Socio-Economic Assessment of Fusion Energy Research, Development, Demonstration and Deployment Programme

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ABSTRACT

Providing safe, clean and affordable energy supply is essential for meeting the basic needs of human society and for supporting economic growth. From the historical perspective, the constantly growing energy use was one of the main factors, which drove the industrialised countries to the current level of prosperity. Meanwhile, in recent decades, the issue of global energy security became a topic of increasing concern in the international policy agenda. On the one hand, the world is facing the problem of exhaustion of most convenient and cheep fuel reserves. The situation is becoming worse, because of the constantly growing demand in developing countries, and the oligopolistic behaviour of major energy exporting countries. On the other hand, the society is becoming more and more sensitive to the environmental pollution problems, caused by the excessive consumption of fossil fuels.

In the face of energy security challenge, national governments ought to implement adequate strategies 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 is relying currently on the consumption of non-renewable fossil fuels, and the development of new safe, clean and resource unconstraint energy technologies is vitally needed. In line with this strategy, the major world economies pursue the 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 resources.

Considering the importance of the projected environmental and economic 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 the demonstration of Fusion technology, given the time span and potential risks of Fusion RDDD programme. 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 ($\approx$ 50%) over the last three decades. The liberalisation of energy sector poses additional problem due to the fact that free markets partially failure to provide public goods, such as basic science and R&D, because of the so-called spillover effects meaning that the firms are not able to appropriate the integral results of their R&D investments.

Regarding the thermonuclear Fusion technology, the decision makers responsible for national energy policies and allocation of public R&D funds may face the following specific questions:

- What is the expected net socio-economic payoff (social rate of return) of Fusion R&D programme, including both internal and external costs and benefits?
- What are the reasonable economic arguments that could justify the increase in public funding of the ongoing and future Fusion R&D activities and would stimulate greater involvement of the private sector?
- What additional value can be obtained through undertaking a more ambitious Fusion R&D programme (*accelerated development path*), which requires bigger number of experimental

facilities, increased funding, and more intense overall efforts of international scientific and industrial community?

In order to provide sound arguments for policymakers seeking to optimise public R&D funding, a robust socio-economic evaluation of the whole Fusion research, development, demonstration and deployment (RDDD) programme is needed.

At the present stage, prospective analyses of Fusion technology have been emphasised mainly on the investigation of technological issues, estimation of the direct costs of Fusion power and analysis of its potential role in future energy systems. Meanwhile, methodological tools and practical studies aiming at a more comprehensive socio-economic assessment of global long-term energy R&D programmes, such as Fusion, are still incomplete. The primary difficulty concerns the evaluation of positive externalities that may reveal through different types of spillover effects, including but not limited to knowledge, network and market spillovers. While the presence of these effects has been identified in the economic theory and confirmed by empirical studies, their quantitative analysis in the specific case of large scale energy R&D programmes represents some methodological lacuna and deserves further investigation.

Another problem relates to the methodology of cost-benefit analysis, 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 pro-active management of different implementation stages, e.g. expanding the production, if market conditions are favourable, or abandoning, if R&D process appears to be unproductive. 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. A particular challenge consists in the need for adequate treatment of different types of uncertainty in the model structure, parameters and input data.

Accordingly, the main objective of this thesis consists in complementing the existing studies with an in-depth analysis of the positive externalities (spillover benefits) of Fusion RDDD programme and calculation of its strategic real options value subject to different managerial strategies throughout demonstration and deployment stages. Net social present value of Fusion RDDD programme and potential impact of Fusion R&D activities on the economic performance of the involved private companies are estimated using an integrated modelling framework, which includes the following components: (1) assessment of technological potential for deployment of Fusion power plants based on the simulation of multi-regional long term electricity supply scenarios with PLANELEC model; (2) economic evaluation of Fusion RDDD programme and analysis of different implementation strategies using Real Options model; (3) estimation of the economic value of spillover benefits from participation in Fusion R&D projects at the microeconomic level with the help of financial evaluation model; (4) strategic evaluation of Fusion RDDD programme, taking into account both spillover benefits and real options value, and policy recommendations.

Key words: Thermonuclear Fusion, R&D, Evaluation, Real Options, Spillovers

RÉSUMÉ DE LA THÈSE

L’accès aux sources d’énergie sûrs, propres et au prix raisonnable est essentiel afin d’assurer les besoins basiques de la société humaine ainsi que de maintenir la croissance économique. De point de vue historique, la consommation constamment grandissante de l’énergie était l’un des facteurs-clé qui avait permis aux pays industrialisés d’atteindre le niveau actuel de prospérité. Cependant, durant les dernières décennies le problème de sécurité énergétique globale est devenu le sujet des préoccupations grandissantes dans la politique internationale. D’un côté, le monde doit faire face au problème d’épuisement des réserves d’énergie les plus opportuns et les moins chers. La situation devient de plus en plus tendue à cause de la demande croissante des pays émergents et le comportement oligopolistique des principaux pays exportateurs. D’autre côté, la société devient sensible aux problèmes de la pollution environnementale causée par la consommation excessive d’énergie fossile.

Face au challenge de la sécurité énergétique, les gouvernements nationaux doivent implémenter des stratégies adéquates orientées vers la libéralisation des marchés d’énergie, la diversification du mix énergétique, l’amélioration d’efficacité énergétique, l’encouragement des investissements dans les infrastructures énergétiques et la promotion de l’innovation dans le secteur énergétique. A long terme, le dernier point devient de plus en plus important, parce que le monde dépend actuellement sur la consommation d’énergies fossiles non-renouvelables, et le développement de nouvelles sources d’énergie sûre, propre, abondante est la nécessité vitale. En conformité avec cette stratégie, les plus grandes économies du monde poursuivent le programme conjoint de la recherche et développement sur la technologie de Fusion thermonucléaire qui représente de multiples avantages grâce à la sécurité intrinsèque, l’absence des émissions de CO_2, l’impact relativement faible sur l’environnement, l’abondance et la distribution uniforme dans le monde des réserves de carburants nécessaires.

Compte tenu l’importance des bénéfices attendus de la Fusion au niveau environnemental et économique, la question est levée si le montant de son financement actuel est suffisant et quelle pourrait être la stratégie optimale pour la prochaine étape de démonstration en considérant la durée et les risques potentiels du programme entier de recherche, développement, démonstration et déploiement (RDDD) de la Fusion. Pour mettre ces questions dans leur contexte, il faut considérer les tendances actuelles dans le financement des programmes de recherche et développement dans le domaine d’énergie qui a vu un déclin drastique ($\approx$ 50%) au cours des trois dernières décennies. La libéralisation du secteur énergétique pose un problème supplémentaire vu le fait que les marchés libres partiellement n’arrivent pas à fournir les biens publiques tels que la science basique et la recherche et développement à cause du phénomène qu’on appelle les spillover effects (effets induits) signifiant que les entreprises ne sont pas capables à approprier l’intégralité des résultats de leurs investissement dans la recherche et développement.

En ce qui concerne la technologie de Fusion thermonucléaire, les décideurs responsables des politiques énergétiques nationales et d’allocation des fonds publiques peuvent faire face aux questions suivantes :

- Quel est le rendement socio-économique net espéré du programme de recherche et développement de la Fusion, y compris ses coûts et bénéfices internes et externes ?
- Quels sont les arguments économiques valides qui peuvent justifier l’augmentation du financement publique des activités de recherche et développement de la Fusion ainsi que stimuler la participation plus importante du secteur privé ?
- Quelle valeur supplémentaire peut être obtenue au cas où un programme plus ambitieux de recherche et développement de la Fusion est mise en place, lequel prévoit l’accélération de toutes les activités et demande un nombre plus important d’installations expérimentales,

exige une augmentation de financement et intensification des efforts des communautés scientifiques et industrielles internationales ?

