 tHM)												
UOX	801	2 527	613	2 040	565	1 760	550	1 870	585	1 900	556	298
MOX	26.8	123	21.2	100.3	19.8	88	3.23	0.50	3.05	0.30	3.10	0.15
Particle	-	-	136.7	4	131.6	445	5.9	21.6	17.95	93.56	7.9	10.70
HLW inventory (1000 tHM)	10.25	48.60	7.74	35	6.13	29	23.25	103.8	23.83	117	9.97	101.56

Assuming an evolutionary HTGR reactor and fuel design, these evolutionary scenarios show that a small reduction in the heavy metal mass content of spent fuel to be handled in the back-end can be achieved but that front-end operations are not altered significantly. (The fission product heat and toxicity are the same for all scenarios because of identical energy release.) The most significant change relates, except for E-4, to the reduction in reprocessing capacity needs due to the reducing fraction of UOX-fuel to be reprocessed while keeping the separated TRU-stock as low as possible. Despite the small improvements in front- and especially back-end by the introduction of HTGRs in the nuclear reactor park, the reliance on natural resources and especially on geological disposal needs remains very important and probably non sustainable. The next set of cases introduce fast reactors and close the fuel cycle at least partially.

IV.3 Transition towards fully closed fuel cycles

Closure of the nuclear energy system for all TRUs is the appropriate approach to reducing waste buildup and ore drawdown as has been identified by many previous studies [29-30]. This is studied here for the cases C1, C2, C3 described previously. Multiple variants of these scenarios can be cited, i.e. essentially based on the reprocessing policy and the allocation policy of the separated TRUs. The combination of aqueous and dry reprocessing capacity deployment, the allocation of separated TRUs, the use of MOX in LWRs are just three of the many degrees of freedom defining the multiple variants.

Figures 10, 11 and 12 show the reactor park evolution for the three scenarios C1, C2 and C3 respectively. These scenarios show the evolution towards an increasingly closed nuclear fuel cycle without ever achieving full closure within this century. The first scenario represents a modest evolution from previous evolutionary scenarios by introduction of only 5% fast breeder reactors SFRs with a high conversion ratio of 1.7 in nuclear developed countries, essentially intended to breed fissile material for use in

LWRs or other reactors and thus reducing the need for withdrawal of natural uranium resources. The second, C2 scenario follows the same strategy but 20% SFRs (with CR=1.7) are introduced as a greater fraction of the reactor park in order to show the potential trade-off that can be made in scenario C3 through the introduction of battery-type STARH2-reactors. These STAR-H2s are not breeders – being only fissile self sufficient with no loss of Pu during use in the long-lived core (residence time of 20 years).

This C3-scenario is representative of a rather advanced nuclear energy system where developing countries have preferentially deployed fissile preserving STAR-H2's of 20 year refueling interval rather than net fissile consuming LWR's and using fissile material derived from back end waste management operations in developed country regions.

Figure 12 clearly shows the large park fraction worldwide that STARH2's might occupy enabled by the availability of sufficient fissile material (i.e. Pu and depleted uranium) coming from the reprocessing of LWR-UOX and MOX fuels and from breeding in the SFRs in developed regions or regional centers. Here, the SFRs clearly play a role as regulating mechanism defining the amount of fissile material available for use in LWRs (i.e. MOX) and STARH2 next to serving their own needs. The TRU-inventory in the total nuclear energy system for the C1 and C3 scenarios as well as previous BAU-scenario is shown in figures 13 to 15.

Figure 10 Reactor park evolution for scenario C1.

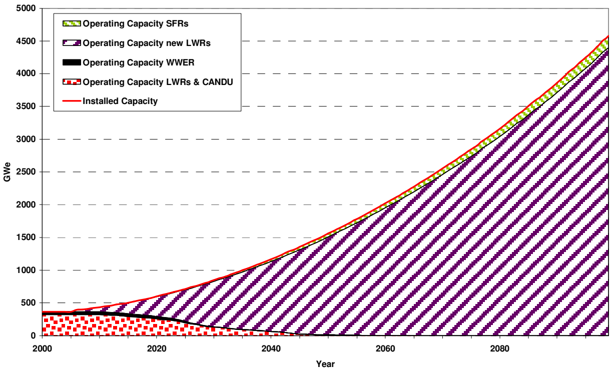
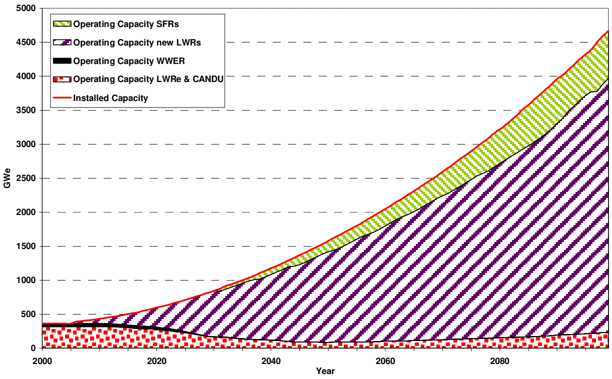


