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Nuclear power more profitable than coal if funded with low cost capital: A South-African case study

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Abstract - *This study summarizes and expands on economic simulation results from the author's reviews of the South-African Government's Draft Integrated Energy Plan (IEP) and Integrated Resource Plan Update 2013 (IRP Update). The Levellized Cost of Electricity (LCOE), as a function of the pre-tax Weighted Average Cost of Capital (WACC%) and the pre-tax % rate of return and the pre-tax nominal profit per unit power sold (R/kWh), as a function of the electricity selling price, are compared for a new Generation III nuclear plant and a new pulverized coal plant with Flue Gas Desulphurization (FGD), built in South Africa. All monetary amounts are expressed in constant real 2012 South African Rand (R), i.e. inflation has been removed. An exchange rate of R8.01/$ was assumed. Since the key economic features of HTRs and Generation III water-cooled nuclear plants are similar, e.g. high initial capital cost followed by low fuel and other variable costs and long plant lives, these results for Generation III nuclear plants are also applicable to HTRs.*
The results show that the LCOE for nuclear increases sharply with the pre-tax WACC%. For low WACC percentages, nuclear power is much cheaper than coal and vice versa. However the pre-tax nominal profit per unit nuclear power sold (R/kWh) greatly outperforms coal for all values of the electricity selling price, even if the nuclear overnight cost increases to the much maligned $7,000/kW-installed. Especially impressive is the result that nuclear already breaks even at R 0.30/kWh while coal will run at a loss until the price is increased to R 0.68/kWh.
This result, that nuclear produces the most profitable power of all readily available sources in South Africa, implies the following power plant construction strategy: Supply the minimum expected new base-load with nuclear plants, augmented by peaking plants, such as hydro and gas turbine in order to balance the constant base-load power supply with the varying demand during different times of day. If, in later years, there should occur fast medium term increases in demand, add plants with shorter lead times. Nuclear then forms the cheap base-load foundation upon which the other technologies are added.

I. INTRODUCTION

There is an increasing global demand for clean energy in order to achieve social and environmental justice for a growing and developing global population. Nuclear power plants are one of the obvious candidates to supply this demand as the technology is reasonably established and nuclear plants can supply affordable, clean and dependable base-load power. The New Generation III and IV nuclear reactors are also some of the safest machines on the planet, as their accident risk have been reduced by an estimated factor 100, compared to the older Generation II nuclear plants. This reduces their expected accident insurance costs, which is the largest component of nuclear external costs, to far below the external health costs of coal plants.

However, nuclear plants are more capital intensive than most other power plant types, e.g. the Overnight Capital Cost for constructing 1 kW nuclear generation capacity is slightly more that double that of a coal-fired power plant. However, Generation III nuclear plants have economic lives of 60 years, compared to only 30 years for coal and 25 to 30 years for wind turbines and PV solar panels. Nuclear plants can also achieve load factors in excess of 90%, compared to only about 85%, 30% and 20% for coal, wind turbines and PV solar plants respectively.

Due to their much higher Overnight Capital Costs, nuclear plants are much more sensitive to the magnitude of the Weighted Average Cost of Capital (WACC%) than coal plants. (See Table 1 for definitions of terms and acronyms.) Therefore if nuclear plants were to be funded with low cost capital, such as the low interest rate loans that are currently available to Eskom, South Africa's State owned power utility, it is to be expected that nuclear will produce clean reliable power more profitably than coal, wind, and solar.

However, the economic model simulations in two recent reports by the South African Government imposed unrealistically high WACC% on the capital costs, which resulted in artificially inflated Levellized Costs of Electricity (LCOE) for nuclear, which lead to calls for the scrapping of South Africa's plans to build 9600 MW new Generation III nuclear generation capacity.

Therefore the present article will attempt to correct these flaws in order to create more realistic economic the model calculations for the profitability of nuclear compared to coal plants.

I.A Definitions and acronyms

Table 1 contains a list of terms and acronyms used. These definitions are given in detail, so as to form an important part of the explanation of the modelling philosophy, assumptions and methods. Therefore it is recommended that readers should pay careful attention to these definitions.

Table 1: Definitions of terms and acronyms

Term/ Acronym	**Definition**
R	South African monetary Rand, also known by the acronym ZAR. Constant 2012 Rands were assumed, with an Exchange rate of R8.01/$.
SA	South Africa
$	United States dollar.
WACC%	Weighted Average Cost of Capital, i.e. the weighted average of the interest rate payable on debt and the rate of return on capital, demanded by the business owner. In this paper only the pre-tax WACC% was used.
Over-night Capital Cost	The cost of constructing a power plant in an instant (overnight), expressed in R/kW-installed. This excludes interest during construction time, costs due to construction delays and owner costs, such as the construction of roads and other civil works on the plant site.
Total Capital Required (TCR)	Overnight cost + the nominal cost of capital during construction (interest + expected return) + owner costs during construction, expressed in R/kW-installed).
LCOE	Levellized Cost of Electricity (R/kWh). This is only the power generation cost, excluding transmission and distribution costs. The LCOE accumulates all costs over the plant life and then levellises it by distributing it over the total number of power units (kWh) produced over the life of the plant. The accumulated cost starts with the Total Capital Required and adds all running costs, overheads and the cost of capital over both the construction time and operational life of the plant, including decommissioning costs (which was distributed as an annuity over the plant life) and external costs.
External costs	Costs that are very real, but are normally borne by society in general, rather than by the plant owner. Examples are nuclear accident costs, death and morbidity due to poisonous polluting chemicals released by coal plants, global climate change cost due to CO_2 emissions etc.
Interna-lising external costs	Using taxes or levies to transfer the external costs from society to the owners of the plants that cause these external costs.
GHG	A gas, such as methane (CH_4) released during rock fracturing for mining shale gas, that causes global warming and thus global climate change in a similar manner to CO_2.
CO_2-equiva-lent	Some GHGs, such as methane, are much more efficient at causing global warming than CO_2, i.e. one ton of GHG may cause the same amount of global warming as, say, 20 tons of CO_2. The CO_2-equivalent of one ton of