Afin de fournir des arguments solides aux décideurs qui cherchent à optimiser le financement public de différents programmes scientifiques, une évaluation socio-économique robuste est nécessaire pour le programme de recherche, développement, démonstration et déploiement de la Fusion dans son intégralité.

Jusqu'à présent, les analyses prospectives sur la technologie de Fusion ont été limitées aux aspects technologiques, l'estimation des coûts directs d'électricité de la Fusion et l'investigation de son rôle potentiel dans les systèmes énergétiques futurs. Cependant, les méthodologies et les études pratiques centrées sur une analyse socio-économique plus compréhensive de grands programmes de recherche dans le domaine d'énergie, tel que la Fusion, restent incomplètes. La difficulté primaire concerne l'évaluation des externalités positives qui peuvent se révéler à travers les effets induits de différents types, y compris les spillover de connaissance, de réseau, de marché etc. Bien que la présence de ces effets soit identifiée dans la théorie économique et confirmée par les études empiriques, leur analyse quantitative dans le cas spécifique de grands programmes de recherche énergétique représente certains défauts méthodologiques et mérite de ce fait une investigation approfondie supplémentaire.

Un autre problème est lié à la méthodologie d'analyse coût – bénéfice laquelle très souvent ignore la valeur cachée des projets de recherche et développement qui résulte de la possible flexibilité dans la prise des décisions managériales. En fait, durant l'exécution des projets leur flux de trésorerie peut être amélioré de façon significative grâce au management active de différentes étapes d'implémentation ; par exemple, le volume peut être augmenté si les conditions de marché sont favorables ou le projet peut être abandonné si les efforts semblent être improductifs. En résultat, la valeur stratégique de n'importe quel projet de recherche et développement normalement est supérieure à sa valeur actuelle nette (VAN) calculée avec la méthode traditionnelle de flux de trésorerie actualisé. Bien que cette approche stratégique à l'évaluation des projets connu sous le nom « options réels » ait été propagée à travers de nombreuses publications scientifiques, son application pratique dans le cas spécifique du programme de RDDD de la Fusion n'a pas encore été suffisamment maitrisée. Le challenge particulier consiste dans la nécessité de traitement adéquat de différents types d'incertitude qui se propage à travers la structure de modèle, les paramètres et les données.

Par conséquent, l'objectif principal de cette thèse consiste à compléter les études existantes avec une analyse approfondie des externalités positives (effets de spillover) du programme de RDDD de la Fusion et le calcule de sa valeur stratégique selon la méthode des options réels compte tenu les différentes stratégies possibles à travers les étapes de démonstration et déploiement. La valeur sociale actuelle nette du programme de RDDD de la Fusion et l'impact potentiel sur la performance économique des entreprises participantes sont estimés à l'aide d'un modèle intégré qui comprend les éléments suivants : (1) analyse du potentiel technologique pour le déploiement des centrales à Fusion basé sur la simulation des scénarios multirégionaux d'approvisionnement en électricité avec le modèle PLANELEC ; (2) évaluation économique du programme de RDDD de la Fusion et l'analyse de différentes stratégies de son implémentation avec un modèle des Options Réels ; (3) estimation de la valeur économique des effets de spillover dus à la participation des entreprises dans les projets de recherche et développement de la Fusion avec un modèle d'évaluation financière ; (4) évaluation stratégique du programme de RDDD de la Fusion compte tenu des effets de spillover et de la valeur des options réels suivie par les recommandations pratiques.

Mots-clé: Fusion Thermonucléaire, R&D, Evaluation, Options Réels, Spillovers

LIST OF ACRONYMES

AFR	Sub-Saharan Africa
AHP	Analytic Hierarchy Process
BETA	Bureau d'Economie Théorique et Appliquée (Strasbourg University, France)
CBA	Cost-Benefit Analysis
CCS	Carbon Capture and Storage
CEE	Central and Eastern Europe
CIS	Commonwealth of Independent States (Russia and other FSU Countries)
CEP	Continuing Value of Projected Economic Profit after Explicit Forecast Period
CERN	European Organisation for Nuclear Research
COE	Cost of Electricity
CPA	Centrally Planned Asia
CTF	Component Test Facility
CV	Company Value
DCF	Discounted Cash Flow
DEMO	Demonstrator Fusion Reactor
DOE	Department of Energy, United States
DTA	Decision Tree Analysis
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortisation
EC	European Commission
ECN	Energy Research Centre of the Netherlands
EDEMO	Early Fusion Demonstrator Reactor
EFDA	European Fusion Development Agreement
EFDA-TIMES	Global Multi-Regional Energy System Model Developed by EFDA-SERF
EJ	Exajoule
EIA	Energy Information Administration (USA)
ENPV	Expected Net Present Value
EP	Economic Profit
ETI	Energy Technology Innovation
ETP	Energy Technology Perspectives Model
EU	European Union
EVA	Economic Value Added
FC	Fuel Cell
FESAC	Fusion Energy Sciences Advisory Committee
FP	Framework Programme for European Research and Technology Development
FPP	Fusion Power Plant
FSU	Former Soviet Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GJ	Gigajoule
Gt	Gigaton
GT	Open Cycle Gas Turbine
GWe	Gigawatt (electrical power)
HDI	Human Development Index
IAC	InterAcademy Council
IAEA	International Atomic Energy Agency
IC	Invested Capital
IEA	International Energy Agency
IFMIF	International Fusion Materials Irradiation Facility
IFRC	International Fusion Research Council
IGCC	Integrated Coal Gasification Combined Cycle Power Plant
IGFCCC	Integrated Coal Gasification Fuel Cell Combined Cycle Power Plant

IIASA	International Institute for Applied Systems Analysis (Laxenburg, Austria)
IPCC	International Panel on Climate Change
IPP	Max-Planck-Institut für Plasmaphysik (Germany)
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LAM	Latin America and Caribbean
LRMC	Long Run Marginal Cost of Electricity Generation
LUEC	Levelised Unit Electricity Cost
MEA	Middle East and North Africa
MSLS	Multiple Assets Super Lattice Solver
MVA	Market Value Added
MWe	Megawatt (electrical power)
MWh	Megawatt-hour
M$	One Million U.S. Dollars
NAM	North America
NEA	Nuclear Energy Agency, France
NGCC	Natural Gas Combined Cycle Power Plant
NIF	National Ignition Facility
NOPLAT	Net Operating Profit Less Adjusted Taxes
NPV	Net Present Value
OECD	Organisation for Economic Cooperation and Development
O&M	Operation and Maintenance
ORNL	Oak Ridge National Laboratory
PAO	Pacific OECD
PAS	Other Pacific Asia excluding Pacific OECD
PC	Pulverized Coal Power Plant
PEP	Present Value of Projected Economic Profit during Explicit Forecast Period
PER	Price to Earnings Ratio
PJ	Petajoule
Planelec-Pro	Planning of the Electric Power Generating System Program
PPCS	Fusion Power Plants Conceptual Study
QMS	Quality Management System
R&D	Research and Development
RD&D	Research, Development and Demonstration
RDDD	Research, Development, Demonstration and Deployment
ROA	Real Options Analysis
ROIC	Rate of Return on Invested Capital
ROV	Real Options Value
RTD	Research and Technology Development
SAS	South Asia
SERF	Programme of Socio-Economic Research on Fusion administered by EFDA
SPB	Spillover Benefits
SPV	Net Social Present Value
SRES	Special Report on Emissions Scenarios
TCV	Tokamak à Configuration Variable
TIPS	U.S. Treasury Inflation-Protected Securities
TWh	Terawatt-hour
UKAEA	United Kingdom Atomic Energy Agency
UN	United Nations Organization
VA	Value Added
WACC	Weighted Average Cost of Capital
WEC	World Energy Council
WEU	Western Europe
W7-X	Wendelstein 7 – X Fusion Stellarator Experimental Project

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"…I believe that the energy problem is *the single most important problem* that has to be solved by science and technology in the coming decades."

