Real Options Valuation of Fusion Energy R&D Programme

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Abstract

This paper aims to perform a real options valuation of fusion energy R&D programme. Strategic value of thermonuclear fusion technology is estimated here based on the expected cash flows from construction and operation of fusion power plants and the real options value arising due to managerial flexibility and the underlying uncertainty. First, a basic investment option model of Black-Scholes type is being considered. Then, a fuzzy compound real R&D option model is elaborated, which reflects in a better way the multi-stage nature of the programme and takes into account the imprecision of information as one of the components of the overall programme uncertainty. Two different strategies are compared: "Baseline" corresponding to a relatively moderate pace of fusion research, development, demonstration and deployment activities vs. "Accelerated" strategy, which assumes a rapid demonstration and massive deployment of fusion. The conclusions are drawn from the model calculations regarding the strategic value of fusion energy R&D and the advantages of accelerated development path.

Key words: thermonuclear fusion, R&D, evaluation, real options

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1. Introduction

Providing safe, clean and economically affordable energy supply is essential for meeting the basic needs of human society and for supporting economic growth. Nowadays, in the face of energy security challenge, national governments are trying to implement different policies aimed at liberalisation of energy markets, diversification of energy supply mix, enhancement of energy efficiency, encouragement of investments in energy infrastructures, and promotion of innovation in energy sector. In a longer term perspective, the latter point becomes increasingly important, because the world relies currently on the consumption of fossil fuels, and the development of new environmentally benign and resource unconstraint energy technologies is vitally needed. In line with this strategy, the leading world economies pursue a joint R&D programme on thermonuclear fusion technology, which represents numerous advantages due to its inherent safety, avoidance of CO_2 emissions, relatively small environmental impact, abundance and world-wide uniform distribution of fuel reserves.

Considering the importance of the projected benefits of fusion, the questions are raised whether the current level of financial support is sufficient, and what could be the optimal strategy to proceed with further R&D and demonstration of fusion technology given the time span, potential risks, and the opportunity cost of capital. To put these questions into the context, one has to consider the current trends in energy R&D funding, which has seen a drastic decline (ca.50%) over the last three decades and that started to gradually increase only in recent years. The liberalisation of energy sector poses additional problem because of the so-called spillover effects, meaning that the firms are not able to appropriate the integral results of their R&D investments, and hence their incentive to finance R&D projects is below the socially optimal level. In this situation, it is expedient to analyse more thoroughly the potential benefits from increasing the public funding of future fusion R&D activities. In order to be consistent such examination would require a comprehensive socio-economic evaluation of the whole fusion research, development, demonstration and deployment (RDDD) programme.

At the present stage, prospective analyses of fusion have been emphasised mainly on the investigation of technological issues, estimation of direct and external costs of fusion power plants, and assessment of their potential role in future energy systems. Meanwhile, an overall economic appraisal of fusion RDDD programme, embracing all of its stages, is still extremely challenging, if even possible. The primary difficulty is explained by the fact that projections need to be made over very long period of time, extending over 100 years, with a multitude of uncertain parameters. Another problem relates to the methodology of cost-benefit analysis itself, which oftentimes ignores the hidden value of R&D projects arising due to the possible flexibility in managerial decisions.

In fact, throughout the course of any R&D project, its prospective cash-flows can be significantly improved by a pro-active management of different implementation stages, e.g. expanding the R&D scope and production if market conditions are favourable, or abandoning if R&D process has reached a deadlock. As a result, the strategic value of any R&D project normally exceeds its net present value (NPV) calculated with the traditional discounted cash flow (DCF) method. Although this strategic approach to capital budgeting, known as *real options*, has been propagated recently in several publications dealing with appraisal of lumpy irreversible investments, its practical application in the context of fusion RDDD programme has not been mastered yet to the required extent.

Accordingly, the main objective of this paper consists in the estimation of the real options value of fusion R&D programme subject to different managerial strategies throughout demonstration and deployment stages. The strategic "expanded" net present value of fusion R&D programme is determined according to flowchart shown in *Figure 1* using an integrated modelling framework, which includes the following components: (1) assessment of the potential strategies for deployment of fusion power plants based on the simulation of multi-regional long term electricity supply scenarios with PLANELEC model; (2)

deterministic NPV calculation according to three selected scenarios; (3) calculation of the expected NPV of fusion RDDD programme in a stochastic probabilistic setting; (4) estimation of the real options value of fusion RDDD programme and analysis of different implementation strategies using several real options models of increasing degree of complexity.

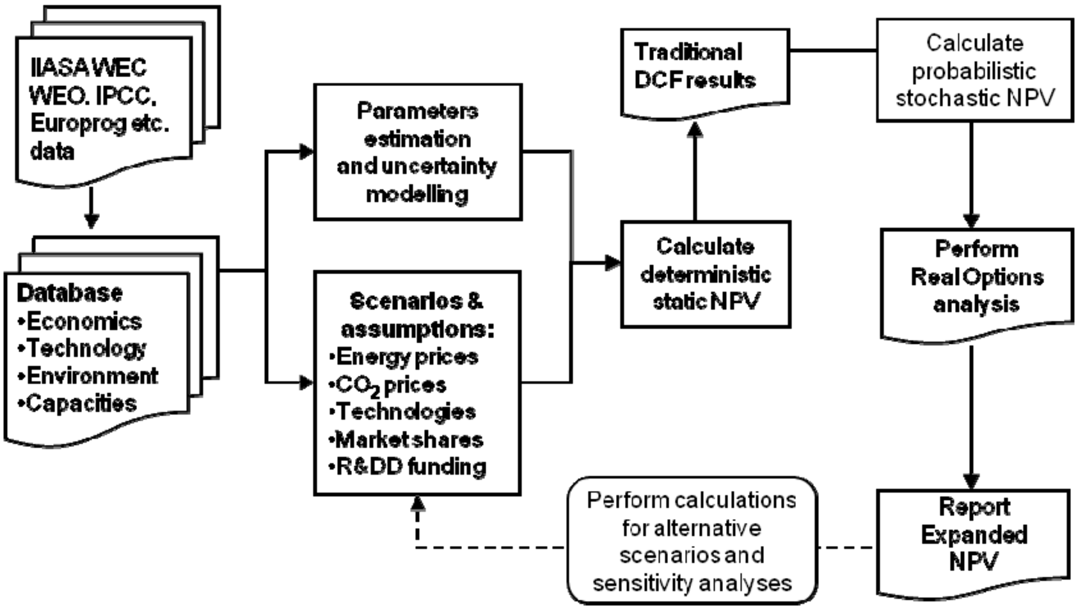

Figure 1. Methodology flowchart

The reminder of this paper is structured as follows. Next chapter provides a brief overview of fusion R&D programme, its up-to-date costs, and the current prospects for next step developments and milestones. Chapter 3 presents the specifics and main methodological approaches suitable for evaluation of long-term energy R&D programmes, such as fusion. Three different real options models ranging from basic investment "call" option model to more complex compound option models using both crisp and fuzzy number formats are specified in Chapter 4. Main numerical assumptions, data inputs and model results are provided in Chapter 5. Finally, the main findings, conclusions and limitations are summarised in Chapter 6.

2. Overview of fusion R&D programme

The history of scientific research on thermonuclear fusion technology accounts already for more than half a century. As shown in *Figure 2* there exist two main approaches to the confinement of plasma and accordingly to the design of fusion energy installations: magnetic confinement and inertial confinement. The magnetic confinement approach aims at obtaining fusion power in steady-state plasmas, similar to the gravitational confinement, which assures ignition in the stars. The inertial confinement aims at obtaining fusion energy in a pulsed manner from micro-explosions repeated at high rate according to the same principle as used in nuclear weapons (IFRC, 2005). The two approaches further diverge into several potential configurations.

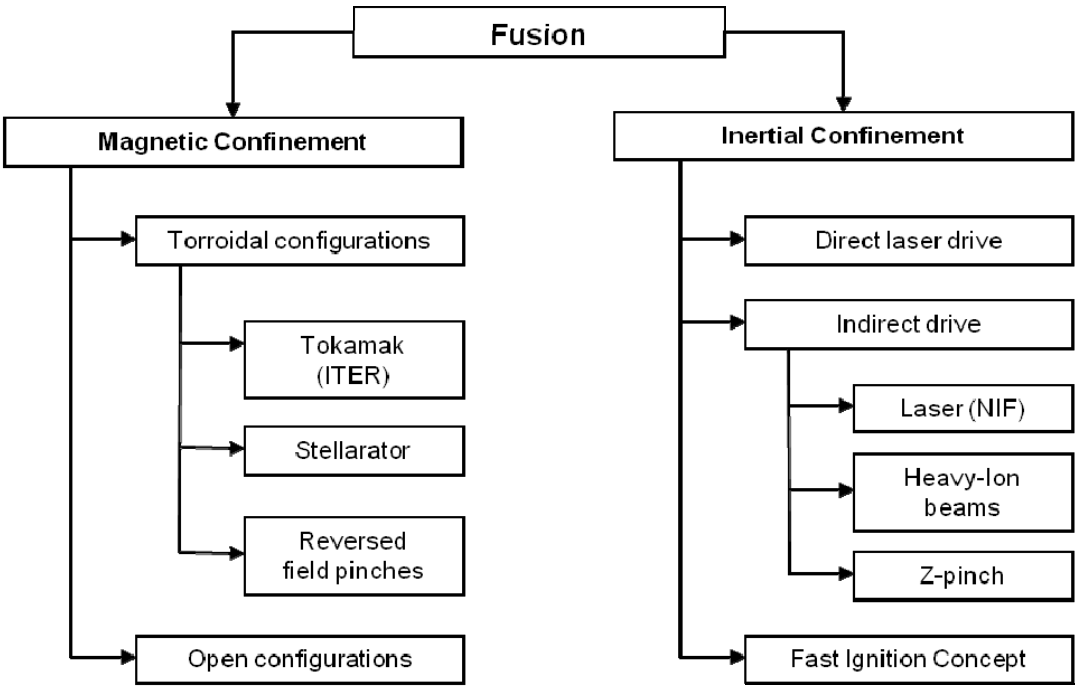

Figure 2. Main approaches to the confinement of fusion reaction

(Source: FESAC, 2004; IFRC, 2005)

Both research lines (magnetic & inertial confinement) are currently pursued by the international scientific community through the construction of large scale experimental facilities, such as JET, NIF, Tore-Supra, ASDEX, TCV, Wendelstein, etc. At the present stage, the research on *Tokamak* concept has achieved the highest progress, and this configuration was chosen for practical implementation at ITER experimental reactor project, which should demonstrate together with International Fusion Materials Irradiation Facility (IFMIF) the scientific and technical feasibility of mastering fusion reaction on the scale of the power plant. The goal beyond ITER / IFMIF is to demonstrate the production of electricity in a demonstrator fusion power plant (DEMO). Further continuation of this reactor-oriented programme would allow for building the first generation of commercial fusion power plants in around 2050.