	this gas will then be 20 tons of CO_2.
OCGT	Open Cycle Gas Turbine. OCGTs are excellent peaking power plants with low capital costs. However, their fuel efficiencies are very low. Since South Africa does not currently have access to affordable natural gas, OCHTs are fuelled with very expensive diesel, which results in very high LCOEs, typically in excess of R 3.00/kWh. Therefore the current aim is to maintain very low load factors on them, such as 10%.
CCGT	Combined Cycle Gas Turbine. CCGTs are load following power plants with higher capital costs than OCGTs. However, their fuel efficiencies are much higher than that of OCGTs. As soon as South Africa secures access to affordable natural gas, CCHTs are expected to play a substantial role by generating valuable load following power at only moderately elevated LCOEs. Load factors in the vicinity of 50% may then be targeted.
IPP	Independent Power Producer.
REIPPP	South Africa's Renewable Energy Independent Power Producer Programme in which Eskom is forced to buy a quota of renewable power from IPPs at increased rates by means of long term power purchase agreements. Rates are decided by a bidding process.
Hidden cost	A costs that is not external, as it is borne by the power utility, but is hidden because it is not explicitly allocated to the plant type that causes it. Intermittency cost is the most obvious example: in South Africa the intermittency of wind and solar PV power plants necessitates the production of expensive peaking or load following power by e.g. OCGTs or CCGTs. These costs are explicitly borne by Eskom. Currently most renewable power in South Africa is procured by Eskom from IPPs in the REIPPP. Its intermittent nature creates load balancing costs which are borne by Eskom, which passes it on to consumers in the form of increased power tariffs. However, neither in the REIPPP nor in the IEP and IRP Update are these intermittency costs explicitly acknowledged as caused by the intermittency of these renewables. Neither are they billed to the IPPs that own the renewable plants that cause these costs. They thus remain hidden costs. Therefore the LCOEs of renewables are reported at artificially low levels, which creates higher public and political support and investments in these intermittent technologies than would have been the case if their hidden costs were acknowledged.

I.B Literature overview

The original energy plan of the Department of Energy (DOE) of the South African Government was the Integrated Resource Plan for Electricity 2010-2030 (IRP 2010-2030) [1]. At the end of 2013/beginning of 2014 it released both its Draft 2012 Integrated Energy Planning Report (IEP) [2] and its Integrated Resource Plan For Electricity (IRP) 2010-2030: Update Report 2013 (IRP Update) [3] for public consultation. The present author reviewed both these latter plans in detail for the Nuclear Industry Association of South Africa (NIASA), which submitted these reviews [[4], [5]] as its official feedback to the South African Government.

Both the IEP and the IRP Update lay excellent foundations for South Africa's energy future as they assembled comprehensive sets of data and sophisticated computer modelling tools. The said reviews, however, pointed out a number of serious flaws in both reports, which skewed their results to the point that their implementation would impact negatively on South Africa's energy security and economy.

Results were especially skewed against nuclear power in that the flaws caused a substantial overestimation of the LCOE of nuclear power and substantial underestimations of the LCOEs of coal, wind and solar power. Therefore several of the planning scenarios in these government reports recommend that Government's planned construction programme for 9600 MW of new Generation III nuclear power plants be delayed, scaled down or even scrapped. According to the reviews [4, 5] the **main flaws that skewed the results of the IEP and IRP Update were:**

- Unrealistically high WACC%/discount rates were used, which discriminated against nuclear due to its high Overnight Capital Cost.
- The intermittency costs of wind and PV solar have not been allocated explicitly to these technologies, i.e. they remain hidden costs which unfairly benefited these technologies.
- Time-of-day electricity selling prices have not been taken into account. This unfairly benefited intermittent PV solar.
- Imported CO_2 and other GHG emissions from coal plants in neighbouring countries and from imported petroleum and natural gas have been ignored. Similarly the risks to both the security of future energy supply and national security, caused by importing a large fraction of South Africa's energy through politically unstable countries, have not been taken into account. These flaws discriminated unfairly against local power sources and unfairly benefited imported coal and hydro power and fossil fuels.
- External costs were not internalised for shale-gas, coal and nuclear. As coal and shale gas have the largest and nuclear the smallest external costs, this unfairly discriminated against nuclear power.
- Unrealistically high future capital cost reductions, due to unrealistically high assumed learning rates for Concentrated Solar Power with thermal storage (CSP), have been used. This unfairly discriminated against nuclear and other sources of dispatcheable power.

I.C Problem statement

In view of the above, the problem to be solved is to correct these flawed model input assumptions by fairly allocating external and hidden costs, using a realistic range of WACC% etc., in order to produce LCOEs and other measures of profitability that will accurately reflect the realities of the South African power market.

I.D Research Aims and Objectives

The general aims are **to**:
- Investigate the sensitivity of the profitability of nuclear and coal power plants to variations in the economic model input assumptions.
- Produce recommendations for appropriate ranges for the most important input model assumptions.
- Based on these realistic input assumptions, produce a range of LCOEs and other measures of profitability that will accurately reflect the realities of South Africa's power market.
- Produce recommendations for a profitable power plant construction strategy for South Africa, based on these simulation results.

The specific objectives are to:
- Calculate a range of LCOEs for nuclear and coal power, as function of the WACC%, with realistic estimates of external and hidden costs taken into account.
- Calculate a range of rates of return, as function of the electricity selling price.
- Calculate a range of nominal profits per unit power sold, as function of electricity selling price.
- Estimate the implications of these coal and nuclear economic results for some of the other power sources considered for South Africa.
- Deduce, from these results, a first approximation of the most profitable power plant construction strategy for South Africa.