Steven Chu

U.S. Energy Secretary
Co-winner of the Nobel Prize in Physics (1997)

(Excerpt from Senate Caucus Briefing on National Academies Report on S&T Funding - 27/10/2005)

1. INTRODUCTION

This chapter introduces the background and the main problematics of the thesis. In section 1.1 the need for development of innovative energy technologies in the face of global energy security challenge is discussed, and the advantages of Fusion technology as a sustainable energy supply option are summarised. The concept of the energy innovation system is explained further and the current trends in energy R&D funding showing alarming signs of underinvestment are emphasised. Section 1.2 clarifies the problem of energy R&D evaluation that represents the main focal point in this thesis. Section 1.3 defines the specific objectives and scope of the research. Section 1.4 outlines the conceptual analytical framework and methodology. Section 1.5 presents the main contributions of the thesis and new features compared to the existing studies. Finally, the overall structure of the thesis is described in Section 1.6.

1.1 Context

1.1.1 Global Energy Challenge and Potential Role of Fusion

Unconstrained access to safe, clean and reasonably cheep energy supply is essential for meeting the basic needs of human society and for supporting economic growth. As confirmed by numerous studies, there is a direct link between per capita energy consumption and human well-being (see ***Figure 1***). The link is particularly strong for non-OECD countries with a Human Development Index (HDI) value of less than 0.8. Very few countries with per capita energy use of less than 2 tonnes of oil equivalent have a HDI score of more than 0.7 (IEA, 2004). Therefore, providing the energy services needed to sustain growth and, conversely, avoiding a situation where lack of access to such services constrains economic development, remains a central policy objective for all nations.

Energy can play a pivotal role in helping to achieve the Millennium Development Goals adopted in the United Nations Millennium Declaration (UN, 2000). According to the InterAcademy Council these goals and the potential contributions of energy services can be summarised as follows (IAC, 2007):

- ***To halve extreme poverty.*** Access to energy services facilitates economic development – micro-enterprise, livelihood activities beyond daylight hours, locally owned businesses, which will create employment.

- ***To reduce hunger and improve access to safe drinking water***. Energy services can improve access to pumped drinking water and provide fuel for cooking.

- ***To reduce child and maternal mortality; and to reduce diseases***. Energy is a key component of a functioning health system, contributing, for example, to lighting operating facilities, refrigerating vaccines and other medicines, sterilizing equipment, and providing transport to clinics.

- ***To achieve universal primary education, and to promote gender equality and empowerment of women***. Energy services reduce the time spent by women and children on basic survival activities (gathering firewood, fetching water, cooking, etc.); lighting permits home study, increases security, and enables the use of educational media and communications in schools, including information and communication technologies.

- ***To ensure environmental sustainability***. Improved energy efficiency and use of cleaner alternatives can help to achieve sustainable utilisation of natural resources as well as to reduce harmful emissions that protect the local and global environment.

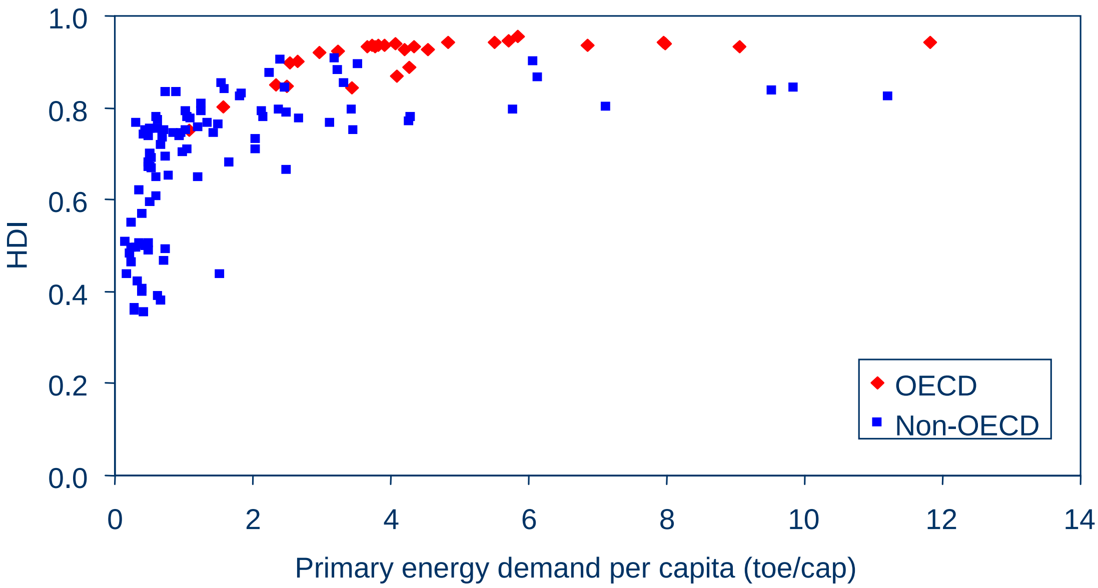

Figure 1. HDI and Primary Energy Demand in 2002 *(Source: IEA, 2004)*

Recognising the importance of energy services for human well-being, it is expedient to recall the main problems associated with the energy use. From the early beginning of the industrialisation era, it became apparent that the increasing energy consumption creates unprecedented burdens on the environment, ranging from deforestation due to fuel wood harvesting to the high level of local air pollution. The advances in science allowed to identify more subtle environmental and human-health effects. So, the combustion of fossil fuels is responsible for emissions of air pollutants including sulphur oxides, nitrogen oxides, soot, etc. that play a major role in the formation of acid rain and the excessive concentrations of fine particulate matters and ozone at the ground level. Energy use is also a major contributor to the release of long-lived heavy metals, such as lead and mercury, and other hazardous materials into the atmosphere.

Energy-related air pollution (including poor indoor air quality from the use of low grade fuels for cooking and heating) not only creates substantial public health risks, especially where emission controls are limited or nonexistent, it harms ecosystems, degrades materials and structures and impairs agricultural productivity (IAC, 2007). In addition, the extraction, transportation and processing of primary energy such as coal, oil, natural gas and uranium are associated with a variety of damages or potential risks to land, water and ecosystems. The wastes generated by nuclear electricity production represent additional disposal and long term storage problems.

While the most obvious environmental impacts from energy production, transformation and use have always been local, significant impacts occur also on a global scale. So, the combustion of fossil fuels accounts for more than half of the total anthropogenic emissions of greenhouse gas (GHG) which is recognised as one of the major contributors to the global warming and climate change. Moreover, the GHG emissions are set to increase over time following the constantly growing energy demand, especially in developing countries. Although the precise implications of the current GHG emissions trajectory remain uncertain, there is a growing body of scientific evidences that human-induced global warming is already underway, and that the related risks for society are very high. The recent Fourth Assessment report of the Intergovernmental Panel on Climate Change identified a number of potential adverse impacts associated with continued warming, including increased risks to coasts, ecosystems, fresh-water resources and human health (IPCC, 2007). In this context, making the transition towards cleaner and preferably zero-carbon emission technologies is widely acknowledged as one of the major challenges for energy policy makers.