The most recent developments in fusion R&D focus on the so-called *Fast Track* approach and the proposal of a *New Paradigm*. In 2001 the "King report" analysed the Fast Track fusion development path concluding that demonstration (DEMO) and commercial prototype (PROTO) stages could be combined into a single step that should be designed as a credible prototype for a power-producing fusion reactor, although in itself not fully technically and economically optimised (King et al., 2001). The technological, economical and organisational implications of accelerated development of fusion were analysed in more details by Cook et al. (2005), who proposed a "road map" for reference Fast Track programme and its even more ambitious variant. It was concluded that in a reference case, high availability operation of DEMO, confirming all the information needed for construction of the first commercial power plant, could occur thirty-seven years after the decision to go ahead with ITER and IFMIF, and the first commercial plant would operate forty-three years after this decision. Furthermore, the inclusion of several ancillary devices and projects ("buttresses"), such as Component Test Facility (CTF), in a variant programme could allow for cutting four years from these dates.

The proposal of a New Paradigm makes another step forward with the idea that fusion R&D and demonstration process could be advanced as much as possible by using already known low-activation materials, such as Eurofer, and avoiding advanced modes of plasma operation. With this approach the fusion electricity production would be demonstrated much sooner (in about 25 years or even in 20 years with the most aggressive approach) by a relatively modest performance "Early DEMO" or "EDEMO" reactor (EC, 2007a). A recent report of the European Commission in view of the preparation of the European Strategic Energy Technology Plan recommends that the present programme should be reinforced with an objective to ensuring success and minimising risk through more intense efforts in technology R&D and increased investments in plasma physics devices that will contribute to the accompanying programme during ITER construction (EC, 2007b).

As regards the costs of fusion R&D activities incurred so far, according to the data cited in Grunwald et al. (2003) the total expenditures on fusion research in OECD countries over the period from 1974 to 1998 amounted to €30 billion, and the annual investments in civilian nuclear fusion research in 2000 were estimated at €1.4 billion. The values of the same order of magnitude are given in IEA briefing paper: over the decade 1990-1999 the governmental funding of fusion R&D in IEA/OECD countries totalled US$ 8.9 billion (in 2001 prices and exchange rates) that roughly corresponds to US$ 0.9 billion per year (IEA, 2003). Some data regarding the total fusion R&D funding during the earlier stages dating back to the 1950s can be found in Rowberg (1999) who estimated total U.S. congressional funding of magnetic fusion R&D during the period 1951-1973 at US$ 2.5 billion and during the period 1974 – 2001 at US$ 13.6 billion (in US$$_{2000}$). Based on these estimates, it is reasonable to assume that up to now the total OECD public funding of civilian fusion R&D did not exceed €50 billion in current prices.

The future cost of fusion RD&D can be extrapolated based on the existing estimates of the investment and operation costs of ITER/IFMIF facilities and assuming some prudent hypotheses about the scale up of these costs for DEMO/EDEMO reactors. So, the agreed budget of ITER amounts to approximately €10 billion, of which €4.6 billion will be allocated to the construction phase (until 2015) and €4.8 billion will be spent during the operation phase (2016 – 2035). The rest of the budget will go to site preparation, ad-hoc design and dismantling (Fiore, 2006). These figures should be complemented by the costs of building and operating IFMIF (ca. €600 mln) and pursuing other fusion-related R&D

activities, including basic science and research on alternative design configurations. According to Grunwald et al. (2003) the investment cost of DEMO is estimated at €8 billion, and the total cost of fusion RD&D over next 50 years could reach €60-80 billion. In a paper of Goldston et al. (2006) the total cost of rather ambitious fusion development plan presuming construction of several competitive DEMO power plants by 2035 amounts to US$ 107 billion.

3. Evaluation of Energy R&D Programmes

Evaluation of fusion technology from its theoretical inception, back in 1950s, to practical deployment expected in the second half of this century is an extremely challenging task because of the large uncertainty and multiple methodological problems. In recent years a body of literature has emerged aiming to provide an appropriate methodological framework for evaluation of publicly funded research (see e.g. Georghiou et al., 2002; Tassey, 2003; Hong & Boden, 2003). The recommendations regarding specific approaches to evaluation of energy R&D programmes were given in Carter (1997), NRC (2005), EC (2005). Meanwhile, the thermonuclear fusion represents a particular difficulty for evaluation because of its very long development cycle, technological complexity and the uncertainty with respect to future technology performance and market conditions.

The expected net economic benefits from development and deployment of fusion will depend on the multitude of factors that include projected energy demand; market share of fusion; specific investment, O&M, fuel costs of fusion and competing technologies; future wholesale prices of electricity and other energy services that can be supplied by fusion; environmental policy regime; availability of public support to initial deployment of fusion; etc. Furthermore, the choice of discount rate may also have a substantial impact on the estimated present value of fusion technology. Considering a very long time span of fusion RDDD programme and the extreme variety of technical, economic and structural indicators that have to be taken into account, it should be recognized that the results of any evaluation would be confronted with a high degree of uncertainty. Accordingly, one of the major challenges in the economic assessment of fusion consists in adequate treatment of the potential risks and various types of uncertainty underlying the modelling assumptions and input data.

The main risks in fusion RDDD are confined essentially to the *performance risk*, i.e. the situation when programme fails to achieve its goals in terms of delivering a practically feasible technology that may supply electrical power on continuous basis at a reasonable cost comparable with the costs of alternative electricity supply options. Another type of risk is represented by the *time risk* meaning that the programme could be further delayed due to some technical problems. The time risk has dual nexus with the *cost risk*: on the one hand, extension of the programme timeline inevitably will require some additional funding; on the other hand, increased funding during the demonstration stage may lead to shortening the technology's time-to-market as it is advocated by the proponents of the accelerated approach to fusion development.

The uncertainties underlying the major types of risk mentioned above are most time *epistemic* by nature, i.e. they can be gradually resolved through the pace of fusion RDDD programme, as more and more scientific and technological knowledge is being accumulated. Meanwhile, some of the uncertainties involved in the evaluation of potential benefits from deployment of fusion power plants could be also *aleatory*, e.g. the future electricity price. Considering that fusion technology will have to fit into the future energy systems, the analysis of potential costs and benefits of fusion has to rely on sophisticated engineering-economic models, which are also confronted with multiple uncertainties, e.g. contextual assumptions, model structure and its mathematical specification, input data and modelling parameters. The evaluation is also facing uncertainty due to inaccuracy and vagueness of human judgements, which are required to collect and assess the necessary data based on the expert opinion. Finally, some pieces of information required for comprehensive cost-benefit analysis could be simply missing, such as the value of private companies' expenditures on fusion R&D that may be kept confidential.

Taking in to account the presence of different types of uncertainty in *ex ante* economic assessment of fusion RDDD programme, an integrated risk & uncertainty analysis framework has to be developed that should allow for representing in a transparent way the potential impact of different uncertain variables and interactions thereof on the estimated net present value of fusion technology. The approach advocated recently in strategic and operations management literature calls for employing a combination of two complementary tools: *scenario planning* and *real options* analysis (see e.g. Alessandri et al., 2004; Driouchi et al., 2009).

Scenario planning as a strategic management tool emerged in the second half of the twentieth century spurred by the needs of defining robust defence strategies in military environment (see Bradfield *et al.*, 2005). Later on, this approach was adapted for civilian use in corporations, with Royal Dutch/Shell scenarios being the most well-known example (see e.g. Schoemaker & van der Heijden, 1992; Shell, 2008). The scenarios are not necessarily forecasts nor visions of the desired future, but rather a well worked over answer to the question: "what would happen if…?" Normally, a set of scenarios is being elaborated, each of them representing one alternative image of how the future could unfold given the range of uncertainties and possible actions. Usually, the scenarios are formulated with the help of formal models, although a more intuitive qualitative approach based on expert opinion is also wide-present.

As discussed in Miller & Waller (2003) the scenarios approach has both strengths and weakness. The advantages concern mainly the possibility to carry out a comprehensive, detail reach, participative analysis of the business landscape emphasising on systemic linkages, uncertainties and contingencies. The major shortcomings consist in the difficulty to quantify scenario inputs and outputs, the risk of biases and the possible lack of consensus among the stakeholders. Another weakness of this approach is related to the rigidity of scenarios, meaning that they are not able to represent adequately the strategic value arising due to pro-active management of the investment projects in the face of uncertain economic environment.

This latter deficiency of scenario approach can be overcome by incorporating in strategic planning the methods of real options analysis. The basic feature of real options approach is that it allows for valuing managerial flexibility, i.e. the ability to take specific actions during the time frame of a given investment project, when the results of previous decisions are being played out and the situational context becomes more apparent. In doing so, the real options analysis considers investment or disinvestment decisions involving capital assets as financial call or put options that provide their holders the right but not an obligation to buy or sell a certain asset during a specified period of time. Without delving into the details of real options approach, it is important here to emphasise the complementary dimensions of both scenario and real options methods, which can be summarised according to Driouchi et al. (2009) as follows. On the one hand, scenario planning can set the landscape to explore the set of options available under different states of nature. On the other hand, real options analysis can advise on how to trigger the exploitation of these options, i.e. either via incremental commitment under favourable conditions or partial reversal in the face of adversity.

The indicative long-term energy scenarios can be formulated based on several well-known studies, which investigated the possible development paths of global energy systems in the context of international debate on greenhouse gas emissions and climate change mitigation. The scenario storylines and numerical projections developed in such publications as IIASA / WEC "Global Energy Perspectives" (Nakicenovic et al., 1998), IPCC "Special Report on Emissions Scenarios" (Nakicenovic & Swart eds., 2000) constitute a sound basis for further analyses. However, fusion as a potential electricity supply option did not receive yet the required attention. Therefore, in order to perform a comprehensive economic evaluation of fusion RDDD programme it is important to complement the existing scenario studies with a detailed assessment of the potential role of fusion power in future energy systems.

