The Use of System Dynamics in Assessing Nuclear Energy System Futures

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

Abstract

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, i.e. DYMOND and more recently DANESS. These models are based on system dynamics modeling used in various industry sectors and allowing 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 need for a system dynamics view on nuclear energy system development, the role that system dynamics modeling may play in drafting nuclear energy system scenarios and the modeling of such system dynamics view of nuclear energy systems in the DANESS-code developed using IThink.

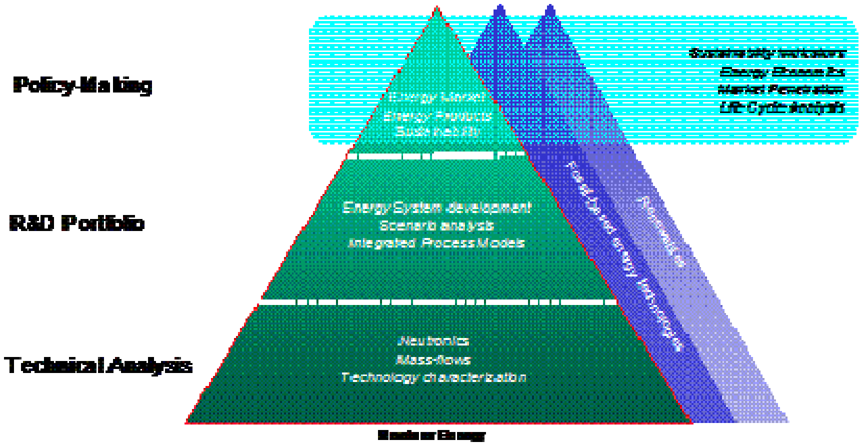
Introduction

Various technical and economic studies have been undertaken in the past few years drafting possible pathways for the development of nuclear energy systems in a sustainable energy future context [1-7]. Most of these studies were technology roadmap studies focusing on the technical capabilities that are or will become available to society in order to advance the use of nuclear energy as a safe, environmental friendly and economic source of energy.

While these technical and economic studies are of highest importance to advance nuclear energy development through international collaboration, only a few studies have looked into the deployment of nuclear energy systems as a whole, i.e. covering the synergistic effects that may be exploited in designing future nuclear reactor parks as well as incorporating the environmental and socio-political dimensions in the decision-making process on sustainable energy futures.

Indeed, addressing the market potential for nuclear energy in various market environments and taking into account all decision criteria or key performance indicators (KPIs) for nuclear energy demands a system dynamics view on nuclear energy as an integrated system. Figure 1 schematically shows the different layers of modeling needs to describe in varying detail (nuclear) energy systems.

Figure 1. Schematic view of three layers in energy assessment models development.



The technical analysis layer focuses on the detailed technical description of the various components of nuclear energy systems, i.e. nuclear reactors and fuel cycle facilities, according to reactor physics, fuel composition changes, safety analysis, radiation protection, economics, and other aspects of these components. A large set of such detailed technical analysis and simulation codes have been developed in the past and some are made available to the international nuclear community through international organizations [8-9].

The second layer consists of integrated process models allowing performing scenario analysis of nuclear energy systems with a main focus on the technical dimension. These codes cover the full supply chain and mass-flow transfer function of one or of a limited set of nuclear reactors in order to give a detailed assessment of important physical parameters or a limited set of economic parameters (e.g. levelized energy generation cost). These codes are also essentially based on dedicated simulation software tools.

The third layer involves the description of nuclear energy systems in terms of sustainability metrics used in policy-support and decision-making on energy policies. While many energy market-penetration models, e.g. ENPEP [10] and MARKAL [11], have been developed in this third layer, a new set of system dynamics and agent-based models are being developed to cover the whole spectrum of sustainability dimensions which is not always the case in these energy market-penetration models.

The use of system dynamics in the modeling of nuclear energy system futures covering the three layers as given in figure 1 is motivated by following considerations:

- Synergistic effects between nuclear reactors and their fuel cycle allow to improve the overall performance of nuclear energy systems which may not be analyzed using existing codes detailing one or only a limited set of nuclear reactors and fuel cycle options, i.e. a systems thinking perspective is therefore appropriate;

- Decision-making on nuclear energy system development has to take into account all criteria used by the stakeholders and modeling these decision-making processes, through feed-back loops, is crucial in understanding the dynamics of such nuclear energy system development in a broader energy policy context;

- Communicating the potential of nuclear energy in sustainable energy development asks for a transparent model environment which is supported and trusted by all stakeholders, i.e. from researchers until policy-makers;

- The dynamics of nuclear energy deployment is of highest importance due to the inherent long time-delays in developing the necessary technology as well as all (in)direct effects of intermediate stocks or processing of nuclear material that may have a decisive impact on the decision-making on nuclear deployment;