*Figure 11. R*eactor park evolution for scenario C2



The increasing separated Pu-stock from LWR-UOX reprocessing and due to the high conversion SFR keeps growing in scenario C2 and might be reduced by use of MOX-ed LWRs or preferably, as scenario C3 shows, by use of the Pu in STARH2s which effectively moves the separated Pu from out-of-pile condition to productive in-pile condition as can be seen in figure 15.

Figure 12. Reactor park evolution for scenario C3

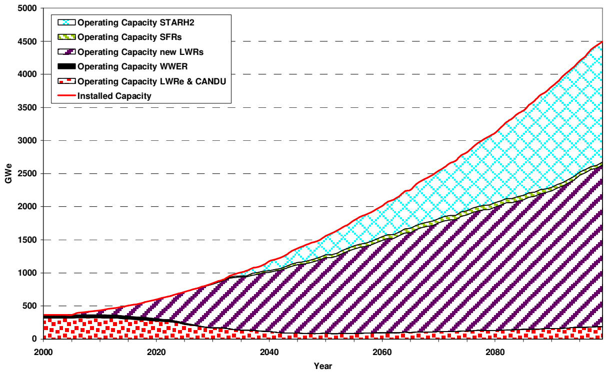


Figure 13. TRU-inventory in the nuclear energy system for the BAU-scenario.

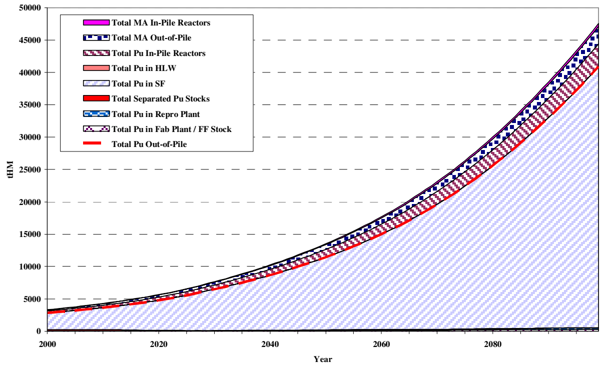


Table 4 shows the front-end and back-end implications of these three scenarios, C1 to C3 and the BAU-scenario. The very significant reprocessing capacity deployment in the C-scenarios results in a reduction in LWR spent fuel that might have to be disposed. While the C2-scenario continues a comparable strategy as scenario C1, i.e. adding SFR breeder reactors and thus resulting in growing separated Pu-stocks, the scenario C3 makes better use of significantly less reprocessing capacity while also reducing the amount of spent fuel residing in the fuel cycle and potentially to be disposed of by placing it in productive use in 20 year core loadings of STARs in countries where growth rate of nuclear energy demand is high.

Figure 14. TRU-inventory in the nuclear energy system for the C1-scenario.

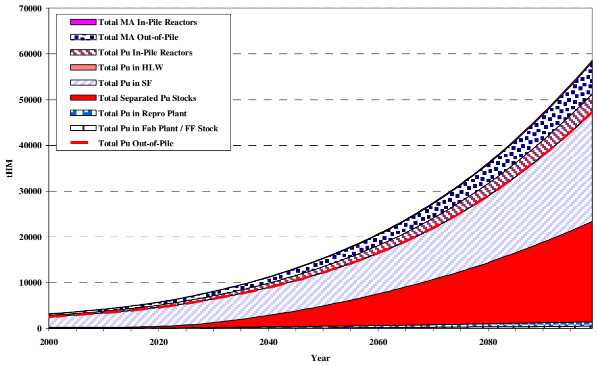


Figure 15. TRU inventory in the nuclear energy system for the C3-scenario

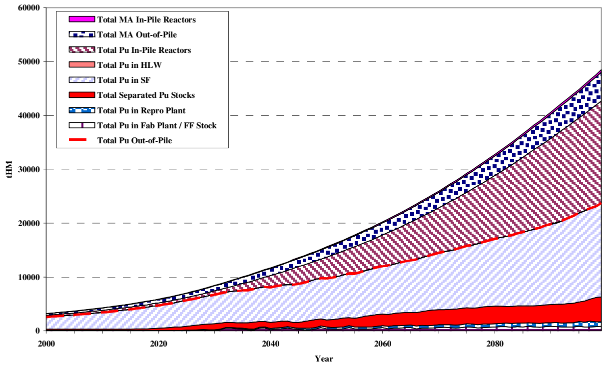


Figure 16 compares the performance for the E and C-scenarios normalized to the BAU-scenario. The C3 approach is seen to provide a good balance by avoiding the ore drawdown and waste buildup of the E scenarios and reducing the recycle deployments of the C1 and C2 scenarios.