Some examples of such fusion scenario studies are represented by the works of Eherer et al. (2004) and Lechon et al. (2005). Using MARKAL-based integrated modelling framework they found that under tight environmental constraints[2] there exists a substantial market window for fusion, which can attain up to 30% of the global electricity production in 2100. Tokimatsu et al. (2003) using global energy-environment model LDNE arrived to the same potential market share of fusion in 550 ppm CO_2 emission cap scenario which, however, reduces to 20% in the case of limited tritium availability at initial deployment stage. Gnansounou & Bednyagin (2007) elaborated multi-regional long-term electricity supply scenarios using a least cost electricity systems planning model PLANELEC and came to the conclusion that under favourable conditions the market share of fusion power could attain up to 20 % in the most developed world regions. Finally, one of the rare examples of the overall economic assessment of fusion RDDD programme is given by the study of Ward et al. (2005) which applied probabilistic decision analysis and calculated the total discounted development cost of fusion technology in the range of US$ 10-20 billion with the total discounted future benefit of US$ 400-800 billion (fusion capturing 10-20% of the electricity market in 50 years time).

There is also a growing body of real options literature that deals specifically with the evaluation of energy R&D projects and programmes. So, Davis & Owens (2003) used real options analysis framework to estimate the value of renewable electric technologies in the face of uncertain fossil fuel prices. They have examined renewable technologies from both the traditional DCF valuation perspective, which does not consider strategic "insurance" value or optimal deployment timing, and the real options perspective. The key finding from their study is that renewable energy technologies hold a significant amount of value that cannot be detected by using traditional valuation techniques. Thus, in order to appropriately value these technologies and the benefits of continued R&D spending, advanced valuation approach such as real options analysis has to be adopted.

[2] Introduction of CO_2 emission caps in order to stabilise global concentration of CO_2 at 550 ppm.

Siddiqui et al. (2005) proposed a binomial lattice compound real options model for evaluating the benefits of US Federal research, development, demonstration and deployment programme for renewable energy technology improvement. They confirmed the idea developed in Davis & Owens (2003) that deterministic DCF analysis typically ignores the uncertainty in the cost of non-renewable energy; the underlying technical risk associated with R&D process; and the possibility for adjustment of R&D efforts commensurate with the evolving state of the world. By applying their real options model in the study of a stylised numerical example they have demonstrated that the option value of existing renewable energy technologies is sizable and it can be further significantly increased with the incremental 20-year R&D effort. The option value of R&D abandonment, however, was found to be relatively modest.

The study of Kumbaroglu et al. (2006) presented a dynamic programming real options model for policy planning that integrates learning curve information on renewable power generation technologies. Their model recursively evaluates a set of investment alternatives on a year-by-year basis, thereby taking into account the fact that flexibility to delay irreversible investment expenditure can profoundly affect the diffusion prospects of renewable technologies. The price uncertainty was introduced through stochastic processes for the average wholesale price of electricity and for input fuel prices. Through the empirical analysis it was found that in the absence of subsidies or other promotion policy instruments, market players can hardly be expected to invest in more expensive renewable energy technologies, especially in a liberalized electricity market environment. Therefore, financial incentives are needed in the short-term, in order to enable a more widespread adoption of renewable energy in the longer run.

Finally, some authors advocated the use of real options approach in the evaluation of fusion RDDD programme. Ott (1992) proposed several real options models of different degree of complexity for examining optimal investment policy for lunar He^3 fusion, the concept that seeks to collect the fuel for fusion reaction on the Moon surface. A more realistic terrestrial fusion technology is considered in the publications of Goldenberg & Linton (2006) and Goldston et al. (2006). Based on the real options analysis they conclude that fusion technology can become a cost effective electricity supply option and the whole fusion R&D is economically justified, since it may constitute an effective hedge against increased cost of conventional power generation using fossil fuels.

4. Real options models of fusion RDDD programme

In order to develop a real options model of fusion RDDD programme, one has to define first the managerial flexibility actions that can give rise to the strategic real options. Next, the main assumptions and data inputs need to be specified. For that purpose, a schematic view of fusion RDDD programme is elaborated, as shown in *Figure 3*, where p_i is the probability of success of R&D and "Demo" stages; T_i is the time to completion of each stage; C_i – construction and operation costs of experimental and demonstration facilities; K_F – investment and O&M costs of commercial Fusion power plants (FPPs); R_F – revenues from Fusion electricity sales.

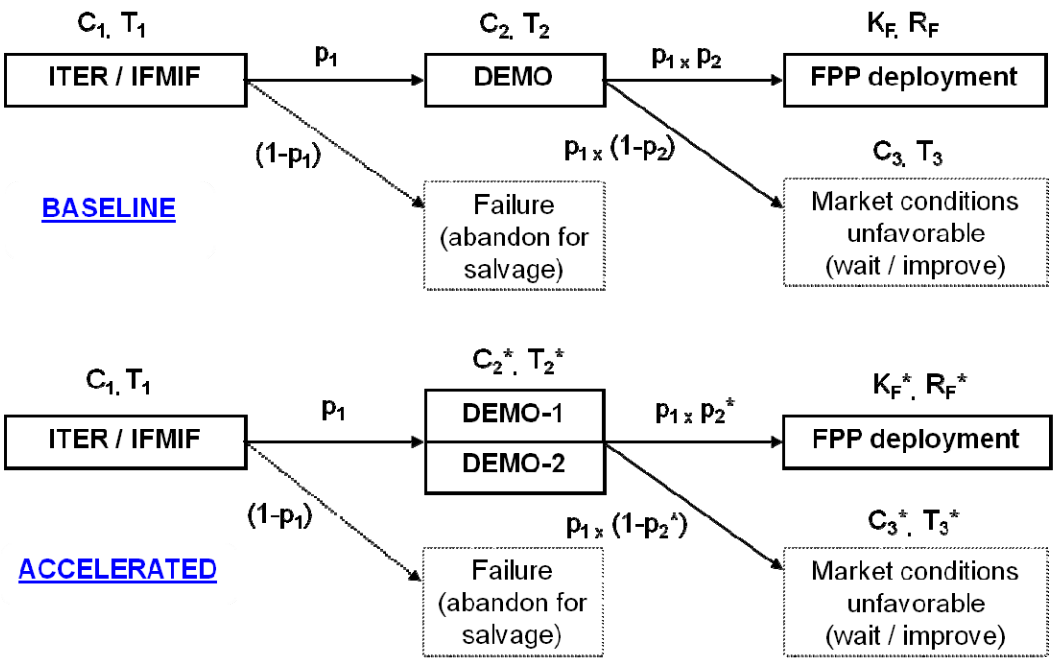

Figure 3. Alternative strategies to realisation of fusion RDDD programme

Two different strategies are considered. According to the "Baseline" only one DEMO reactor is built after completion of ITER / IFMIF stage, whereas in the case of "Accelerated" strategy (*) two or more DEMOs are built simultaneously. The basic idea behind this set up is that building several DEMO reactors of alternative design (e.g. Tokamak vs. Stellerator or any other concept), as it is advocated in Cook et al. (2005), may increase the probability of success of the demonstration stage [$p_2^* > p_2$]. Greater efforts are also likely to reduce the time to completion [$T_2^* < T_2$]. Accordingly, the "Accelerated" strategy is characterised by higher R&D and DEMO costs compared to the "Baseline" [$C_2^* > C_2$]. However, if the market conditions are favourable, then earlier availability of fusion technology may result in a higher value of the whole programme.

4.1 Basic investment option model

The first managerial action, which can be modelled as a real option, consists in the decision to invest in RD&D activities subject to the expected long term benefits from deployment of fusion technology. Such a model can be easily solved using a standard Black-Scholes formula for European call option, and it is helpful for gaining initial insight into the strategic option value of any R&D project. According to Newton et al. (2004) the model assumes that all RD&D expenditures can be treated as immediate, taking the place of the option premium, V. Commercial deployment may occur at a fixed time in the future, the expiry date, T, and the amount of money required to start deployment is a known constant, K. These investment costs take the place of the exercise price. The expected revenues from commercial deployment, X, can be considered as the current price of the underlying asset. It is composed of the expected income from fusion electricity sales, R, and the value of various fringe benefits such as spillover effects and other positive externalities. The remaining model inputs are volatility of the revenue stream, σ, and the risk-free rate, r. The function $N(d_i)$ is the cumulative probability distribution function for standardized normal distribution.

$$V = XN(d_1) - Ke^{-rT}N(d_2) \qquad (1)$$

$$d_1 = \frac{\ln\left(\frac{X}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \qquad (2)$$

$$d_2 = \frac{\ln\left(\frac{X}{K}\right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{T} \qquad (3)$$

Surely, the results that can be obtained with such a model will depend greatly on the input assumptions, especially regarding the future revenues and the costs of fusion power plants. The choice of risk-free rate, expiry time, and volatility may also have a substantial impact on the real option value. As regards the computational algorithms, both analytic approximations and closed form numerical methods (e.g. differential equations and binomial lattice methods) may be equally used, although the latter are usually preferred to value multi-staged projects exceeding two or three stages.

4.2 Compound real option model

Another approach that may reflect in a better way the multi-stage nature of fusion RDDD programme consists in modelling the process as a compound real option. In this case the managerial flexibility can be described as the possibility either to stop the programme or proceed to the next stage after completion of each predecessor step (e.g. the decision to build DEMO reactor after completion of tests at ITER/IFMIF experimental facilities; decision to start commercial deployment of fusion power plants after demonstration of technical and economical viability of fusion technology with DEMO reactor). This can be interpreted as series of “options on options”, i.e. the subscription of the first option (undertaking 1st stage R&D) gives its holder the right to acquire in the future another option (2nd stage R&D or demonstration), which in turn opens the possibility to reap further economic benefits through commercial deployment or just gives its owner the right to proceed to further R&D stages in the case of more complex projects.

Similar to the standard call option, the value of a compound option, or in other terms sequential exchange option, can be estimated using both differential equations and binomial lattice methods. In the first case, it is possible to use the solution algorithm proposed by Carr (1988) based on the earlier works of Margrabe (1978) and Geske (1979), see Appendix I. In the second case, the solution can be obtained by constructing binomial or multinomial lattices using commercially available software packages, e.g. Real Options Super Lattice Solver (Mun, 2009).

4.3 Fuzzy real option model

In recent decades, the fuzzy set theory has been developed and used to represent uncertain or flexible information in many types of applications, such as engineering design, production management, scheduling, etc. According to Wang & Hwang (2007) the fuzzy approach may provide an alternative and convenient framework for handling uncertain parameters such as project costs, benefits, timing, net present value, etc., while there is a lack of certainty in available data. This is because the possible ranges of project parameters and the most plausible values within these ranges can be estimated based on expert opinion. For computational efficiency, trapezoidal or triangular fuzzy numbers are used to represent the above uncertain parameters.

