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Keywords unplanned shutdown, cost, intermittent, accelerator-driven subcritical reactor

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Predicting the Contractual Cost of Unplanned Shutdowns of Power Stations: An Accelerator-Driven Subcritical Reactor Case Study

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Abstract

The growing penetration of intermittent power generation technologies is increasing the importance of operating efficient electricity balancing mechanisms. This paper presents a model for analysing the financial cost to an electricity supplier when a power generator unexpectedly instantaneously shuts down, in the context of the UK National Grid. The simulation probabilistically selects historical market data and includes analysis on the impact on the system buy price of historic unplanned generator shutdowns. A case study is presented for one revolutionary nuclear power station design concept, the Accelerator-Driven Subcritical Reactor (ADSR). The reliability of ADSRs is a key issue facing their future development. The model is used to identify when the economic cost of improving reliability exceeds the cost of unplanned shutdowns. The results are presented in a form that allows the reader to scale the cost of accelerator system failures for any capacity factor and coefficient of reliability, for a range of discount rates and electricity prices.

Key Words: electricity; unplanned shutdown; cost; intermittent; accelerator-driven subcritical reactor

1.0 Introduction

It is widely acknowledged that the growing penetration of intermittent power generation technologies poses challenges to balancing the supply-demand market in electricity grids (UK Energy Research Council 2006). Intermittency is typically associated with renewable energy technologies such as wind and solar, which are anticipated to provide increasing quantities of power to world electricity markets throughout this century. Intermittency causes an immediate need to bridge energy gaps created by generators that suddenly cease to supply electricity and it also adversely affects the loss of load probability of the grid (a loss of load causes grid-wide blackouts/brownouts). Sudden energy gaps have implications for grid balancing mechanisms and grid-wide demands for loss of load for backup capacity.

Regarding backup capacity, the quantity of backup required generally increases with increasing intermittency of generators in the grid. The backup capacity ensures that the loss of load probability of the electricity grid is kept at an acceptably low probability of occurrence. Adding new generation capacity should not significantly increase the risk of a grid blackout/brownout. Reserve capacity is required for all forms of electricity generators, but there is a tendency for intermittent generators to require more than dependable ones.

Intermittent technologies make the operation of electricity grid balancing mechanisms more challenging, due to the lack of predictability as to whether supply contracts will be fulfilled. From the perspective of suppliers, this uncertainty has the potential to incur significant balancing charges for supplying less electricity than contracted to. An approach to dealing with this issue, which has come into existence through attempts to curtail climate change, is to assign intermittent renewable technologies "priority dispatch". The mechanism obliges the grid operator to accept electricity provided by renewable power sources, with the only exception being when doing so would adversely affect the security of supply (EU Directive 2009). Priority dispatch exempts generators from the financial penalties for failing to supply contracted electricity. However, the ever-increasing penetration of intermittent renewable energy generators in electricity markets will eventually make priority dispatch an unsustainable mechanism for operating electricity markets.

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The growing short-term variance in the electricity supplied by generators places increased interest in the efficient operation of balancing mechanisms. To help facilitate analysis of balancing mechanisms, this paper presents a model for identifying the financial cost incurred for failure to supply contracted electricity in the short-term market and the balancing mechanism of the UK. The model addresses instantaneous unplanned shutdowns of power generators and makes predictions using Monte Carlo simulations based on historical data. A case study future technology is discussed, the Accelerator-Driven Subcritical Reactor (ADSR), for which power generation intermittency is a central issue. As a nuclear power generator, ADSRs are not considered to be a renewable form of energy and so will not benefit from priority dispatch regulations.

This paper is structured as follows: in Section 1.1 the ADSR concept is briefly described; in Section 2 details of the UK short-term market and balancing mechanism are given, with emphasis on the financial implications of unplanned shutdowns; in Section 3 the method of simulating the cost incurred during an unplanned shutdown is described; Section 4 introduces the ADSR case study, describing shutdown rates in accelerator systems; Section 5 uses the results from the financial model and the ADSR specifications to analyse which unplanned shutdowns are the most expensive to an ADSR operator; Section 6 identifies the annual cost of ADSR shutdowns; lifetime costs of failure for ADSRs are determined in Section 7; and the findings are summarised in Section 8.

1.1 Accelerator-Driven Subcritical Reactors (ADSR)

At 2006 consumption rates, the uranium fuel supply that can be extracted for less than USD $130 /kgU is expected to last about 100 years (International Atomic Energy Agency (IAEA) 2007). If demand for nuclear power grows however, this timeframe could be significantly reduced. To overcome this issue a number of options are available: large scale spent fuel reprocessing can potentially reduce the raw uranium demand by ~30% (World Nuclear Association 2009); developing commercial nuclear fusion reactors would give the world a nearly sustainable fuel source (International Fusion Research Council 2005); extracting uranium from sea water has the potential to make the uranium supply sustainable over the Earth's lifetime (Cohen 1983); fast fission breeder reactors would significantly increase fuel consumption efficiency; and the thorium fuel cycle has the potential to complement or even replace uranium. Thorium is over three times more abundant than uranium and compared to the uranium thermal cycle (IAEA 1005), 40 times more energy is produced per kilogram of fuel.

The ADSR concept is often envisaged to be a fast reactor (Carminati *et al.* 1993). The principal design feature is that the reactor is coupled to an accelerator system, which supplies neutrons into the core through spallation of a high-energy, high-intensity proton beam. Unique to ADSRs, the external neutron source enables the nuclear reactor to fission sustainably while always remaining in a subcritical state. The operators have additional control over the reactivity of the core by means of adjusting the accelerator system beam power. This increases safety in addition to standard nuclear reactor safety systems and enables ADSRs to follow load effectively.

The accelerator system required by an ADSR poses a great technical challenge. The power, capacity factor and reliability of contemporary high-power accelerators are below ADSR requirements. The world's most powerful contemporary proton beam accelerators reach beam powers of approximately 1 MW. Commercial ADSRs have been specified to require a beam power 10 times that (Ruggiero 1997; Pierini *et al.* 2003). The Livingston chart shows the rate of increase in achievable particle acceleration energies through history (Teng 2001). This chart suggests particle accelerator design will soon be capable of delivering the beam power required by an ADSR.

2.0 The UK Electricity Market

Electricity grid operators seek to balance supply and demand in the grid at all times. When the grid is not in balance it is termed to be either "short" or "long". A long system has a greater supply than demand, and a short system is the reverse case. The electricity supplied by individual generators within the system is similarly named, such that a short generator is helping balance a long system, and a long generator would be contributing to a long system's imbalance. During an instantaneous unplanned shutdown, a generator is short of its contracted sales.

Electricity grids use a balancing mechanism to make supply corrections and also to financially settle differences between the contracted and actual electricity supplied. When a system is short or long, the grid operator will use its ancillary services to correct the imbalance. These services take a variety of forms: voltage and frequency monitors of supplied electricity to ensure "quality" of supply (these are in use at all times); rapid response spare capacity to balance the system; contracts with large consumers, such as factories (the consumer is contracted to change its demand when required) to balance the grid; and power stations that can generate electricity even during full grid shutdowns, to enable restarts following catastrophic supply failures (Parliamentary Office of Science and Technology 2001).

The UK National Grid balancing service is provided by ELEXON. Publicly available records are kept for three prices relevant to the cost of electricity supply imbalances. There are the Market Index Price (MIP), which is the wholesale price of electricity; the System Buy Price (SBP); and the System Sell Price (SSP). Regardless of whether the system is long or short, the SBP is the price paid by an operator for the contracted electricity sales that it is short of and the SSP is the price paid to an operator for their contracted sales in excess of their contracts (i.e. for being long). The SBP and SSP are non-negotiable prices: they are formulaically fixed by the current state of the market (ELEXON 2006). The electricity supplier agrees liability to pay the SBP and to be paid the SSP when entering into the British Electricity Trading and Transmission Agreements (BETTA) (UK National Grid 2009). The formulas that dictate the SBP and SSP give rise to one of the four scenarios described in Table 1. The actual values of the SBP and SSP at any point in time are predominantly determined by the magnitude of imbalance and the MIP.

	System is Long	**System is Short**
Operator is Long	The operator is paid the SSP for the excess electricity it has generated. The SSP is low as the electricity is not needed.	The operator is paid the SSP for the excess electricity generated. The SSP is high as the excess electricity has helped bring the system back into balance.
Operator is Short	The operator has to pay the SBP for not generating as much electricity as contracted to. The SBP is low as the shortfall has helped bring the system back into balance.	The operator has to pay the SBP for not generating as much electricity as contracted to. The SBP is high as the grid operator has to use its ancillary services to balance the grid.

Table 1: Electricity grid and operator imbalance secenarios. An instantaneous unplanned shutdown of a generator will make an operator short.

When generators unexpectedly shutdown, the generator owner pays long competitors for supplying its consumers with electricity, if the system is short the remaining imbalance is covered by the ancillary services. The price charged to the operator reflects the degree of difficulty of balancing the system. Long competitors are to be paid a price which is governed by the current state of the market and when ancillary services are required, the grid operator charges the price that recovers their costs. The latter case is typically more expensive than the prior.

Standard practice in BETTA is for electricity sales to be made in blocks of 30 minute periods (1 period = 30 minutes). There are thus 17520 periods in a 365 day year. The UK historical SBP data for the period 1st March 2005 to 28th February 2009, inclusive, are shown in the time-series in Figure 1. Nominal prices have been adjusted to 2009 money (January and February only) using the UK consumer price index on a month by month basis.