- The time-dimension in economic and environmental aspects of nuclear energy is very important due to the long technical and economic life-times of the facilities involved and the variety of environmental impacts to be assessed. This time-dimension needs explicitly treated by any integrated process model of nuclear energy systems and this is not always the case in existing codes;

- Allowing scenario analysis, i.e. what-if analysis, in a transparent and quick way is very important to create a deep understanding of nuclear energy system development dynamics by all stakeholders. This demands a nuclear energy system model allowing calculating 100-year time-span simulations on modern PCs in less than a few minutes in order to become an interactive learning tool for all stakeholders involved;

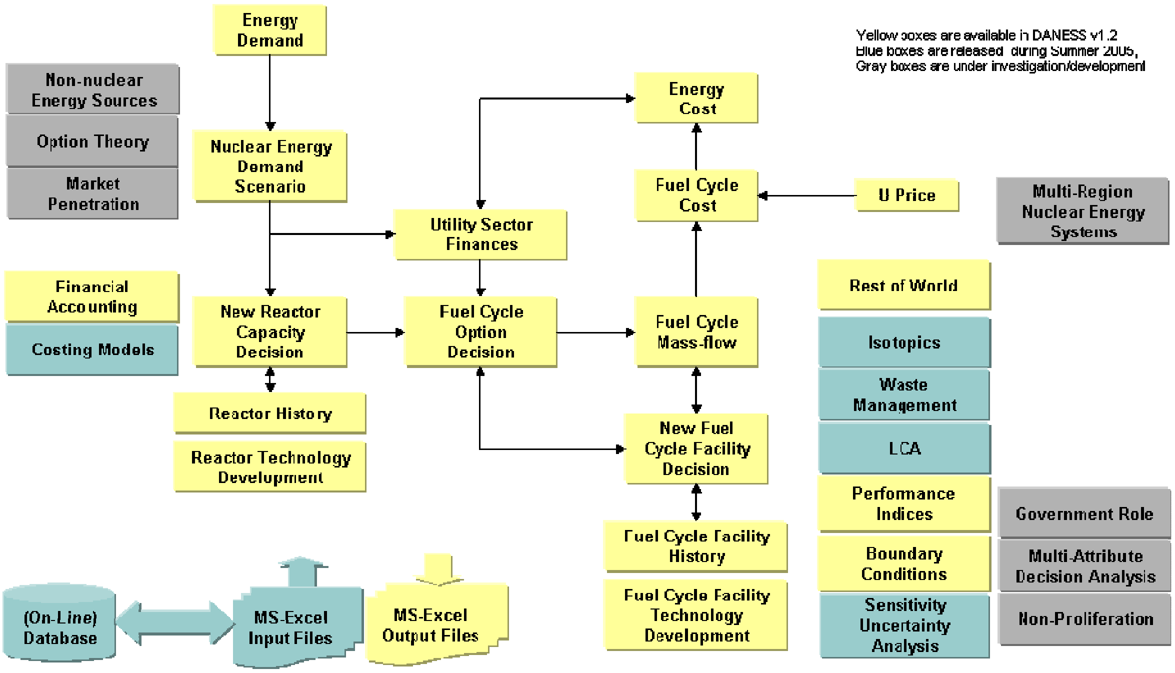
- Finally, uncertainty and sensitivity analysis is very important to investigate the main dependencies of results on input parameters and to calculate the propagation of uncertainty distributions throughout the model.

Argonne National Laboratory has recognized early in 2000 the need to develop such new simulation systems covering the whole spectrum of facets in mapping the development pathways for nuclear energy. The DYMOND [12] and DANESS [13] codes are the result of this effort and the DANESS-code will be described in some more detail in what follows.

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

DANESS is composed of different interconnected sub-models each of those intended to perform a specific part of the system dynamics simulation (i.e. lower and second layer in figure 1). Figure 2 shows the overall architecture[1] of the DANESS-model where the following sections will detail the sub-models.

Figure 2. DANESS-architecture



Exogenous defined nuclear energy demand scenarios are given as input to the current DANESS-model. Starting from an existing reactor park, the model aims to match this demand by generating energy with a varying mix of reactors. New reactors will be ordered depending on their technological readiness level, their economic performance, pre-set user preferences for reactor park fractions, and fissile material availability. The DANESS-model allows using economic decision making where the type of reactor to be ordered at each moment will be based

---

[1] The figure only shows the main interconnections between the sub-models.

on the bus-bar cost of generating electricity. The user may also set a preferred distribution of new reactor types upon which the DANESS-model aims to follow this preferred park composition as long as fissile material availability allows. The economic decision making sub-model will prefer investment in those reactor and fuel cycle combinations that render the full bus-bar cost of energy generation minimal. The full bus-bar cost accounts for capital costs, O&M costs, fuel cycle costs, externalities, taxes and any other cost considered by the user. Each reactor type follows a technological development path (according to 9 technological readiness levels) and each reactor is traced from ordering until shutdown and decommissioning. Up to 10 different reactor types may be simulated in parallel. Each reactor type may have different characteristics such as different fuel types, thermal characteristics, licensing and construction times, costs, and these may also vary over time.

