Preparing to the Near-Term Deployment of New Nuclear Fission Technologies: A SD Analysis of the Nuclear Market's Behaviors

Edoardo Cavalieri d'Oro[1]
Michael Golay[2]

Abstract:

A method of overall analysis for a compared evaluation of various nuclear fission and fourth generation units is here described. In this paper a series of questions related to the near-term deployment of new nuclear technologies in the US is answered and validated by reproducing the mechanisms that drove the nuclear market to the actual configuration. First, an historical overview of the development and sustainability of nuclear power technologies was carried out. Subsequently, the mechanisms that control the main balances were pointed out and reproduced by means of model of the form often used to project market competition ad hoc configured for the case of the energy production by nuclear power. The simulated scenarios and the sensitivity analysis highlight the considerable weight represented by the characteristic parameters of the technological lock-in phenomenon. The estimates of technical and economical parameters further confirm the importance of their evaluation.

Key words:
Nuclear Power, Competition, Nuclear Market, Logistic Behaviors, Lock In, Learning by Doing, Generation IV, Nuclear Power Technologies, Cost of Electricity Analysis.

---

[1] The article summarizes a more complex series of studies contained in a MS thesis that has been conducted by the author under the supervision of the co-author. To contact the author write to edo@mit.edu.

[2] Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology.

Introduction

The need of nuclear power and the forecasted development of the fourth generation nuclear power plants is still an open debate. Plants incorporating new designs would be safer and more efficient than the existing ones, and incorporating significant technological advances. The United States Department of Energy (DOE) is conducting an activity called the Generation IV initiative in response to the need for renew the development of advanced nuclear energy systems. The goal of the Generation IV initiative is to identify and develop next-generation nuclear energy systems that can be commercially deployed no later than 2030 and that offer significant advances in the areas of sustainability, safety and reliability, and economics. But new plants have to be more competitive in terms of costs; the long term viability of nuclear power generation lies in the industry's capability to keep its costs competitive with those for alternative forms of generation, primarily baseload coal-fired power plants. Over the past decades, the nuclear industry has succeeded in reducing costs of production significantly. The history of their initial development is then going to be useful in order to understand those mechanisms that drove the nuclear market to the final configuration that helped some technologies to succeed. The most outstanding mechanism in terms of importance, uniqueness and significance was undoubtedly the "lock-in effect": if technologies operate under dynamic increasing returns (often thought of in terms of learning-by-doing or learning-by-using), then early use of one technology can create a snowballing effect by which that technology quickly becomes preferred to others and comes to dominate the market (Cowan Robin, 1990; Brian, Arthur W., 1989).

In order to draw markets characterized by the already mentioned mechanisms, we made use of the System Dynamics methodology.

This paper reports the principal findings of a study that started in 2001 whose aim was the mechanisms describing the future adoption and use of new nuclear technologies. This research has been conducted at the MIT Nuclear Engineering Department and was published in a thesis format at the end of 2002. Since then the model that has been built had been modified over it is here presented in a schematic form inspired by the poster session that I personally exposed at the last SD Annual Conference in Boston.

Section I and II of this paper give an overview of model's layout and its basic assumptions. In Sec. III, the detailed model structure is provided. The definition of the scenarios analyzed together with the results of the study are described in Section IV. Finally, a discussion of the obtained results and some future utilizations of the model are given in Section V.

I. Model Assumptions

The evolution of the nuclear power reactor market in the United States after the early 1960s can be seen as the latter stage of a positive feedback process. In such process if one technology, in advance of its competitors, makes a large movement along its learning curve, the others will be hard pressed to compete, finding it difficult if not impossible to enter the market. The first technology to get significantly ahead of its rivals is likely to dominate the market (Cowan Robin, 1990; Brian, Arthur W., 1989).

The model simulates the development of the nuclear power system within the country over a time period that varies between 20 and 50 years. The reference nuclear market has been represented trough a supply and a demand curve.

The model is formulated:

1) In continuous time as means of a set of differential equations with time periods varying between 20 and 50 years,
2) The reference nuclear market has been represented by a supply and a demand curve.
3) The supply chain implements the learning by using curve that in turn reduces marginal costs and consequently the price of electricity,
4) The single contribution, as given just by one of the competing technologies, also affect the whole industry's demand,
5) The different technologies compete on the basis of their initial capability to respond to the technological specifics and by means of their ability to increase speedily their installed capacity.

A MSA (Market Share Attractiveness) algorithm that:

- measures the resulting position of the competing nuclear concepts within the market place,
- allocates the orders of new unit among competitors.

The model is driven by a logistic diffusion semi-exogenous demand that considers:

- the possible assessments of the market in response of learning's cost escalations,
- degenerations of the market's orders due to unforeseen shocks of construction costs.

Most of the variables expressed are aggregated using criteria whose aim is to emphasize the overall system behavior than reproducing it with accuracy. The work's audience is the decision maker . Therefore the model has to be intended as a tool useful for reproducing scenarios of interest and underlining the rules played by the mechanisms prevailing within the market.

In order to facilitate the comprehension of model's structure in the following page we provide a list of the variables and parameters utilized:

TABLE 1: Variables and Parameters used by the US_Nuke_Energy_SD0205.

Demand var:

EIDr	Reference Industry Demand Elasticity[dmnl]
Ds	Demand Curve Slope [Units/(milli$/KWh)]
NMSr	Reference Nuclear Market Size [Units]
PFr	Reference Fossil Price [milli$/KWh]
$Pa_i(t)$	Average Price[milli$/KWh]
ID(t)	Industry Demand[Units]
NMS(t)	Nuke Market Size[Units]
NP(t)	Potential Nuke[Units]
NA(t)	Nuke Adopted[Units]
dNA(t)/dt	Nuclear Adoption Rate[Units/Year]
NEMax(t)	Maximum Nuke Erosion [Units/Year]
ENMR(t)	Erosion Nuke MktRate[Units/Year]
CN(t)	Canceled Nuclear Units[Units]
NPPE	NPP Erosion for Unforseen Events[1/Year]
g	Energy Growth [%]

Market var:

