FINANCING THE COST OF DECOMMISIONING NUCLEAR POWER PLANTS AND SPENT FUEL MANAGEMENT: THE SWEDISH MODEL

Lars Bergman
Stockholm School of Economics

Ulf Jakobsson
Research Institute for Industrial Economics
History of the Swedish nuclear power

- The first commercial nuclear reactor was taken into operation in 1972, and in 1985 twelve reactors at four locations were in operation.

- The Three Mile Island accident in 1979 led to strong public opposition against nuclear power, and as a result of a referendum in 1981 it was decided that nuclear power should be phased out from the power supply system before 2010.

- However, to date only two reactors have been closed, Barsebäck 1 in 1999 and Barsebäck 2 in 2005, and the remaining ten reactors are now allowed to operate as long as the owners wish and they comply with the safety regulations.
Nuclear power in Sweden 2014

• Ten reactors are in operation
  – Total installed capacity: 9 363 MW
• Expected number of remaining years of operation:
  – Forsmark 1-3: 26, 27 and 31
  – Oskarshamn 1-3: 8, 20 and 31
  – Ringhals 1-4: 11, 11, 27 and 29
• Annual nuclear power production is around 60 TWh, corresponding to around 40 % of total annual power production in Sweden
  – Estimated annual production after 2014: 73,2 TWh
  – Estimated total production 2014-2045: 3 952 TWh
• Ownership (via ownership of subsidiaries):
  – Vattenfall: 4 687 MW (50 %)
  – E.ON.: 2 774 MW (30 %)
  – Fortum: 1 787 MW (19 %)
Spent fuel management and storage

- The method to handle the decommissioning of the nuclear reactors and the management and storage of spent nuclear fuel is called the KBS-3 method.
- In accordance with this method all radioactive waste will eventually be put into a permanently closed repository.
- The time horizon of the plan is more than 100 years.
- The estimated remaining costs are around 100 Billion SEK (approximately 14.5 Billion USD).
Cost structure

The costs of the decommissioning and waste management & storage "project" has three drivers:

1. The mere existence of industrial activity generating a non-trivial amount of radioactive waste
   - Leads to research & development of waste management and storage methods, and construction of transportation and storage facilities

2. The number of reactors that eventually have to be decommissioned
   - Leads to development of methods and construction of facilities for decommissioning nuclear reactors and transportation of radioactive material

3. The amount of radioactive waste generated
   - Defines the capacity needs of the system, and the amount of transportation and handling of radioactive waste activities
The financing model

• At the time of the phase-out decision concerns about the financing of the future costs of decommissioning the nuclear reactors and the management & storage of the spent nuclear fuel lead to new legislation and the implementation of a detailed “model” for financing these costs.

• A key feature of the model is that nuclear power producers (NPPs) are responsible for all costs related to the decommissioning of the reactors and the management & storage of the spent fuel.
  — NPPs are fully owned subsidiaries of the major power companies, i.e. Vattenfall, E.ON. and Fortum.
The financing model: Basic components

- A charge on electricity produced by the NPPs
- The resulting revenues are accumulated in a fund, the Nuclear Waste Fund (NWF)
- The NPPs are compensated by NWF for "accepted" decommissioning and waste management & storage costs
- The owners of the NPPs also have to provide collateral for unexpected costs and not yet paid charges
Determination of the charge

The charge is set so that the present value of revenues plus the value of the NWF in each individual period are equal to the present value of decommissioning and waste management & storage costs, i.e. by the formula

\[ F(t) + \sum_{t=1}^{T} \frac{a(t)n(t)}{(1 + r)^t} = \sum_{t=1}^{T} \frac{d(t)}{(1 + r)^t} \]

where:

- **F(t)**: Value of NWF at time t, SEK
- **a(t)**: Nuclear electricity charge at time t, SEK/Kwh
- **n(t)**: Output of nuclear electricity during period t, kWh
- **d(t)**: Decommissioning and waste management & storage costs during period t, SEK
- **r**: Discount rate
- **T**: Time at which all generated waste is stored and the final repository is closed

Cost estimates, as well as the discount rate, are re-evaluated every third year.
The initial goal

• The initial goal was that the generations which consumed the nuclear electricity should carry the future costs for decommissioning of the reactors and the management & storage of spent fuel.