The fuel cycle mass-flow model incorporates 21 fuel cycle steps, ranging from mining until disposal and calculates other quantities such as fresh fuel needs, interim stored spent fuel, separated actinides inventories and their isotopic composition. Up to 10 different fuel types may be simulated in parallel. Each fuel type may have different characteristics and different paths to follow through the fuel cycle where these may vary over time. Cross-flow of fissile material between these fuel types is possible and the allocation of fuel type to reactor type may be function of time. For instance, a light-water reactor (LWR) may start as uranium-oxide (UOX) fuel-loaded and may switch to partial mixed oxide (MOX) loading as soon as enough plutonium is available.

Fuel cycle facilities also have different characteristics and several technological options per fuel cycle step are available. The user may choose, for instance, that UOX fuel is reprocessed using aqueous reprocessing technology, MOX using advanced aqueous and metallic fast reactor fuel using dry reprocessing technologies. These technologies may have different loss fractions (per element), different transit times, costs, etc. Again, each fuel cycle facility that is considered in the simulation follows a life-path from ordering until decommissioning where the expenses at each moment are traced. The technologies follow a technology development path covering 9 technological readiness levels where the duration of each step may be different among technologies and may vary over time.

All the costs, licensing and construction times, technology development steps, loss fractions, and others may be experiencing learning curves with individual learning curve coefficients.

The DANESS-model checks the availability of fissile material for the different fuel and reactor combinations and will order new fuel cycle facilities or will change the reactor park fractions or fuel cycle options according to the decision criteria set forward by the user. The user may also choose to define a fuel cycle facility deployment scenario. If economic decision-making is used, the DANESS-model will try to follow the path forward leading to minimal bus-bar costs.

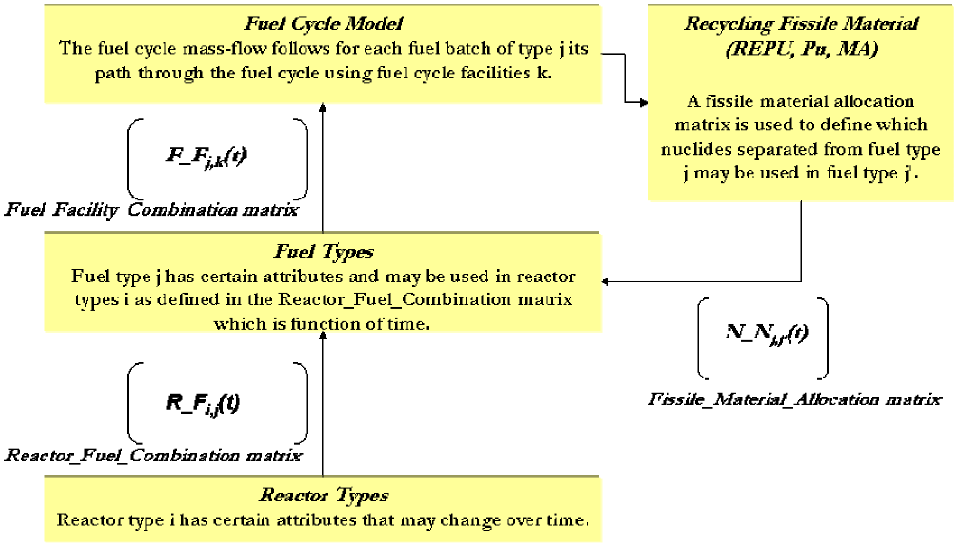
A uranium price sub-model may be used to vary the uranium price as function of the depletion of natural uranium resources. This sub-model takes account of expected exploration expenses, already mined uranium and expected uranium resources availability. Depending on the size of the region simulated, the depletion of the available uranium resources will be calculated taking into account the needs of the rest of the world.

Flexible approach of 'allocation-matrices'

A flexible approach in the DANESS-model is the use of 'allocation-matrices' between reactors, fuels and fuel cycle facilities. This allows the application of a systems-thinking approach in its broadest sense, i.e. each combination of reactor, fuel, fuel cycle facility and fuel cycle option may be simulated and these combinations are conditioned by multiple feedback loops. Choosing the correct characteristics for reactor, fuel and fuel cycle facilities remains the responsibility of the user. This approach also allows to pre-set DANESS for certain applications, i.e. freezing the 'allocation-matrices' to a certain scenario allowing to configure DANESS for use by less experienced DANESS-users within specific constraints.

This approach is based on an uncoupling between reactor and fuel types, as well as between fuel types and fuel cycle facilities. This allows the 10 different fuel types being combined with the 10 different reactor types according to technical constraints defined by the user and this combination of reactor and fuel types may evolve as well over time. The same applies to the combination between fuel type and fuel cycle facility. Figure 3 shows this basic uncoupling of the three dimensions: reactors, fuels and fuel cycle facilities.