II. SIMULATION METHODS

1. An economic model for each plant was created in an Excel spreadsheet. All simulations were normalised to 1 kW installed "name plate" power generation capacity. Cash flows were created according to the cost and other data provided in the Tables 18 and 19 of the IRP Update (3). Modifications to these assumptions are listed below. Incomes streams were generated by using the construction schedules and load factors to calculate the amount of power produced in each year, from the start of construction till the last year of the economic life of each plant. A range of assumed selling prices for one kWh of power was used to convert the power production streams to revenue streams, as function of electricity selling price.
2. It was assumed that Government invested 100% of the capital costs in the form of equity. Interest on loans was thus not relevant. The WACC% thus became identical to the rate of return demanded by Government on its capital investment. This is a conservative assumption, especially regarding nuclear, as the cost of equity is generally much higher than the cost of debt. At present the SA treasury demands a minimum real WACC of slightly below 9%,

while Eskom can borrow on the international market at about 3% real.

The % return on capital invested was calculated for each case by applying Excel's standard Internal Rate of Return (IRR) function to each cash flow stream. The selling price of electricity was then varied until the resulting rate of return corresponded to the WACC% assumed to be demanded by Government, for a range of WACC percentages.

3. For the economic model simulations of the original reviews of the IEP and IRP Update, the post-tax returns on invested capital was used as the starting point for analysing the profitability of each plant. However, for the present study the post-tax return was replaced with the **pre-tax** return. The reason for this was the following: from the perspective of a private company, only the post-tax profit remains available for distribution to the shareholders as the return on their invested capital and therefore only the post-tax profit is viewed as valuable and thus as the true profit of the company. However, from a societal point of view, the tax paid by the plant owner to Government also contributes to the total revenue which society derives from the plant and therefore the pre-tax return should be viewed as the more relevant measure of the societal benefit of the plant. Since Eskom is State owned, it makes even more sense to analyse the profitability of each plant from a societal point of view, rather than from the perspective of shareholders of a private company.

II.A Calibration study

A calibration study was first conducted to check the accuracy of the present models. The calibration was done by trying to replicate the results of the IRP Update by using the same assumptions, e.g. all external and hidden costs were ignored. The nuclear and Pulverised Coal (with FGD) plants were simulated from the start of construction to the end of their respective economic lives of 60 and 30 years, as assumed in the IRP Update.

The result was that, just as in the IRP Update, the LCOE for nuclear power was slightly higher than that of coal. However Table 18 of the IRP Update calculated this difference as R 0.11/kWh compared to only R 0.03/kWh for the present study. It was not clear what caused this R 0.08 difference. There are a large number of small methodological issues that was not clearly described in the report of the IRP Update, for instance it was not clear whether the total expenses for each year was allocated at the beginning, middle or end of each year, which would in each case have produced slightly different results. However, the facts that the observed trends were identical for the IRP Update and the present study and the observed differences in results were small, was taken as sufficient proof that the two models were similar, though not identical and that the present model can thus be used to approximate the model of the IRP Update. On this basis the more realistic modelling of the present study commenced.

II.B Realistic modelling assumptions

Expected and pessimistic cases were simulated for each plant. As a conservative measure, in view of the fact that in the last few decades things in the nuclear industry seldom turned out better than expected, no optimistic cases were simulated.

External costs of nuclear power

The external costs of nuclear power, coal and shale gas were assessed in some detail in Par. 2.1.10. of the author's review of the IRP Update [5], which will be summarised here:

A very high cost estimate of $1.6 Trillion/accident [6] for the cost of a Fukushima-style nuclear accident with large releases of radioactivity was tentatively accepted, while it was at the same time pointed out that this estimates is probably unrealistically high: evacuation costs contributed about 80% of this cost estimate, while the much lower actual health costs of death and morbidity, due mostly to radiation induced cancers, were below 20%. The very large extent and long durations of such evacuations appear to be driven by irrational fear of radiation and appears to be out of sync with the much smaller estimates from literature of the actual health costs produced by the adverse health effects of ionising radiation.

However, even these very high assumptions of nuclear accident costs resulted in negligible external health costs for Generation III nuclear reactors. These calculations were based on simulation results from literature that the risk of such serious nuclear accidents for Generation III (and Generation IV) nuclear plants have been reduced by roughly a factor 100, compared to the older Generation II nuclear plants. This reduction in risk was achieved by means of the introduction of inherent passive safety features. Although this number has not been proven definitively and may contain substantial uncertainties, it was accepted as an input parameter for the present simulations. From this it was estimated that if the global nuclear fleet were to be replaced by Generation III nuclear plants the global nuclear accident rate of the global nuclear fleet would diminish from the current one very serious accident in roughly 25 years to only one accident in roughly 2500 years. Based on this drastically reduced accident risk, the Levellised cost of the nuclear accident risk for Generation III reactors was calculated to be R 0.005/kWh [5]. It was further assumed that a ring-fenced specialised global nuclear insurance scheme will be created that will cover the full risk of nuclear accidents, but only for the new low risk Generation III nuclear plants. The insurance premium for this scheme was estimated by doubling the assumed cost of the nuclear accident risk to R0.01/kWh, in order to allow for a reasonable return on the insured risks. The external costs of nuclear accidents were thus internalised by adding this insurance premium to the environmental levy in the nuclear cost data.

The current US nuclear waste fee of $0.001/kWh was translated to an equivalent of R 0.008/kWh for South Africa, which was added to the nuclear environmental levy, which resulted in a total environmental levy of R 0.018/kWh. This is neither an external nor a hidden cost as internationally the nuclear waste disposal costs are explicitly allocated to and paid for by each nuclear power plant owner. However it is treated here under external costs because it was ignored in the IRP Update.