Fuzzy approach to real option valuation has been investigated in several publications. Carlsson & Fuller (2003) introduced a heuristic real option rule in a fuzzy setting, where the present values of expected cash flows and expected costs are estimated by trapezoidal fuzzy numbers. Tolga & Kahraman (2008) performed fuzzy multi-attribute evaluation of R&D projects using a real options model. Ran et al. (2004) proposed a fuzzy pattern for evaluation of compound R&D option. Collan et al. (2009) proposed a new fuzzy pay-off method for real option valuation implying that the weighted average of the positive outcomes of the fuzzy pay-off distribution is the real option value.

Grounding on the above literature, the following fuzzy real option model can be proposed for evaluation of fusion RDDD programme. Let us define, first, the main concepts and notations of the fuzzy sets and fuzzy numbers. Let X be the universe, $A=\{(x,\mu_A(x)), x\in X\}$ is a fuzzy set, where $\mu_A : X \mapsto [0,1]$ represents the degree of membership of x in A. The closer the value of $\mu_A(x)$ is to 1, the more x belongs to A. The λ-cut of A, $A^\lambda=\{x\in X, \mu_A(x)\geq\lambda\}$ is the set of elements x such that their membership function is greater or equal to the threshold $\lambda\in[0,1]$.

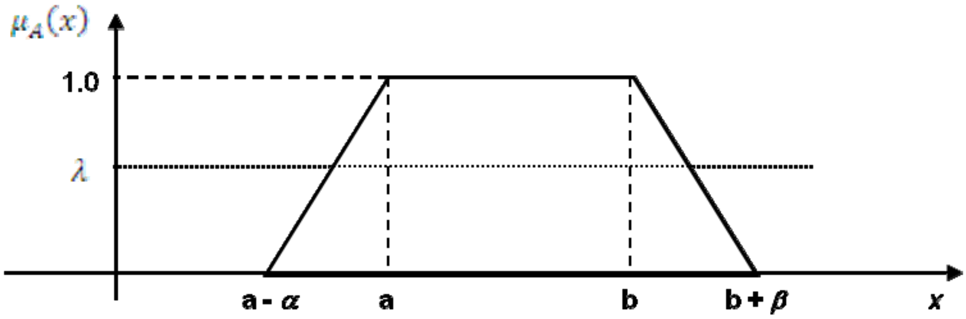

Figure 1. Representation of uncertain value with trapezoidal fuzzy number

A trapezoidal fuzzy number (*Figure 4*) is a normal and convex fuzzy set that can be defined by a quadruple $A=(a,b,\alpha,\beta)$, where α and β are respectively the lower and the upper bounds of the fuzzy number, and $[a,b]$ is the core. A trapezoidal fuzzy number is defined by the following membership function:

$$A(x)=\begin{cases} 1-\frac{a-x}{\alpha} & \text{if } a-\alpha\leq x<a \\ 1 & \text{if } a\leq x<b \\ 1-\frac{x-b}{\beta} & \text{if } b\leq x<b+\beta \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

A triangular fuzzy number is a special case of trapezoidal fuzzy number with a = b.

According to Carlsson & Fuller (2003) for a trapezoidal fuzzy number $A=(a,b,\alpha,\beta)$, its possibilistic mean (or expected) value can be calculated as

$$E(A)=\frac{a+b}{2}+\frac{\beta-\alpha}{6} \quad (5)$$

and the possibilistic variance as

$$Var(A)=\frac{(b-a)^2}{4}+\frac{(b-a)(\alpha+\beta)}{6}+\frac{(\alpha+\beta)^2}{24}. \qquad (6)$$

Suppose, the present value of expected revenues from deployment of fusion technology can be estimated using a trapezoidal fuzzy number, $\tilde{X}=(x_1,x_2,\alpha,\beta)$ meaning that the most possible values lie in the interval $[x_1,x_2]$, and the upward and downward potentials are given respectively by $(x_2+\beta)$ and $(x_1-\alpha)$. In the same manner, the present value of the expected costs during deployment and RD&D stages can be defined respectively as $\tilde{K}=(k_1,k_2,\alpha',\beta')$ and $\tilde{C}=(c_1,c_2,\alpha'',\beta'')$.

Then, the fuzzy real options value can be determined using the following formulae:

$$FV=\bar{\tilde{X}}N(d_1)-\bar{\tilde{K}}e^{-rT}N(d_2) \qquad (7)$$

$$d_1=\frac{\ln\left(\frac{E(\tilde{X})}{E(\tilde{K})}\right)+\left(r+\frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \qquad (8)$$

$$d_2=d_1-\sigma\sqrt{T} \qquad (9)$$

where, $E(\tilde{X})$ is the possibilistic mean present value of the expected revenues, $E(\tilde{K})$ is the possibilistic mean value of the expected deployment costs, and $\sigma=\sigma(\tilde{X})$ is the possibilistic variance of the expected revenues. Carlsson & Fuller (2003) proposed the following transform of the equation (7) into fuzzy numbers:

$$FV=(x_1,x_2,\alpha,\beta)N(d_1)-(k_1,k_2,\alpha',\beta')e^{-rT}N(d_2)= \qquad (10)$$

$$\left(x_1 N(d_1)-k_2e^{-rT}N(d_2),\ x_2 N(d_1)-k_1e^{-rT}N(d_2),\ \alpha N(d_1)+\beta' e^{-rT}N(d_2),\ \beta N(d_1)+\alpha' e^{-rT}N(d_2)\right).$$

In a similar way a fuzzy pattern can be derived for valuation of a compound real R&D option (see Appendix II).

5. Input assumptions and results

Initial step in the estimation of strategic *real options* value of fusion RDDD programme consists in the calculation of its expected net present value (ENPV) excluding potential effects of different managerial actions on the prospective cash flows. Such analysis can be performed using two different approaches. One method consists in the computation of fusion ENPV according to several scenarios elaborated in a deterministic setting with a number of exogenous assumptions regarding the evolution of key value driving factors. Second approach is based on a stochastic probabilistic setting, which allows for random fluctuation of key parameters within predefined value ranges, while assuming a specific probability of success for each programme stage.

5.1 Deterministic case

Elaboration of the discounted cash flow model of fusion RDDD programme requires assessment of the following input parameters:

- Public costs incurred during “R&D” and “Demo” stages
- Further RD&D costs (both public and private) aimed at improving the performance of fusion power plants during “Deployment” stage
- Private costs associated with the construction and operation of fusion power plants
- Revenues from sale of fusion electricity
- Time framework and discount rate.

A general influence diagram explaining the impact relationships among different input parameters is shown in *Figure 5*. Subsequent sections provide a detailed analysis of each of the main factors that may have a tangible effect on the expected NPV of fusion RDDD programme. Numeric assumptions are provided for three scenario variants: *pessimistic* and *intermediate* scenarios (“A” and “B” respectively) roughly correspond to the “Moderate Introduction” and “Massive Deployment” scenarios developed in Gnansounou &

Bednyagin (2007). The third *optimistic* scenario ("C") reflects the main hypotheses adopted in the UKAEA study (see Ward et al., 2002).

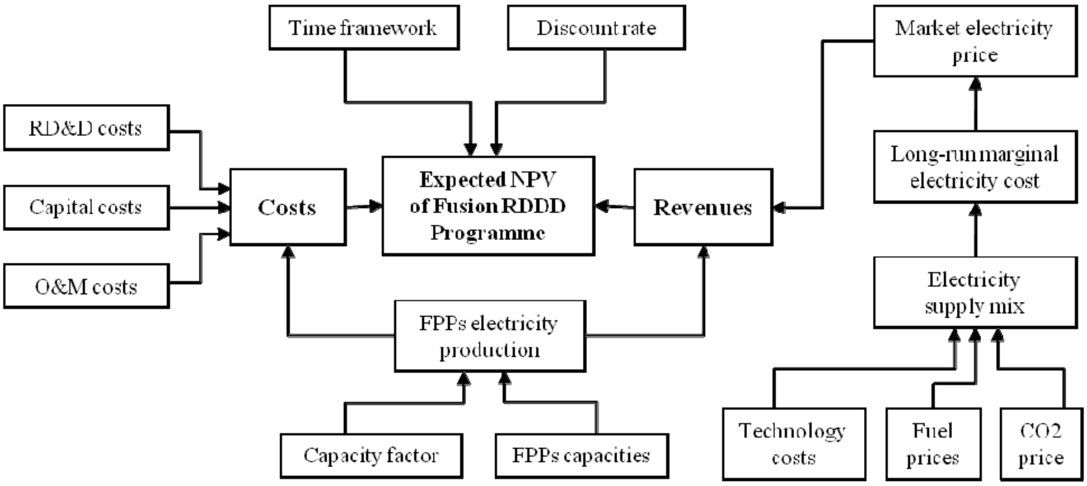

Figure 5. Fusion ENPV influence diagramme

5.1.1 Initial public RD&D costs. The current estimates of the total costs related to the construction and operation of major fusion RD&D facilities such as ITER, IFMIF, DEMO alongside with the costs of other supporting RD&D activities can be summarized as follows. It can be expected that the total public investments in fusion RD&D will be in the range € 60 - 100 billion. Assuming that these works would be finished by 2050, these figures correspond to the annual expenditures of €1.4 billion in less ambitious scenario "A", €1.9 billion in the intermediate scenario "B", and €2.4 billion in the most optimistic scenario "C", which envisages the construction of several DEMO reactors.

5.1.2 RD&D costs during deployment stage. It can be expected that investments in fusion RD&D activities will continue after the start of construction of commercial fusion power plants, i.e. after 2050. The costs of specific public policy measures aimed at supporting the deployment of fusion power plants, likewise, fall into this category. Furthermore, it can be assumed that the total amount of public funds invested in these activities (*Table 1*) would gradually reduce from initial relatively high values to nearly "zero" value, meaning that fusion technology became mature and fully assimilated be the private sector.

Table 1. Assumed costs of fusion RD&D and other public support measures during deployment stage

	Scenario A	Scenario B	Scenario C
Annual costs in 2051 (€ billion)	1.2	1.6	2.0
Duration (yrs)	50	50	50
Dynamics through 2051-2100	*Linear reduction to "zero" value by 2100*		

5.1.3 Fusion power plants' construction & operation costs. In order to estimate the total costs due to construction and operation of fusion power plants (FPPs) the following parameters have to be assessed: fusion *electricity production cost* which will be determined by the specific investment and O&M costs; the *total electricity production* of fusion power plants which will depend on the total number of FPPs expected to be built and put in operation each year during the considered time period (2051-2100) and their capacity factors. Market competition among different power generation technologies may also affect the expected volumes of electricity production of fusion power plants. For simplicity, these effects are treated through adoption of different fusion build up rates corresponding to the three main scenarios.