Figure 3. The basic model approach of DANESS allows a high degree of flexibility in combining reactor types, fuel types and fuel cycle facilities.



For example, a reactor initially loaded with UOX may gradually be loaded with MOX where the MOX-fuel will use MOX-fabrication plants instead of UOX-fabrication plants and may therefore need the construction of such a fabrication plant. The fraction of reactor cores being MOX-loaded may then become a function of available MOX-fabrication capacity, the amount of spent UOX-fuel that can be reprocessed and other variables such as economic performance or others.

This approach allows a high degree of flexibility to simulate whatever nuclear energy system the user wants to consider and allows analyzing the symbiosis between different reactor systems. For instance, if less than 10 reactor types or less than 10 fuel types are to be simulated the model will set the remaining 'non-active' reactors and fuels on-hold. Another example involves the use of fuel types that may follow different fuel cycle paths. For instance, for fast reactor driver and blanket fuel, the user may specify that the driver fuel is reprocessed by dry reprocessing techniques (using the attributes for dry reprocessing) where the blanket fuel is reprocessed by an aqueous process with different attributes (losses, transit time, costs …). Reactors, for instance LWRs, may be considered changing fuel loading over time, e.g. UOX to partial MOX-loading or may change conversion ratio for fast reactors needing different fuel types for the different conversion ratios. As indicated, it's up to the user to define the technically possible and intended combinations between reactor types, fuel types and fuel cycle facilities.

By using the three defined matrices, as shown in figure 3, the user may construct any kind of nuclear energy system as long as, of course, the technical attributes of reactors, fuels and fuel cycle facilities match in reality. The matrices themselves are calculated during the simulation and may - if the user allows - change over time as several decision and feedbacl loops relating to mass-flow, economics or other considerations apply.

Brief Description of the sub-models in DANESS

Energy-demand scenario model

The DANESS-model is an energy-demand driven model of nuclear energy systems where the energy demand scenarios are exogenously defined. Energy demand scenarios may be selected from IIASA/WEC [14] or other studies, exponential growth scenarios or custom defined by the user. The nuclear energy demand may be decomposed in electricity, water desalination, hydrogen and other process heat demand. Each of the reactors may be parameterized to deliver a combination of these energy demands.

The energy market penetration of nuclear energy compared to other energy conversion technologies (gas, coal, renewables) has been simulated using the ENPEP/BALANCE code [10] and DYMOND/DANESS. While it is possible to include non-nuclear energy conversion technologies in DANESS, this more general energy market penetration modeling is currently not considered for implementation in DANESS as other more elaborate codes exist for this energy market modeling.

Rest of World model

Depending on the geographical region that is being considered, this model will include the corresponding energy demand scenario data for the rest of the world in order to calculate the depletion of natural uranium resources next to other macro-economic parameters. Obviously, a simulation of the worldwide nuclear energy system will imply that the data in this model become zero.

Energy utility strategic model

The DANESS-model does not simulate individual utilities but simulates the general behavior of the utility sector over longer time periods. The question to produce energy according a certain energy demand will result in an increasing demand for investments in new generating capacity and thus an increasing demand in funds to finance this growth. Any new investment in generating capacity will therefore be evaluated on its net-present-value and the market value-added that it will bring to the utility sector. The net-present-value of an investment is influenced by the financial situation of the utility sector but is also influenced by governmental action through tax regulations, funds, price premiums, etc. This sub-model grasps the essence of this financial evaluation of utilities and incorporates the essential decision drivers for utilities to invest in new (nuclear) generating capacity.

Reactor and Fuel Cycle Facility Technology development models

Each new reactor type or fuel cycle facility has to emerge from R&D-activities and will evolve in technological readiness according a specific development path, in general a typical S-curve covering in total 9 steps. This sub-model traces the technological readiness level for each reactor type and fuel cycle facility and incorporates elements that may influence the development path. For instance, preferential government funding may accelerate certain developments, demand from market, … The output of this sub-model is a list of available technologies that may be ordered in the new capacity decision model or new fuel cycle facility decision model.

New Reactor Capacity Decision model

The need to invest in new generating capacity is driven by the projected shortage of energy generation by the existing park and by shutting-down existing nuclear capacity. From the set of technologically available reactor types and constrained by fuel cycle mass-flow and financial considerations this model will simulate the decision-making process to invest in new capacity and this based on a generic market penetration model.

New Fuel Cycle Facility Capacity Decision model

In analogy with the above, this model simulates the investment in new fuel cycle facilities. New facilities will be constructed based on the projected need for fuel cycle operations and the foreseen shutdown of older facilities as well as the technological availability of the intended fuel cycle facility. The user may also decide to specify a given facility deployment scheme. This model excludes financial constraints to invest in fuel cycle facilities and only gives the cumulative investment needed to develop a certain nuclear energy system. It is considered in this version that existing fuel cycle companies will, anyhow, build the requested fuel cycle capacity or that new fuel cycle companies would emerge as the demand for fuel cycle services grow. No limiting feedback loops are currently implemented in this model.