External costs for coal power

The main external costs of coal power are health costs, i.e. the costs from death and morbidity due to the adverse health effects of poisonous chemicals release in the smoke of coal-fired power stations. The European external cost estimates of the so-called ExternE study [7] was used as a basis for the external cost of coal. Based on the assumption that the population density in South Africa is lower than in Europe, a reduced rough estimate of R 0.26/kWh [5] was calculated for the external cost of coal. This estimate suggests that the R 0.005/kWh external health cost of Generation III nuclear is about 50 times smaller than that of coal power. However the actual health risk for coal can be reduced strongly by placing coal plants in locations with very low population densities or in places where smoke diffusion path-ways will lead the emitted poisons away from population centres or by installing improved types of filters in the smoke stacks of coal plants. Such a detailed analysis of the health risk is, however, a mammoth task that falls outside the scope of the present study.

Input assumptions for the Expected Case for nuclear and coal

Except where indicated otherwise, all input data for both the coal and nuclear plants was taken directly from Table 18 of the IRP Update (3). Therefore only the most important data are summarised here:

- For the expected case, i.e. our Base Case, the IRP Update's Overnight Capital Cost for Generation III nuclear power plants of $5,800/kW-installed (i.e. R 46,458/kW-Installed) was used.
  For coal it was less than half of that at R 21,572/kW.
- Owner cost was assumed to be 17% of the overnight cost for nuclear and 20% for coal. The logic behind a lower percentage cost for nuclear is that the large increases in Overnight costs from Generation II to Generation III nuclear was caused by the development cost of the new inherent passive safety features. Since there is little reason to believe that these safety features will increase owner costs at the sight, the percentage owner cost should be lower for generation III than for Generation II nuclear plants.
- As it was assumed that all cash for the Capital Expenditure (CAPEX) was supplied as capital investments (i.e. equity) by the owner of Eskom, i.e. Government, there were no loans and thus no interest on debt. However the full WACC% was applied to all equity transactions, i.e. to the yearly cash flow stream, viewed from the owner's perspective, over the whole life of the plant, including the construction period. This is a conservative assumption as it is normally cheaper to fund CAPEX with debt than with equity.
- The construction schedules for single plants from the EPRI report [8], which should not be confused with the construction schedules for whole fleets from the IRP Update, was used, i.e. a 6 year CAPEX schedule for nuclear (i.e. 15%, 15%, 25%, 25%, 10% and 10%) and a 4 years schedule for coal (i.e. 10%, 25%, 45%, 20%).

- Modelling start in 2012 and all costs are expressed in 2012 Rands. The real fuel cost of coal of R 0.172/kWh from the IRP Update was then escalated to the export parity price (R 0.375) by increasing it by 5% real per year for 16 years, starting in 2013, after which it was kept constant. Reasons for the expectation that the South African coal price will escalate to export parity was supplied in Par. 2.1.9 of the review of the IRP Update [5]. This export parity price was, however, kept constant.
- The exchange rate of R8.01/$ from the IRP Update was used. This is optimistic in view of the current weakness of the South African Rand (R10/$ - R11/$). However it is very hard to predict what the average exchange rate may be over the up to 72 years modelled in this study. It should also be noted that a weaker rand will similarly hit coal, as it will push up both capital expenditure and the export parity price of coal, and wind and solar because they rely mainly on imported technologies. Furthermore it is likely that South Africa will buy its nuclear plants from one of the BRICS countries, whose economies are not necessarily linked to the US$.
- For nuclear, all external and environmental costs, including nuclear waste management and insurance against nuclear accidents, were included as described above.
- However, for coal the Expected Case assumes the external cost to be only the full carbon tax of R120/ton CO_2, which was announced by Government. This resulted in an external cost of only R 0.11/kWh.

  This tax was not gradually phased in from the 40% starting point, as announced by Government, as it was assumed that the coal plant will in reality be built later on, so that the full carbon tax will already have been phased in by that time. This differs from the IRP Update, which did not include any carbon tax in its Base Case. However, since Government has already announced its intentions to introduce this tax, it was viewed as the appropriate default value for the "business as usual case".
- Plant lives of 60 years for nuclear and 30 years for coal of the IRP Update was used unaltered. It should, however, be noted that the latest South-African Medupi coal power station has a designed plant life of 50 years. Such long plant lives are only economically viable in cases where sufficient coal reserves are available at the site. However the logic for not upgrading the coal plant life for the present study to 50 years was as follows: international pressure to cut CO_2 emissions is expected to increase over the next few decades. Every new coal plant commissioned can thus be expected to bring forward the date at which South Africa will hit a future cap on CO_2 emissions, which will probably force the decommissioning of one of the older dirtier coal plants, which will then effectively terminate the period in which CAPEX for the construction of the new plant will result in a net increase in SA's power production. This point should then be modelled as the effective decommissioning age of the new plant, which can be expected to be closer to 30 rather than to 50 years.
- Full once-off plant refurbishment costs, i.e. 15% of Overnight Cost and 5 months loss of production, were used for the nuclear plant and were spread out around year 35. Since the coal plant was already decommissioned after year 30, no refurbishment costs were assumed.
- Full decommissioning costs of 15% of Overnight Cost for nuclear and 20% for coal were included, earmarked for rehabilitation of the sites at the end of plant life. This was paid over to a decommissioning fund in the form of an annuity during each year of productive plant life. Due to large dilution by the discount rate over the long plant lives, the nett effect on the LCOE's were insignificant.
- The pre-tax, as opposed to the post-tax, WACC% was used, in line with the IRP Update.

Pessimistic Cases: The pessimistic case for nuclear tries to capture the first-of-a-kind scenario where everything than can go wrong often do go wrong, resulting in very high overnight costs and extreme construction delays. For coal the Pessimistic Case assumes similar schedule overruns and uses high values for the external costs. The data from the Expected Cases was therefore modified as follows to create the Pessimistic Cases:

- The nuclear overnight cost was increased from $5,800 to $7,000/kW-installed. While it is true that nuclear overnight costs in the region of $8,000/kW have recently been reported, the assumption is here that if the overnight cost goes above about $7,000/kW, South Africa will abandon the nuclear project and therefore such cases are not relevant for this study.
- For coal the external cost was upgraded from only the carbon tax of R 0.11/kWh to the full

environmental cost of R 0.26/kWh, as described above.