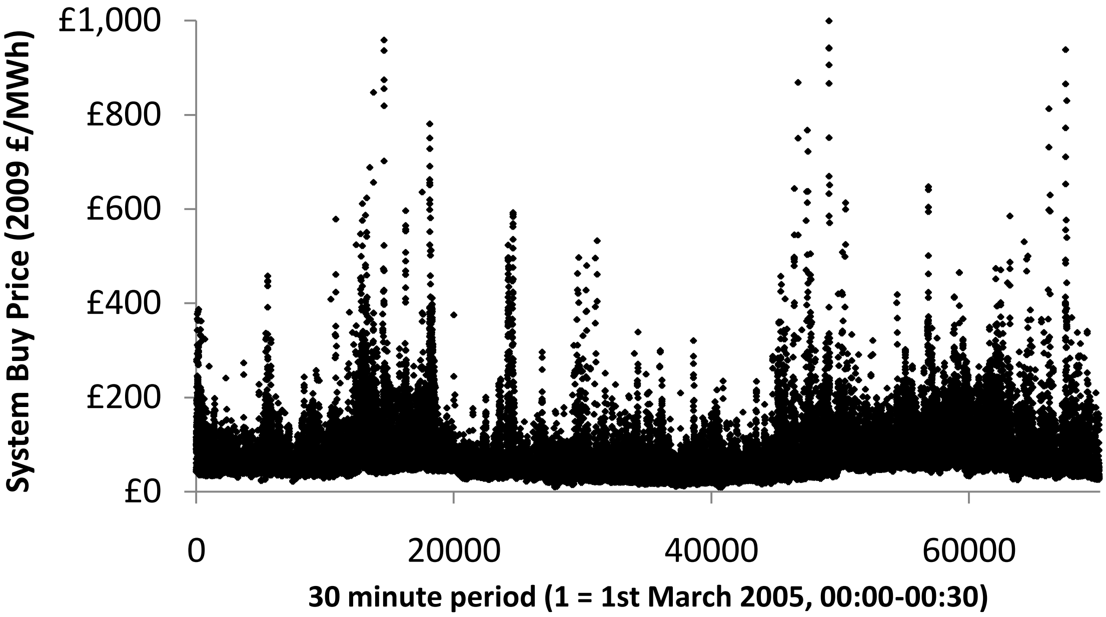

Figure 1: The historical SBP in the UK electricity market (1st March 2005 to 28th February 2009, inclusive) in 2009 money.

In practice, an electricity supplier experiencing a full scale failure of one of its electricity generators will either switch on a generator within its own fleet or attempt to buy short-term supply contracts from competitors – whichever is the more economic course of action. The SBP can therefore generally be considered the worst case price that must be paid. Standard practice is for short-term contracts to be 30 minutes, 2 hours or 4 hours in duration (McClay 2008). For the case study presented in this paper, the use of other generators owned by the ADSR operator is not considered. All of the energy is either purchased from the system or from short-term contracts.

It is noted for the ADSR case study that these generators require the engineering necessities of particle accelerator technology beyond that achieved by contemporary facilities (Bowman *et al.* 1992; Carminati *et al.* 1993), in addition to the requirements of existing nuclear power stations. Nuclear power stations are capital cost intensive. An ADSR will require engineering of greater complexity than contemporary nuclear power stations. It is thus expected that ADSRs will be even more capital cost intensive. Due to this, it is anticipated that an ADSR would provide base load electricity (Pouret *et al.* 2009). To minimise uncertainty, base load generators operate on long-term contracts spanning months to years (McClay 2008). It is therefore expected that a seller of ADSR produced electricity will take the sales price dictated by the rest of the market; the described model has been designed in consideration of this and therefore in the model the long-term average MIP (i.e. the mean MIP of the considered 4 year period) is used as the price of electricity sold. This is £57.44 /MWh (2009 money).

3.0 Predicting the Cost of an Unplanned Shutdown

At any given point in time the price of electricity in a liberalised market is defined by numerous factors, including: the time of day, weather conditions, social events, bidding behaviour of energy suppliers, the technical condition of their power generators, transmission infrastructure, fuel supply, energy security and many more. Simulating how supply and demand are met in a wholesale market is a complex field of study. Modelling markets through agent-based simulation techniques is an active field of study (Weidlich and Veit 2008). Contemporary agent-based models, however, simplify market environments and are not able to microscopically provide accurate predictions of future electricity prices (Huisman *et al.* 2007). Instead of attempting to simulate the conditions of an electricity market, in the analysis presented in this paper unplanned shutdowns of an electricity generator are simulated to have occurred at points in time from a data set of historic electricity prices.

In this analysis the maximum failure duration considered is 24 hours. It is selected primarily because beyond this time electricity suppliers can be reasonably confident that they will have arranged short-term contracts to cover the entire energy gap (Hall 2009). Continuing costs beyond 24 hours are therefore comparatively well defined. Furthermore, as is later shown in Figure 7, for the ADSR example, lengthier shutdown durations would be decreasingly significant to the total cost of failure due to their infrequent occurrence.

A base load generator tends to operate under long-term contracts. An unscheduled shutdown of such a facility would cause an energy supply shortfall proportional to its declared net capacity. This analysis uses an example of a 600 MWe generator. The "works" electricity (that which is produced and used on site) to power subsystems is assumed to be already subtracted, yielding this 600 MWe total. In the described scenario, a failure causes a 300 MWh per 30 minutes shortfall. The cost incurred for a restart is not considered in this analysis.

The duration of failures have been grouped into 30 minute periods (often referred to simply as "periods"). Thus following the commencement of a failure, period 1 refers to the time range from 0 to 30 minutes, inclusive; period 2 refers to >30 minutes to 1 hour, inclusive; etc. This approach is used so that failure durations synchronise with short-term contracts, which are purchased in minimum blocks of 30 minutes (1 period).

The volatility of the SBP and MIP are significant for single failures. Figure 1 shows that the SBP can vary by in excess of an order of magnitude. The timing of a failure is therefore important. The model randomly generates a historical date and 30 minute period of the day for a failure to occur in. The associated historical SBP and MIP are used as the market conditions during the failure. No account has been made for maintenance work being intelligently scheduled, such that a facility is preferentially offline at certain times of the year.

3.1 The Effect of Instantaneous Unplanned Shutdowns on the SBP

It has been hypothesised that it may not be fair to simulate failures directly using historical SBP data. At a given point in time, the SBP in a grid where there has been an unplanned shutdown of a 600 MWe generator would not necessarily the same as the SBP if no such failure had occurred. This idea has been investigated through analysis of market data following historical instantaneous unplanned power station shutdowns in England and Wales, for which the data were provided by The UK National Grid. All unplanned shutdowns of generators selling between 400 and 800 MWe over the time period 1st March 2007 to 10th June 2009 have been considered in the analysis; this is 146 shutdowns (exclusive of a handful of shutdowns that were disregarded due to incomplete data entry). For these shutdowns the SBP during the first 24 hours of failure (or as much of that period as possible if the shutdown was brief; 57 of the shutdowns exceeded 24 hours in duration) has been compared to the SBP for the corresponding unit of the day, each day, for 2 weeks before and after the shutdown commencement. The ± 2 weeks timeframe was chosen because it: (1) as closely as possible represents the market/weather/social conditions that might have occurred on the day of the shutdown, if it had not occurred and (2) provides a reasonably large sample size to smooth out market volatility, but not so large that issue (1) is no longer satisfied. The findings are presented in Figure 2.

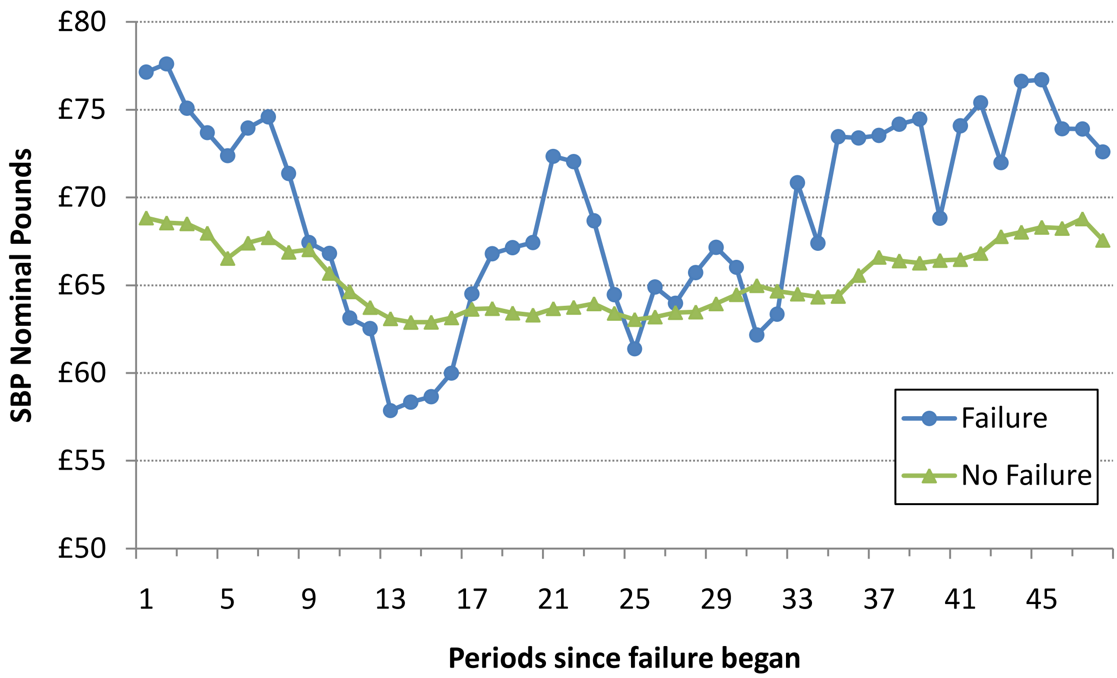

Figure 2: The average SBP following the commencement of unplanned shutdowns of 400 – 800 MWe power generators (blue circles) and the average SBP for the same unit of the day for ± 2 weeks before/after the shutdowns (green triangles).