• Given the structure of the electricity market it was assumed that the charge (SEK/kWh) would be added to the price of electricity and thus effectively be paid by the consumers.
The new goal

• After the 1996 deregulation of the electricity market the market price of electricity reflects marginal rather than average power system cost (which was the case in the past)
• As nuclear power is intramarginal capacity most of the time the charge can no longer be added to the electricity price
  – Thus the charge is effectively paid by the NPPs
• The goal of the system was then reformulated:
  – Instead of protecting future generations of consumers the system should protect future generations of taxpayers (who would have to step in if the NPPs could not honor their obligations)
Performance of NWF up to 2012

- As of 1996 NWF has been managed as an independent fund by a separate public agency
  - Before 1996 the fund was just an account at Riksbanken (the Central Bank of Sweden)
  - At the beginning of 2014 the value of NWFs assets was around 50 Billions SEK (approximately 7,1 Billions USD)
- NWF is required to have a risk-averse strategy and thus only invests in government and other low-risk bonds
  - In spite of that the average real rate of return on NWFs assets 1996-2012 was above 5 % per annum
  - But the currently low interest rates have changed the long term real rate of return expectations of NWF
Current issues

• The view of the regulator, Swedish Radiation Safety Authority, is that the discount rate should reflect current interest rates and thus be in the range 1-2 %

• The regulator also insists that the NWF plus the present value of future revenues should be equal to the present value of expected future costs at all times

• If the government, who has the final say, accepts these views the nuclear electricity charge will increase very significantly
Emerging problems

• Significantly higher nuclear waste charges will have a considerable financial impact on NPPs
  – NPPs are in effect forced to make financial investments in a fund with rates of return well below the return on NPP equity

• The most important effect of significantly increased charges on nuclear electricity is that the existing nuclear reactors are likely to be closed down much earlier than previously envisaged
  – The loss of electricity resulting from premature phasing out of nuclear reactors could be in the range 2 000 – 3 000 TWh
  – The resulting loss of revenues will undermine NPPs ability to honor their obligation to cover all decommissioning and waste management & storage costs
The marginal cost of nuclear electricity

The marginal cost of electricity generated by existing nuclear reactors (disregarding the risk for accidents) is equal to the variable cost and the present value of the future cost of handling and storing the extra waste, i.e.

\[ c(t) = v(t) + m(t) \]

where:

\[ m(t) = \sum_{\tau=t}^{T} h^\tau(\tau)(1 + r)^\tau \]

and

- \( v(t) \): Variable fuel and operating cost at time \( t \)
- \( c(t) \): Marginal cost of nuclear electricity at time \( t \)
- \( m(t) \): Present value at time \( t \) of the cost of handling and storing waste generated by one extra unit of generated nuclear electricity during time period \( t \)
- \( h^\tau(\tau) \): Cost of handling and storing one unit of waste generated in period \( t \) during period \( \tau \)
- \( r \): Discount rate
NPP incentives to produce

From a social point of view production of nuclear electricity is desirable as long as

\[ c(t) = v(t) + m(t) \leq p(t) \]

where \( p(t) \) is the (competitive) price of electricity.

But from the point of view of the NPPs production is desirable only if

\[ v(t) + a(t) \leq p(t) \]

Obviously the relation between \( m(t) \) and \( a(t) \) is crucial!
Observations

• It follows from the definitions that $a(t)$ to a larger extent than $m(t)$ depends negatively on the discount rate, i.e. lower $r$ leads to higher $a(t)$

• Thus, at a sufficiently low discount rate

$$v(t) + a(t) \geq p(t)$$

even though

$$v(t) + m(t) \leq p(t)$$

• Thus NPPs will stop producing electricity even though the (social) marginal cost is lower than the marginal willingness to pay for electricity, i.e. the competitive price
Need for a new model

• The design of the financing model apparently creates unexpected problems, and there is thus a need for a revised model.

• The key task when designing an alternative model is to separate the need for additional capital in NWF from the NPPs incentives to produce electricity.