- Tensions in the South African energy debate are currently running high about the massive delays and thus cost overruns experienced during construction of the South African Medupi and Kusile coal power stations, which were produced mainly by labour unrest and the inexperience of management. Many analysts warn that similar problems should be expected during the planned nuclear new-build program and that schedule and cost overruns should thus be expected and could render nuclear power unaffordable in South Africa. In order to accommodate these fears, the construction durations for single plants from the EPRI report [8] was doubled. Thus the 6 year CAPEX schedule for nuclear was spread out over 12 years and the 4 years schedule for coal over 8 years. These pessimistic assumptions are expected to be valid only during the construction of the first few plants, where after learning is expected to take place so that construction schedules should approach those of the Expected Case.

III. RESULTS

In Figure 1 the resulting LCOEs were plotted as a function of the pre-tax WACC% assumed to be demanded by Government from Eskom. The Expected and Pessimistic cases are shown for both coal and nuclear.

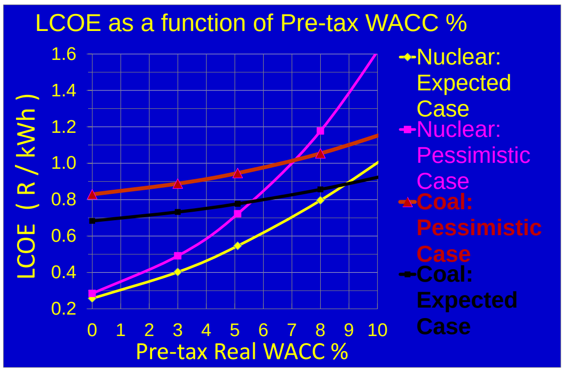

Figure 1: *Levellised cost of electricity (in constant 2012 Rand) for nuclear and coal, as a function of the pre-tax real WACC%, for both the Expected and Pessimistic Cases.*

The data in Figure 1 presupposes that a plant owner can demand the same WACC% for each plant type and that different electricity selling prices can then be demanded in order to realise the demanded WACC% for each plant type. Such different selling prices for different power technologies are in fact currently being awarded in the subsidised tariffs of the REIPPP. However, in the reality of a well-functioning free market, this will not be the case. All plant types would rather receive the same selling price, provided that they provide the same quality power and that external costs have been internalised by means of environmental levies, and would thus yield different % returns on their capital investments. This situation is modelled in *Figure 2*: the % return received by Government on its capital investment, including taxes (i.e. the % pre-tax return generated by Eskom), is plotted as a function of electricity selling price. This is compared for the Expected coal and nuclear cases

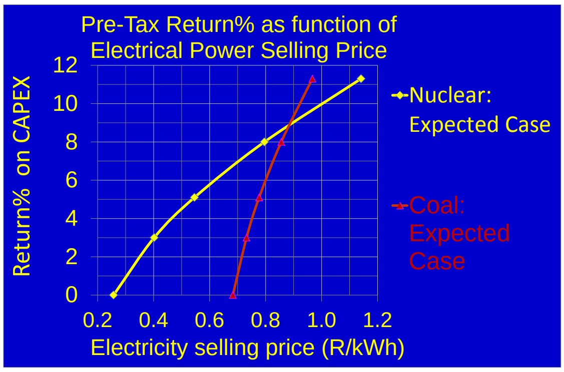

Figure 2: Rate of return % on capital, as a function *of electricity selling price (= generation cost).*

This graph shows nuclear produces much higher % rates of return when the electricity selling price is lower than about R 0.80/kWh, but crosses over at R 0.88/kWh.

Figure 3 transformed the % pre-tax returns of *Figure 2* to nominal pre-tax profits per unit power sold (R/kWh), as function of the electricity selling price. This was done by multiplying the % return with the Total Capital Required (R/kW) to obtain the nominal yearly profit (R/KW/Year) for 1 kW installed generation capacity. This was then divided by the total number of power units produced per year (kWh/Year), in order to yield the nominal pre-tax profits per unit power sold (R/kWh).

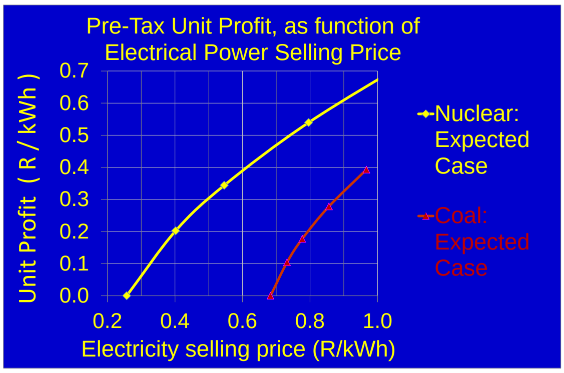

Figure 3: Nominal profit per unit power sold (R/kWh), as function of electricity selling price.

Surprisingly nuclear now greatly outperforms coal for all values of the electricity selling price, in fact for all electricity prices below R 0.90/kWh, nuclear produces more than twice the profit of coal. The reason for this switch is as follows: *Figure 2* suggests that since the % return for coal crosses over and is thus higher than for nuclear for electricity selling prices above about R 0.88/kWh, coal will be more profitable than nuclear in this higher electricity selling price range. However, it should be remembered that the Total Capital Required for 1 kW of the pessimistic case nuclear capacity is more than twice that of coal. At the cross-over point of R0.88/kWh, both plants generate the same 9% pre-tax return on invested capital. However, since the Total Capital Required for the nuclear plant is more than double that of the coal plant, the same 9% rate of return will produce a nominal yearly return for the nuclear plant of more than twice that of the coal plant, which translates into a nominal profit per kWh power sold for nuclear that is also more than twice that for coal. The nuclear plant is thus, in nominal terms, much more profitable than the coal plant.