The earlier works performed with PROCESS systems code model (Hender et al. 1996) showed that the cost of fusion electricity is dependent on several key technical parameters, namely: net electric power, thermodynamic efficiency, availability, normalised plasma pressure, and Greenwald normalised plasma density. According to Hamacher & Bradshaw (2001) the cost of fusion electricity can be further broken up as follows: capital costs for fusion reactor core (39%); balance of plant (23%); costs for the replacement of divertor and blanket during operation (30%); fuel, operation, maintenance and decommissioning (8%). The electricity cost of four main fusion design concepts considered in European PPCS study was estimated in the range of 50 to 90 €/MWh (Maisonnier et al., 2005). A most recent review of the economics of fusion power was made by Han & Ward (2009). Based on their estimates of capital, fixed O&M and variable O&M costs and assuming 5%

interest rate for annuity payments, 40 years lifetime and 80% capacity factor, the future cost of fusion electricity can be estimated in a range of 40 to 50 €/MWh for mature and early FPPs in basic configuration and from 33 to 40 €/MWh for mature and early FPPs of advanced concept.

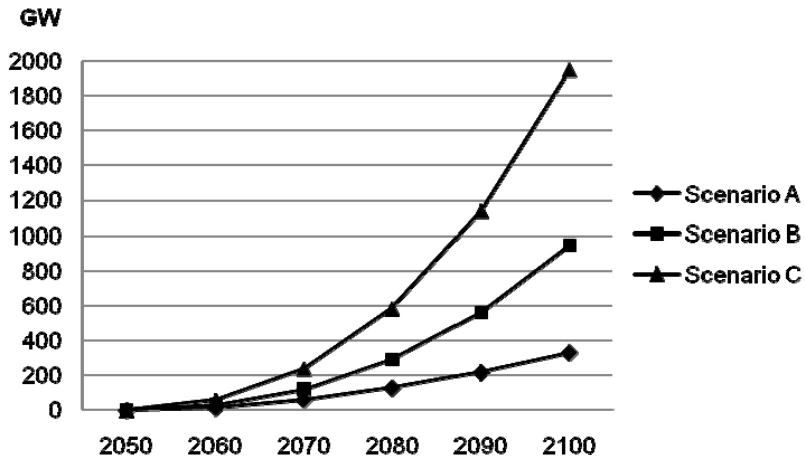

Figure 6. Projected fusion power capacities in three scenarios (source: authors' estimation)

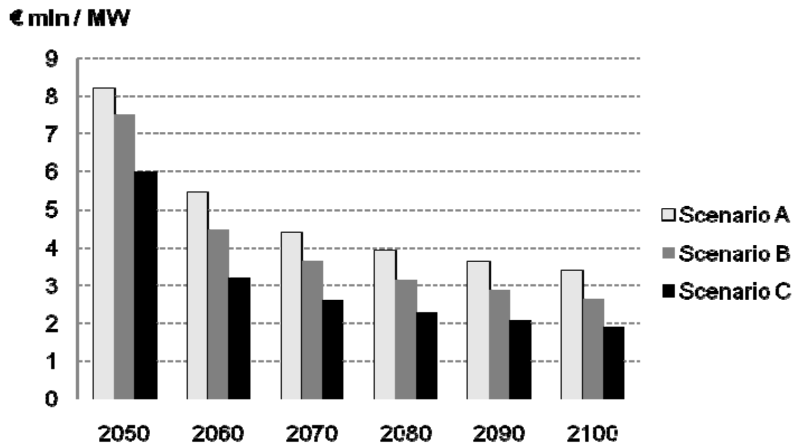

Figure 7. Estimated specific capital costs of fusion power plants (source: authors' estimation)

The total fusion power generation capacities that are expected to be in operation each year of the considered period (up to 2100) in all three scenarios are shown in *Figure 6*. Based on the corresponding annual build-up rates and assuming a rather conservative 10% learning rate, the specific costs can be estimated for fusion power plants of different vintages as shown in *Figure 7*. It is worth noting that during the initial deployment period (2050-2070) the costs of FPPs decline steeply from relatively high values for 1st of a kind FPP to 10th of a kind FPP, while during the subsequent periods the cost reduction is less significant. This can be explained by the properties of experience curve function. It is also assumed that initial capital cost in optimistic scenario "C" will be lower compared to other scenarios due to more intensive efforts throughout R&D and "Demo" stages.

Taking into account the projections of fusion technology costs made in Gnansounou & Bednyagin (2007) and the estimates of Han & Ward (2009) the following values of annual investment and O&M costs have been chosen in order to define the average electricity production costs of FPPs in three scenarios (*Table 2*). These costs represent the indicative weighted average costs for the whole 50 years period from 2051 to 2100. The total costs due to construction and operation of FPPs can be further estimated as a function of year-specific fusion COE and annual fusion electricity production subject to the scenario-specific fusion build-up rates and FPPs capacity factor.

Table 2. Assumptions on average costs of fusion power plants

	Scenario A	Scenario B	Scenario C
Specific capital cost (mln €/MW)	4.0	3.1	2.2
Investment annuity per power plant [a] (mln €)	350	270	190
Annual O&M costs [b] (mln €/MW)	0.15	0.12	0.11
Fusion COE [c] (€ / MWh)	55	43	34

[a] assuming 5% interest rate, 40 years lifetime and 1500 MW unit capacity
[b] include both fixed and variable O&M costs
[c] assuming 80% capacity factor

5.1.4 Revenues from fusion electricity sales. The revenues from sale of electricity produced by fusion power plants will depend on the future market electricity price and the actual amount of fusion electricity generation during each year of the considered period (2051-2100). As discussed in previous section, the annual fusion electricity production will depend on the total capacity of FPPs being in operation and their capacity factor (assumed to be the same 80% in all three scenarios). As regards the future electricity price, in theory it is expected to equalize the future long-run marginal cost (LMRC) of electricity generation.

According to the most general definition LMRC is equal to the marginal cost of supplying an additional unit of electricity when the installed capacity of the system, under specified reliability constraints, is allowed to increase optimally in response to the marginal increase in demand (see e.g. Porat *et al.*, 1997). A simplified approach consists in calculating LRMC based on operational and capital costs of individual technologies that may be considered as marginal electricity supply options (see e.g. Reinaud, 2003). Such a technology should represent a least cost option for expansion of a given electricity system in medium-to-long term perspective assuming that there is no excess capacity which could provide additional electrical load and that primary energy resources utilised by this technology are available on the market at prices, which do not undermine its economical competitiveness. In general, conventional power generation technologies such as advanced coal and combined cycle natural gas may be considered as marginal electricity supply options for the time horizon 2050, when fusion technology is expected to enter the market.

According to the calculations performed in Bednyagin (2010), including sensitivity analyses to different levels of fuel and CO_2 prices, the full cost of electricity (i.e. LRMC) that can be produced by the representative marginal technologies falls in to the range of €26 to €112 per MWh. The lower bound is represented by coal IGCC technology under assumptions of 50% reference coal price and "zero" CO_2 price, and the upper bound is represented by NGCC technology under assumptions of 200% reference natural gas price and maximum €50 per tCO_2 price. By excluding the variants envisaging doubled fuels' prices and the CO_2 price below €20/t, the LRMC range is narrowed to €45 to €90 per MWh. It is interesting to note that this price range corresponds well to the actual average monthly prices for base-load electricity observed during 2006 – 2009 in European electricity market, which were in the range €32 - 100 per MWh according to EEX (2009) data. Meanwhile, this price range is significantly below the projected wholesale electricity prices hypothesised in UKAEA study of Ward et al. (2002) which are in the range of €70 - 130 per MWh. Accordingly, it was decided to perform further evaluation based on the price diapason of €50 - 100 per MWh.

5.1.5 Timeframe and discount rate. Two additional factors which intervene in the evaluation of prospective costs and benefits of fusion technology concern the time framework of the analysis and the discount rate. In the deterministic case, the length of fusion RD&D activities (42 years from 2009 to 2050) is set up constant and equal for all three scenarios, although it is a rough approximation considering that the increased funding may lead to shortening of the time to market. This issue will be investigated more thoroughly while performing ENPV calculations in a stochastic probabilistic setting. As regards the timeframe of publically supported fusion "deployment" period, it is limited in this study to 50 years (i.e. up to the time horizon of 2100) assuming that afterwards fusion technology could be fully up-taken by the private sector.

The choice of discount rate is driven by the following considerations. Firstly, it is reasonable to assume that during the initial publicly funded R&D and "demonstration" stages fusion could benefit of a relatively low discount rate, equal to the typical interest rates on long-term governmental borrowing (i.e. 2.0 – 4.0 %), and that during "deployment" stage the applied discount rate should be increased to the level of commercial interest rates for first-class long term borrowings (i.e. 5.0 – 7.0 %). Another consideration may call for applying a higher discount rate during RD&D stage and a lower rate during deployment stage reflecting the higher degree of risk during initial programme stages. This approach coincides with the proposal of Weitzman (2001) who suggested application of declining discount rates in social welfare analysis, namely 4% for *immediate* future (1 to 5 years), 3% for *near* future (6 to 25 years), 2% for *medium* future (26 to 75 years) and 1% for *distant* future (76 to 300 years). Newell & Pizer (2004) proposed also the concept of uncertain discount rates, which may follow mean-reverting or random walk stochastic process. They found that traditional approach using constant discount rate may significantly underestimate the value of the economic effects expected to occur at time horizons of 70 years or more in the future. Considering that the choice of appropriate social discount rate remains a highly debated topic in scientific and policy literature (see e.g. Groom *et al.*, 2005) it was chosen to set up a constant discount rate of 4% for all scenarios in the deterministic case (with consecutive sensitivity analyses) and to perform the evaluation using uncertain stochastic discount rates varying in the range of 3% to 5% in the probabilistic case.

5.1.6 Results of deterministic analysis. According to the most pessimistic scenario "A" the net present value of fusion RDDD programme remains negative (– €50 billion) meaning that given the related set of assumptions regarding technology costs and market electricity prices, the revenues from operation of projected capacity of fusion power plants are not sufficient to cover the costs of preceding fusion RD&D activities. This situation, however, does not exclude the possibility that benefits will exceed the costs in a more distant future (i.e. beyond 2100) when technological learning and market forces will drive down the production costs. Two other scenarios (*Table 3*) indicate a substantially positive net present value of fusion RDDD programme, namely €95 billion and €559 billion, confirming the idea that under reasonable assumptions, development and deployment of fusion technology may bring about important net economic benefits due to creation of a novel environmentally friendly and economically competitive electricity supply option.