Figure 2 shows the SBP (in nominal money) for 48 periods following the commencement of a failure averaged over all of the unplanned shutdowns. Also shown for each of the 48 periods is the average SBP for the corresponding period of the day, each day, for ± 2 weeks averaged over all of the shutdowns. The data show that the change in the SBP due to a sudden loss of 600MWe from the grid supply is small compared to the absolute SBP. It is concluded that any correlation between unplanned shutdowns and the SBP is not significant. The historical SBP is therefore used in the model without modification, i.e. no correction is made to account for the fact that the sampled historical SBP is taken (in most instances) at a point in time when no unplanned shutdown had occurred.

3.2 Arranging Short-Term Contracts

As a failure extends over 24 hours, traders progressively arrange short-term contracts to bridge the energy gap until all of the energy is purchased privately rather than from the system. In the described model the price paid for these private contracts is defined to be equal to the average historical MIP over the time the contract is active for. Explicit data for the success rate of arranging contracts are not publically available. Operators in the commercial industry have provided guidance (Hall 2009). Using this information the authors have made assumptions for representative modelling regarding the success rate of arranging contracts. The full details of this representative modelling are given in the Appendix. In summary, failures begin with zero private contracts and after 24 hours all electricity is purchased from private contracts. The intervening period follows a volatile stochastic process, which is a linear increase in the quantity of electricity purchased privately from time 0 to 24 hours.

The average cost of private and system purchased electricity (weighted by the quantity purchased) is the predicted average cost per MWh of buying electricity during a failure. This changes period by period. Three example iterations of the price evolution and also the success rates of arranging private short-term contracts are shown in the charts in Figure 3. The iterations are not representative of the simulated failures; they were chosen to highlight interesting outcomes and the uncertainty associated with such an event.

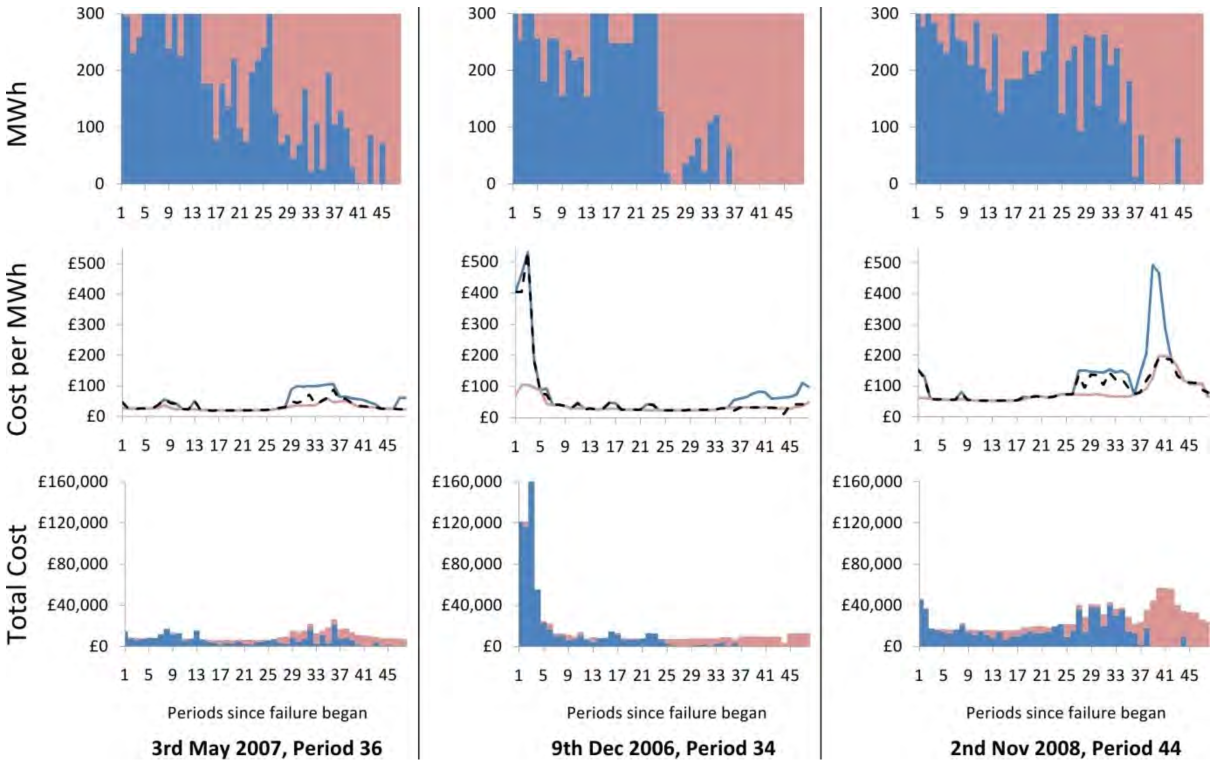

Figure 3: Three iterations from simulating the cost of a 24 hour (48 periods) in duration failure. The quoted dates and periods refer to the sampled historical data for the SBP and MIP. Each iteration has three vertically aligned spectra associated with it. Top: are stacked histograms of the distribution of private contracts (light red) and electricity purchased from the system (dark blue). Middle: are stacked histograms of the total cost of buying electricity for each period, the costs of system and privately purchased electricity are shown in dark blue and light red, respectively. All x-axes are in 30 minute periods following the commencement of failure. Money is quoted in 2009 pounds.

A company can make a profit during individual 30 minute periods of a failure. This requires the SBP and/or MIP during the failure to be less than the operator's contracted sales price of electricity. In reality such profits tend to be smaller than the losses incurred during the failure as a whole, but it is possible to turn a net profit during a failure. In such cases the opportunity cost remains significant.

3.3 The Cost of a 24 Hour Shutdown

To demonstrate the model, a failure 24 hours (48 periods) in duration has been simulated for 10,000 iterations. The histograms in Figure 4 show the profit/loss made during each simulated failure and the opportunity cost. In the framework of the model, the running costs of the facility are assumed to be constant at all times. The model is thus insensitive to facility operating cost changes during a failure (i.e. staff, fuel, equipment, etc.). The opportunity cost is therefore the difference between the profit/loss made and the gross profit expected to have been made if no failure had occurred. Gross profit during business-as-usual periods is constant in the model framework (£629,000 /day; assuming fixed rate running costs of £13.76 /MWh[1]). The histograms in Figure 4 show that for a 24 hour (48 periods) shutdown the model returns a mean loss of £271,000 and a mean opportunity cost of £883,000. Both distributions have a standard deviation of £430,000 and a skew of –1.7.

[1] *This running cost is specific to nuclear reactors. It assumes O&M costs of £8.34 /MWh; Fuel costs of £4.22 /MWh; and combined decommissioning and geological disposal fund costs of £1.19 /MWh. These are the costs from (Kennedy 2007), escalated to 2009 money at a rate of 2.7%*

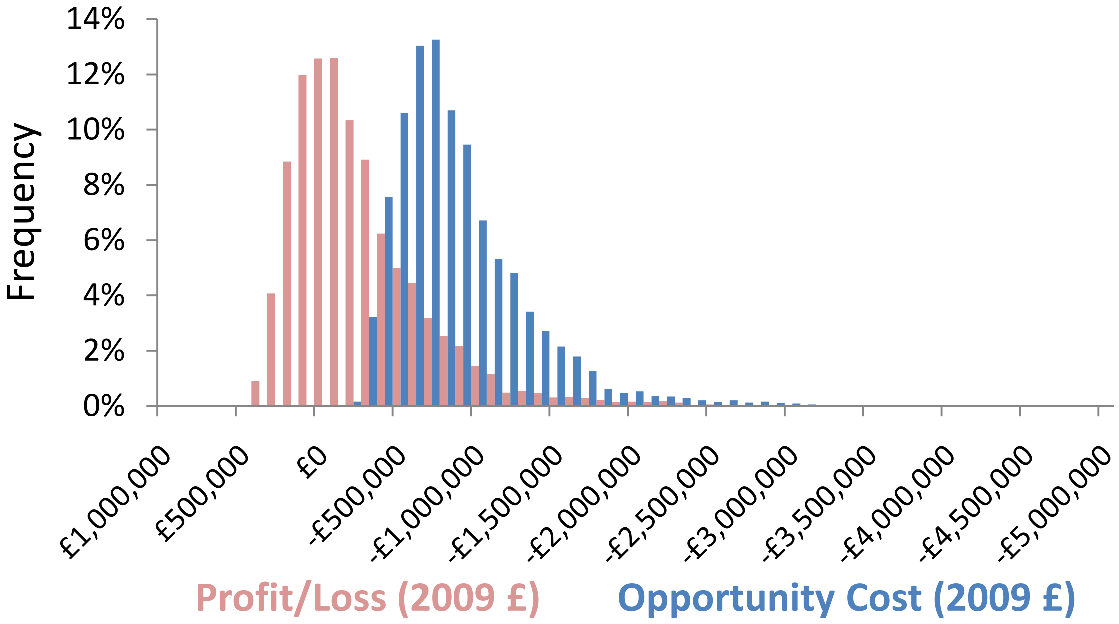

Figure 4: A frequency distribution of a 10,000 iteration simulation showing the profit/loss (light red) and opportunity cost (dark blue) of a 24 hour (48 period) unanticipated failure of an ADSR power station selling 600 MWe.