Admittedly this is a non-standard way of measuring profitability: normally capital is viewed as the scarce resource and therefore the % return on invested capital is used as the measure of profitability. The logic would thus be that, since capital required to procure 1 kW of coal capacity is less than half that of 1 kW of nuclear capacity, one could more than double the nominal profit from coal power by using the same capital required for 1 kW of nuclear capacity to procure more than 2 kW of coal capacity. However, in South Africa this is not the case since the country has a limited power market and is not surrounded by strong economies that could take up the extra power. Doubling the planned nuclear capacity with cheaper coal stations will thus produce oversupply of the market, resulting in falling prices. However, since coal becomes unprofitable very quickly, due to its high fuel cost, if electricity prices drop, as was shown in *Figure 2* and *Figure 3*, this strategy will thus not produce similar profits than the nuclear strategy. In this analysis the point of departure is thus that not only capital, but also the business opportunity is a scarce resource. So, where *Figure 2* showed that above an electricity price of R 0.88 coal provides better returns on the invested capital, *Figure 3* show that for all the tested values of the electricity price, nuclear gives better returns on the limited business opportunity, i.e. on each kWh of available demand for power.

It should of course be borne in mind that since the Total Capital Required for the nuclear plant is more than twice that of the coal plant, the risk that Government assumes is also more than twice that for coal. However, it is here assumed that since Eskom has a Government guaranteed monopoly in the South African power market, the actual financial risk associated with Eskom's power generation is very low. It should further be remembered that the greatest risk that faces new Generation III and IV nuclear plants is political risk, i.e. the situation where a Green political party suddenly imposes high taxes on the private nuclear industry, as recently happened in Germany and other countries. However, with Government the owner of the South African nuclear power generation fleet, the risk that Government will impose such crippling measures on its own nuclear power plants is very small. Therefore the investment risk can be assumed to be small.

When the electricity selling price drops below R0.70/kWh, the ratio by which nuclear outperforms coal skyrockets to infinity as the nominal profit of coal quickly drops towards zero.

Even more impressive is the result that nuclear already breaks even at an electricity selling price R 0.26/kWh, provided that Government is willing to accept a zero return on capital, while coal will run at a loss until the price is increased above R 0.68/kWh. The nuclear break-even price is thus 62% lower. this means that if electricity prices were to plummet during a serious economic crisis, the owner of a nuclear plant would be in a much better position as he cut prices much more drastically than coal and still make a modest return.

IV. DISCUSSION OF RESULTS

IV.A Strategies to reduce the LCOE

At low WACC%, the LCOE is insensitive to high Overnight Costs

Figure 1 showed that, for low real pre-tax WACC%, the LCOE for the Pessimistic Nuclear case, with its $7,000/kW overnight cost converged towards that of the Expected Nuclear Case with its lower overnight cost of $5,800/kW. At these low WACCs the LCOE became insensitive to the nuclear overnight cost.

In South Africa many economists warned that if the Overnight Cost of nuclear were to escalate from the $5,800/kWh assumed in the IRP Update to the much higher $7,000/kW-installed, experienced for the new Areva EPRs at Flamanville and Olkiluoto, the proposed new-build program of 9,600 MW nuclear generation capacity 'could bankrupt South Africa'. In response to these warning the IRP Update set an upper limit for the nuclear Overnight Cost of $6,500/kW, above which the nuclear new-build program would be abandoned.

However Figure 1 shows that, although the nuclear LCOE is very sensitive to the value of the Overnight Cost for high WACC%, for low WACC% nuclear will produce much lower LCOEs, irrespective of the higher overnight cost. Therefore, if the nuclear project can be funded with low interest rate loans, high overnight costs will not lead to excessive LCOEs.

Replace the limit on the Overnight Cost with a limit on the LCOE

This suggests that the actual power cost for South Africa's new nuclear power plants will depend much more on the funding model used than on the Overnight Cost of these plants. For example a nuclear plant with the Expected Overnight Cost of $5,800/kW and funded with a real pre-tax WACC of 6% will produce power at a LCOE of R 0.86/kWh, which is 8% more expensive than the R 0.80/kWh for the Pessimistic $7,000/kW Nuclear Case, if funded with a WACC of 4%.

This suggests that the upper limit of $6,500/kW for the nuclear Overnight Cost, stipulated in the IRP Update, makes little sense. These government plans should thus much rather put an upper limit on the LCOE, which depends on the combination of the Overnight Cost and the WACC%. Furthermore it would make much more economic sense to apply this limit on the LCOE equally to all low carbon power sources, rather than to single nuclear out for punishment, while gladly subsidising more expensive sources such as intermittent PV solar.

Accept a low WACC% in order to stimulate economic growth by supplying cheap electricity

The low pre-tax real rate of return region in which nuclear produces such low LCOEs will probably not be attractive to private investors, interested only in maximising their profit and minimising their risk. However the main interests of the South African Government is fighting Global Climate Change by reducing CO_2 emissions and stimulating job creation for the poor by stimulating economic growth in especially the energy intensive primary and secondary sectors of the economy, such as mining. This can be done by supplying cheap electricity to the South African economy. It has been shown above that nuclear is a much cheaper source of electricity than coal, provided that Government be prepared to accept WACC% below 9% (for the Expected Cases) on its investment. Many countries, especially Germany, currently fight Global Climate Change by subsidising low carbon renewable power sources, e.g. wind and PV solar, i.e. they sell the renewable power they buy from IPPs at a loss. The South African REIPPP program also subsidises renewables as the prices paid to the IPPs + the hidden intermittency costs borne by Eskom, suggest that Eskom makes a loss on the REIPPP. If the South African Government were to to fund the nuclear new-build program by accepting real pre-tax WACCs on its investment in Eskom below 9%, this would still mean that Government is making a modest % profit, which is more acceptable than suffering a loss through subsidising intermittent renewables.