Le(t)	Learning Curve [dmnl]
LCexp	Learning Exponent [dmnl]
K	Learning Strength [%]
$MC_i(t)$	Marginal Cost [milli$/KWh]
$MC_{Vi}(t)$	Marginal Var. Cost [milli$/KWh]
$MC_{Fi}(t)$	Marginal Fixed Cost [milli$/KWh]
$P_i(t)$	Price [milli$/KWh]
Pt(t)	Total Price [milli$/KWh]
$\varepsilon 1$	Sensitivity to price [dmnl]
$Patt_i(t)$	Price Attribute [dmnl]
L	Importance Normalization Factor[dmnl]
I_k	Importance Overall Success[dmnl]
w_k	Prob. Success Perfor. Area [dmnl]
OSP_i	Overall Success Probability [dmnl]
$\varepsilon 2$	Sensitivity to Initial Design[dmnl]
$Datt_i(t)$	Initial Design Attribute[dmnl]
$A_i(t)$	Attractiveness [dmnl]
At(t)	Total Attractiveness [dmnl]
$OS_i(t)$	Order Share [%]
NMKt(t)	Nuke Mkt Share [%]
$NMK_i(t)$	Total Nuke Market [Units/Year]

Supply generation var:

$OR_i(t)$	Order Rate[Units/Year]
$CURI_i(t)$	Capacity Under Regul. Insp[Units]
$CURIR_i(t)$	Cap. Under Regul. Insp. Rate [Units/Year]
$CUC_i(t)$	Capacity Under Construction[Units]
$IC_i(t)$	Installed Capacity[Units]
$OLR_i(t)$	On line Rate[Units/Year]
$RR_i(t)$	Retired Rate[Units/Year]
$SH_i(t)$	Shutdowns[Units]
$Pow_i(t)$	Power per Unit[Net MWe/Unit]
$GCR_i(t)$	Grid Connection Rate [Net MWe/Year]
$ICp_i(t)$	Installed Power Capacity[Net MWe]
$ICpa_i(t)$	Average IC Power [Net MWe/Unit]
$RPR_i(t)$	Retired Power Rate[Net MWe/Year]
NGt(t)	Tot Net Generation[Billion KWh]
RRt(t)	Total Retired Rate [Units/Year]

Time constants:

τ_{Pi}	Permit Time [Years]
τ_{Ci}	Construction Time [Years]
τ_{Li}	Lifetime [Years]
τ_{Lr}	Reference Life Time[Years]
τ_{Cr}	Reference Construction Delay[Years]
τ_{Pm}	Minimum Permit Time [Years]

Cost generation var:

Cfu	Fuel Cost [milli $/(KWh)]
Com	O&M Cost [milli $/(KWh)]
Ccc	Capital Cost [milli $/(KWh)]
$Uc_i(t)$	Uranium Cost [$/kg]
$Oom_i(t)$	O&M Cost per Unit Power [$/kWe/Year]
$Oc_i(t)$	Overnight Cost [$/kWe]
T_f	Tax Fraction [%]
f	Capacity Factor [%]
R	Discount [1/Year]
Mg	Mortgage[1/Year]
I	Inflation [1/Year]
B	BurnUp [MWe*Day/ton]
η	Plant Thermodynamic Efficiency[%]

II. Model Conceptualization

A model capable of assembling and simulating the phenomena observed within a complex system such as the nuclear market, is hard to define because of the heterogeneity of the variables involved and of some modeling obstacles such as:

- The presence of mechanisms characterized by non-linearities that are typical of markets described by domination.
- The heterogeneity of the variables involved in the representation of the overall electricity market including factors hard to be managed by ordinary models.
- The relevant presence of feedback mechanisms to be captured as network size expansion.

The SD approach, reveals useful to pass all these obstacles and to analyze dynamic patterns. Its validity is well tested and the literature provide a wide range of models used to describe cycles in power plant construction (J. Sterman, 2000).

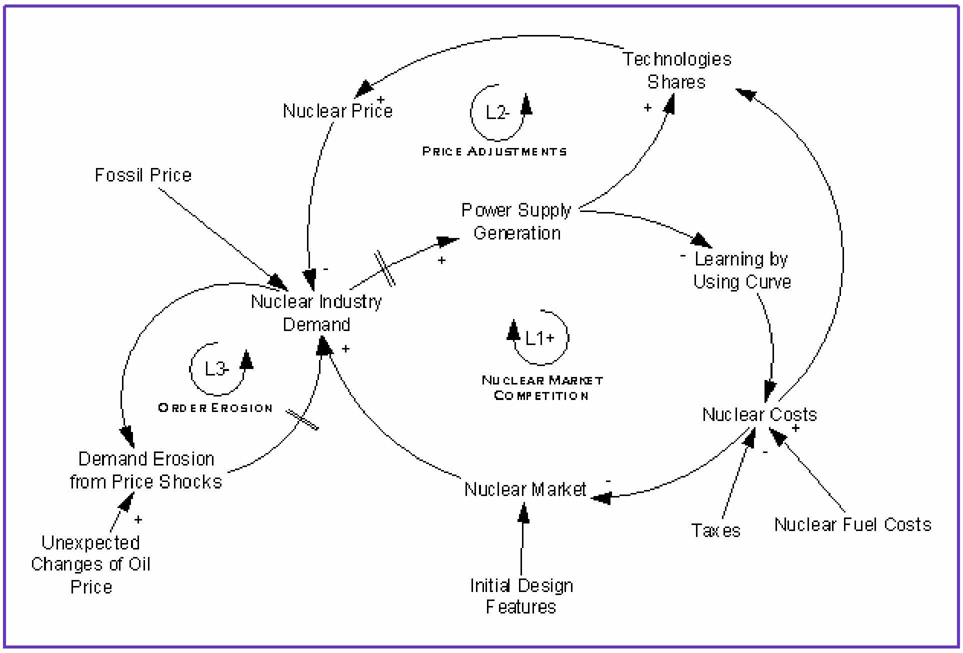


Fig. 1: Diagram of the US_Nuke_Energy_SD0205 Model. The relationships between the differential variables are represented by the arrows. L1, L2 and L3 represent recursive (feedbacks) relations among the main variable.

L1: this feedback into account the double contribute of Initial Design Specifications and Learning by using effects. It is responsible for the allocation of the ordered units within the nuclear market.

L2: The second feedback loop simulates the penetration of the nuclear market within the whole energy market. The price of the electricity produced is assumed to be the key-variable to compete.

L3: The last feedback incorporates undesired effects that force the nuclear market to cancel orders during the construction phase[1].

Input Acknowledgements

By observing the historical trends, we conducted a preliminary input acknowledgments in order to study the relationships existing between the order rate of nuclear power plants and the growth rate of the energy demand.