Reactor and Fuel Cycle Facility History models

Once reactors and/or fuel cycle facilities are ordered they will follow a certain life-cycle which may differ between reactor types and between fuel cycle facility types. These two models trace the different steps in the life-cycle of reactor and fuel cycle facilities respectively and feed back to the above mentioned decision models on available capacity, projected capacity in the nearby and long-term future and the replacement capacity to be foreseen.

Two decision-moments are explicitly included in the reactor history model, i.e. the decision to order a new reactor and the decision to start commercial operation of a reactor. The first decision is, as said before, triggered by the forecasted energy generation shortage by the nuclear energy system compared to the demanded nuclear energy. The second demand is triggered by the actual balance of generation and demand and influences the average capacity factors of reactors.

Fuel cycle mass-flow model

The fuel cycle mass-flow model is the kernel of the DANESS-model and treats all aspects of the fuel cycle for different fuel types according to 21 possible fuel cycle steps. All fuel cycle operations, including stocks and delays, are modeled where feedback of fissile material from reprocessing a certain fuel into another type of fuel is made possible. Up to 10 types of fuel may be followed in parallel.

Fuel cycle costing model

This model calculates the levelized fuel cycle costs for the different reactors and fuel types. The levelized fuel cycle cost takes into account the different timing of operations for each fuel batch of a certain fuel type and recombines these costs on reactor level using one or several types of fuel. This sub-model also calculates the net-present-value for the whole fuel cycle for a reactor type. This latter calculation is used in investment appraisals for new reactors.

U-Price model

The evolution of the price of natural uranium is an important given for long-term nuclear energy system optimization. This model of the evolution of the uranium price takes into account the exploration for new natural uranium resources, the depletion of existing mines and the long-term supply and demand balance. It does not simulate short-term (spot-market) price evolutions but it does provide a model of this uranium price. The price is finally provided as input to the fuel cycle costing model.

Energy costing model

In analogy to the fuel cycle costing model this model calculates the actual and net-present-value of the energy produced by each reactor type. The energy cost is divided in a capital cost term, an O&M cost term and a fuel cycle cost term. Each of these cost terms is calculated and feeds the new capacity decision-making model for investment appraisals of new reactors.

Government role model

The government may have different mechanisms through which the development of a nuclear energy system may develop. Government may influence the spent fuel charges, tax rates on investments, risk-premium reductions for new technologies, R&D-funding, and more. This model allows the user to simulate the long-term policy impacts of changing these indirect means of governmental action and their impact on the various other sub-models of DANESS. The full functionality of this model is only available in the source-code developer's version of the code as this model may need customized settings for local (national) policies.

Costing models

The previous costing models include capital, operation & maintenance and fuel cycle costs as well as assessment of costs associated to licensing, owner's cost, decommissioning and others. For each of these cost-categories, more detailed cost models may be implemented and some of these cost models are considered for implementation in the code.

Isotopics and Waste management

The latest version of DANESS includes the follow-up of the isotopic composition of fuels. In total some 23 isotopes for actinides and some selected fission products are followed allowing calculating the impact on various nuclear fuel cycle facilities, especially on waste management. A specific model is implemented to calculate the heat load of the potential US geological repository Yucca Mountain and thus to calculate repository capacity expansion possibilities through reduction of actinides and some fission products confined in the waste.

Life Cycle Analysis

Life cycle analysis (LCA) functionality is under development to address the environmental dimension of nuclear energy in more detail. This LCA-model shall trace the (in-)direct emissions from nuclear energy systems in some detail allowing to perform post-processing using specific LCA-models developed by international research organizations.

Multi-regional nuclear energy systems

An additional dimension in the DANESS code consisting of simulating in parallel up to six world regions each with its own nuclear energy system deployment scenario is currently being developed aiming to address specific issues in worldwide nuclear energy system deployment.

Sensitivity/Uncertainty analysis

Based on IThink's possibilities to perform sensitivity and uncertainty analysis, DANESS offers the possibility to perform various sensitivity/uncertainty analyses on various parameters. This functionality is rather unique among the various integrated nuclear energy systems under development today.

DANESS MS-Access Attributes database.

Input of the more than 2000 parameters for a simulation is performed through an easy-to-use MS-Access database allowing information retrieval from previous simulations, archiving technology characteristics (reactors, fuels, fuel cycle facilities and others), and organizing all the data needs for a simulation. The DANESS-model includes graph-functions and allows transferring all the results of a simulation into a template MS-Excel file. This template-file also allows automatic graphing of the results and facilitates comparison between simulations. The link between the database and the model can be automatically updated but is not necessary if the initial data does not change between different simulations.

DANESS-Output MS-Excel template

The results of DANESS-simulations are available in MS-Excel format enabling a smooth and fast visualization of the results. Graphs of the main variables in the simulation are automatically drafted where the format of the output-files also allow direct comparison between different simulations.