The National Grid has regulations regarding the quality of electricity sent into the grid (UK National Grid 2009). These requirements are with regard to parameters such as the voltage and frequency stability, electrical noise and phase angle. It is not clear if a shutting down generator will meet these requirements, but there is the potential for significant power transients to cause difficulties. Due to this uncertainty, short shutdowns, are not considered in this work (i.e. shutdowns <½ hour in duration). For all shutdowns that are considered (shutdown durations >½ to 24 hours in duration), it is assumed that the quantity of electricity supplied to the grid instantly reduces to zero. It will take time to restart the system again, this period is not accounted for in the described model.

The profit/loss made and opportunity costs of failures for each 30 minute period ranging from >½ to 24 hours have been simulated for 1,000 iterations each in the same fashion as the 24 hour failure shown in the spectra in Figure 4. The mean and standard deviation of the losses made and opportunity costs are shown in the spectra in Figure 5.

4.0 ADSRs – Contemporary Accelerator Systems

A 1st-of-a-kind ADSR power station is envisioned to require an accelerator system with a power rating of up to 10 MW (Carminati *et al.* 1993). This is approximately an order of magnitude more than typical high-power accelerators operational today (see ISIS, PSI, LANSCE, NuMI and SNS[2], and note that these accelerator systems are all purpose built research facilities). Particle beam shutdown durations range from microseconds upwards in duration. It is not anticipated that shutdowns shorter than one second will measurably affect the power output (Pierini *et al.* 2003). Beam shutdowns longer than one second are termed "trips".

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[2] *ISIS accelerator at the Rutherford Appleton Laboratory (RAL), the proton accelerator at the Paul Scherrer Institut (PSI), the Los Alamos Neutron Science Centre (LANSCE) at Los Alamos National Laboratory, the Neutrinos at the Main Injector (NuMI) beam line from the proton accelerator at Fermilab and the Spallation Neutron Source at Oak Ridge National Laboratory.*

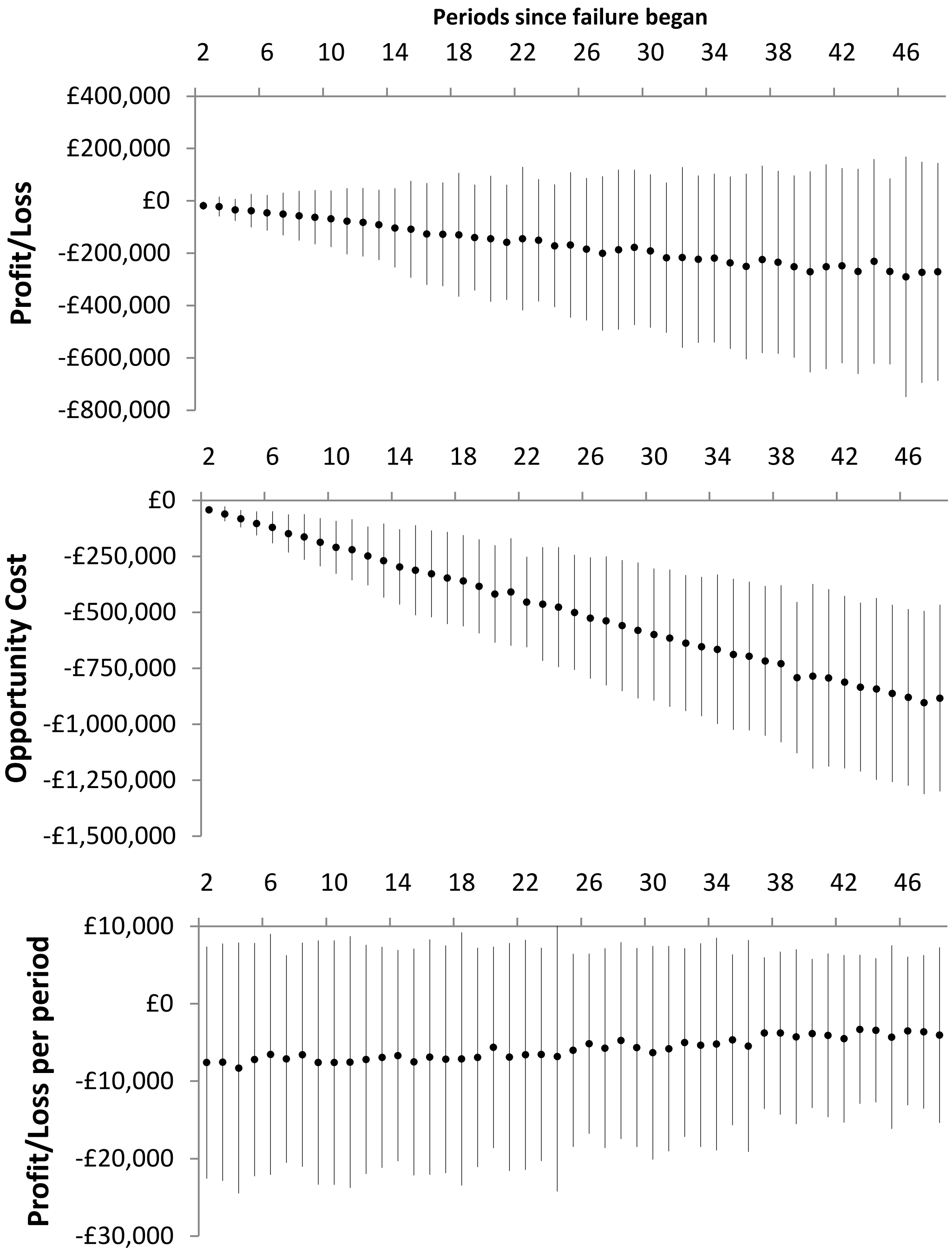

Figure 5: For the range 2 to 48 periods and in 2009 money: (Top) the average loss made due to a failure, (Middle) the average opportunity cost of a failure and (Bottom) the average profit/loss made in any given period following a failure. There is a skew to the standard deviation of the data in all spectra, in the same fashion as the histogram in Figure 4. The skew increases in its significance for longer failure durations. The oscilations in the mean values can be eliminated by increasing the number of iterations of the model. This has not been done as the oscilations are significantly smaller than the standard deviations and because increasing the number of iterations is computationally time demanding.

Accelerator systems require maintenance time in order to deliver the highest possible quality of beam during scheduled operation. The required maintenance time determines the achievable capacity factor of the accelerator system. For the whole ADSR facility, the realised capacity factor results from considering both the accelerator system and the rest of the nuclear power station. It is not anticipated that the ADSR can improve on the capacity factor achieved in other nuclear power station designs. Therefore the maximum possible availability of an ADSR is expected to be 85% (Massachusetts Institute of Technology 2003; University of Chicago 2004; Kennedy 2007). Contemporary accelerator systems operate with a capacity factor of 65% (Galambos *et al.* 2008). In this paper the simple assumption is made that the capacity factor of an ADSR will fall in the range

(65-85)%, the paper therefore also assumes that the accelerator and reactor maintenance schedules are perfectly harmonised.

The beam availability during scheduled operation for five major accelerator facilities has been reported (Galambos *et al.* 2008). In the Galambos *et. al.* (2008) paper, availability is defined to be the proportion of time that beam is provided on the primary target divided by the total scheduled beam time. The variable is therefore equivalent to the reliability coefficient of the accelerator system. The SNS is reported to be available 73% of the time. This facility is less mature than the others and this is considered normal. The SNS availability is expected to increase with time. A second facility, NuMI, is available 70% of the time. The majority of its failures are related to the primary target. The accelerator proper has an availability of approximately 90%. The remaining three facilities (ISIS, PSI and LANSCE) achieve a mean availability of 87%. The majority of the beam unavailable periods are due to failures in the accelerator itself. Across all facilities for which data have been collected, the relationship between trips of a given or greater duration and trip frequency is consistent. The data follow a –2/3 power law (Galambos *et al.* 2008; Findlay 2009), such that increasing trip duration decreases trip frequency.

In the model described in this paper beam trips are grouped into 30 minute periods. The longest considered beam trip, and hence the least frequent beam trip, experienced by the hypothesised ADSR facilities is a 23½ to 24 hour (48 periods) shutdown. The spectrum in Figure 6 shows the frequency of beam trips of durations 2 to 47 periods relative to a single 48 period shutdown. Unless otherwise stated, the work presented in this paper assumes that this frequency relationship will remain constant as accelerator reliability is improved.

It happens that Figure 6 is representative of the total number of trips an accelerator is likely to experience if it suffers unplanned shutdowns for 0.8% of 40 years (i.e. if it suffers one 48 period trip and associated shorter trips over its lifetime). Existing accelerator systems suffer approximately 8 times this number of trips over 40 years. The beam trip data (Galambos *et al.* 2008; Findlay 2009) indicate that there is a 50% uniform distribution about the mean frequency of trips; this is included as vertical lines in Figure 6.