In the period that goes from 1953 to 1980 (from the first year to the last a commercial order was placed), the demand for nuclear energy units showed two main peaks. (See Fig. 2)

As a result the American growth rate recorded at that time was 7% per year. The nuclear industry experienced an immediate take off of the "nuclear business" giving rise to a five year period of increasing nuclear orders. However, in 1967 the peak value was reached and followed by a decline which marked a negative difference between the orders of subsequent years. The reasons for this decrease in the demand growth rate, according to some experts, can be related to:

1. The economy, and as an obvious consequence, the economic growth rate always oscillate during history as a natural matter of fact.
2. Vendors' capability in making forecasts is subject to errors. These errors in predicting the future demand of Nuclear Electricity affect the construction process
3. Referring to the previous consideration, the nuclear power plant construction process is characterized by High Inertia due to the complexity and length of the construction phase.

Our interpretation can be therefore summed up as follows:

A) "Under favorable circumstances the nuclear unit demand proportionally follows the energy growth rate, which in turn follows the economic growth rate of the country".

B) The nuclear system is vulnerable and sensitive to social and political externalities as well as to economic changes. The particular nature of the nuclear system prevented the ordered units from having an increasing and continuous development over the considered period of time.

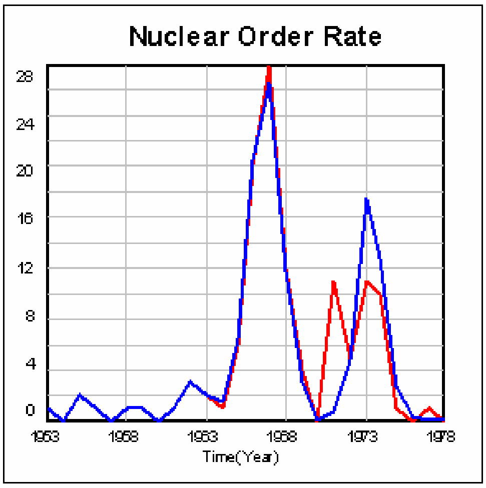


Fig. 2: NOR, Blue = simulated , red = actual data.

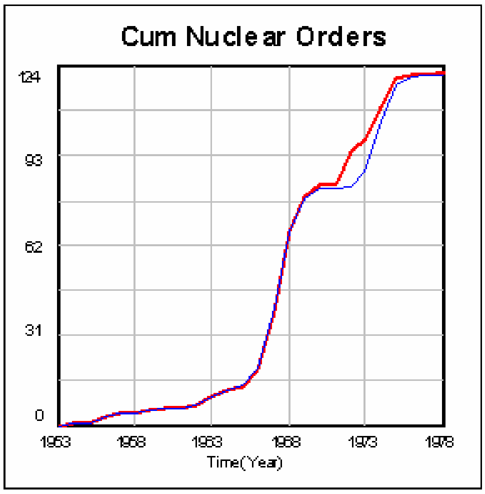


Fig. 3: Orders cumulated by the Nuclear Industry.

In terms of mathematical modelling the choice of a function that is proper to describe the sequence of phenomena already described is the *logistic function*.

III. Model Structure

The Industry Demand

The total industry growth is described by means of a s-shaped logistic function. The choice of shaped use fell on the simple logistic function essentially because of its immediate comprehensibility. The logistic function expresses the decision to build new NPPs as a diffusion process: nuclear units going trough the supply chain are represented by the adoption rate that regulates the flow between the potentially ordered units and the units that have been actually chosen for adoption. In other words, the Nuclear Adoption Rate, NAR, is the rate of change of the number of adopted units, NA that is calculated on the basis of the Nuclear Market Size, NMS, and of the energy growth coefficient, g (time subscripts are omitted for purposes of clarity):

$$\frac{dNA}{dt} = NP \cdot g \cdot (NA/NMS) \qquad (1)$$

Where dNA/dt is the adoption rate for the nuclear market that, depending on the different policies, defines completely the total nuclear orders rate, NOR, or only a fraction of it in the case we assume that, for future scenarios, part of the new nuclear generation can be given by the recovery of old already built power plants, RR, thus:

$$NOR = \frac{dNA}{dt} + \frac{dRR}{dt} \qquad (2)$$

The number of clear power units potentially adopted by the market, NP, is determined by the difference between ID (the number of units available in the market at the price Pa) and the current number of adopted units.

Price

The total nuclear industry order rate is then influenced by price trends. For simplicity we assumed a linear relation between the average price of electricity, P_a, and the Industry Demand ID[3]:

$$ID = MIN[NMS_0, NMS_r \cdot MAX(0, 1 + D_s \cdot (P_a - P_r)/NMS_r)] \qquad (3)$$

The variable ID represents the number of units in the nuclear marketplace that will in equilibrium be chosen for investment in new nuclear capacity as a function of the average

[3] A similar formulation can be found in J. Sterman et al., 1995.

price available in the market. The slope, D_s, is calculated by selecting a reference point for price and nuclear market size, and the demand elasticity at that point.
The price of the electricity produced via nuclear power is given by the use-weighted average of the marginal costs of all the competing technologies in the market. The weight directly descends from the single NMKs (Nuclear technologies' Market Shares) as computed by simply dividing the respective installed capacity by their sum.

$$NMK_i = IC_i / \sum_{j=1}^{n} IC_j \qquad (4)$$

The Attractiveness Factor

The design and construction of new nuclear technologies is based upon technical and economic requirements, as well as other requirements resulting from non-proliferation, environmental and safety policies. Due to the different nature of the several requirements and the difficulty deriving from their overall evaluation, a unique evaluation parameter that incorporates all of the mechanisms (or attributes) is needed for our model. First, we decided to summarize all the possible categories of attributes into two main attributes, i) Learning effects on costs and the ii) Initial design requirements.

The former is calculated by means of a positive feedback and it is described by dynamical quantities, the latter, defined as a static attribute, portrays the capabilities of the i-esim technology concept at the time it enters the market. As a result the unique evaluation parameter of Attractiveness depends on both a static and a dynamic attribute:

$$A(t)_i = \exp(OSP_i) \cdot \exp(Cost_i(t)) \qquad (5)$$

Consequently the Order Share function, OS, allocates orders among the different technological competitors within the market. The i-esim OS fraction of the order rate is assigned to each technology, according to the following formula[4]:

$$OS_i = \frac{A_i}{\sum_{j=1}^{n} A_j} \cdot OR \qquad (6)$$

[4] This formula has many desirable properties and several features and its popularity in equilibrium analyses of marketing competition is well known; since reaching equilibrium is by no means a sure thing, using the so-called MSA algorithm suggests that the path toward equilibrium deserves a share of attention. Equilibrium analysis of markets is especially useful if the market cannot reach equilibrium.