The most appropriate values for these modelling assumptions, such as appropriate discount rates and funding models; the relationship between sufficient power supply and economic growth; intermittency costs of renewables; were discussed in detail in the reviews of the IEP [4] and IRP Update [5]. In summary it will thus suffice to say that Eskom is currently borrowing on the international capital markets at a real interest rate of 3%. This shows that a real pre-tax WACC of 3 to 9% is not at all unreasonable.

This stands in sharp contrast to the unrealistically high real pre-tax WACC and real discount rates of 11.3% demanded in the modelling of the IEP. It was these unrealistically high costs of capital that led to over estimations of the LCOEs for nuclear and thus resulted in the negative conclusions drawn by this report about the nuclear new-build program.

Negotiate low interest rate loans from vendor countries

Having said this, Figure 1 does clearly demonstrates the one weakness of nuclear power: if funding for nuclear construction can only be obtained at very high WACC% (or discount rates), the nuclear LCOE will shoot up dramatically to much higher than that of coal (and even higher than PV solar). This problem can be mitigated by taking active steps to obtain funding at low WACC%. One strategy could be to make affordable funding part of the tender specifications for South Africa's nuclear new-build program. Russia has already offered such a deal to South Africa and therefore other competitors can be expected to follow suite. Rather than selecting the tender with the lowest Overnight Cost, the tender with the most affordable combination of Overnight Cost and WACC%, as indicated by the resulting LCOE, should then be selected.

It should further be noted that interest rates are determined by the perceived investment risk. It has already been shown that for Generation III and IV nuclear, the actual nuclear accident risk is negligibly low. However the political risk is high, as has been demonstrated in the case of Germany. Government can, however, remove this political risk by supplying legal guarantees against unwarranted political interference. This will automatically reduce the interest rate at which the project can be funded, which will remove the financial risk and will thus virtually guarantee cheap, clean and dependable nuclear power.

Comparison with renewables

Since it is widely accepted that, in South Africa, coal power is normally cheaper than wind and solar power, especially if the load balancing costs of these intermittent renewables are added, the present result that, for low WACC%, nuclear power will be cheaper than coal also suggests that nuclear will be cheaper than wind and PV solar. However a detailed analysis of this question is referred to a follow-up study.

From the IRP Update it is clear that only hydro-power can supply clean reliable and dispatcheable power cheaper than these low nuclear LCOEs, and therefore hydro-power capacity should obviously be expanded as much as possible. Unfortunately South Africa is a very dry country and thus large amounts of cheap hydro-power can only be imported across the borders of several neighbouring countries, which may leave South Africa very vulnerable normal supply interruptions and even to political blackmail. Therefore the amount of imported power should be limited to a level that South Africa can afford to do without during a crisis.

IV.B Price resistance

In the past South Africa enjoyed abundant cheap coal supplies. Eskom has also in the past been subsidised by Government directly or indirectly and thus South Africa had the cheapest power tariffs in the world for decades. However good quality coal reserves are now starting to decrease substantially and export of high quality coal has increased sharply. Therefore coal prices have lately risen sharply and appear to be escalating towards export parity. Therefore consumers never bothered to invest in energy efficiency measures and thus Eskom never experienced significant price resistance. However the recent spate of very sharp electricity price increases, aimed at obtaining cost reflective tariffs in view of increasing coal costs and extensive labour unrest, caused especially energy intensive industries to invest substantially in energy efficiency technology. Eskom is thus, for the first time in its history, experiencing substantial price resistance.

Figure 2 showed that the real pre-tax rate of return on investment for coal increases much faster with electricity selling price than for nuclear. Therefore coal produced much higher rates of return for electricity selling prices above R 0.88/kWh and *vice versa*. However, the said price resistance suggests that Eskom will be boxed into the lower electricity selling price range, in which the Expected Nuclear Case generates a much higher rate of return than the Expected Coal Case. In fact coal starts to operate at a loss below R 0.68/kWh, while nuclear remains profitable down to R 0.26/kWh. The break-even electricity price for the Pessimistic Nuclear Case is thus a massive 62% lower than for the Expected Coal Case.

IV.C Risk and Net Present Value versus % rates of return

A comparison of *Figure 3* to *Figure 2* showed that while, above an electricity selling price of R 0.88/kWh, the real pre-tax % rate of return for the Expected Coal Case is much higher than for the Expected Nuclear Case, the real pre-tax nominal profit per unit power sold (R/kWh) is much higher for the Expected Nuclear Case for all values of the electricity selling price. It was explained that this is due to the much higher Total Capital required for nuclear, which implies that a fixed % rate of return on the Total Capital Required will result in a much higher nominal profit for nuclear.

In terms of fundamental economic theory this means that, for identical rates of return, building 1 kW of nuclear generation capacity will produce a Net Present Value (NPV) of more than twice that of 1 kW of coal power capacity, due to the much higher Total Capital Required for the nuclear project. The main conclusion to be drawn from this result is that using the rate of return as the main indicator of profitability of a project is not an optimal approach if the magnitudes of the capital investments of the two projects differ substantially.

If, however, both projects carry high risk, the higher NPV obtained from the larger capital investment should not be seen as a benefit, as it comes at the cost of also taking on much higher risk. In such a case the extent to which the produced % rate of return exceeds the risk adjusted WACC% should be viewed as the main indicator of the profitability of each project. However, it has been argued above that the actual operational risks for Generation III and IV nuclear plants are very low, as their nuclear accident risks have been reduced to insignificant values, due to drastically improved safety features. Strategies have also been proposed to mitigate political risks, which will ensure low interest rate loans, which will strongly mitigate the financial risks.

In principle the NPV for smaller capital projects can be scaled up by executing more of these small projects, i.e. the NPV of 1 kW coal generating capacity can be doubled by building 2 kW coal generation capacity, which would result in a similar NPV than 1 kW of nuclear generation capacity.