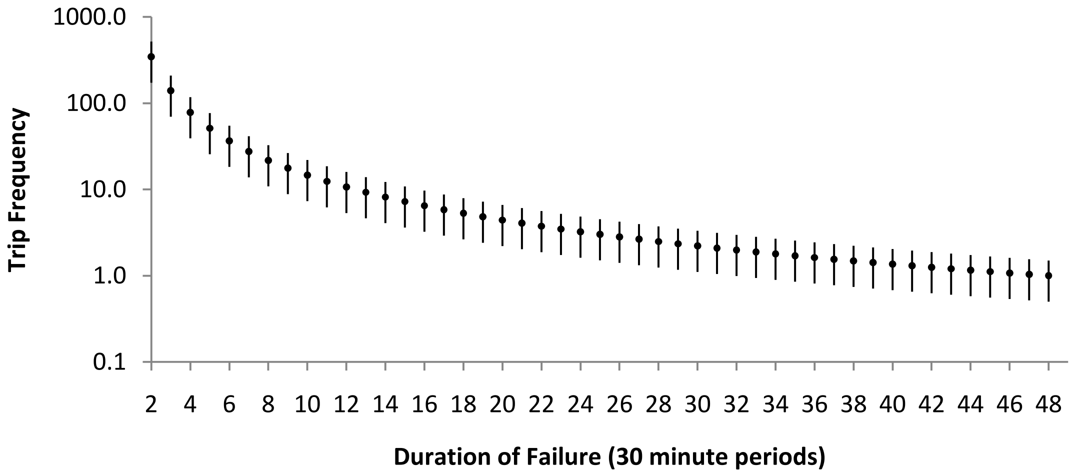

Figure 6: Frequency of shutdowns for the range 2 – 48 periods, relative to the frequency of a single 48 period shutdown. The vertical bars indicate the 50% uniform uncertainty on the mean trip frequency.

5.0 ADSRs – The Relative Cost of Trips of Varying Duration

The frequency of trips of varying duration relative to one another has been presented in the spectrum in Figure 6 and the cost of failure of any single trip has been defined in Section 4.0. For 10,000 iterations, the opportunity cost of failure (prior to accounting for inflation and Discounted Cash Flow (DCF)) for the trips in Figure 6 has been generated. Per period, the cost of all trips has been summed. This identifies the financial significance of the different failure durations relative to one another, see Figure 7.

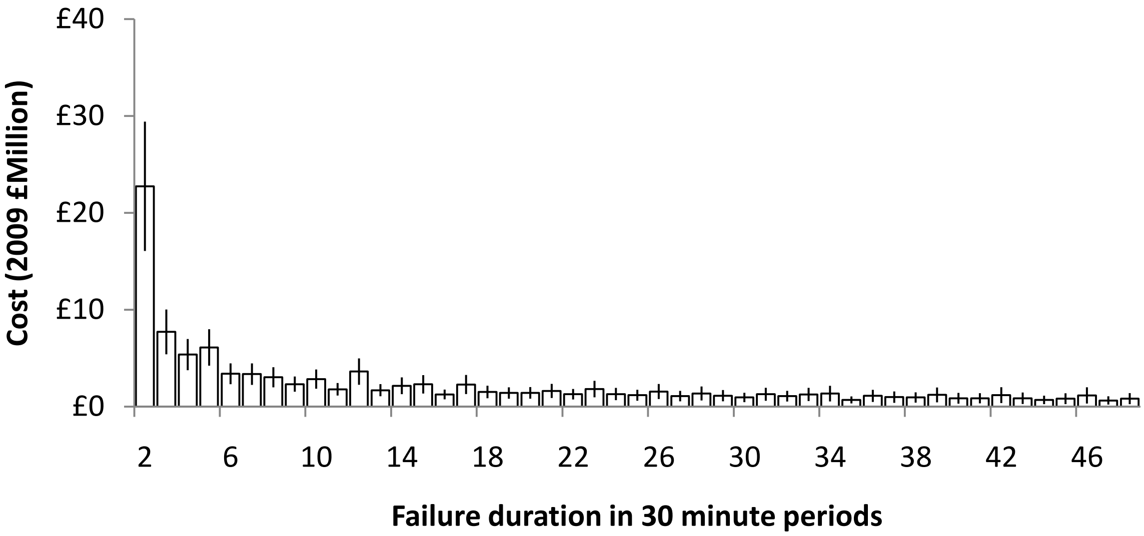

Figure 7: Cost of all trips in each 30 minute period of trip duration, relative to a mean frequency of a single 48 period trip. The standard deviation is 30% of the mean for 2 period shutdowns and it linearly increases relative to the mean to 70% for 48 period shutdowns. The oscilations in the mean values can be eliminated by increasing the number of iterations of the model. This has not been done as the shape of the correlation between cost and failure duration is clear from the 10,000 iterations and because increasing the number of iterations is computationally time demanding.

For the results shown in Figure 7 there is uncertainty both in the 50% uniform distribution about the mean trip frequency and the cost incurred during each specific failure, which is dependent on the factors described in Section 3.0. In cases where the generated number of failures for a given trip duration is not an integer, the fractional trip has a probability of being counted, which is a function of the magnitude of the fraction. This removes partial trips, ensuring that trips either occur or do not occur, preserving the validity of the standard deviation measured by the simulation.

Within the calculated uncertainties, the spectrum in Figure 7 shows that if an ADSR were to operate with a contemporary accelerator system, the collective cost of all failures of a given duration is greater than the collective cost of all failures of a longer duration. Although the cost of the individual shutdowns is less, the frequency of their occurrence is far greater. This raises a possible issue that failures shorter in duration than those considered by the model (i.e. those lasting less than 30 minutes) will deserve consideration from a financial perspective in the future.

6.0 ADSRs – A Scalable Opportunity Cost of Failures

The findings presented at the end of this section allow the reader to choose their own capacity factor, reliability coefficient, inflation rate and discount rate for an ADSR. From these inputs the Present Value (PV) cost of failure can be determined for all unplanned accelerator shutdowns throughout the lifetime of an ADSR. To reach this point (Sub-section 6.2), first in Sub-section 6.1 the annual cost of failure is predicted for an unplanned shutdown rate of 1% of a year (3.65 days). The cost of failure is calculated on an annual basis for the purpose of later applying inflation and DCF. Once the lifetime PV cost of failure is determined for this nominal percentage point failure rate, equations are given enabling the reader to scale to their desired reliability coefficient.

6.1 ADSRs – PV Cost of Unplanned Shutdowns for an Accelerator that Fails for 1% of a Year

It is assumed that trips occur uniformly and randomly. No account is taken of the learning time in the initial years of accelerator operation, such as is currently the case for the SNS (Galambos *et al.* 2008), see Section 4.0. This analysis assumes that the structure of the electricity market remains constant into the future: the absolute price of electricity will change in line with the selected inflation rate, but the daily degree of volatility of the SBP and MIP is constant.

The model generates the trips that occur in a single year of operation using the –2/3 power law for the relative frequency of differing trip durations (see Section 4.0) and a mean unplanned shutdown time of 1% of 12 months. The cost of failure for each trip is individually generated by probabilistically selecting from the distributions defined in Section 3.0. The spectrum in Figure 8 shows the resulting opportunity cost of failure per year for 10,000 iterations of simulation.

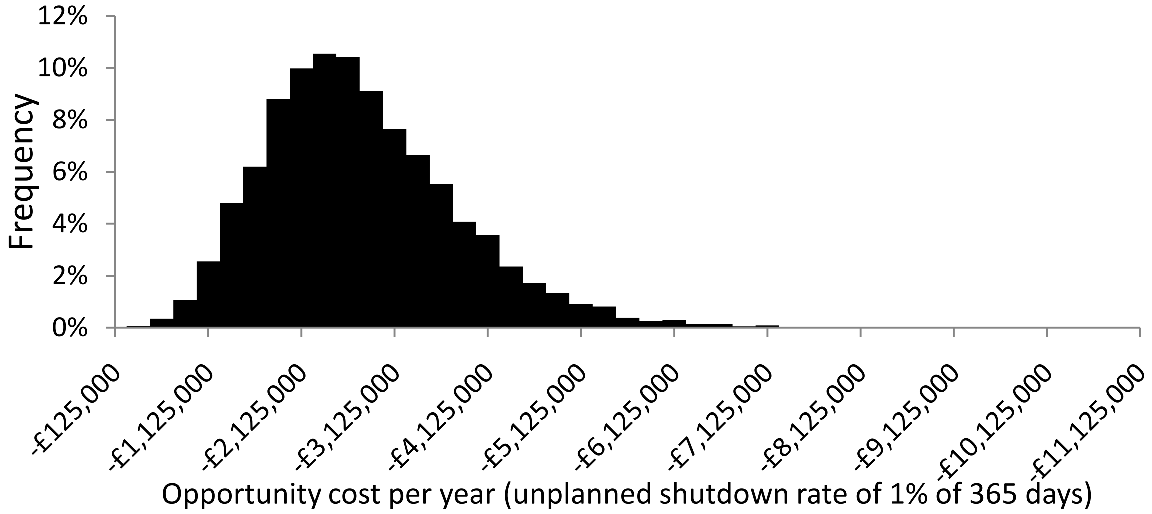

Figure 8: The opportunity cost per year to an ADSR operator for an accelerator system, which trips for a mean of 1% of the year. The mean of the distribution is £ 2,895,000 and the standard deviation is £1,045,000 in 2009 pounds.

The spectrum in Figure 8 shows the distribution of the annual cost of failing to supply electricity for one percentage point of a year to an ADSR. The lifetime cost of failure is calculated next. The cost of failure for each of the 40 years of operation is probabilistically generated from the distribution in Figure 8. Each progressive year of operation has its cost inflated and discounted for a range of rates, obtaining the 2009 PV cost of failure for the lifetime of an ADSR with a nominal trip rate of one percentage point of its life. For 1,000 iterations, the result is shown in Figure 9. The flow chart in Figure 10 depicts the methodology that has been described in this sub-section of the paper.