Inspection of the Single Attributes

We provide here the properties of each of the two attributes composing the Attractiveness function. The Initial Overall Success Probability defines the initial value of attractiveness of every technology to compete as given by the initial design specifications. The second attribute concerns with cost's escalation and it shows a recursive nature or feedback.

The Learning Feedback

The learning effect experienced by operators, builders and suppliers produces, over time, a positive reduction of the global costs required to install a plant. The importance of learning in repetitive production processes is well documented in the literature (Joskow and Rozanski, 1979. Lester and McCabe, 1993). All these studies have focused on the increase in labor productivity (in producing particular products) that is associated with increases in cumulative output. Other studies investigated the problems specifically related to the economy and profitability of nuclear energy in the first decade of the nuclear rush period (Cantor and Hewlett, 1988).

The observed cost variation is proportional to the amount of "learning by using" accumulated by plant operators, which is in turn proportional to the number of units produced per year. In the model we used Zimmerman's data interpretation which states that: "Doubling the accumulated experience reduces capital and O&M costs by ten per cent". As a matter of fact, the Investor or, more generally, the decision maker will be positively influenced by a cost function that progressively reduces as time pass; in other words the preview given by an investor about a specific power plant is based on the investment analysis carried out in the previous Sections together with an innovation function which takes into account the "state of progress" gained by the technology from its discovery until today. This Innovation function is universally known as the Learning Curve and the cost payoffs arising from the continued use of a given technology is part of investor's point of view: "The investors, when estimating the costs involved in installing a plant, must take into account the position of the technology within its respective learning curve" (J. Sterman et al., 1995). The main evaluation attribute for investors is represented by costs; they take into account this decisional variable when allocating the available orders of new plants. These behaviors are expressed by the MSA algorithm that allocates orders on the basis of the lower cost.

As expected, the series of highlighted relations is of a recursive nature; the direct proportionality between the considered input (the cumulative power produced until the considered instant in time) and the output (the cost decrease function) lead to the closure of a loop. This direct proportionality, as well as the existing relations between the intermediate variables, implies that the loop, established between costs and allocated plant orders, is positive.

The Learning Attribute

The rate of new installations measured in number of units installed is therefore accumulated in the variable level defined as Le:

$$dLe(t)/dt=OLR \qquad (7)$$

The resulting factor of cumulative learning that is normalized for the value of this assumption at the beginning of a simulation and elevated to an exponent that guides the velocity of learning, supplies the characteristic learning curve, thus:

$$Le=[IC(t)/IC_0]^{\gamma} \qquad (8)$$

Where Le is a constant coefficient used to calibrate the initial experience value.
The result obtained coincides with the previous hypothesis that the decreasing function varies with the accumulation of energy produced by the set of installed reactors. The velocity of such a decrease is given by the value of the exponential that, based on values provided by literature supplies (Cantor and Hewlett, 1988) to the resulting learning curve as a declining effect on the costs in regards to those historically observed.
The exponent γ determines how strong the learning curve is and should be negative (costs fall as cumulative experience growth). Since k, the fractional cost reduction per doubling of experience, has a more intuitive meaning than the exponent γ, it is convenient to formulate γ in the model as a computed constant:

$$\gamma=\ln\left(1\text{-k}\right)/\ln(2)=\log_2\left(1\text{-k}\right) \quad \text{With } k=10\% \qquad (9)$$

The unit cost of nuclear is then derived from the “learning by using” function already defined in which variable costs decline with the cumulative volume on past investments in nuclear technologies, summed to the constant contribute given by fixed costs.

$$MC(t)=Cost_V \cdot Le+Cost_F \qquad (10)$$

In nuclear power reactors variable costs are mainly defined by Capital expenditures plus Operation and Maintenance costs while fixed costs are simply the Fuel costs (the following Section provides a method for evaluating unit marginal costs).

Marginal Costs: Lifetime Levelized Busbar Costs

Costs, for a particular energy source, are given by variable and fixed costs:

$$MC=MC_V+MC_F \qquad (11)$$

In the case of a generic plant that produces electricity there are three main costs to consider i) capital costs ii) operation and maintenance costs, iii) fuel costs. The first two are considered fixed costs and the third is a variable cost therefore subject to the energy production. The levelized unit cost of production, in cents per kilowatt hour, at the busbar (plan/transmission line interface) is obtained by equating levelized revenue to levelized expenditures for capital cost, operation and maintenance and fuel costs.

$$MC_V = C_{cc} + C_{OM} \tag{12}$$

$$MC_F = C_{FU} \tag{13}$$

We compute the levelized unit cost of production, or marginal unit cost, MC, by the sum of all the costs, that with presence of learning effects, as stated by Equation (10), is:

$$MC(t) = (C_{cc} + C_{OM}) \cdot Le(t) + C_{FU} \tag{14}$$

Then, by means of the following embellishments, and through further simplifications of levelized cost formula[5], we described the MC quantity as provided by Equation (15).

- The cost of money (interest paid on borrowed funds) is given by a weighted sum of specified returns on bonds and anticipated returns on stocks.
- The carrying charge rate further considers that bond interest is tax deductible (which may or may not be the case everywhere and for all time).
- Future expenses are escalated at rate I per year.
- The plant capital cost at time zero is computed from an overnight cost (i.e., hypothetical instantaneous construction), corrected for escalation and interest paid on borrowed funds over a construction period starting τ_{cr} years before operation.

$$MC = k_1 \left[\frac{1}{f} \cdot O_{OM} \left[1 + \frac{I \cdot \tau_{Lr}}{2} \right] + M \cdot \frac{1}{f} \cdot Oc \left[1 + \frac{I + R}{2} \right]^{\tau_{cr}} \right] Le + k_2 \frac{U_c}{\eta \cdot B} \left[1 + \frac{I \cdot \tau_{Lr}}{2} \right] \tag{15}$$

The Lifetime levelized cost formulation is a useful construct because it permits a single valued numerical comparison of alternatives having vastly different cash flow histories.

The Initial Design Attribute

When evaluating the appeal of a given technology, or more specifically of a reactor/fuel concept, once its design has been completed, its features are still unknown from a deterministic point of view. However there are various approaches available, which can

[5] Driscoll, M.J.,2001. Notes from the MIT Class: *Nuclear Energy Economics and Policy Analysis*.

provide the necessary evaluation parameters. It is the aim of this Section to illustrate one of these evaluation criteria[6].