Table 3. Deterministic NPV of fusion RDDD programme (€ billion)

	Discount rate				
	2%	3%	4%	5%	6%
Scenario A	-122	-75	-50	-36	-27
Scenario B	562	238	95	31	3
Scenario C	2692	1226	559	253	110

Source: authors' calculation

As confirmed by the sensitivity analyses, the estimated NPV of fusion RDDD programme is highly dependent on the chosen level of discount rate. This is not surprising considering a very long term nature of the study and the fact that potential benefits of fusion are far distant in the future, while the costs are incurred from the outset. As such, the choice of a lower discount rate, e.g. 2%, results in a more than 5-fold increase of the value of net economic benefits, while a higher discount rate in line with the commercial borrowing interest rate (i.e. 5% and above) substantially reduces NPV of fusion RDDD programme, which is still positive in two out of three scenarios.

The results of scenario analyses elaborated in deterministic setting clearly indicate the range of uncertainties underlying the evaluation of fusion technology. Both epistemic technical uncertainty (e.g. regarding the cost of fusion electricity) and aleatory market uncertainty (e.g. regarding the future electricity prices) contribute to the extreme variation of the estimated NPV of fusion RDDD programme. Nevertheless, considering that the assumptions of scenario “A” and scenario “C” represent respectively the worst and the best cases, it can be reasonably concluded that the real world conditions will lie somewhere in between, and hence the numerical projections corresponding to the intermediate scenario “B” may provide a sound guideline for further analyses using stochastic probabilistic simulation technique.

5.2 Probabilistic case

An important limitation of the scenario approach presented in the previous section consists in the fact that both the costs and benefits are assumed to occur in a certain amount at a given time irrespective of the actual pace of fusion RD&D programme and the possibility to react to the future market conditions. These shortcomings can be overcome by performing additional calculations within a stochastic probabilistic setting, where specific probabilities of success are assigned to each programme stage, and the main model variables (such as duration, costs, revenues, discount rate) are allowed to vary stochastically according to certain probability density functions. On top of this, the possible effects of different managerial actions can be evaluated through a combination of probabilistic simulation and scenario analyses.

Table 4. Main assumptions in probabilistic simulation

	Unit	Minimum Value	Likely Value	Maximum Value
R&D stage				
Annual costs	€ billion	-	1.6	-
Duration	yrs	-	22	-
Probability of success	%		90	
Demo stage				
Annual costs	€ billion	1.2	2.3	4
Duration	yrs	15	20	25
Probability of success	%	70	80	85
Deployment stage				
R&D support costs [a]	€ billion	1.2	1.6	2.0
Duration	yrs	-	50	-
Average annual fusion electricity production				
2051 - 2060	TWh	45	90	181
2061 - 2070	TWh	256	515	1030
2071 - 2080	TWh	668	1461	2922
2081 - 2090	TWh	1218	3023	6117
2091 - 2100	TWh	1945	5382	10975
Fusion cost of electricity				
2051 - 2060	€/MWh	51.3	64.5	78.4
2061 - 2070	€/MWh	43.6	54.8	66.7
2071 - 2080	€/MWh	39.4	49.3	61.1
2081 - 2090	€/MWh	36.4	45.6	57.3
2091 - 2100	€/MWh	34.3	42.9	54.6
Market electricity price	€/MWh	50	75	100
Discount rate	%	3	4	5

[a] reference values for year 2051, for subsequent years linear reduction to “zero” value is assumed

Table 4 summarizes the main assumptions and hypotheses which underlie the simulation of the basic case derived from deterministic middle-course scenario “B”. Compared to the previous deterministic scenarios, which used specific annual cost of electricity and installed capacity figures, in the stochastic probabilistic setting fusion power plans are distinguished according to different vintages corresponding to five 10-years sub-periods, which may follow after successful demonstration of fusion technology expected to occur by 2050. Accordingly the data for fusion COE and annual electricity generation presented in *Table 4* should be considered as weighted average values for each specific sub-period, e.g. 2051-2060, 2061-2070, etc. The drawback of this assumption is that NPV calculation becomes less accurate (i.e. NPV is slightly overestimated compared to the deterministic case) due to discounting. Again, like in deterministic case, the overall time framework for deployment of fusion power plants is bounded to 50 years assuming that afterwards fusion will enter technology diffusion phase, which will be taken on charge entirely by the private sector.

Considering that in the case of long-term prospective analyses embracing several decades it is practically impossible to find any rigid statistical inference that could describe variation of *per se* highly uncertain data, it was decided to use mainly triangular probability distribution function, which is typically used as a subjective description of a population for which the relationship between variables is known but data are scarce or practically inexistent. It is based on the knowledge of minimum and maximum values and an *inspired guess* as to what the modal value could be. The software employed for stochastic probabilistic analysis is “Risk Simulator”, version 5.3 (Mun, 2009b). This Monte Carlo simulation, forecasting and optimisation software is written in Microsoft.Net C# programming language and it functions as add-on together with standard MS Excel spreadsheet software. In all simulations the number of trials was fixed at 2000 with a unique seed sequence.

The simple fact of introducing probabilities of success for each programme stage, i.e. R&D and “Demon”, while using the most likely values, reduces significantly the expected NPV compared to the results of deterministic scenario analyses. In such probabilistic simulation there is a possibility of making some loss after initial programme stage (e.g. if R&D efforts are unfruitful), some even bigger loss after next stage (e.g. if demonstration fails to provide a marketable product) and gaining some positive cash flow if the overall programme is successful. As a consequence, the expected NPV of fusion RDDD programme resulting from the combination of all three possible outcomes is lower (€61 billion) compared to the deterministic case (€95 billion in case of scenario "B" that roughly corresponds to the alone positive outcome).

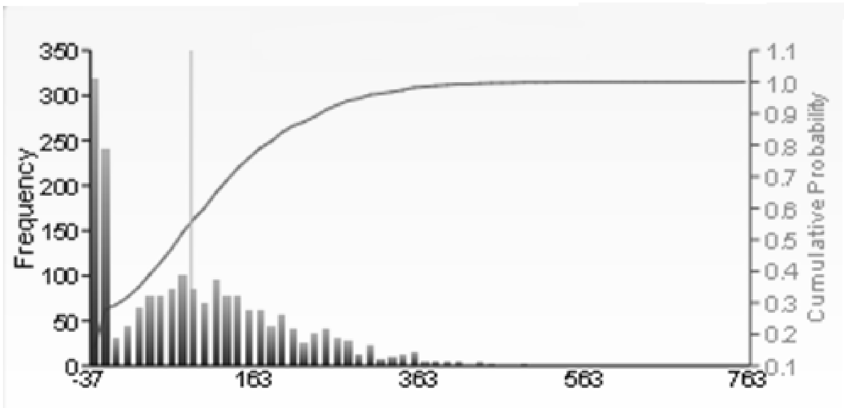

Figure 8. Expected NPV of fusion RDDD programme in case of stochastic probabilistic simulation

The results of stochastic probabilistic simulation of the most general case are shown in *Figure 8*. Here, the future electricity prices, fusion production volumes and fusion cost of electricity are allowed to vary stochastically. The correlations are introduced between all three factors: positive correlation between electricity price and production volumes, and a negative correlation between production volumes and fusion COE. Another important assumption is that amount of RD&D funding, probability of success and duration of the "Demo" stage are also allowed to vary stochastically. Negative correlation is implied between the amount of funding and the stage duration, while positive correlation is assumed between the funding and the probability of success. The funding of the "Demo" stage is positively correlated with further R&D and public support funding during "Deployment" stage and negatively correlated with fusion COE during initial 10 years deployment period. Fusion COE is also negatively correlated with further R&D and support costs during all five 10-years periods. The results of the stochastic probabilistic simulation indicate a substantial positive expected NPV of Fusion RDDD programme equal to €73 billion with 124% volatility in the case of fixed discount rate (4%) and €85 billion with 129% volatility in the case of stochastic discount rate. The expected NPV of programme revenues amounts to €324 billion, while ENPV of the programme costs is equal to €203 billion.

5.3 *Results of real options analyses*

Table 5 summarizes the main assumptions and data inputs underlying the calculation of the real options value of fusion RDDD programme. Numerical data for each variable of the real options model, i.e. duration and costs of R&D and "Demo" stages, transitional probabilities of success, the costs and revenues of fusion power plants, their total capacity and annual production generally correspond to the assumptions of the stochastic probabilistic simulation specified above. Annualized volatility of expected returns was estimated using the following formula:

$$\sigma = \frac{\sigma^*}{\sqrt{T}} \tag{11}$$

where σ^* is the overall volatility of expected returns from fusion power plants estimated using Monte-Carlo simulation and T is the time period preceding the start of commercial deployment.

Table 5. Main assumptions in fusion RDDD real options model

	Unit	"Baseline" Strategy	"Accelerated" Strategy
R&D stage			
Duration	yrs	22	22
Probability of success	%	90	90
Annual costs	€ billion	1.6	1.6
Demo stage			
Duration	yrs	20	15* – 19
Probability of success	%	80	81 – 85*
Annual costs	€ billion	2.3	4.0
Deployment stage			
Duration	yrs	50	50
Expected costs	€ billion	203	214 – 261*
Expected revenues	€ billion	324	341 – 417*
Volatility	%	6.6%	6.7 – 6.9* %
Risk free rate	%	2.25	2.25

The reference risk free rate (2.25%) is taken as a mean value of the daily US real long-term borrowing rates for TIPS[3] with remaining maturities of more than 10 years calculated for the period from January 2003 to September 2009. Numerical assumptions for R&D stage (ITER / IFMIF) are the same in both scenarios. The values marked with asterix (*) correspond to the main variant of "Accelerated" strategy according to which a supplementary € 15 billion (undiscounted) funding of fusion "Demo" stage results in increasing the probability of success by 5% and shortening of the stage duration by 5 years. Considering the uncertainty underlying these assumptions further sensitivity analyses have been carried out (1-3 % increase in the probability of success and 1-3 years reduction of the stage duration). Given this uncertainty range the probability-weighted discounted costs and revenues of fusion power plants have been finally estimated using Monte-Carlo simulation, which also provided the estimates of the revenues' volatility.