Another issue that dominates national, regional and international energy policy debates is related to the energy security problem. The Green Paper of the European Commission "Towards a European Strategy for the Security of Energy Supply" stipulates that the European Union's long-term strategy for energy supply security "must be geared to ensuring … the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development" (EC, 2001). According to Gnansounou (2008) the following factors contribute to raise the concerns about the growing energy insecurity: the current trends in the evolution of global economy and geopolitical changes, particularly the rapid economic growth in emerging economies (e.g. China, India); the strain on oil and natural gas reserves; the concentration of most of these reserves in unstable regions; the threat of sabotages on energy supply infrastructures; the political tensions in Middle East including Iraqi war and Iranian nuclear programme; and finally, the hang to government appropriation of oil and gas sector in many energy exporting countries.

In the near to medium term, energy security concerns are almost certain to focus on oil and, to a lesser extent, on natural gas. As demand for these resources grows, and as reserves of relatively cheap and readily accessible supplies decline in different world regions, the potential for supply disruptions, trade conflicts and price shocks is likely to increase. Already, there is a concern that the current situation of tight supplies and high and volatile prices is exacerbating trade imbalances, slowing global economic growth and directly or indirectly complicating efforts to promote international peace and security. The problem is particularly acute for many developing countries that devote a large fraction of their foreign exchange earnings to oil imports, thus reducing the resources available to support investments needed for economic growth and social development (IAC, 2007). In a longer term perspective, it is evident that the problem of the exhaustion of fossil fuel reserves will become more and more severe, and the world will have to gradually switch to alternative energy supply options.

The conclusions from joint IEA/NEA workshop on electricity supply security emphasised on three main groups of aspects that should be taken into account in the analysis of energy supply security for electricity generation sector (IEA/NEA, 2005):

- "upstream" aspect – dependence on imported fuels, especially growing dependence on natural gas imported from Russia and Middle East (Algeria) that creates a risk of supply disruptions and sustained price increase due to cartel agreements.

- "downstream" aspect – security of power supply for the final consumers which can be affected by transient failures in electricity generation and transmission / distribution networks, mainly due to underinvestment in respective capacities.

- "time frame" for analysing electricity supply security – market players tend to be focused on short and medium term issues, while governments are obliged to consider the issue in long term perspective.

The broadly accepted solutions to cope with the energy security challenge include: strengthening of the energy markets; diversification of the energy supply mix by promoting alternative and renewable energy sources and expanding nuclear power; enhancing energy efficiency in industry, buildings and road transport; encouraging innovation and investing in energy R&D; reinforcement and modernisation of the electric power infrastructure; increasing market share of domestic fuels; expanding the strategic petroleum reserve, etc. While some decision makers prefer the market mechanisms for optimising energy supply mixes, the others call for more intense government intervention arguing that free markets fail to provide adequate level of energy security. Furthermore, considering the global nature of the energy security challenge and the continuing trend towards globalisation of the world economy, it is clear that any policy seeking to ensure the security of energy supply for a given country or region has to be implemented through a peaceful negation process which copes with the strategic aspirations of the major energy exporting countries and other market players such as developing economies.

With the inevitably approaching peak in the production of conventional hydrocarbon fuels, such as oil and natural gas, predicted by M. King Hubbert (see e.g. Hubbert, 1956; Greene *et al.*, 2003), it is expedient to look at the alternative energy supply options that are already available or expected to enter into the market place in medium-to-long term perspective. While different forms of renewable energy (hydro, wind, solar, biomass, geothermal, etc.) should remain on the top of the energy policy agenda, the resurgence of nuclear power may prove to be an efficient complementary option. Indeed, the advanced nuclear technologies could bring about substantial benefits through lessening the dependence on imported hydrocarbon fuels, reducing the greenhouse gas emissions and giving additional impetus to national manufacturing industries. On the other hand, nuclear power is facing multiple critics on different economical, environmental and political issues that may substantially hinder its market penetration. Another important alternative for large scale power generation is represented by the coal-fired power plants equipped with CO_2 capture and sequestration functionality. This technology is still in the demonstration stage and, in principle, it could become an economically viable option under the condition that sale of CO_2 emission reduction credits will allow to offset its higher investment and O&M costs compared to other technologies.

Looking at the second half of the century we have to admit that controlled thermonuclear Fusion is probably the most prominent technology that satisfies the criteria of a sustainable energy supply option. The potential merits of Fusion are widely acknowledged in scientific literature and policy reports (see e.g. IEA, 2003; Ongena & Van Oost, 2006). The typically cited advantages include: worldwide availability of practically inexhaustible and cheap fuel (deuterium and lithium), inherent safety, modest amount of relatively short-lived radioactive wastes, absence of CO_2 emissions or other atmospheric pollutants. The feasibility of this technology has been successfully demonstrated in recent years with Joint European Torus (JET) reactor producing 16 MW of Fusion power. In the meantime, several important scientific and technological issues remain to be solved to make Fusion work reliably on the scale of a power plant, including sustaining a large volume of hot plasma for long periods of time at pressures that allow a large net energy gain from Fusion reaction (EC, 2007a). Such Fusion power plant needs very special materials designed into complex components capable of resisting the extreme conditions required for continuous high power outputs.

The ongoing international Fusion R&D programme is addressing these challenges, and the recent Fusion power plant conceptual studies, including full lifetime and decommissioning costs, suggest that if the technological criteria are met, Fusion can be economically competitive with other low-carbon electricity supply options (see Maisonnier *et al.*, 2005). The agreement to build ITER (International Thermonuclear Experimental Reactor), which should demonstrate the feasibility of magnetic confinement Fusion on the scale of the power plant, could be considered as a major step forward to mastering Fusion technology. The goal beyond ITER is to demonstrate the production of electricity in a demonstrator Fusion power plant (DEMO), which is expected to be constructed by 2030-2035 and for which the conceptual design activities are already under way. Accordingly, the full-scale deployment of commercial Fusion power plants could start by 2050 or even earlier if a more ambitious Fusion R&D programme is undertaken.

1.1.2 Energy Innovation System

Finding the right solutions to the global energy problems depends greatly on the capability of energy industries to innovate. The technologies delivering energy services have been constantly improving over time leading to the creation of very complex and capital intensive infrastructures, while fostering the exhaustion of fossil fuel reserves. Nowadays, the increasing concerns about adverse environmental impacts, security of energy supply and the need to ensure sustainable development have raised the question whether the existing energy system is capable to meet those challenges for the next decades (see e.g. Sagar & Holdren, 2002). To answer this question one has to look at the specifics of the innovation process in energy sector, and to examine if available funding and incentives are sufficient to promote R&D and market deployment of advanced energy technologies. Let's recall first the main postulates of the theory of innovation and technological change, and then proceed with a more detailed analysis of the energy innovation system.

The traditional "linear" model of innovation, as first defined by Joseph Schumpeter (1934, 1939) describes innovation as a process of continuous flow through the stages of basic research to applied research to technology development and diffusion. This model implies that the best measure to amplify the output of useful new technologies is to increase the inputs, i.e. enhance the possibility of inventions by investing more funds in R&D. This concept is known as *technology-* or *supply-push*. The alternative view proposed in the works of Griliches (1957) and Schmookler (1966) advocates that demand for products and services is more important in stimulating innovation than advances in the state of knowledge, so-called *demand-pull*. The need for understanding innovation and its consequences from macro-economic point of view was highlighted in the work of Solow (1957) which estimated the relative importance of different factors to economic growth and concluded that the largest contribution to growth did not come from increases in labour or capital productivity, but from technical change.