At the beginning of each study, that precedes the design, specifications about design techniques or targets are made available to designers, who have to respect these directions when designing a new technology. The various directions or goals[7] are different in nature. Their diversity also affects their measurability and requires evaluation criteria that allow conglobing the different effects into one or more parameters, in order to assess the efficacy of the observed technology. The presented proposal aims at grouping the various technical specifications given by goals into one single parameter of evaluation which will be referred to as Overall Success Probability.

Despite its uncertainties (it contains all of the uncertainties of its constituting factors) the Overall Success Probability is a useful parameter, which can provide an immediate initial evaluation of the Attractiveness of each technology in terms of Initial Design. The resulting attribute of attractiveness can be considered as the only value available to a decision maker before the construction of a new technology. Initially it can only avail of the assigned design specifications and the competing technologies which necessarily derive from such specifications.

Further considerations leading to a final decision will have to wait until the new technology has been tried and inspected. Any previous evaluation of technical performances and production costs is unreliable. Only after the first tests and installations will a given technology benefit from an expanded network, use and consequent cost escalation. In other words only after the first installations have been completed the positive effect of the technological development give its contribution.

Design Goals: The Overall Success Probability

The effort to evaluate reactor/fuel cycle concepts has advanced to the point of defining a set of performance goals (see Table 2), but not to formulation of a method for integrating the performance of a concept in their terms into an overall performance score. The proposed method, is based upon the contribution of each performance metric to the overall success probability of the concept. Different versions of success will be important at different stages of the deployment cycle of a concept. Examples of different forms of success are the following:

- Successful creation of a new, practical technological option
- Successful deployment of an initial reactor/fuel cycle system
- Successful widespread deployment of an initial reactor/fuel cycle system
- Successful utilization of a fleet of reactors and fuel cycle on a long-term basis

Regardless of the version of success considered, the performance attributes of Table II.B.1 are all relevant to the overall probability of success (otherwise the justification for

[6] It is based on an approach proposed in these last years' study of the Generation IV reactors. (Golay M.W, 2001).

[7] The Gen. IV roadmap process identified the development of a set of technology goals that may enable the successful realization of new nuclear energy systems. These goals are divided into categories in the areas of sustainability, safety and reliability, economics.

the goal must be questioned). In the method proposed here we attempt to reflect this relevance quantitatively.

Each performance area will have an importance for overall success, I_i, i.e. a performance area rated as Important-to-Success would have nine times as much influence upon success as one rated as being Unimportant-to-Success (See Table 3).
The overall success probability of a concept, OSP, is obtained as

$$OSP=\frac{1}{L}\sum_{i=1}^{M} I_i \cdot w_i = \frac{1}{L}\sum_{i=1}^{M} I_i \cdot \sum_{t=1}^{4} p_{it} S_t \qquad (16)$$

where: L= Importance normalization factor $=\sum_{i=1}^{M} I_i$, M =number of areas of performance being evaluated and w_i =probability of success in i-th performance area.

The presented method represents the criterion we used to determinate the Initial Design Attribute of the Attractiveness variable.

Eq. (16) provides the desired performance score for any reactor concept in terms of an identified set of performance metrics; Table 4 computes the OSP using, for example, the values which are the most likely to occur for the AP600 technology.

Table 2: Categories of Reactor/Fuel Cycle Performance Goals.

Sustainability	***Safety & Reliability***	***Economics***
SU1 Material Resource Consumption	SR1Occupational Safety & Reliability	EC1 Capital Cost
SU2 Waste Disposal	SR2 Core Damage	EC2 Capital Cost Volatility
SU3 Proliferation Resistance	SR3 Emergency Planning	EC3 Operations & Maintenance Costs

Table 3: Categories of Importance for Overall Success of an Individual Area of Concept Performance.

Category Number	**Importance Category**	**Importance Quality Category Contribution to Overall Success**
1	Important-to-Success	0.9
2	Somewhat-Important-to-Success	0.7
3	Somewhat-Unimportant-to-Success	0.3
4	Unimportant-to-Success	0.1

Table 4: Illustrative Example: The four Performance Categories for the AP600 technology

Performance Category	**i=1CapitalCost**	**i=2 Core Dmg.Frequency**	**i=3 FuelConsumption**	**i=4Proliferation**
Importance Quality	0.9	0.9	0.3	0.1
• Excellent	0.1	0.3	0.1	0.2
• Acceptable	0.2	0.5	0.7	0.5
• Marginal	0.6	0.4	0.2	0.3
• Failing	0.1	0.1	0	0
Performance Area Quality Probability	0.44	0.55	0.64	0.62
Importance-Weighted Contrib. to OSP	0.40	0.49	0.20	0.06
⇒ Overall Success Probability (Eq. (16)) = 1.15/2.2 = 0.52				

The Supply Chain

We stated the generic reactor's life-cycle to be similar to a chain of subsequent radioactive decays (or in a more practical context to the behavior of an assembly line).

The way the chain captures behavior is given by a set of equations that represent the "life" of the average nuclear power plant that goes from its initial ordering and ends with a final shutdown. The characteristics times are computed as the average of their total values.

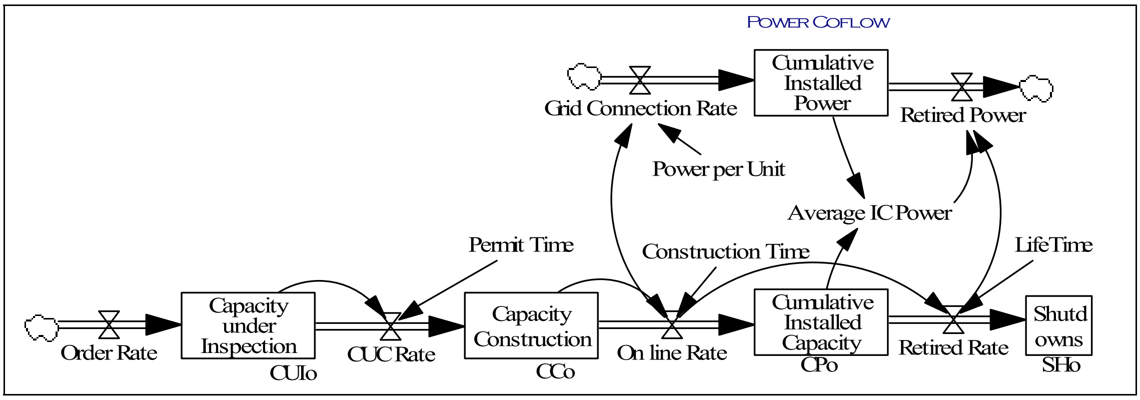


Fig 4: The Reactor Life-Cycle is modelled by means of accumulated stocks (represented by boxes). The flows between two sequent stocks is regulated by a characteristic times.