However, such an approach is only possible in a market with ample room for capacity expansion. In South Africa's case, Eskom already has a Government-backed monopoly in the power market and therefore already supplies almost the full South African power demand. Therefore increasing the coal NPV by replacing the planned 9,600 MW of nuclear generation capacity with 19,200 MW of coal generation capacity is not an option as that would flood the power market and would lead to a price collapse or unutilised power supply, which will reduce Eskom's profits.

In view of the limited amount of power the South African market can absorb, nuclear's ability to deliver at least twice the profit/kWh power sold indeed looks very attractive from Government's point of view.

V. RECOMMENDATIONS

Stimulate job creation with cheap power

Rather than aiming to maximising its returns from Eskom's electricity sales, a better way for the South African Government to view electricity generation, is to use it to stimulate the economy by supplying abundant cheap power to industry. In view of South Africa's abundant mineral resources which are currently mostly being exported in unbeneficiated form, it would be more productive to add value locally and to then export beneficiated products. Such a move may greatly increase South Africa's GDP, which will greatly benefit job creation and poverty reduction, which will also increase Government's tax revenues. It was shown above that in the extreme case where Government would be willing to sell the power at zero profit, break-even nuclear power would cost 62% less than break-even coal power, which could strongly stimulate job creation.

Profitable power plant construction strategy

The results of the present study suggest the following construction strategy:

- Concerns have been raised in South Africa that the long lead times of nuclear plants would make it impossible to respond to sudden increases or decreases in demand and that the nuclear option will thus lead to regular periods of oversupply or power shortages. However, this pitfall can be avoided by making long term construction commitments to supply only the minimum expected growth in base-load demand with nuclear plants, independent of short term increases in demand over and above this minimum demand. This means that only a modest fraction of total demand will be supplied by nuclear, which will limit the total amount of capital that Eskom will have to borrow, which will limit the impact on South Africa's credit rating.

- Peaking plants, such as hydro and gas turbines should be added simultaneously, in order to supply the demand peaks during specific times of day.
- If the yearly demand were to then grow faster than the minimum supplied by nuclear, other plant types which have much shorter lead times than nuclear, such as gas, PV solar, wind turbines and, to a lesser extent, coal can then be rolled out quickly in order to supply this excess demand.
- Nuclear then forms the cheap base-load foundation upon which the other technologies are added.

VI. CONCLUSIONS

All stated objectives have been achieved in that:

- A range of LCOEs was calculated for nuclear and coal power, which include hidden and external costs. It was shown that for low real pre-tax WACC%, even the Pessimistic $7,000/kW nuclear Overnight Capital Cost Case produced much lower LCOEs that the Expected Coal Case.
- A range of rates of return were calculated as function of the electricity selling price. Below an electricity selling price of R0.88/kWh, nuclear provided much higher rates of return than coal. The break-even price of nuclear was an astounding 62% lower than for coal.
- A range of nominal profits per unit power sold was calculated as function of electricity selling price. Nuclear provided much higher nominal profits, typically more than double, for all values of the electricity selling price. This is because the Net Present Value of 1 kW nuclear generation capacity is typically double that of 1 kW coal capacity. Since the economics of Generation IV HTRs can be expected to be similar to that of Generation III water-cooled nuclear plants, these results can be expected to also apply to HTRs.
- It was estimated that these results imply that, especially in view of the hidden intermittency cost of wind and PV solar, nuclear will produce power cheaper than these intermittent renewables.
- An estimate of the most profitable power plant construction strategy for South Africa was presented. In this strategy nuclear forms the cheap low-carbon base load power source upon which peaking plants, i.e. gas turbines and hydro power, and short lead times plants, i.e. wind turbines, PV solar and possibly coal is added
- The aim of this plan should not be to provide Government with the highest rate of return on its investment in Eskom, but rather to supply abundant cheap power to the economy, in order to stimulate economic growth and job creation. For this purpose, nuclear is far better than coal.

VII. PROPOSALS FOR FUTURE STUDY

The following follow-on studies are proposed:

- Comparison of Generation III nuclear to wind and PV solar. Gas turbines can be used as load balancing plants. Accurate estimates of these load balancing costs should then be calculated and should be accurately allocated to nuclear wind and solar respectively, in order to create a truthful comparison between base-load nuclear and these intermittent renewables.
- Simulation of the economic potential of producing load following power with Generation IV HTRs. The increasing deployment of intermittent renewables is creating an increasing market for peaking and load following power sources. The known ability of HTRs to do load following may result in their power output fetching higher prices, which may create a lucrative niche market for them.

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IX. REFERENCES

[1] Department of Energy (DOE) of the Republic of South Africa. Integrated Resource Plan for Electricity 2010-2030 (IRP 2010-2030). Revision 2, Final report, 25 March 2011. 2011.

[2] Department of Energy (DOE) of the Republic of South Africa. Draft 2012 Integrated Energy Planning Report. (IEP). 2013.

[3] Department of Energy (DOE) of the Republic. Integrated Resource Plan For Electricity (IRP) 2010-2030: Update Report 2013. 2013, 21 November.

[4] Serfontein, Dawid E. Review of: Draft 2012 Integrated Energy Planning Report (IEP), released by the South African Department of Energy. December 2013. Nuclear Industry Association of South Africa (NIASA). 2013. Review.

[5] Serfontein, Dawid E., Review of: INTEGRATED RESOURCE PLAN FOR ELECTRICITY (IRP) 2010-2030 UPDATE REPORT 2013, released by the South African Department of Energy. Feb. 2014. Nuclear Industry Association of South Africa (NIASA). 2014. Review.

[6] Eberl, Jakob and Darko Jus, The year of the cat: Taxing nuclear risk with the help of capital markets, Energy Policy, 51 (2012), 364–373.

[7] European Commission, External costs - Research results on socio-environmental damages due to electricity and transport, Directorate-General for Research, Directorate J-Energy, Brussels, 2003.

[8] Electrical Power Research Institute (EPRI), Power Generation Technology Data for Integrated Resource Plan of South Africa - Technical Update, April 2012.