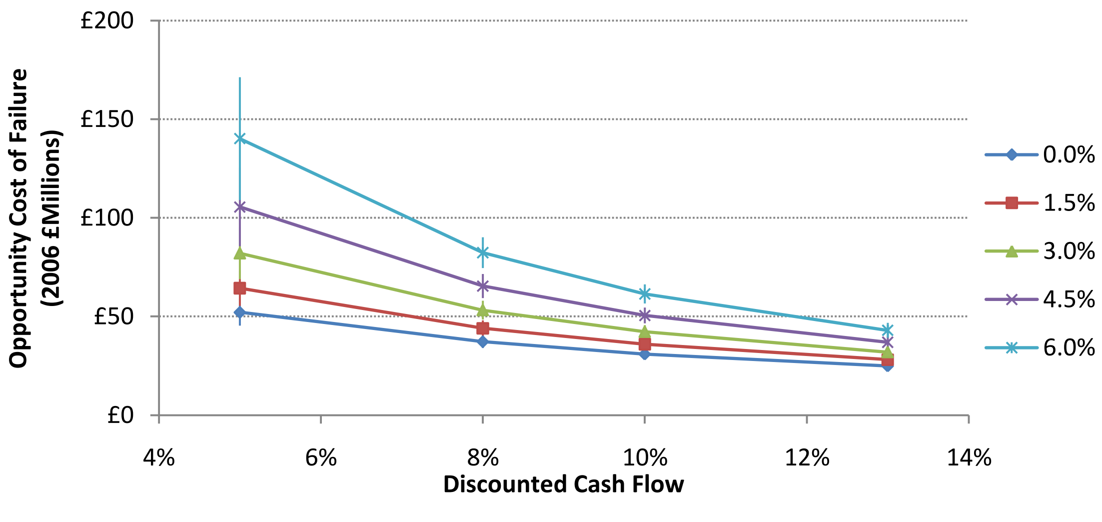

Figure 9: The 2009 PV cost of failure to an ADSR that nominally experiences unplanned accelerator system shutdowns for 1% of a 40 year life. The real discounted cash flow rate is on the x-axis, a range of real electricity price inflation rates are identified in the legend. The lines linking the datum are not fitted curves; they are included only to help guide the eye.

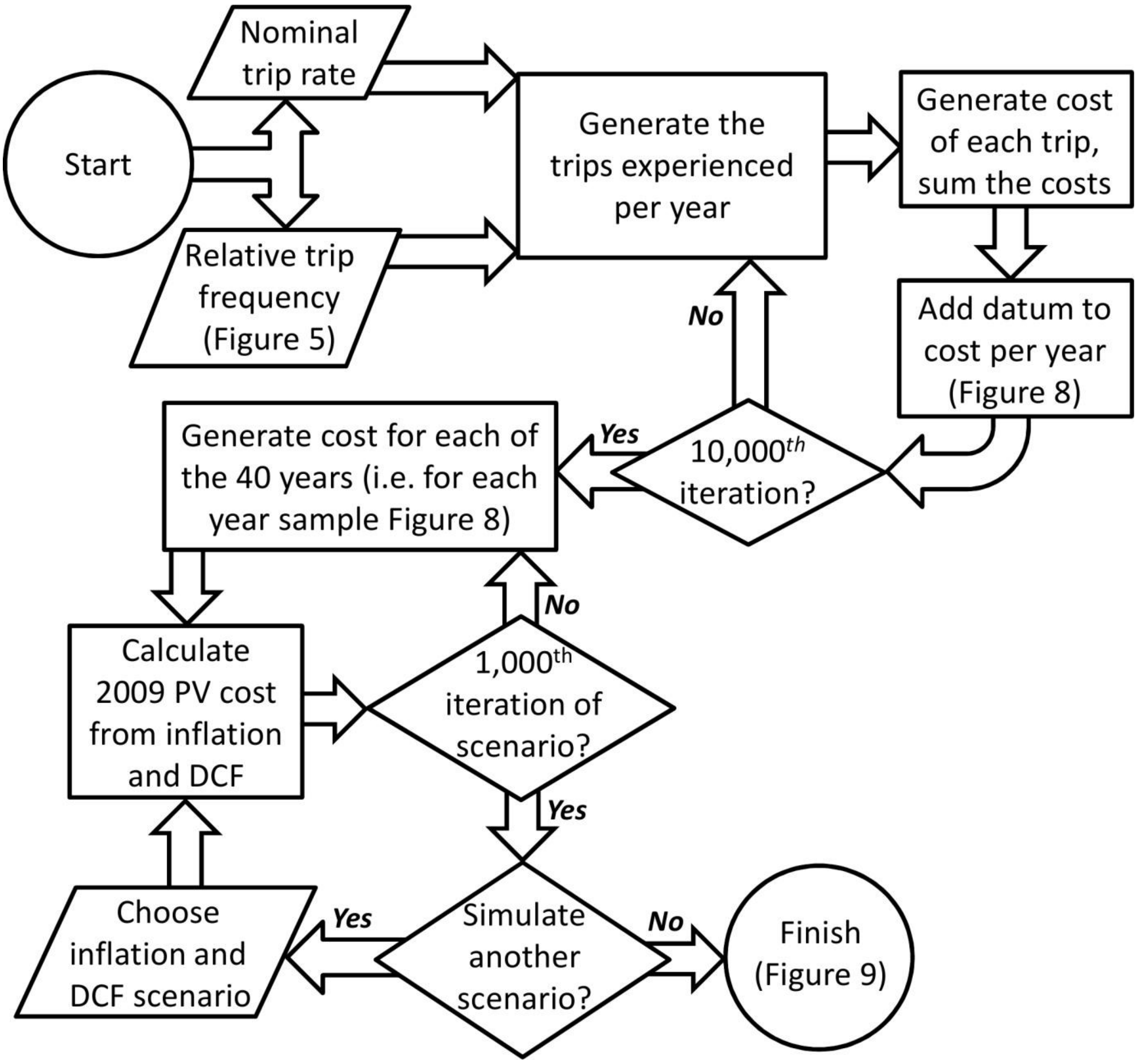

Figure 10: Flow diagram depicting the process of identifying the PV cost of failure for an ADSR that nominally experiences unplanned accelerator system shutdowns for 1% of its life. The first stage of iterations identifies the cost of failure per year of operation. The second stage identifies the lifetime 2009 PV cost of failure.

6.2 ADSRs – Scaling the Cost of a Single Percentage Point Failure Rate to a User-Selected Rate

For a selected inflation and discount rate, the cost of a nominal trip rate of 1% can be scaled by the factor, X, which is a user-chosen failure rate. The ADSR operational availability and accelerator system reliability coefficient determine X, see next paragraph. The cost of failure for a 1% trip rate, $CoF_{1\%}$, scales to the cost of failure for the chosen failure rate, CoF_X, by the equation: $CoF_X = \sum_0^X CoF_{1\%}$. Handling the calculation as a summation of the number of percentage points and not a multiplication of the total (i.e. $CoF_X = CoF_{1\%} \times X$) is necessary in order to calculate the standard deviation more accurately, the mean is identical in each approach.

To identify the failure rate, X, the reader chooses an ADSR Operational Availability, OA, (the proportion of the year that the ADSR is scheduled to sell electricity for) and accelerator system reliability coefficient, R, both expressed as percentages. The failure rate is then given by: $X = OA \times (1 - R)$. The reader can determine the predicted 2009 PV cost of failure for the entire lifetime of a single ADSR facility by the following four steps: (1) choose an ADSR operational availability, accelerator system reliability coefficient, electricity inflation rate and discount rate; (2) use Figure 9 to identify $CoF_{1\%}$ for the selected inflation rate and discount rate; (3) identify the value of X from the chosen operational availability and reliability coefficient; and (4) scale $CoF_{1\%}$ to CoF_X using the determined factor X.

There are limits to the accuracy of modelling the cost of failure in such a way that the reader is later able to scale the cost to their needs. If X is not an integer then the histogram distribution in Figure 8 will differ for the fractional component of X. This will perturb the standard deviation by increasing it. The inconsistency is at its maximum at the midpoint between integers, but even at this extreme the effect is not significant when compared to the uncertainty associated with inflation and discount rates, and the other assumptions. The scalable approach to modelling is also limiting in that the spectrum in Figure 9 is only applicable to facilities with a lifetime of 40 years. However, for longer lifetimes than 40 years, the PV of cash flows in the years greater than 40 would have an insignificant impact on the total PV cost of failure.

7.0 ADSRs – Examples of the Potential Cost of Failure

In order to contextualise the potential cost of failure, three example situations under which an ADSR may operate are detailed in this section of the paper. All cases assume that the ADSR(s) are operated by a combined manufacturer and energy company. For each, the total 2009 PV cost of failure is identified.

7.1. The European Experimental Accelerator Driven System Project

As a part of the European Commission's Framework Programme 7, studies have preliminarily investigated the application of accelerator-driven nuclear reactor technology in partitioning and transmuting radioactive waste[3]. The goal of this process is to reduce the quantity of high level radioactive waste, which results from the nuclear fission power generating industry. The issue of poor ADSR reliability has been approached by this working group in Work Package 3 (WP3) of their project (Pierini *et al.* 2003). The Preliminary Design Studies – eXperimental Accelerator Driven System (PDS-XADS) team detail an approach to accelerator operation using a three-stage LINear ACcelerator (LINAC) design involving a superconducting LINAC. Through de-rating, fault tolerance and redundancy of a highly modulated accelerator system, they believe it is possible to design a system that experiences trips of duration greater than one second only 5 times per year. An ADSR with an accelerator of the reliability of contemporary accelerators (operating at a capacity factor of 75%) would expect a mean of 210 trips per year for the time range >30 minutes to 24 hours. The inclusion of trips in the range >1 second to 30 minutes will significantly increase this total. The PDS-XADS team already includes trips of duration <30 minutes in their assessment.