A power co-flow defines finally the installed quantity of cumulative MWe installed available for electricity production every year at the grid. This formulation allows to pass from [Units] to [Net MWe] produced and to determine the experience cumulated[8].

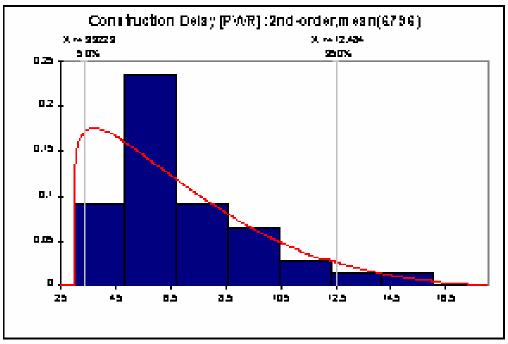


Fig. 5: Construction Delay distribution (PWR).

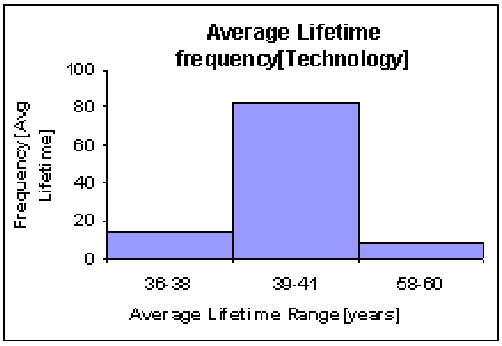


Fig. 6: Average lifetime of a LWR.

[8] If we were simply looking for the quantity installed power/year, we would observe that the quantity is obviously linked to the cumulative number of units installed and its calculation should be easily provided by the multiplication of the cumulative installed units with the average power of a nuclear unit. On the other hand, this simple operation neglects the dynamic properties of the power chain measured in [Net MWe] associated to the primary supply chain [unit]. This is particularly true if i) The size of plants varies over time (meaning that over historical periods builders should follow different size specifications); ii) The order rate which drives the supply chain varies over time (J. Sterman, 2000). We assumed constant plant sizes but order rates that are varying over time.

IV. Model Results

We here provide a series of scenarios conducted by means of the US_Nuke_Energy_SD0205 model, both, by studying the past behaviors, and, by running possible future simulations. We are giving a limited set of results, as our mains focus in this paper is the presentation of the model together with the reasons lying behind the conceptualization of the model. However, by simply varying the input parameters, it is possible to use it to formulate a wide range of scenarios. The scenarios presented therefore constitute a sampled number of situations that had been chosen in order to summarize the model's potentiality and behaviors of interest.

IV.A Model Calibration: Evidence of a Duopoly Competition

By using our model, first we prove its adherence to the lock-in effect, as historically shown by the Installed capacity of the two technologies to compete. The competing technologies follow a more complex scheme of strategy; the presence of learning curves suggests that early learning entrants can achieve sustained competitive advantage by rapidly building capacity, and thus by pricing aggressively can preempt further competition.

IV.B Market Instabilities from Sensitivity Analysis

A sensitivity analysis of the behavior of the main variables involved in the Lock-In phenomenon can be found in this Section. Most of the presented scenarios focus on the instability effects structurally contained in the lock-in mechanism.

IV.C World Calibration: LWR's Supremacy

The following is an extension of the previously mentioned method of optimization to the large scale World Case.

IV.D Conservative Policy: Plants' Replacement on Site

After a first initial phase of installations, nuclear reveals to be uncompetitive and governmental policies encourage nuclear utilities only to re-install the retired nuclear stations in order to maintain the same installed capacity, in term of number of plants, we have at this day.

IV.A Model Calibration: Evidence of a Duopoly Competition

In this Section, the focus is on the calibration of the LWR's supply chain. The results are obtained by testing the supply chain with the input that effectively verified over the twenty years period which the nuclear US industry had been placing orders of new units. The US_Nuke_Energy_SD0205 model makes use of a simple logistic function that constitutes the rate of material input in building the plant that precedes the connection to the grid. The results obtained constitute an interesting and accurate exercise in terms of model calibration of the supply chain and of their validity extends to the MSA algorithm responsible for the orders' allocation.

BWR technology plays the role of one of two competitors within the ideal marketplace. The assumption of a duopolistic competition approximately respects the observed US nuclear market. With the introduction of the Generation IV family of reactor technology, or by using the model on a largest context (i.e. the worldwide market), the marketplace has to take into account the contribution of other technologies. The Model's extension to the complete portrayal of the world market (with the addition of GAS and CANDU technologies) is in Section IV.C.

The optimization works under the constraints given by the IC historically observed curve and by the final number of retired reactors. It follows a synthetic results' explanation first for BWRs and then for PWRs.

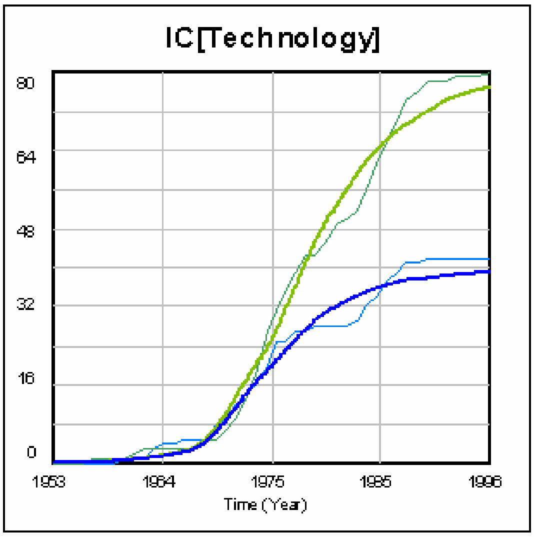


Fig. 7: Installed Light Water Reactors (US).

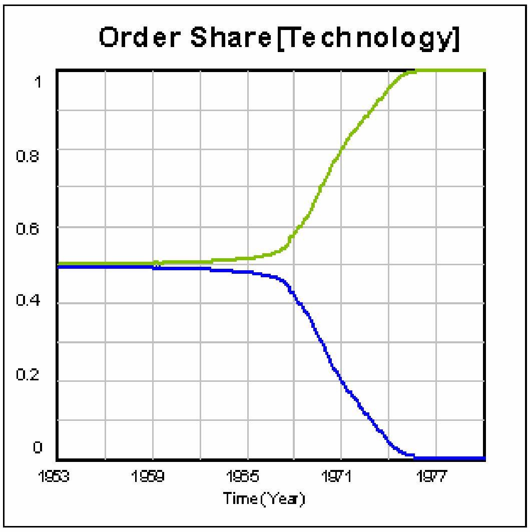


Fig. 8: Corresponding Order shares (US).