Further advancements in the innovation theory gave birth to broader approaches to understanding technological change and innovation. The concept of *induced innovation* emphasises on market drivers and analyses the impact of changes in the economic environment on the rate and direction of technological change. The notion of induced technological change was first introduced by Hicks (1932) who noted that changes in relative prices of production factors, such as labour or capital, would spur the development and diffusion of new technologies in order to economise on the usage of the more expensive production factor. Starting from the 1960s, this notion of induced (or 'endogenous') technological change has been used by the so-called *endogenous* or 'new' *growth theory* in order to account for economic growth and technological changes endogenously within a macro-economic modelling analysis. This theory examines the role of positive externalities that can not be appropriated by the individual firm undertaking R&D activities. Embodied in different forms of knowledge or physical capital, these positive externalities, also known as spillovers, create increasing returns to scale, thereby ensuring steady long-run economic growth.

The *evolutionary theory* of technological change was pioneered by Nelson and Winter (1982). This approach builds on two foundations – the Schumpeterian model of innovation, and the idea of "bounded rationality" which assumes that decision-makers are limited in their ability to gather and process information and so, rather than being perfectly rational profit maximisers, they make decisions that satisfy their most important criteria. Another concept of innovation is represented by "*path dependent*" models. The idea behind this approach is that the successful innovation and take up of a new technology depends on the path of its development, including the particular characteristics of initial markets, the institutional factors governing its introduction and the consumers' expectations. This concept was promoted in the works of Arthur (1994) who was particularly interested in increasing returns to adoption, i.e. positive feedbacks meaning that the more technology is adopted, the more likely it is to be further diffused.

The evolutionary and path dependency approaches emphasise the importance of past decisions, embodied in technologies, infrastructure and institutions, constraining present innovation, while the induced technological change approach stresses the long-run importance of changes in relative prices of production factors. The complementarity of these concepts suggests that they could be the elements of a more general theory, which defines innovation as a systemic, dynamic, non-linear process, involving a diverse range of interacting actors, giving rise to both positive and negative feedbacks between different stages of technology development (Foxon, 2003). This picture emphasises the importance of knowledge flows between different actors; expectations about future technology, market and policy developments; environmental, political and regulatory risk; and the institutional structures that affect incentives and barriers.

Figure 2 represents a schematic view of such interconnected dynamic framework which in the terminology of Sagar & Holdren (2002) can be defined as "Global Energy Innovation System". Innovation in energy sector is driven by the consumers' demand for safe, environmentally sound, resource unconstraint and affordable energy supply. Initially, it goes through the stages of *basic research* aimed at improved understanding of natural phenomena, such as plasma in the case of thermonuclear Fusion; and *applied R&D* aimed to development of specific applications. Then follow the stages of *demonstration* (construction of prototype installation), *deployment* (construction of 1^{st} of kind energy facility), and *diffusion* (construction of N^{th} of kind facilities).

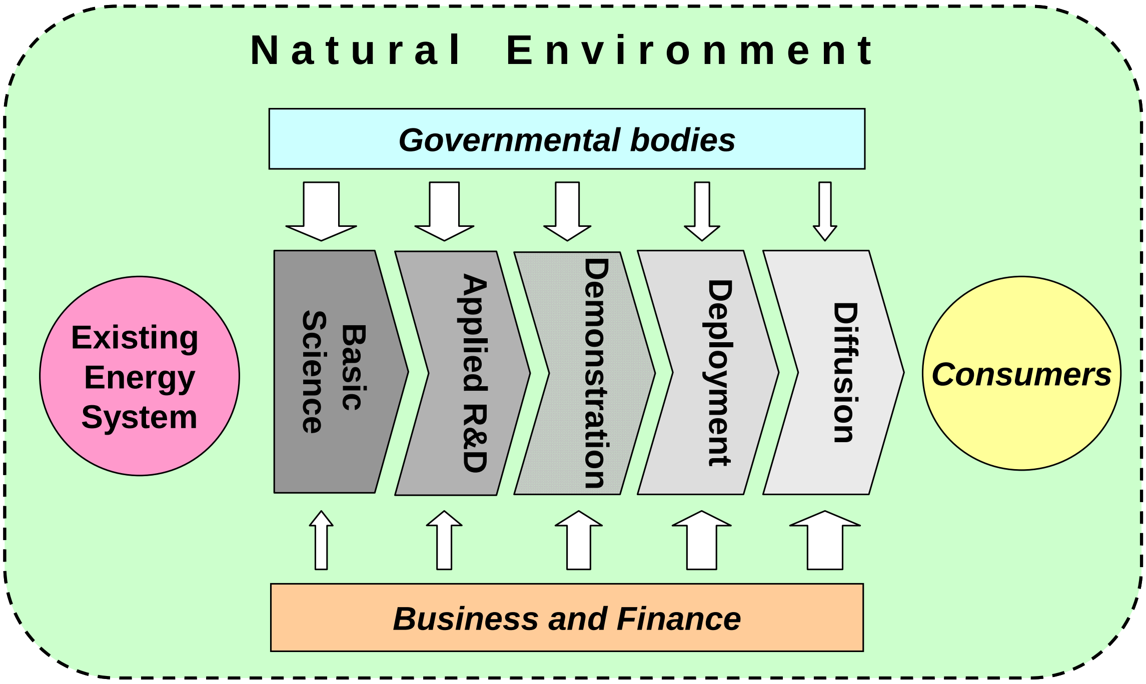

Figure 2. Global Energy Innovation System *(adapted from Foxon, 2003)*

The new technologies must fit into the existing energy infrastructure and they ought to compete with other technological options. Hence, the existing energy system, including the facilities under construction and the technologies under development, constitutes a tangible element of the energy innovation system. Natural environment enters into the system as a provider of primary energy resources and an absorbent of the atmospheric emissions and other pollutants released through energy transformation and final use. The governmental bodies through the dedication of public funding, human capital and research infrastructure ensure the technology "push", while the private sector through participation in publicly sponsored R&D and through investment of its own resources provides the market "pull" for innovative technology. The size of fleshes indicates the relative importance of the efforts applied by the public authorities and the private companies at each stage of the innovation process.

Specifics of the innovation process in energy sector have been thoroughly analysed in the paper of Gallagher *et al.* (2006). They defined "Energy-Technology Innovation" (ETI) as the set of processes leading to new or improved energy technologies that can augment energy resources; enhance the quality of energy services; and reduce the economic, environmental and political costs associated with energy supply and use. These processes include initial conceiving; study; building, demonstration and refining in specific environments from research laboratory to commercial market place; and propagation into widespread use. Accordingly, innovation does not consist of R&D phase alone; it is not complete unless it includes further steps through which the new technologies or improvements attain practical application on the market. It has been also emphasised that ETI may play a key role in reconciling some of the "contradictory" energy policy goals, such as increasing reliance on coal while reducing GHG emissions (e.g. through adoption of coal with CO_2 capture and storage), increasing domestic oil production while reducing the impact on natural environment (e.g. due to enhanced oil recovery technologies), etc.

The political questions about energy technology innovation do not concern the general need for it, which is recognised to be an absolute must, but rather about "how much of what kinds is needed how quickly, about how to make it more efficient and effective, about how and by whom the needed activities should be conducted and managed, and about how it should be paid for" (Gallagher *et al*., 2006). Accordingly, it is important to develop a deeper understanding of the current patterns in energy technology innovation, to analyse its performance metrics, and to determine the possible policy measures that would allow for bridging the gap between what is needed and what is actually happening on the worldwide scene.

Any technological innovation system, in general, and energy technology innovation, in particular, can be assessed by using a set of quantitative and qualitative indicators. Quantitative metrics may include: R&D spending; the number of programmes, partnerships, scientific and engineering staff; the number of scientific and technical publications; the number of patents filed, granted and cited; technology performance (efficiency, specific costs, emission factors); the life-cycle (S-shaped) technology growth curves; learning rates; etc. Overall success or failure of the programmes and projects as well as their different managerial aspects can be assessed by using qualitative techniques, including surveys, case studies, etc. The programme performance indicators can be also classified into four categories: inputs, outputs, outcomes and impacts. It is worth noting that each of these metrics has its own advantages and drawbacks. Therefore, both approaches – quantitative and qualitative – should be considered as complementary, and several indicators must be used in combination in order to provide a more accurate and comprehensive picture of the innovation process.