5.3.1 Results of analysis with basic investment option model. According to the results of the computations using both Black-Scholes differential equation and binomial lattice methods the strategic real option value, which may be created through undertaking fusion RD&D activities, amounts to €245 billion in the case of Baseline strategy. This value substantially exceeds the projected costs of fusion RD&D estimated over the period 2009 – 2050 at €36 billion (discounted to base year 2009). Accordingly, the strait forward conclusion from this calculation is that fusion RD&D is definitely worth undertaking, because it creates a much more valuable option for future revenues. Clearly such a result is prone to exhibit a large degree of uncertainty. Therefore, additional sensitivity analyses were carried out in order to understand the relative impact of the main input parameters in Black-Scholes formula.

As it can be seen on the "spider" diagram (*Figure 9*), the real option value of fusion RDDD programme is driven mainly by the expected revenues (exercise price in Black-Scholes formula). The relative impact of other factors, such as expected costs (negative) as well as

[3] Treasury Inflation-Protected Securities (see www.treas.gov/offices/domestic-finance/key-initiatives/tips.shtml)

time to expiration and risk-free rate (both positive), is much lower, while the impact of the volatility is practically negligible. It is also worth noting that even a negative expected return, e.g. at the point "- 50%" corresponding to the expected net loss of €40 billion (the other parameters being unchanged), creates a positive option value of €84 billion, which is substantially higher compared to the estimated costs of fusion RD&D activities. This can be explained by the extremely long lead time of fusion technology, which creates a significant upside potential over 40 years and beyond, even at a relatively small value of the annual volatility of expected returns.

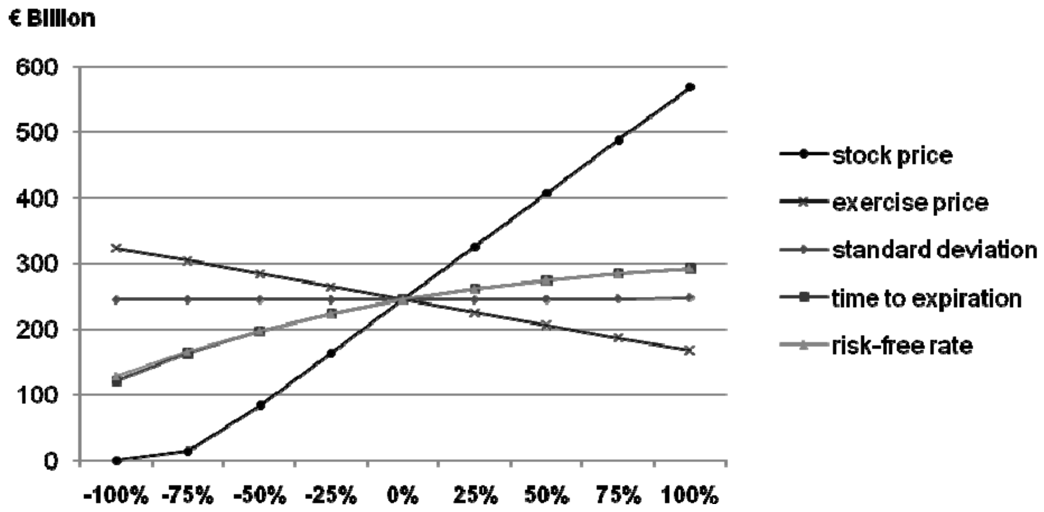

Figure 9. Sensitivity of real option value to input parameters in Black-Scholes formula

The analysis of "Accelerated" strategy characterised by the higher costs during demonstration stage and consequently by a higher probability of success and a shorter time-to-market brings to the conclusion that it can be even more profitable to pursue a more ambitious fusion RD&D programme, because the real option value increases in this case by €58 billion. Considering that this estimate is based on the assumption that supplementary funding of fusion "Demo" activities may lead to the increase of the stage probability of success by 5% and shortening of the time-to-market by 5 years, it is worthwhile to investigate the possible outcome of less optimistic cases.

Under the most pessimistic assumptions of only 1 % increase of the probability of success and 1 year shortening of the time-to-market, the real options value increases by €11 billion, compared to "Baseline" strategy, that is close to the incremental cost of fusion demonstration activities (see *Figure 10*). This result highlights the importance of the real options analysis, which allows for better planning of fusion RD&D process by performing a more comprehensive assessment of the expected programme payoffs and identification of potential downsides.

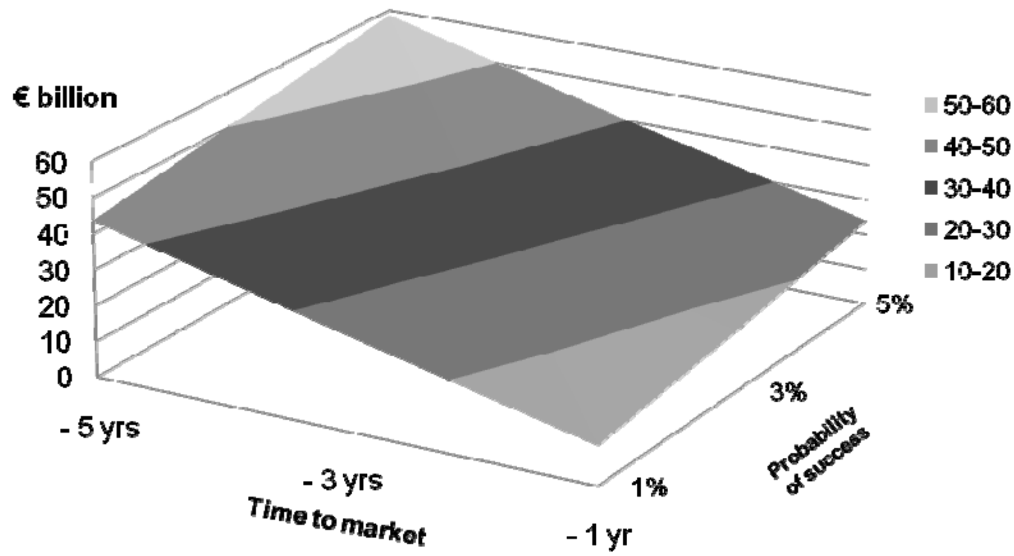

Figure 10. Increment of the real option value subject to different assumptions regarding increase of the probability of success and shortening of the time-to-market

5.3.2 Results of analysis with compound real options model. A more precise estimation of the real options value that may be created through individual stages of fusion RDDD programme can be obtained with the help of multi-staged compound real options model. Let us consider first the most simple two-stage option comprising RD&D and deployment stages. Based on the equations (II.1-II.9) given in Appendix II, and using the same assumptions as for valuation of standard European call option, the strategic value of the RD&D stage can be estimated at €231 billion in the case of "Baseline" strategy and €285 billion in the case of more ambitious "Accelerated" strategy.

Further refinement can be introduced into the analyses of fusion RDDD programme by distinguishing separate RD&D stages, e.g. sequential construction of ITER and DEMO reactors. In this case the strategic real option value of the initial R&D stage can be assessed more precisely. The solution for such a multi-phase compound option can be obtained by performing series of lattice calculations, i.e. the real option value of the initial R&D stage (€ 226 billion in the case of "Baseline" strategy) can be computed through backward induction based on the valuation lattice of the subsequent "Demo" stage, that in turn is calculated based on the valuation lattices of the underlying asset (FPPs revenues) and the final "Deployment" stage option, which both will have the same terminal and intermediate nodes' values as in the case of standard European call option.

5.3.3 Results of analysis with fuzzy real options model. Based on the three deterministic scenario calculations, discussed in chapter 5.1 above, the following values (in € billion) have been chosen in order to represent in the form of trapezoidal fuzzy numbers the expected revenues and costs of fusion RDDD programme:

NPV revenues:	(200, 350, 100, 200)
NPV deployment costs:	(150, 250, 30, 100)
NPV RD&D costs:	(36, 42, 2, 8) .

The upper core values roughly correspond to the estimated costs and revenues of deterministic intermediate scenario "B"; the lower core values are somewhat in between scenario "B" and pessimistic scenario "A" estimates; the lower bounds replicate the scenario "A"; the upper bounds correspond to the optimistic scenario "C" in terms of deployment and RD&D costs and median value between scenario "B" and scenario "C" in terms of revenues.

In order to calculate the fuzzy real options value with basic "Black – Scholes" type model of European call option we have to compute first the possibilistic mean and variance according to the equations (5) and (6) as follows:

$$E(\tilde{X}) = \frac{200+350}{2} + \frac{200-100}{6} = 292 \quad ; \quad E(\tilde{K}) = 212 \quad ; \quad E(\tilde{C}) = 40 \; ;$$

$$Var(\tilde{X}) = \frac{(350-200)^2}{4} + \frac{(350-200)(200+100)}{6} + \frac{(200+100)^2}{24} = 16875.$$

Given these values, we can further calculate the annualised volatility and the values of $N(d_1)$ and $N(d_2)$ coefficients according to the equations (8), (9) and (11):

$$\sigma(\tilde{X}) = \frac{\sqrt{16875}}{292\sqrt{42}} = 6.87\% \quad ;$$

$$N(d_1) = N\left(\frac{\ln\left(\frac{292}{212}\right) + \left(0.0225 + \frac{0.0687^2}{2}\right) \times 42}{0.0687\sqrt{42}} \right) = N(3.0643) = 0.9989 \; ;$$

$$N(d_2) = N\left(3.0643 - 0.0687\sqrt{42}\right) = N(2.6189) = 0.9956 \; ,$$

where the value of 42 years is the time to maturity of the option corresponding to the duration of fusion RD&D activities, and 2.25% is the risk-free rate. Both values are the same as in non-fuzzy "Baseline" case.