Results obtained by running the US_Nuke_Energy_SD0205 Model into the domestic market, which is characterized by the duopoly competition between the two LWR technologies: BWR (blue line) and PWR (green line).

IV.B Market Instabilities from Sensitivity Analysis

A sensitivity analysis of the behavior of the main variables involved in the lock in phenomenon can be found in this Section. Most of the presented scenarios focus on the instability effects structurally contained in the lock-in mechanism[9].

We are showing results in term of the OR, Order Share, quantity and its variations under different possible circumstances (i.e. Overnight Cost variation, See Fig. 9).

By observing the Order Share behavior we found evidence of technology mix instabilities arising from the MSA formulation. In fact, the MSA market exhibits some surprising and complicated dynamical properties (Farris and Pfeifer, 2001) which, depending on the different values assumed by its single attributes, can either: quickly reach equilibrium (or lock-in state) and move chaotically on a path that never reaches equilibrium (Mix Instability).

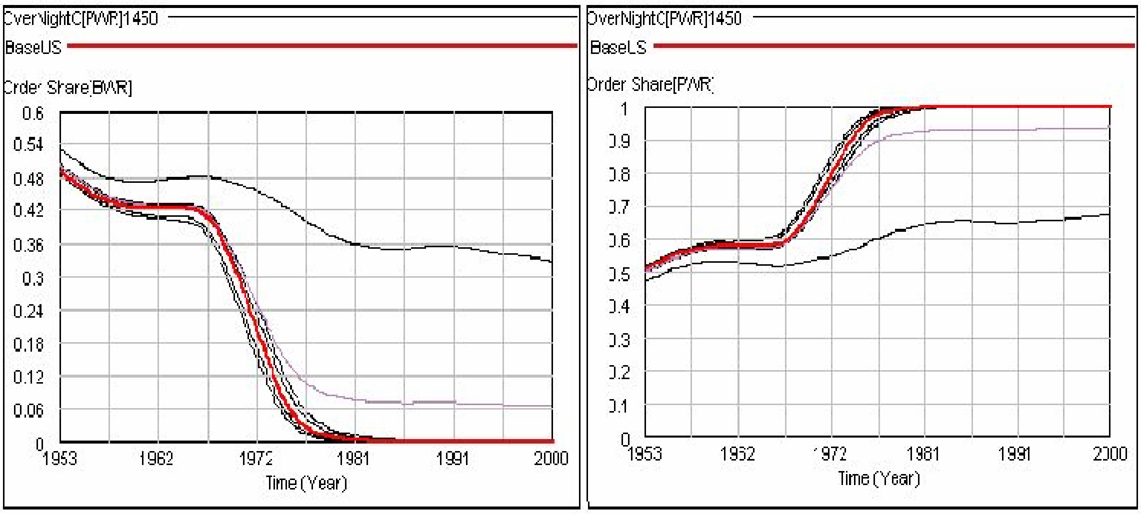


Fig. 9: The results coming from the sensitivity analysis are given in term of the OR, Order Share, quantity and its variations under different possible circumstances (i.e. ID overnight costs variations around their average value of 1400 $/KWe).

The Sensitivity Analysis, as it is illustrated in this graph, shows the presence of instability and, more precisely, of the Lock-In mechanisms. As the overnight cost parameter varies in proximity of the its average value (1400 $/KWe), the Order Share function acquires a totally different behavior. From an initial total domination of the PWR technology, the situation gradually changes until the other competing technology comes to dominate the market.

[9] Sensitivity testing is the process of changing your assumptions about the value of constants in the model and examining the resulting output for change in values.

IV.C World Calibration: LWR's Supremacy

We here provide an overview based on the results coming from a world's calibration of the reactor life-cycle. The following is an extension of the previously mentioned method of optimization to the large scale World Case.

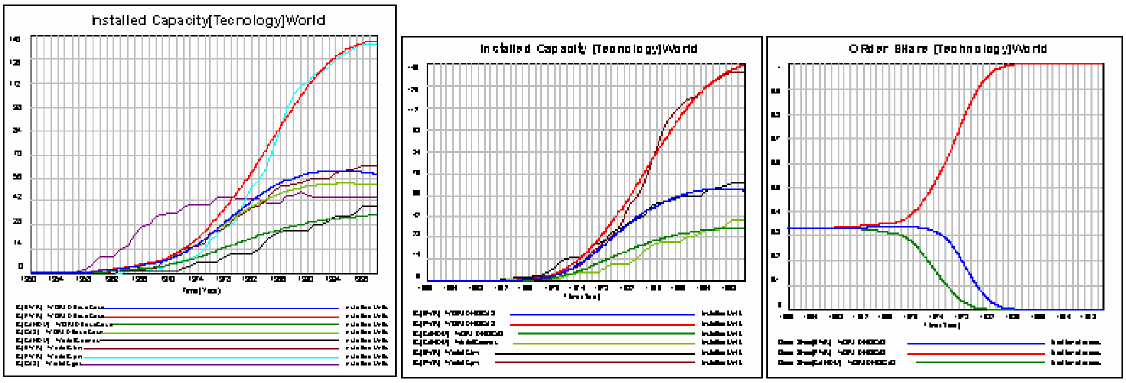


Fig. 10: from the left to the right, Installed Capacity, IC, over the world (including BWR, PWR, CANDU and GAS technologies), Installed Capacity and the respective Order Share, OR, function (without the GAS family).

The Gas reactor family does not to conform to the actual data set. The reasons for this are explained by the following elements involved in the judgment:

1. The role played by the domestic policy of each country
2. The Local Development of CANDU and Gas Reactor Technologies
3. The lack of accuracy of the model extended to the world case

VI. D Conservative Policy: Plants' Replacement on Site

After a first initial phase of installations, nuclear reveals to be uncompetitive and governmental policies encourage nuclear utilities only to re-install the retired nuclear stations in order to maintain the same installed capacity, in term of number of plants, we have at this day. In this case, the future order rate had been simply calculated by replacing the rate of retired units; in order to maintain the capacity currently installed, we need to shift the retirement rate backward to the time which allows contractors to build the new plants.