1.1.3 Underinvestment in Energy R&D

The research & development is the area which potentially may offer one of the highest rates of return on invested capital as confirmed by numerous studies, see e.g. Mansfield *et al.* (1977); Hall (1996); Jones & Williams (1998). However, because of the intrinsic nature of R&D activities, characterised by the difficulty to predict the final result and the high volatility of payoffs, the private sector is often lacking the incentives to invest in R&D. It is especially the case of basic research, because of its complexity, immense requirements in human and capital resources, and the problem with appropriation of R&D results. On the other hand, basic science and R&D are capable to generate important positive externalities, which are beneficial for the whole society. That justifies the public policy intervention, which is supposed to correct the market imperfection and to provide support for R&D in most promising domains.

The key questions faced by the authorities in the design of R&D policies can be summarised as follows: (1) which programmes to support and how much public funds to invest in R&D; (2) what is the optimal allocation of available funds among multiple R&D programmes; and (3) what are the best organisational mechanisms to provide the incentives for researchers and to promote R&D funding by the private sector? A glimpse at the global R&D expenditures in OECD countries shows a sustained growth at annual pace of approx. 3.5% in real terms (OECD, 2008a). Meanwhile, the structure of EU public R&D spending within the past Framework Programs (FP) shows a tremendous shift in the priorities from energy towards other sectors (see ***Figure 3***). While in the first Framework Programme energy – related RTD activities accounted for approx. 66%, in FP6 the share of energy RTD declined to 11.6% with a further reduction foreseen in the ongoing FP7 to 10.5% (Renda *et al.*, 2008). The same tendency is also observed in the USA, where energy R&D as a percentage of total R&D spending has fallen from 10% in 1980 to 2 % in 2005 (Kammen & Nemet, 2005).

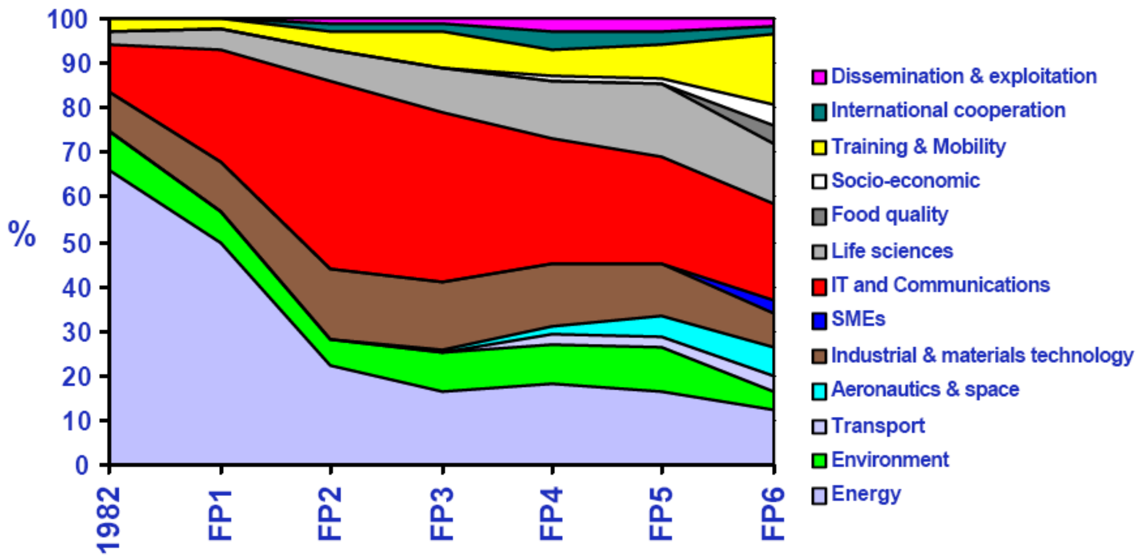

Figure 3. Changing Priorities in Framework Programmes for European RTD
(Source: EC, 2004)

In the 25-years period between 1981 and 2005, the total energy research, development and demonstration (RD&D) investments in IEA / OECD countries have decreased by a factor of 1.7 to about $US\$_{2007}$ 10.2 billion[1], while the whole R&D investments have increased by a factor of 2.5 to about $US\$_{2007}$ 860 billion in line with the economic growth (OECD, 2008a,b). While 2.5%

[1] Hereinafter, the term "billion" signifies thousand of millions (10^9) and the term "trillion" signifies million of millions (10^12) according to the "short" numerical scale.

of the global GDP is invested in scientific R&D, energy R&D funds are about 1% of the gross value of the Total Primary Energy Supply (which is about US$ 2 trillion in 2005), about 0.45% of the value of the Total Final Energy Consumption (which is about US$ 4.5 trillion in 2005), and about 0.15% of the value of the energy systems including the end-use devices (Tosato, 2005). Meanwhile, in other sectors (e.g. drugs & medicines, instrumentation equipment, telecoms) R&D intensity attains 10% of net industry sales (Margolis & Kammen, 1999).

The structure of total energy RD&D budgets in IEA countries is shown in ***Figure 4***. According to the statistics collected in OECD Energy Technology RD&D database the public expenditures on Fusion technology have declined in line with the general trend from record high € 1.3 – 1.4 billion[2] in the beginning of 1980s to € 0.7 – 0.8 billion in the middle of 2000s. Compared to other energy supply options, over the past decade, Fusion share in energy R&D investments has declined from 11% in 1996-97 to 7.5 % in 2006 in favour of renewable energy and hydrogen technologies (OECD, 2008b).