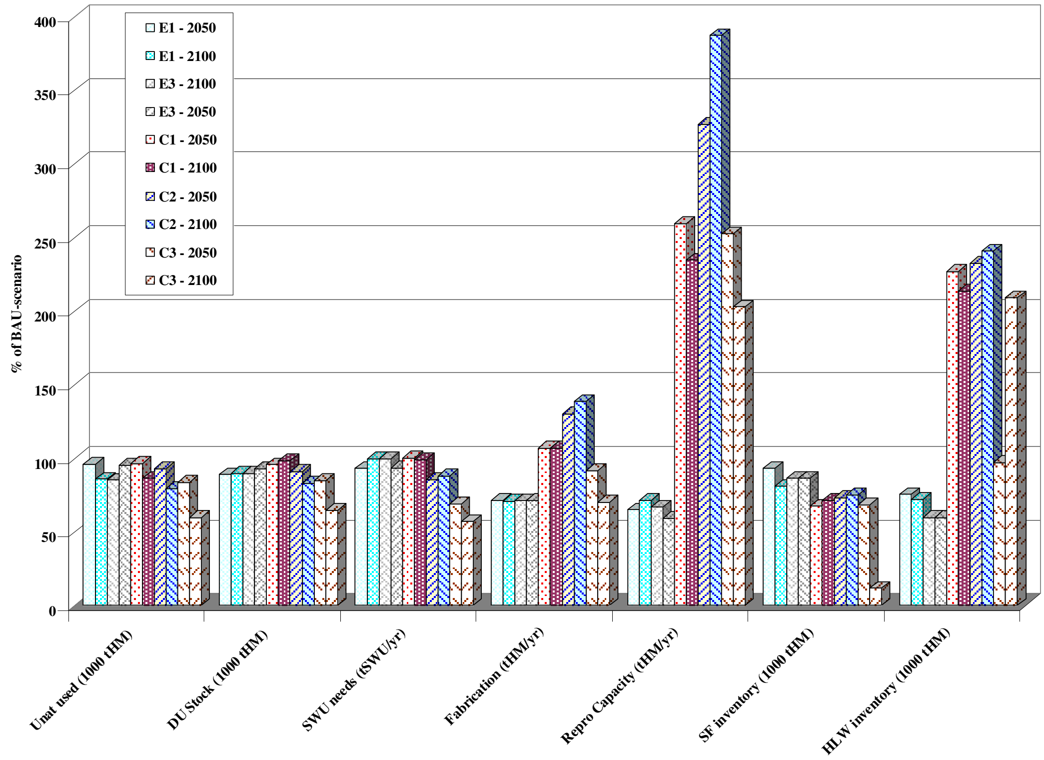
Assessing the future of nuclear energy as part of a sustainable energy mix is a multi-multidisciplinary and multi-dimensional exercise which needs to take into account the temporal and business climate differences between various regions in the world. This paper reported on a multi-region nuclear energy system analysis showing that regional fuel cycle centers serving small fast reactors, i.e. STAR-H2, having long refueling intervals can simultaneously reduce the amount of spent fuel in developed and transitioning regions while serving the energy needs for developing regions. The main part of the reactor park in developing countries could consist of such STAR-H2s complemented with LWRs. Only a small fraction, i.e. about 5%, of the reactor park in the developed countries needs to exist of high-conversion fast reactors. An important advantage of such scenario compared to other scenarios in this paper is the important reduction in reprocessing needs in developed and transient regions compared to the evolutionary scenarios.

Further analysis is ongoing to assess various variants to these scenarios including lower conversion ratios for the SFRs, combined HTGR and STAR-H2 use in developing countries, as well as scenarios considering full closure of the fuel cycle including burner and breeder fast reactors, perhaps sited at regional fuel cycle centers.

V. CONCLUSIONS

The use system dynamics models has shown to be very important to assess the potential future nuclear energy system scenarios taking into account all sustainability aspects. Argonne National Laboratory has developed appropriate system dynamics mdoels for such sustainability assessment of nuclear energy systems using system dynamics models since the year 2001. Today, the developed code DANESS is one of the few codes worldwide allowing to simulate such complex socio-technical aspects of future nuclear energy system scenarios and this paper provided a summary of some of the results on multi-regional nuclear energy systems scenarios obtained using this DANESS-code.

Figure 16. Comparison of front-end and back-end indicators for scenarios C1, C2 and C2 normalized to scenario BAU
(see also table 4).



REFERENCES

[1] US/DOE, ‘Generation-IV Roadmap’, 2002.