• A new model should:
  – Retain the responsibility of the NPPs to cover all costs of decommissioning and management & storage of the spent nuclear fuel
  – Include a charge on nuclear electricity generation, reflecting the marginal decommissioning and waste management & storage costs
Alternative models

• We consider three alternative models, each one with two components:
  – A charge (SEK/kWh) on NPPs equal to the marginal cost of managing and storing spent fuel
  – A mechanism to collect and accumulate funds to cover the remaining decommissioning and waste management & storage costs in excess of the value of NWF

• This mechanism could be designed in three different ways:
  1. An annual charge (SEK/MW) per unit of initially installed nuclear capacity, with the revenues accumulated in NWF
  2. A requirement on the owners of NPPs to maintain an internal fund in which the value of the assets, together with the value of NWF, are equal to the present value of the remaining future costs of decommissioning and management & storage of spent fuel
  3. A charge on the consumption of nuclear electricity (SEK/MWh)
Alternative model 1

- A charge on nuclear electricity equal to $m(t)$, i.e. the cost of managing and storing the waste generated by one unit of nuclear electricity.
- A per unit of initially installed capacity charge, $s(t)$, defined by

\[
F(t) + \sum_{t=1}^{T} s(t)k(t)/(1 + r)^t = \sum_{t=1}^{T} (d(t) - m(t)n(t))/(1 + r)^t
\]

where

$k(t)$: Total initially installed nuclear capacity (MW)
Comments on Alternative model 1

• NPPs have incentives to use the nuclear reactors as long as the relevant marginal cost is below the market price of electricity (and the safety requirements are fulfilled)

• The financial consequences for NPPs of lower interest rates are essentially the same as under the current model
Alternative model 2

- A charge on nuclear electricity equal to \( m(t) \), i.e. the cost of managing and storing the waste generated by one unit of nuclear electricity
- A per unit of initially installed capacity charge, \( s(t) \), defined by

\[
F(t) + \sum_{t=1}^{T} \frac{q(t)}{(1 + r)^t} = \sum_{t=1}^{T} \frac{(d(t) - m(t)n(t))}{(1 + r)^t}
\]

where

\( q(t) \): Addition to company internal fund in period \( t \)
Comments on Alternative model 2

• NPPs have incentives to use the nuclear reactors as long as the relevant marginal cost is below the market price of electricity (and the safety requirements are fulfilled)

• The financial consequences for NPPs of lower interest rates depends on the management rules for the company internal fund
Alternative model 3

- A charge on nuclear electricity equal to $m(t)$, i.e. the cost of managing and storing the waste generated by one unit of nuclear electricity
- A charge on nuclear electricity consumption defined by

$$F(t) + \sum_{t=1}^{T} w(t)y(t)u(t)/(1 + r)^t = \sum_{t=1}^{T} (d(t) - m(t)n(t))/(1 + r)^t$$

where

$w(t)$: Charge on the consumption of nuclear electricity in period t (SEK/MWh)

$y(t)$: Share of nuclear electricity in total electricity consumption

$u(t)$: Total consumption of electricity during period t
Comments (1) on Alternative model 3

- NPPs have incentives to use the nuclear reactors as long as the relevant marginal cost is below the market price of electricity (and the safety requirements are fulfilled)
- The financial consequences for NPPs of lower interest rates are reduced to a minimum
- But consumers are probably less happy, and a system for determining the charge $w(t)$ has to be implemented
Comments (2) on Alternative model 3

• The charge on nuclear electricity consumption would resemble the current charge for supporting renewable electricity
  – While the renewable electricity is determined by the market price of "green" certificates the nuclear electricity charge would be administratively determined

• This model would be in line with the initial goal that the generations benefitting from nuclear power should pay the full cost for nuclear electricity
Concluding remarks

• The Swedish model for financing the cost of decommissioning the nuclear reactors and managing and storing the spent fuel worked well as long as real interest rate were high

• With low interest rates, and a competitive electricity market where nuclear is intramarginal capacity, the design of the nuclear charge may cause serious problems and undermine the ability of NPPs to honor their obligations

• A new model, separating the incentives to use the nuclear reactors from the need to accumulate capital in NWF, is badly needed