Model-environment of DANESS

DANESS is build using system dynamics software, i.e. IThink [15]. DANESS consists of about 8 200 relations between the approximately 16 000 variables, 2 600 stocks/conveyors and about 6 000 flows. The model-file is 39 Mb large. A 100-year simulation in one-month time-steps covering typically a world nuclear reactor park takes less than a few minutes on modern PCs which is a very important criterion when DANESS is used as on-line simulation code for training and educational purposes as well as for uncertainty/sensitivity analysis.

Benchmarking and validation of DANESS

The validation of DANESS through benchmarking is a multi-year activity covering different disciplines and organized in cooperation with various DANESS-users. There are multiple facets to the validation of this kind of large integrated nuclear energy systems model code:

- *Sub-model validation*: the concept of DANESS as an integrated nuclear energy system model covering various facets, i.e. mass-flow up to economics and life-cycle analysis, makes that the validation of such a code asks for a multi-phased approach, i.e.
    - *Validation of individual sub-models whenever another comparable model is available.* The mass-flow calculations in DANESS are verified using well-known and internationally validated/benchmarked codes such that DANESS makes use of best knowledge and characterization of reactors and fuels available. The mass-flow analysis in DANESS is then validated by use of test-cases reported in other studies or, if possible, by blind benchmarks with comparable mass-flow codes.

  - *Isolation of various sub-models for validation when no comparable model is available*. Some sub-models in DANESS do not have an analogue which is readily available for validation/benchmark purposes. This is the case for the government role model, accounting model and U-Price model. These models have been derived from other studies or models without having these tested in comparable integrated model situations. The validation of DANESS in these cases is based on isolating these sub-models and verifying their performance using some idealized and well-characterized cases. The interaction between these sub-models with the other validated sub-models is then once again tested in some simplified and well-characterized cases. However, comparable codes for so-called blind benchmarking are not available and this limits the full validation of DANESS.

- *Full model validation*: two codes have been developed by ANL, i.e. DYMOND and DANESS. The main difference between these two codes is that DYMOND is a customized model for the US nuclear energy park and is also a more continuous model where DANESS is fully parametrical and is based on some discrete modeling of certain sub-models (mass-flows, loading patterns in reactors, fuel cycle infrastructure expansion …). DYMOND does not included all sub-models of DANESS but allows to verify a significant part of DANESS relating to mass-flow analysis, fuel cycle expansion decision-making, … and this essentially by user-specified deployment scenarios in DYMOND which are recalculated by DANESS using the inherent decision-making capability of DANESS.

Collaboration with other DANESS-users and other organizations having some comparable sub-models is ongoing extending the validation of DANESS.

Use of DANESS

The use of DANESS is focused on scenario-analysis of different development paths for nuclear energy systems and this from a governmental, utility or R&D perspective. Its intended use comprises:

- *Analysis of development paths for nuclear energy*: the impact of new developments in nuclear reactor development and fuel cycle operations may be analyzed from an integrated perspective. The impact on inventories in the fuel cycle, on costs of energy generation, waste production as well as the level of compliance with sustainability goals can be analyzed.
- *Integrated process model for the cost-benefit analysis of specific new technologies* (reactor or fuel cycle facilities) in order to guide the R&D or engineering design of new facilities. In an early phase of R&D or system development project is the evaluation of system performance and the projection of system costs crucial for the economic evaluation of these projects. Early R&D stages as well as the pre-conceptual design stage involve the design and costing of large-scale systems with significant extrapolation of data obtained from the R&D-program. An integrated

process model (IPM) including mathematical representation of the key system physics and using cost-scaling relationships enables to analyze the optimization parameters for the industrial system and the economic viability of the final system.

- *Parameter scoping for new designs*: in analogy with the above use as IPM DANESS can assist in analyzing the possible impacts of new technologies in complete nuclear energy systems and help guide the R&D-effort identifying the key development drivers for new technologies and the trade-offs between these parameters. For instance, a trade-off will exist in multiple recycling fuel cycles between the burn-up of the fuel and the separation yield in order to maximize the net reduction of transuranics (TRUs) going to waste. Guidance in preferential key R&D directions may be obtained through analysis of the impact of changing technological characteristics of reactor and fuel cycle facilities (including learning effects).
- *Economic analysis of nuclear energy systems*: utilities operating nuclear plants are continuously striving to minimize the energy generation costs. DANESS can be used as a tool to calculate today's and projected nuclear energy costs based on different development scenarios of price, technical characteristics of plant, fuel cycle operations and costs as well as impact of government regulation. This analysis may be done on a short-term as well as on a long-term time horizon.
- *Life cycle analysis* (in preparation): Total life cycle ecological impact of the proposed nuclear energy park development pathway is currently being modeled. This modeling encompasses activities upstream of facility deployment, facility operation, and downstream waste handling and decommissioning steps in the life cycle.
- *Government role*: governments willing to analyze the role of nuclear energy in a sustainable energy future may seek to analyze the possible policy-tools to be used to influence the energy sector to (re-)invest in nuclear energy or to change the fuel cycle option with a more sustainable but economic perspective. Facility for exercising several policy options are included in DANESS, i.e. R&D-funding, tax rates, price premiums, prototype funding, risk-premium reduction for investments, …
- *Educational use*: the ability to simulate different fuel cycle scenarios and the impact and role of different reactor types may facilitate the understanding of nuclear energy systems in nuclear engineering education as well for the broader public, including policy-makers. The architecture of the model facilitates the transparency of the simulation results.