[2] IAEA, INPRO Users Manual, in preparation.

[3] National Waste Management Organization, choosing a Way Forward – Draft Study Report, May 2005, Canada, www.nwmo.ca

[4] V. Meckoni, R.J. Catlin, L.L. Bennett, ‘Regional Nuclear Fuel Cycle Centres – IAEA Study Project’, IAEA, Vienna, Proceedings International Conference on Nuclear Power and its Fuel Cycle, Salzburg 1977.

[5] B. Pellaud, A. Bonne, M. Raynal, K.W. Han, ‘Important Factors for Multinational Radioactive Waste Repositories’, Proceedings of TUCSON Waste Management 1999 Conference, March 1999.

[6] IAEA INFCIRC 640, ‘Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report’, February 22, 2005.

[7] L. Boucher, J.P. Grouiller, COSI – A Simulation Software for a Pool of Reactors and Fuel Cycle Plants, ICONE-13, Beijing, China, May 16-20, 2005.

[8] D. Millington, OSIRIS: An Obejct Oriented Software Tool for Modelling the Logistics, Economics and Environmental Impact of the Nuclear Fuel Cycle, M&C 2003, Avignon, France, September

[9] C. Zimmermann, ORION, private communication.

[10] M. Khoroshev, IAEA, private communication.

[11] C. Mehmet, VISTA, IAEA, www-nfcis.iaea.org

[12] A. Yacout, L. Van Den Durpel, D. Wade, P. Finck, Scenarios for the Expanded Use of Nuclear Energy, ICAPP 2004, Pittsburg, US, June 13-17, 2004.

[13] L. Van Den Durpel, A. Yacout, D. Wade, H. Khalil, DANESS – Dynamic Analysis of Nuclear Energy System Strategies, Global 2003, New Orleans,

November 16-20, 2003.

[14] E. Schneider, Ch. Bathke, M. James, NFCSim: A Dynamic Fuel Burnup and Fuel cycle Simulation Tool, Nuclear Technology, Volume 151, Number 1, July 2005, pp. 35-50.

[15] K. Pasamehmetoglu, SINEMA Simulation Institute for Nuclear energy Modeling & Analysis, Workshop role of Simualtion for the Nuclear Fuel Cycle, MIT, Boston, USA, October 21, 2004.

[16] E. Ichimura, Quantitative Evaluation of Nuclear Fuel Cycle with SuperSTARTM Code, The RRTD 2nd International Workshop on Nuclear Fuel Cycle – Nuclear Fuel Cycle from the Viewpoint of Disposal Site Utilization, Aomori Gennen Technology Center, Aomori, Japan, March 24 - 25, 2003

[17] OECD/IEA, ETSAP, MARKAL – Market Allocation Model, www.etsap.org/markal/main.html

[18] ANL, ENPEP - Energy and Power Evaluation Program, www.dis.anl.gov/CEEESA/ENPEPwin.html

[19] IIASA, MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact, www.iiasa.ac.at

[20] System Dynamics Organization, www.systemdynamics.org

[21] US-DOE, AFCI - Advanced Fuel cycle Initiative, www.nuclear.gov

[22] Dennis L. Meadows et al., The Limits to Growth, Universe Books, New York, 1972

[23] Nakicenovic N., Grubler A., McDonald A. (Editors), Global Energy Perspectives, International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, Cambridge, United Kingdom (1998).

[24] D. Wade, R. Doctor, K. Peddicord, STAR-H2: A Battery-Type Lead-Cooled Fast Reactor for Hydrogen Manufacture in a Sustainable Hierarchical Hub-Spoke Energy Infrastructure, GENES/ANP 2003, Kyoto, September 15-19, 2003.

[25] L. Van Den Durpel, A. Yacout, D. Wade, H. Khalil, DANESS – Dynamic Analysis of Nuclear Energy System Strategies, Global 2003, New Orleans, November 16-20, 2003.

[26] L. Van Den Durpel, A. Yacout, D. Wade, Development of Integrated Systems Dynamics Models for the Sustainability Assessment of Nuclear Energy, this conference.

[27] A. Yacout, L. Van Den Durpel, D. Wade, P. Finck, Scenarios for the Expanded Use of Nuclear Energy, ICAPP 2004, Pittsburg, US, June 13-17, 2004.

[28] L. Van Den Durpel, D. C. Wade, H. Khalil, A. Yacout, Dynamic Analysis of Nuclear Energy System Strategies for Electricity and Hydrogen Production in the USA, Global 2003, November 16-20, 2003.

[29] US/DOE, ‘Generation-IV Roadmap’, 2002.

[30] OECD/NEA, Comparison of ADS and FR in Advanced Nuclear Fuel Cycles, Paris, France, 2002.