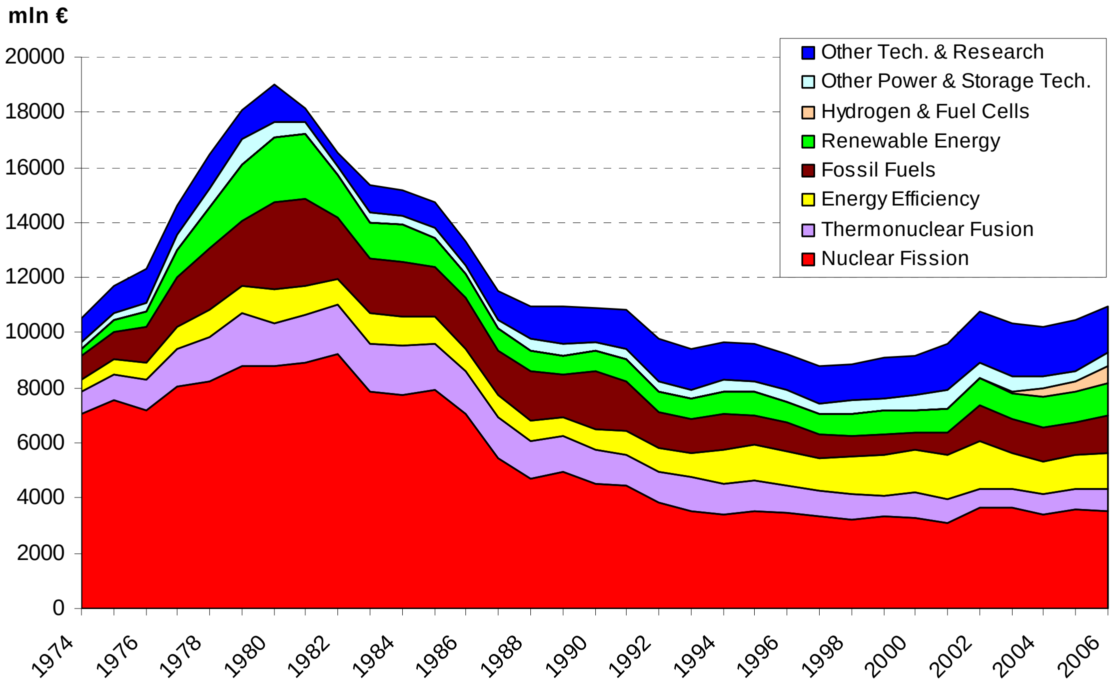

Figure 4. Total Energy RDD Budgets in IEA Countries *(Source: OECD, 2008b)*

The analysis of these figures suggests the idea that there exists a risk of underinvestment in energy R&D, in general, and the research on Fusion technology, in particular, that may cause significant problems for meeting the energy needs of the society in a long term perspective. The problem of underinvestment in energy R&D has been emphasised in the recent publications of Bernardini (2004) and Kammen & Nemet (2005). Furthermore, the ongoing liberalization process in energy sector creates additional threats, because of the limited ability of the free markets to account for all social costs (Bureau & Glachant, 2006) and to channel private investments towards long-run strategic R&D programmes (Dooley, 1998). All these facts lead to

2 € in 2006 prices and exchange rates

the conclusion that a rethinking of the existing practices of energy R&D programmes evaluation and a revision of the current energy R&D policies and allocated budgets are vitally needed.

1.2 Problem Definition: Evaluation of Long-term Energy R&D Programmes

One of the main reasons, why energy R&D is running the risk of underinvestment, is related to the practical difficulty to estimate the returns of long-term energy R&D programmes, such as Fusion. Indeed, considering a limited availability of R&D funds and the competition for them among multiple programmes, the decisions makers responsible for allocation of public R&D budgets may be facing the following specific questions:

- What is the expected net socio-economic payoff (social rate of return) of Fusion RDDD programme?
- What are the reasonable economic arguments that could justify the increase in public funding of Fusion R&D and would stimulate greater involvement of private sector?
- What is the best strategy to proceed with the demonstration of Fusion technology that would maximise the expected socio-economic benefits from its future deployment?

To answer these questions one needs to perform a comprehensive analysis of the different technological, economical, environmental and societal aspects of Fusion RDDD process. The evaluation of Fusion should include, on the one hand, some reasonable estimates of the current and future Fusion RD&D costs. On the other hand, it needs the assessment of prospective cash flows from construction and operation of Fusion power plants that will be influenced by a multitude of technological and economical factors. Considering a very long time span of the programme, which extends over several decades, and taking into account the possibility that deployment of Fusion may be delayed because of some unforeseeable technical problems and unfavourable market conditions, the results of such analysis are inevitably confronted with a high degree of uncertainty.

Moreover, according to the recent R&D evaluation practice and scientific literature it is recommendable to consider all social costs and benefits, including negative and positive externality effects, while allocating public funds among multiple R&D programmes (e.g. Jaffe, 1996; Tassey, 2003). Although the evaluation of negative externality effects caused by atmospheric emissions and other forms of pollution has been successfully mastered with the help of integrated Energy - Economy - Environment models, at the same time, the assessment of positive externalities revealed through different types of spillover effects still represent a significant problem because of methodological lacuna and the deficit of empirical studies.

In this situation, it is important to analyse the existing methods of R&D programmes evaluation in energy and other domains, and to elaborate on this basis an adequate analytical framework and practical tools that would allow for versatile assessment of Fusion RDDD programme, including its internal and external costs and benefits. A comprehensive assessment of the potential risks and the expected net social returns of Fusion RDDD programme will allow for optimising the allocation of both public and private funding. The methodological approach developed hereby can be also used in the evaluation of other long term energy R&D programmes, e.g. Generation

IV nuclear fission and coal with CO_2 capture & sequestration. This research can be also useful for private companies seeking to estimate the strategic benefits from involvement in Fusion and similar R&D programmes.

1.3 Objectives and Scope of the Research

As it was mentioned above, due to a very long development cycle and the intrinsic complexity of Fusion technology, its expected economic benefits can be estimated only with a high degree of uncertainty. Therefore, the decision makers seeking to optimise public R&D funding need to perform a more comprehensive socio-economic assessment of Fusion RDDD programme which extends beyond the evaluation of direct economic effects. The typical components of social cost – benefit analysis (CBA) are represented in ***Table 1***. The distinction is made usually between *private* costs and benefits (at the level of individual participants) and *social* costs and benefits (at the level of government and the whole society).

Table 1. Types of Private and Social Costs and Benefits

	Individual Partners	**Programme Sponsor (Government)**	**Society**
Benefits	Increase in Net Earnings, Profits Additional Benefits from Transfers Non-Economic Benefits	Tax Revenues Decrease in other Subsidies	Increase in National Income (direct effect) **Spill-over effects (indirect effect)** **Strategic Options**
Costs	Opportunity Cost of Participation Direct Participation Cost Loss of Subsidies from Other Programmes	Tax Costs Project & Administration Costs	Opportunity Costs (cross earnings from other potential programmes) Programme Costs

Source: adapted from EC (2002)

Accordingly, the general intention of this thesis consists in performing a more comprehensive socio-economic evaluation of Fusion technology emphasising on the quantitative assessment of the positive externality effects and taking into account the value of the strategic options arising due to flexibility in the managerial decisions throughout demonstration and deployment stages. In this context, the existence of valuable externalities and a substantially positive net social present value should be considered as a clear indication for increasing public funding and other types of support.

The main objective of this study consists in elaboration and practical testing of the methodology that would allow for estimating total socio-economic returns of Fusion RDDD programme subject to the underlying ucertainty. It grounds on the in-depth analysis of the technological and economical trajectories of the global energy system. Special focus is made further on the evaluation of spillover benefits of selected Fusion R&D projects and estimation of the strategic option value of the whole Fusion RDDD programme. Ultimate goal consists in elaboration of a decision-aid tool for analysing different Fusion implementation strategies and optimising Fusion RDDD funding subject to the expected net social present value.

The specific tasks pursued in the thesis include:

- Estimation of the potential contribution of Fusion technology to the future energy mix through elaboration of global long-term electricity supply scenarios;
- Identification of the main types and specific examples of positive externality effects (spillovers) of Fusion RDDD programme;
- Elaboration of the methodology for quantitative assessment of spillover benefits of the ongoing Fusion R&D projects; case study of Wendelstein 7 - X stellarator project;
- Elaboration of the integrated methodological framework that would allow for taking into account spillover benefits and options value in the socio-economic assessment of Fusion RDDD programme;
- Prospective evaluation of Fusion RDDD programme and its different implementation strategies aiming to provide policy recommendations.

The experience from similar studies shows that a comprehensive *ex ante* evaluation of indirect effects of large scale R&D programmes, such as Fusion, is a hardly feasible task. Accordingly, it was decided to concentrate the analyses in this thesis on the *ex post* evaluation of indirect socio-economic effects of an exemplary Fusion R&D project (Wendelstein 7-X stellarator, currently under construction in Greifswald, Germany [3]). In the follow-up work, the evaluation can be extended to include other Fusion R&D projects, such as ITER. Another essential point consists in the estimation of the potential size of future Fusion technology market and the analysis of the economic implications of different Fusion implementation strategies that requires an adequate treatment of the underlying risks and uncertainties.