While this list is not exhaustive, it does indicate the type of applications where DANESS is intended for. Again, the use of DANESS is not aimed at predicting the future but merely on helping to project and analyze different nuclear energy development paths in a consistent way.

Simple examples of applications

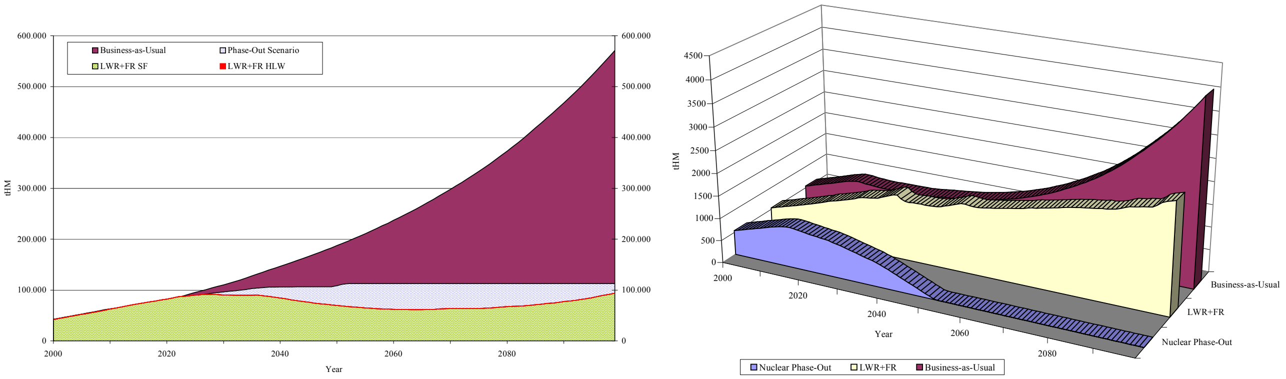
Two typical simplified examples of applications will be given to illustrate the diversity in applications that may be addressed with DANESS.

Closing the Nuclear Fuel Cycle

The US-DOE has started the Advanced Fuel Cycle Initiative (AFCI) [5] aimed at developing advanced fuel cycle technologies rendering the use of scarce natural resources and the arising of highly radioactive waste to a minimum. This involves closing the nuclear fuel cycle for all actinides thereby alleviating the continuous need for new repositories. A significant reduction, a hundred-fold, of the radiotoxicity in the repository is also achieved allowing to drastically shorten the long-term stewardship for such repositories by better managing the heat load and radiotoxicity of the buried waste.

Several advanced nuclear fuel cycle scenarios are under consideration where a quick and comparative analysis is needed to assess the different available options and to guide decision-makers in prioritizing resources. DANESS is used by ANL to perform these kind of comparative analysis between different advanced fuel cycles with respect to the mass-flows and resulting stocks of fuel and separated materials as well as the resulting economic picture for the government and utilities. An expected nuclear energy demand growth in the US of 2%/yr after 2010 is used to illustrate the effects of the different fuel cycle scenarios on the variables investigated. Figure 4 shows a typical result of the comparison of the amount of spent fuel disposed in repository and the actinide inventory in the fuel cycle for three scenarios. The three scenarios are nuclear phase-out, business-as-usual of the existing reactor park with new orders of LWRs and a LWR+FR type of nuclear energy system with FRs acting as TRU-burners. In this latter case, a user-defined reprocessing capacity deployment scenario was used with 5 000 tHM/yr LWR-UOX reprocessing capacity in place by mid-century and a doubling by the end of the century.

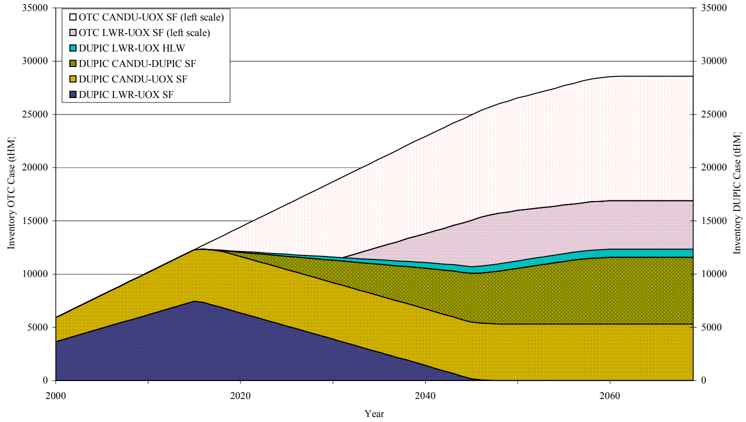
Figure 4. Comparison of the amount of spent fuel and high level waste to be disposed in repositories for three US nuclear energy system scenarios. Right figure shows the corresponding amount of actinides in the fuel cycle (i.e. out-of-reactor and out-of-repository) for the three scenarios