Over 40 years, a trip rate of 5 per year corresponds to 200 trips in the facility lifetime. If reliability were achieved such that there are only 5 trips greater than 1 second per year and assuming that the current –2/3 power law relationship for trip frequency remains true after such a degree of engineering, the majority of the 200 trips will be significantly less than one full 30 minute period in duration. In this eventuality the cost of failure would be nearly zero. After such an extreme degree of engineering, the assumption made in this work of a –2/3 power law relationship for trip frequency may no longer be applicable; also, although the accelerator may very quickly be available once again, a reactor core restart following an ADSR shutdown may take considerably longer; and thirdly, there may be rules in place that forbid the restart of a subcritical reactor core without external approval from the regulator, this will take time.

Assuming that the –2/3 power law is not applicable, the cost of failure has been simulated by assuming that all 200 shutdowns are 24 hours in duration. In this limit, the lifetime cost of failure (prior to accounting for inflation and DCF) is £164 million, the PV cost of failure is presented for a range of inflation and discount rates in Figure ***11***. For a central case in the simulated scenarios (inflation rate of 3% and DCF of 8%), this corresponds to a 2009 PV cost of failure of £75 million.

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[3] *See European Commission Framework Programme Contract Number: FIKW-CT-2001-00179*

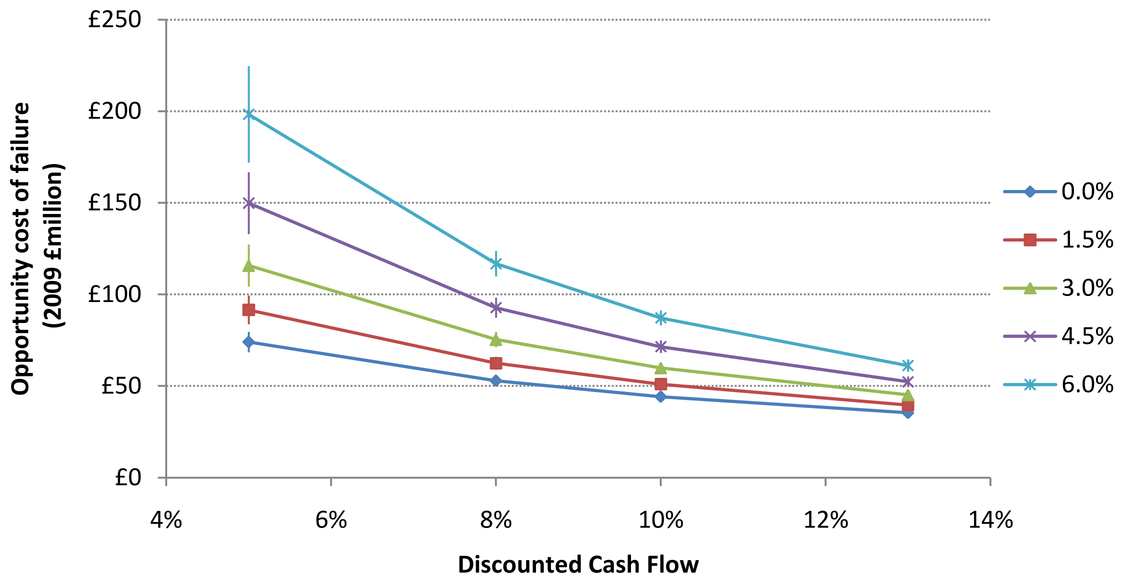

Figure 11: The 2009 PV cost of failure predicted to be incurred by an ADSR that experiences exactly 5 trips per year of 24 hours in duration for a 40 year operational lifetime. The legend refers to the range of simulated real inflation rates.

7.2 A Single ADSR with Current day Accelerator Availability

To improve reliability and hence reduce the cost of failure, Research and Development (R&D) is required and higher component costs may result. If the cost of the R&D and components exceeds the saving made by avoiding failures, then it is not in the interests of a commercial company to pay for them. To a private operator the value of an ADSR is optimised by only performing R&D when its cost is less than the cost incurred by the failures.

To realise a device as reliable as the PDS-XADS specifications, significant R&D is required. Determining the cost of failure due to an accelerator system with present day specifications defines the upper limit a private company should spend on R&D to optimise the value of an ADSR. This upper limit is the cost of failure difference between present day technology and the PDS-XADS system.

Assuming the ADSR will operate at a capacity factor of 75% for a 40 year operational life and a reliability coefficient of 90%, as is achieved by seasoned contemporary accelerator systems, a facility would suffer unplanned shutdowns for $X = 9.7\%$ of its lifetime, i.e. the mean cost of failure for chosen inflation and discount rates is given by the spectrum in Figure 9, scaled by a factor of 9.7.

For one of the central presented scenarios (an inflation rate of 3% and a DCF of 8%), it is predicted that the PV cost of failure of a contemporary accelerator system would be 9.7 $\times$ £53 million (£514 million) over the facility lifetime. Comparing this to a device that experiences five 24 hour long beam shutdowns per year (PV cost of failure: £75 million), it is concluded that it is financially not worth spending more than £439 million (2009 £) on improving contemporary accelerator technology to the performance specified by the PDS-XADS group. This R&D budget will increase if regulations or reactor core restarts require more time than accelerator repairs need and the budget will decrease if the –2/3 power law does continue to represent the rate at which beam trips occur in an accelerator which has had its reliability improved to a rate of 5 per year.

7.3 The Value of Engineering Improved Reliability for an ADSR Fleet

With regard to the value of engineering improved reliability of an accelerator system, the benefit of the R&D to the private company is increased as an increasing number of ADSR power stations are constructed. To better identify the maximum expenditure on R&D for which value is still added to an ADSR, a fleet is considered.

The total cost of failure for a fleet of ADSRs is not a direct multiplication of the single facility cost by the number constructed, except in the unlikely case that all of the ADSRs are built in parallel. The value of spending money on R&D in the present to increase the reliability of the n^{th}-of-a-kind ADSR in a given future year is increased as a function of the real electricity inflation rate and then decreased as a function of the DCF rate.

To aid in quantifying the value of R&D expenditure, an example scenario for the roll-out of a fleet of 10 ADSRs has been simulated. The structure of the fleet roll-out is detailed in Table 2. This analysis has been performed in the same way as for a single ADSR. The reader may scale the cost of failure from $CoF_{1\%}$ to any unplanned shutdown rate of their choosing. A range of inflation and discount rate scenarios for the 2009 PV cost of failure is presented in the spectrum in Figure 12.

This cost projection assumes that all ADSRs have identical capacity factors, are equally reliable and operate for 40 years. For comparison, in the spectrum in Figure 13 the cost that would be incurred by a fleet of ADSRs with the specifications of five 24 hour in duration trips per year is presented.

Facility Number	How long in years after the 1st facility before it goes online
1st	0
2nd	2
3rd	3
4th	4
5th	4
6th	5
7th	5
8th	6
9th	6
10th	6

Table 2: A scenario for the timing of the roll-out of a fleet of ADSR facilities.

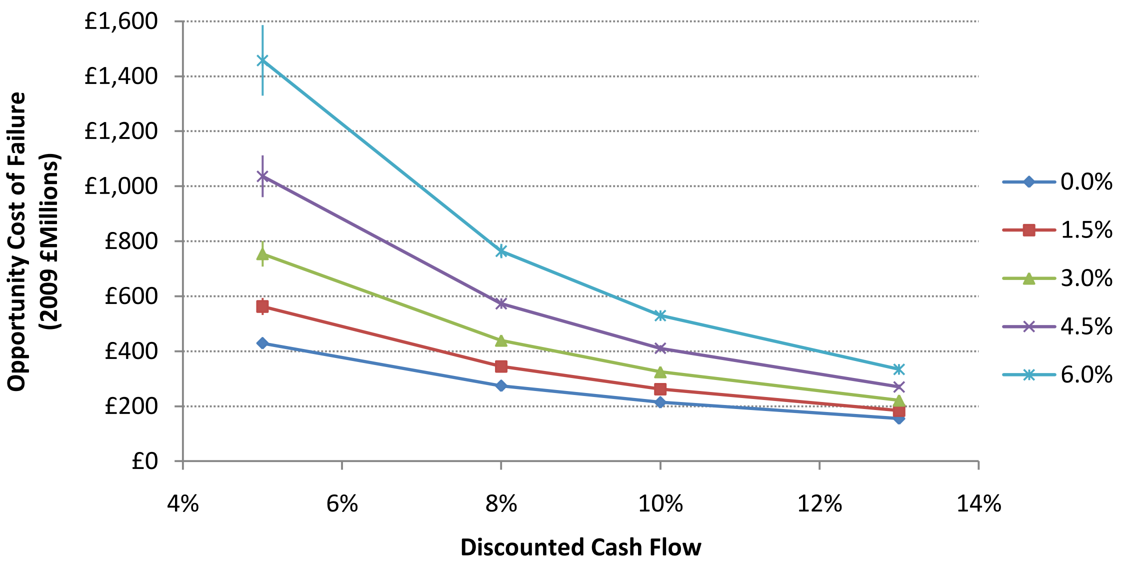

Figure 12: The cost of failure for a fleet of ADSRs (see text) that each experience a nominal unplanned accelerator system failure rate of 1% of a 40 year life. The legend refers to the range of inflation rate scenarios that have been simulated.