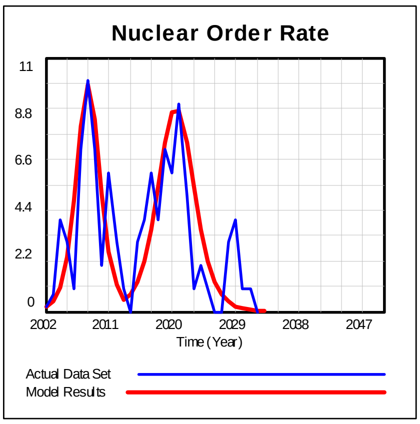
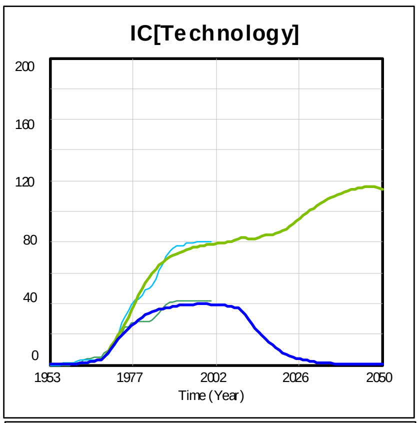


Fig. 11: Results seems to reveal that , by keeping the same trend nuclear was having in the past (PWR domination) in the next 50 years, if no changes are going to occur, BWR will extinguish in a input scenario where nuclear maintain the IC it shows today.



V. Conclusions and Future Projects

In this paper we have presented a model that conglobe the main mechanism that characterize the nuclear energy market. Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems.

We have shown that lock-in is a common phenomenon in the nuclear market; with the implication that non-locked-in long term distributions may only be achieved trough non-market mechanisms (i.e. via government intervention).

More importantly, our studies demonstrate the actual precarious stability of the Order Share function, which usually has the role of defining the choices of technological mixes. Such mixes, in fact, are often defined a priori and kept constant within the scenarios represented or varied arbitrarily (Papathanasiou, D., D. Anderson, 2001).

Therefore, this work sets concrete grounds for possible extensions of the model. The number of directions that can be subsequently represented is nearly unlimited; There is a wider array of potential roles and options for deploying nuclear power plants, including more detailed price analysis and the coal and gas generation, that should be incorporated to the model's core structure.

The possibility of applying this representation to a world model, capable of aggregating more than one country, has been tested and proven. Nevertheless the values of the parameters that resulted from the research carried out at a global level should still be only seen as basis for a further study of the lock-in phenomenon and of nuclear reactor orders.

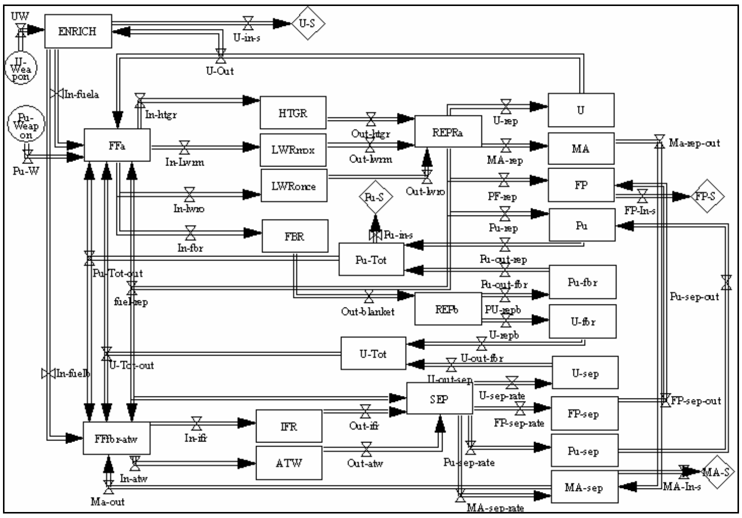


Fig. 12: Sketch view of the Fuel Cycle scheme.

This work shows the grouped and obtained results, and paves the way for a further development of this study which will be carried out with the constructed model for the simulation of future scenarios that should include two main features :

- ✓ Fuel Life Cycle Effects on Costs
- ✓ The Effect of Externalities

VI. References

Brian, Arthur W., 1989. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *Economic Journal* 99: 116-131.

Cowan Robin, 1990. Nuclear Power Reactors: A Study in Technological Lock-in. *Journal of Economic History* 50: 541-567.

Fisher, J.C., and Pry, R. H., 1971. A Simple Substitution Model of Technological Change. *Technological Forecasting and Social Change* 3: 75-88.

Fujii Book, 1994. Technical Data of Individual Nuclear Power Plants All Over the World.

Golay, Michael W., 2001. A Probabilistically-Based Method For Integrating Reactor/Fuel Cycle Attribute Metrics Into An Overall Attractiveness Rating. *Prepared for use of Generation-IV Evaluation Methods Group (EMG).*

Joskow, Paul L., George A. Rozanski, 1979. The effects of Learning by doing on Nuclear Plant Operating Reliability. *The Review of Economics and Statistics* 61: 161-168.

Kamani, Aneel, 1985. Strategic Implications of Market Share Attraction Model. *Management Science* 31(5): 536-547.

Lester, Richard K., Mark J. McCabe, 1993. The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation. *The Rand Journal of economics* 24: 418-438.

McDonald, C.A. and K.F. Hansen, 2001. Modeling the US Electricity Energy Social-Political Environment: A global Warning Nuclear Power Policymaking Construct. *MIT Center for Advanced Nuclear Energy System* NFC-TR-034.

Driscoll, M.J.,2001. Notes from the Class: *Nuclear Energy Economics and Policy Analysis*.

Papathanasiou, D., D. Anderson, 2001. Uncertainties in Responding to Climate Change: on the Economic Value of Technology Policies for Reducing Costs and Creating Options. *The Energy Journal* 22(3): 79-114.

Paul Farris, Phil Pfeifer, 2001. Why is Five a Crowd in the Market Share Attraction Model: the Dynamic Stability of Competition. *Darden School of Business Administration, University of Virginia.*

Sterman, John D. 2000. *Business Dynamics: System Thinking and Modeling for a Complex World*. Irwin: Mc Graw-Hill.

Sterman, John D., Rebecca Henderson, E. D. Beinhocker and Lee I. Newman, 1995. A Behavioral Analysis of Learning Curve Strategy. *Sloan School of Management MIT and McKinsey and Company*.

The Future of Nuclear Power. *An Interdisciplinary MIT Study*, 2003.