DUPIC Nuclear Fuel Cycle Development

Those countries having a mix of LWR and CANDU reactors might consider developing the so-called DUPIC nuclear fuel cycle. Spent LWR fuel is dry reprocessed through the use of the OREOX process where the fabricated fuel is recycled in CANDU reactors. A DANESS simulation, using unit costs as reported in literature [4], indicates the evolution of the aggregated bus-bar cost of electricity generation for a reactor park of 12 LWRs and 4 CANDUs. Figure 5 shows the evolution of the amount of spent fuel over time for this reactor park (assuming 60 years lifetime for reactors without new reactors being ordered). The levelized fuel cycle costs for the fuel for LWRs are calculated as 5.9 mills/kWhe, for CANDU-UOX 4.8 mills/kWhe and for CANDU-DUPIC fuel 6.8 mills/kWhe.

Figure 5. Spent Fuel Amount for a mixed LWR-CANDU reactor park with different fuel cycle options, i.e. once-through and DUPIC.



Future developments

DANESS is currently used in different projects. Based on this experience feedback new add-ins will be developed in the coming years. Developments currently under consideration are:

- Extending the cost database and implementation of scaling laws for these costs for reactor and fuel cycle facilities.
- Refinement of economic decision model by including market mechanisms and specific models for financial parameters, e.g. risk premium, …
- Integration of macro-economic energy balance.

Both ANL's integrated nuclear energy system models DYMOND and DANESS have been developed initially based on a technical description of nuclear energy systems with subsequently integration of environmental and socio-political aspects of nuclear energy. Interaction with other research groups in these fields, not essentially in the nuclear energy domain, is sought in order to improve these environmental and socio-political aspects and the decision-making processes in these fields.

Conclusion

A new code DANESS for the dynamic analysis of complex nuclear energy systems has been developed. This code allows the user to simulate all aspects of a varying mix of reactor and fuel types including the economic performance of such systems. The code is based on system dynamics modeling and further expansion of the model to cover all sustainability dimensions in the assessment of nuclear technology is envisaged.

The strength of using system dynamics in this quite large nuclear energy system model relates to the combined capability of performing detailed supply chain simulation while also incorporating decision-making feedback loops and all this in a transparent model environment. This allows using the DANESS-model from a technical level up to an energy policy support level while allowing incorporation of different decision-making feedback loops in assessing energy policy options.

References

[1] US/DOE, December 2002, GIF-002-00, *A Technology Roadmap for Generation IV Nuclear Energy systems*.

[2] MIT, July 2003, *The Future of Nuclear Power*

[3] OECD/NEA, Paris, France, 2002, *Trends in the Nuclear Fuel Cycle*.

[4] OECD/NEA, Paris, France, 2002, *Comparative Study of ADS and FR in Advanced Nuclear Fuel Cycles*.

[5] US-DOE, January 2003, *Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research*.

[6] OECD/NEA, Paris, France, 1994, *Economics of the Nuclear Fuel Cycle*.

[7] The European Technical Working Group in ADS, April 2001, *A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration*.

[8] OECD Nuclear Energy Agency (NEA), Data Dank (www.nea.fr).

[9] International Atomic Energy Agency (IAEA), Nuclear Science Division (www.iaea.org).

[10] Energy and Power Evaluation Program (ENPEP), (http://www.dis.anl.gov/CEEESA/ENPEPwin.html).

[11] Market Allocation (MARKAL), (http://www.etsap.org/Tools/MARKAL.htm).

[12] A. M. Yacout, R. N. Hill, L. Van Den Durpel, P. J. Finck, E. A. Schneider, C. G. Bathke and J. S. Herring, PHYSOR 2004, Chicago, Illinois, April 25-29, 2004, *Dynamic Analysis of the AFCI Scenarios*.

[13] L. Van Den Durpel, A. Yacout, D. Wade, H. Khalil, Global 2003, New Orleans, USA, November 16-20, 2003, *DANESS: dynamic analysis of Nuclear Energy System Strategies*, (www.daness.anl.gov).

[14] Nebojsa Nakicenovic, Arnulf Grubler, and Alan McDonald, World Energy Council, International Institute for Applied Systems Analysis, 1998, '*Global Energy Perspectives*', Published by Cambridge University Press ISBN 0-521-64569-7.

[15] IThink (www.iseesystems.com).