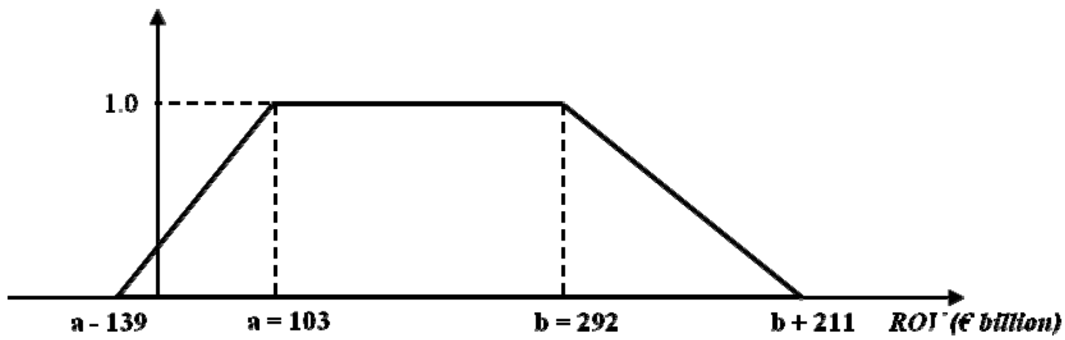

Figure 12. Fuzzy real option value of fusion RDDD programme

By plotting the initial fuzzy numbers of the expected revenues and costs and the calculated values of $N(d_1)$ and $N(d_2)$ into the equation (10) we obtain the real option value of fusion RDDD programme in the format of a trapezoidal fuzzy number, as illustrated in *Figure 11*. The calculated fuzzy number **(103, 292, 139, 211)** signifies that the most possible real option value of fusion RDDD programme lies in the range between €103 billion and €292 billion with the least possible downside value of – €36 billion (negative) and the least possible upside value of €503 billion. Compared to the results of a more traditional real options valuation approach based on singleton crisp numbers, the fuzzy method allows for taking into account a larger palette of eventual outcomes, e.g. the inclusion of potentially higher net total returns reflected in the optimistic scenario “C” and potential net losses according to the pessimistic scenario “A”.

In a similar way, using equations (II.1-II.7) given in Appendix II, we can estimate the fuzzy value of a compound real R&D option. In this case, one additional step should be performed consisting in the calculation of the critical price ratio. In line with the findings of usual real options analysis, the core range of the computed fuzzy value of compound R&D option **(76, 269, 144, 213)** is smaller compared to the underlying fuzzy investment option, while the lower and upper bounds are slightly bigger. Finally, using the equation (5) the possibilistic mean of this trapezoidal fuzzy number was estimated at €184 billion, which is 18.5% smaller compared to the result of traditional “crisp” compound option valuation.

6. Conclusions

The overall conclusions from the analyses presented above can be summarized as follows:

Both deterministic and probabilistic calculations indicate that potential revenues from deployment of fusion technology substantially outweigh the RD&D and deployment costs, except for deterministic scenario “A” which is based on the most pessimistic assumptions, and hence it is worthwhile to pursue further R&D and demonstration activities. Compared to the deterministic scenarios, the evaluation of the expected NPV of fusion RDDD programme in a stochastic probabilistic setting may provide a better estimate of the total programme costs and returns. This is due to the fact that a larger number of the underlying factors, oftentimes acting in opposite directions, are allowed to vary simultaneously; therefore the resulting estimates can be considered as more robust. Another advantage is that such stochastic probabilistic simulations provide the necessary estimates (i.e. expected costs, revenues, volatility) for more advanced strategic analysis using real options approach.

The real options analysis suggests that a substantial strategic value of fusion RDDD programme is being ignored by the traditional NPV approach. This value is created due to uncertainty about the future energy markets conditions (e.g. there is a potential of high upward swings because of the exhaustion of fossil energy reserves and introduction of more stringent environmental regulation). The programme managers are also able to limit potential losses and increase the revenues through different flexibility measures (e.g. the decision to postpone deployment if market conditions are unfavourable or to accelerate build-up of fusion power plants if there is a strong demand and attractive prices for electricity).

The study confirmed the idea that inclusion of hidden real options value provides a more comprehensive picture of the total expected economic returns. So, the expanded strategic net present value of fusion RDDD programme, estimated in this paper, is equal to €330 billion: €85 billion probabilistic ENPV + €245 billion real option value. This result is in line with the findings of other researchers, e.g. Ward et al. (2005) who estimated the total discounted future benefit of fusion in the range of US$ 400 – 800 billion in a typical calculation without probability of failure and in the range of US$ 100 – 400 billion including failure probability.

The results of the real options valuation of "Baseline" and "Accelerated" strategies indicate that a more ambitious fusion RDDD programme assuming an increased public funding during the demonstration stage and accelerated construction of two or more fusion DEMO reactors of alternative concept may result in a higher economic return that could be substantially bigger than the increment of the programme costs. This result is confirmed by the calculations using both simple Black-Scholes investment option model and a more complex compound option model.

In the context of fusion RDDD programme, the use of compound real option model is more preferable compared to the simple European call option model, because it allows to focus the evaluation on the ongoing and next-step stages (i.e. R&D and "Demo") that exhibit a higher relevance for current decision-making process.

The proposed possibilistic fuzzy real option model offers an efficient way to cope with the uncertainty in the evaluation of fusion RDDD programme. The main advantage compared to the traditional scenario-based and real option valuation methods, which both use crisp numbers, consists in the fact that fuzzy sets allow for transforming linguistic variables (e.g. degree of confidence) into numerical values. Furthermore, as the programme progresses through its successive stages (construction of ITER / IFMIF, construction of DEMO), the technical (epistemic) uncertainty will be gradually resolved, and hence the existing fuzzy estimates of the expected programme NPV and its strategic real option value can be narrowed, thereby providing a more reliable guidance for decision making.

Besides the value created through bringing to the market a new energy supply option that could also have a significant "insurance" value in case of unforeseen events, the potential impacts of fusion RDDD programme may include other economic and social benefits, e.g. due to non-electric applications and technological spin-offs towards other industrial sectors, technology exports and reduction of fossil fuel imports, enhanced energy security and avoidance of conflicts over scarce resources, improved natural environment, regional economic development, etc. These positive externalities, or in other words spillovers or indirect effects, also should be taken into account in the socio-economic evaluation of fusion RDDD programme, and this work represents a further direction in the pursuit of the analyses presented in this paper.

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Appendix I.

The value of a compound option, *W*, can be calculated with the following formulae:

$$W[V(X,K,T),C,t] = X N_2(h_1, d_1; \rho) - K e^{-rT} N_2(h_2, d_2; \rho) - C e^{-rt} N_1(h_2) \quad (I.1)$$

$$h_1 = \frac{\ln\left(\frac{X}{Q}\right) + \left(r + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \quad (I.2)$$

$$h_2 = h_1 - \sigma\sqrt{t} \quad (I.3)$$

$$d_1 = \frac{\ln\left(\frac{X}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \quad (I.4)$$

$$d_2 = d_1 - \sigma\sqrt{T} \quad (I.5)$$

$$\rho = \sqrt{\frac{t}{T}} \quad (I.6)$$

subject to the boundary conditions:

$$V(X, K, T) \geq W(V, C, t) \geq 0 \quad (I.7)$$

and terminal condition:

$$W(V,C,0) = \max\left[0,\ X N_1\left(d_1\left(\frac{X}{K}, T-t\right)\right) - K e^{-r(T-t)} N_2\left(d_1\left(\frac{X}{K}, T-t\right)\right) - C\right], \quad (I.8)$$

where

V – value of the underlying “second stage” option;

X – expected revenues from deployment of Fusion power plants;

K – investment and O&M costs of commercial Fusion power plants;

T – time to expiration of the underlying option (years);

t – time to expiration of the compound option (years);

C – construction and operation costs of R&D and DEMO facilities;

N_1 – cumulative standard normal distribution function;

N_2 – cumulative bi-variate normal distribution function with correlation coefficient, ρ;

σ – volatility of the revenue stream;

r – risk-free rate;

Q – critical price ratio.

The critical price ratio (Q), above which the second exchange option should be acquired by paying the exercise price at time t, can be obtained by solving recursively the following equation:

$$C = Q N_1\left(\frac{\ln\left(\frac{Q}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{T-t}}\right) - K e^{-r(T-t)} N_1\left(\frac{\ln\left(\frac{Q}{K}\right) + \left(r - \frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{T-t}}\right). \quad (I.9)$$

Appendix II.

Based on Ran et al. (2004) and Wang & Hwang (2007) the following fuzzy pattern can be derived for valuation of a compound real R&D option:

$$FW = \tilde{X} N_2(b_1, d_1; \rho) - \tilde{K} e^{-rT} N_2(b_2, d_2; \rho) - \tilde{C} e^{-rt} N_1(b_2) \quad \text{(II.1)}$$

$$b_1 = \frac{\ln\left(\frac{E(\tilde{X})}{Q}\right) + \left(r + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \quad ; \quad b_2 = b_1 - \sigma\sqrt{t} \quad \text{(II.2)}$$

$$d_1 = \frac{\ln\left(\frac{E(\tilde{X})}{E(\tilde{K})}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \quad ; \quad d_2 = d_1 - \sigma\sqrt{T} \quad \text{(II.3)}$$

$$\rho = \sqrt{\frac{t}{T}} \quad \text{(II.4)}$$

$$\sigma = \frac{\sqrt{Var(\tilde{X})}}{E(\tilde{X})} \quad . \quad \text{(II.5)}$$

The first term of the equation (I.1) gives the risk neutral expectation of the fusion RDDD programme returns, the second term gives the expected deployment costs at time T, and the last term is the expected demonstration costs at time t. The expected costs and returns are estimated based on their possibilistic mean and variance values. The critical value Q can be obtained by solving recursively the following equation

$$Q N_1\left(\frac{\ln\left(\frac{Q}{E(\tilde{K})}\right) + \left(r + \frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right) - E(\tilde{K}) e^{-r(T-t)} N_1\left(\frac{\ln\left(\frac{Q}{E(\tilde{K})}\right) + \left(r - \frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right) - E(\tilde{C}) = 0 \, . \quad \text{(II.6)}$$

According to the concepts and computational principles of fuzzy numbers given in literature (see e.g. Zadeh, 1965) the following fuzzy pattern can be applied to value a compound R&D option:

$$FW = (x_1, x_2, \alpha, \beta) N_2(b_1, d_1; \rho) - (k_1, k_2, \alpha', \beta') e^{-rT} N_2(b_2, d_2; \rho) - (c_1, c_2, \alpha'', \beta'') e^{-rt} N_1(b_2) = \quad \text{(II.7)}$$

$$\big(x_1 N_2(b_1, d_1; \rho) - k_2 e^{-rT} N_2(b_2, d_2; \rho) - c_2 e^{-rt} N_1(b_2), \; x_2 N_2(b_1, d_1; \rho) - k_1 e^{-rT} N_2(b_2, d_2; \rho) - c_1 e^{-rt} N_1(b_2),$$

$$\alpha N_2(b_1, d_1; \rho) + \beta' e^{-rT} N_2(b_2, d_2; \rho) + \beta'' e^{-rt} N_1(b_2), \; \beta N_2(b_1, d_1; \rho) + \alpha' e^{-rT} N_2(b_2, d_2; \rho) + \alpha'' e^{-rt} N_1(b_2)\big) \quad .$$

Thus, the fuzzy pattern of the value of compound R&D option is also a trapezoidal fuzzy number.

Figures

Tables