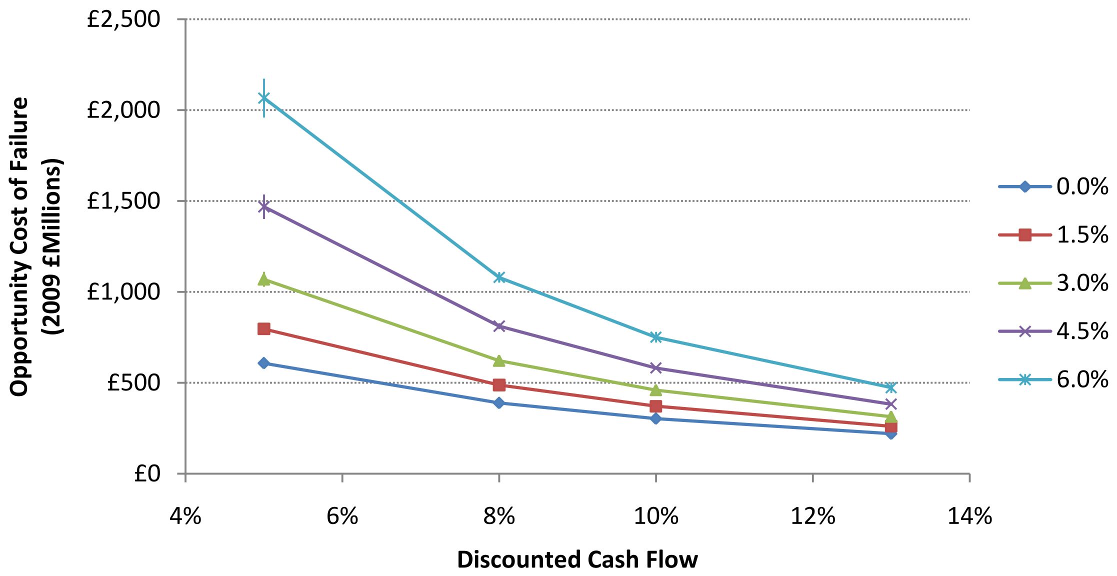

Figure 13: The cost of failure for a fleet of ADSRs (see text) that each experience exactly 5 trips per year of duration 24 hour for a 40 year life. The legend refers to the range of inflation rate scenarios that have been simulated.

8.0 Summary

A financial model that predicts the contractual cost of an instantaneous unplanned shutdown of a power station to an electricity supplier has been demonstrated. The model is based on historical electricity data and uses a probabilistic Monte Carlo approach to simulating the MIP, SBP and success rate of arranging short-term contracts. Within this analysis it has been demonstrated that, historically unplanned shutdowns of power stations within the UK National Grid have not had a significant impact on the SBP during the failure. The mean opportunity cost of failure (in 2009 money) of a 24 hour shutdown is predicted to be £883,000.

Although applicable to all power generators, the methodology used in this model demonstrates one way of eliciting information regarding the economic factors affecting intermittent power generators. This is a potentially useful tool to have at the disposal of people involved in commercial power sectors, especially in consideration of the increasing role intermittent technologies are expected to have in future power markets.

In the context of the model, a case study example of one potential future power generator, the ADSR nuclear power station, has been examined. The ADSR design poses serious engineering challenges, with the reliability of the accelerator system being prominent among them. Poor accelerator reliability causes frequent ADSR shutdowns; each beam trip has a significant financial cost associated with it, reducing the value of a commercial ADSR to a private investor.

The cost of failure has been predicted for a power generator with a reliability profile of contemporary particle accelerator systems, selling 600 MWe to the UK electricity market. The costs of individual failures of durations ranging from >30 minutes to 24 hours have been determined. It has also been identified that, for an ADSR, the cumulative cost of all trips of a given duration is greater than the cumulative cost of all trips of a longer duration.

The lifetime cost of failure for a single ADSR and a fleet have been identified for an accelerator system that experiences unplanned shutdowns for a nominal 1% of a 40 year lifetime. The nominal cost can be scaled by the reader to their needs by their choosing an ADSR capacity factor, accelerator system reliability coefficient, electricity inflation rate and a discounted cash flow rate. From those inputs the PV lifetime cost of failure for an ADSR with design specifications of their choosing can be determined by a four-step process. There is wide potential for this process to be applied to other forms of power generators.

The ADSR accelerator design as proposed by the PDS-XADS team (Pierini *et al.* 2003) has been discussed. It has been determined that for a single ADSR (at a capacity factor of 75%, using an inflation rate of 3%, and a DCF rate of 8%) a private investor should not spend more than £439 million (2009 £) on eliminating unplanned accelerator shutdowns between contemporary reliability levels to that of five 24 hour beam shutdowns per year. For a fleet of 10 ADSRs, the expenditure should not exceed £3,646 million. The cost incurred during the restarting of the ADSR system is not taken into account in these budgets, nor are changes in the running costs due to failures. The cost of trips of durations <30 minutes are also not included in the quoted numbers. These could potentially contribute significantly to the cost of failure associated with each trip, this is because the regulations with regard to restarting an ADSR following an unplanned shutdown will strongly influence the duration an ADSR is shutdown for following a beam trip.

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Appendix – Representing the Arrangement of Short-Term Contracts

The following describes the way in which private short-term contract arrangements have been modelled.

In the UK BETTA system, 4 hour contracts may begin at the intervals: 03:00, 07:00, 11:00, 15:00, 19:00 and 2300. Two hour contracts may also begin at these times, and also at the midpoint of the intervals between these times. Thirty minute contracts may begin at the beginning of any period of the day. Trading of short-term contracts ceases 1 hour prior to delivery. The representative modelling uses a two-stage approach to simulate the signing of contracts. First, probabilities of success are assigned to represent traders arranging contracts of durations 30 minutes, 2 hours and 4 hours (1, 4 and 8 periods), see Table 3 for details of the probabilities. The probability of success in arranging a contract has been set to linearly increase as the time following the commencement of a failure increases.

It is known that initially following the commencement of a failure a company has no short-term contracts arranged (and that it is not allowed to arrange them for during the first hour of failure) and communication with industry operators (Hall 2009) indicates that after 24 hours usually all of the electricity is purchased from short-term contracts. It has been assumed that the amount of electricity purchased from private contracts increases linearly between hour 1 and 24. The specific input probabilities and contract sizes used in this section of the model have not derived from measured data; they are arbitrary numbers, chosen to give a linear, stochastic and highly volatile distribution. The potential for mismatch between the model and reality is expected to be less than a factor of 2. The overall impact of this potential error is significantly less than a factor of 2, as it affects only the difference in price between the SBP and MIP, and not the absolute price paid for electricity.

	Probability of agreeing contracts		
30 minute period since the failure began	**30 minute contract**	**2 hour contract**	**4 hour contract**
1 – 2	-	-	-
3 – 24	50%	50%	50%
25 – 47	75%	75%	75%

	Maximum contract size (MWh/period)		
30 minute period since the failure began	**30 minute contract**	**2 hour contract**	**4 hour contract**
1 – 2	-	-	-
3 – 12	100	75	50
13 – 24	150	125	100
25 – 47	200	175	150

Table 3: Criteria for arranging short-term contracts during a failure. The top table shows the probability of arranging contracts 1, 4 and 8 periods in duration. When contracts are agreed, the bottom table details their maximum size. The actual size is derived from a uniformly distributed random integer with a minimum value of 1 MWh/period.

At each of the intervals at which BETTA allows a contract to begin, the model gives a chance for the operator to succeed in arranging the contract, by means of a random number generator. A detailed example follows of a 14 hour (28 periods) failure that begins at 12:00: Gates have already closed for the first two periods following the commencement of a failure (i.e. at 12:00 and 12:30), no private contracts may be arranged at these times. The model gives a 50% chance of arranging single period contracts in each period from the 3rd to the 24th (i.e. at 13:00 and every 30 minutes until 23:30, inclusive), and there is a 75% chance of arranging them in the 25th to 28th periods (at 00:00 and every 30 minutes until 01:30, inclusive); in parallel, at the 3rd, 7th, 11th, 15th, 19th, 23rd periods (13:00, 15:00, 17:00, 19:00, 21:00 and 23:00) there is a 50% chance of arranging a contract that will last

2 hours and in the 27th period (01:00) there is a 75% chance; finally 4 hour contracts have a 50% chance of being arranged at the 7th 15th and 23rd periods (15:00, 19:00 and 23:00).

The second stage of the representative modelling determines the size of successfully agreed contracts from the first stage. The quantity of energy purchased is determined by a uniformly distributed random integer, which has a minimum value of 1 MWh/period. The maximum value is determined as a function of time elapsed since failure commencement and duration of the contract, see Table 3 for details. For example, if the model has determined that a 2 hour contract is agreed in the 17th period following commencement of a failure, the size of that contract will be a randomly generated number in the range (1-125) MWh/period; it will last 4 periods.

When simulating the arrangement of these contracts, in highly successful iterations there can be more energy than the required 300 MWh/period available for purchase. In these cases the ADSR operator purchases no more than the required 300 MWh/period. It preferentially accepts 4 hour (8 period) contracts over 2 hour (4 period) ones, and 2 hour contracts over 30 minute (1 period) ones. For contracts that are still active after fixing the ADSR, it is assumed the operator sells the excess electricity back to the market at the same price at which it purchased it.