1.4 Conceptual Analytical Framework and Methodology

In recent years, a body of literature has emerged aiming to provide appropriate methodological framework for evaluation of publicly funded research (e.g. Holdsworth, 1999; Georghiou *et al.*, 2002; Tassey, 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 market conditions and technology performance. According to Georghiou *et al.* (2002) there is no single methodology, which can address all aspects of socio-economic impacts of international multi-years RTD programmes. Therefore, a portfolio of complementary approaches is needed in order to analyse the different types of effects revealed through different time and space dimensions.

[3] see http://www.ipp.mpg.de/ippcms/eng/pr/forschung/w7x/stand/index.html

In principle, any R&D project or longer-term programme can be considered as an investment project which normally undergoes a series of quantitative (profitability) and qualitative (due diligence) assessments before the final decision to invest can be taken by the management. The traditional approach to capital budgeting implies that investment decisions should be taken based on the estimation of the project's prospective cash flows discounted with appropriate risk-adjusted discount rate. The results of profitability analysis are usually presented in the form of the project's net present value (NPV) which can be calculated using the formula (1.4.1) or any similar metric (internal rate of return, pay-back time, etc.)

$$NPV = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+i)^t} \tag{1.4.1}$$

where

R_t – estimated revenues at time t

C_t – estimated costs at time t

i – discount rate

T – project lifetime.

The discounted cash flow (DCF) analysis is normally performed in a deterministic setting by making a projection of the direct costs and revenues of project activities – e.g. in the case of Fusion – the research, development, demonstration, and deployment costs and the revenues from Fusion electricity sales. The credibility of analyses can be improved by making several alternative scenarios regarding the possible evolution of the project's costs and benefits.

This thesis proposes to amend this basic evaluation framework with several extensions. First of all, it is suggested to include in the analysis the value of indirect socio-economic benefits (positive externalities represented by different types of spillover effects). In this case, the net present value formula can be rewritten in the following way:

$$SPV = \sum_{t=1}^{T} \frac{DR_t + SPB_t - TC_t}{(1+i)^t} \tag{1.4.2}$$

where

SPV – net social present value of Fusion RDDD programme

DR_t – direct revenues from Fusion electricity sales at time t

SPB_t – spillover benefits at time t

TC_t – total costs (both internal and external[4]) at time t.

[4] Although the evaluation of negative externality effects (external costs) represents an important issue in the analysis of modern energy systems, this topic falls beyond the scope of this thesis since it was extensively studied by other authors, see e.g. Hamacher *et al.* (2001) for comparison of different electricity supply options, including Fusion. Considering that external costs of Fusion represent only a small fraction, in this thesis they were included for simplicity reasons in the estimated total costs of Fusion technology.

The second extension consists in departing from traditional deterministic analysis framework and performing DCF calculations in a stochastic probabilistic setting using Monte Carlo simulation technique in order to provide a better representation of the underlying unceratinties. For that purpose the key driving factors of the overall programme costs and benefits are allowed to vary stochastically and specific probabilities of success are assigned for each programme stage. Thereby, the expected net present value (ENPV) of Fusion RDDD programme is computed as a probabilistic mean value of a large spectrum of all possible results ranging from complete failure to extraordinary success.

In case of probabilistic simulation the total discounted benefits and total discounted costs of Fusion RDDD programme can be approximated with the following formulas:

$$\widetilde{TDB} = \sum_{t=1}^{T} \frac{\widetilde{SPB}_t^{R\&D} + \tilde{p}_{R\&D} \times \widetilde{SPB}_t^{Dem} + \tilde{p}_{R\&D} \times \tilde{p}_{Dem} \times (\widetilde{EP}_t \times \widetilde{FEG}_t + \widetilde{SPB}_t^{Dep})}{(1+\tilde{\imath})^t} \tag{1.4.3}$$

$$\widetilde{TDC} = \sum_{t=1}^{T} \frac{\tilde{C}_t^{R\&D} + \tilde{p}_{R\&D} \times \tilde{C}_t^{Dem} + \tilde{p}_{R\&D} \times \tilde{p}_{Dem} \times (\widetilde{COE}_t \times \widetilde{FEG}_t + \tilde{C}_t^{Dep})}{(1+\tilde{\imath})^t} \tag{1.4.4}$$

where

$\widetilde{TDB}$ – expected total discounted benefits of Fusion RDDD programme

$\widetilde{TDC}$ – expected total discounted costs of Fusion RDDD programme

$\widetilde{FEG}_t$ – expected Fusion electricity generation at time *t*

$\widetilde{EP}_t$ – expected market electricity price at time *t*

$\widetilde{COE}_t$ – expected unit cost of Fusion electricity production at time *t*

$\tilde{\imath}$ – stochastic discount rate

$\tilde{p}_{R\&D}$; $\tilde{p}_{Dem}$ – expected probabilities of success of Fusion “R&D” and “Demonstration” stages

$\tilde{C}_t^{R\&D}$; $\tilde{C}_t^{Dem}$ – expected investments during Fusion “R&D” and “Demonstration” stages

$\tilde{C}_t^{Dep}$ – expected costs of public support to commercialisation of Fusion during “Deployment”

$\widetilde{SPB}_t^{R\&D}$; $\widetilde{SPB}_t^{Demo}$; $\widetilde{SPB}_t^{Dep}$ – expected value of spillover benefits during “R&D”; “Demonstration” and “Deployment” stages.

It is worth noting that expected investments during “R&D” and “Demonstration” stages ($\tilde{C}_t^{R\&D}$; $\tilde{C}_t^{Dem}$) are positively correlated with expected probabilities of success ($\tilde{p}_{R\&D}$; $\tilde{p}_{Dem}$) and negatively correlated with time parameter (*T*). In this way the effect of increased RD&D funding on the expected NPV of Fusion RDDD programme can be apprehended. The probabilities of success may be also defined as singleton values or could be allowed to vary stochastically. The same refers to the discount rate ($\tilde{\imath}$), see Chapter 4.2 for more detailed discussion of these issues.

The third amendment proposed in this thesis consists in development of a real options valuation framework, which allows to grasp in the quantitative assessment of Fusion RDDD programme the strategic value arising due to managerial flexibility subject to market uncertainty. Indeed, the traditional "static" NPV approach ignores the possibility of proactive management of programme cash-flows, whereby the potential losses in case of unfavourable market conditions or any other obstacles can be reduced, while in a contrary situation the potential gains can be augmented through follow-up investments. Therefore, according to real options theory (see e.g. Trigeorgis, 2000) the strategic "expanded" net present value of any investment project characterised by a high degree of uncertainty and at least partial irreversibility should be determined as a sum of its static NPV and its real option value.

Versatility of real options approach allows for elaborating two different views on the socio-economic assessment of Fusion RDDD programme. On the one hand, the investments in Fusion R&D and demonstration activities can be seen as a "compound" real option, which opens opportunity to acquire another investment option entitling for certain, hopefully positive, cash-flows from deployment of Fusion power plants. By comparing the estimated value of this compound RD&D option with actual financial outlays of Fusion RD&D activities the decision-makers can verify whether it is worthwhile to pursue the ongoing programme and determine the upper limit up to which it may be reasonable to increase Fusion RD&D funding given the current state of knowledge and the level of uncertainty. Furthermore, the fact of the imprecision of available information and subjective nature of human judgements can be also taken into account through performing real options calculations with possibilistic fuzzy numbers.

On the other hand, the potential spillover benefits during future demonstration and deployment stages may be factored into the overall socio-economic evaluation of Fusion RDDD programme by valuing them as a specific type of "expansion" real option within a more complex sequential compound option model. Elaboration of this real options interpretation of spillover effects represents one of the main innovative contributions of this thesis because it allows for making a reasonable *ex ante* pecuniary evaluation of the overall programme's spillover benefits. Accordingly the following high level formula can be applied for determining the strategic net social present value of Fusion RDDD programme:

$$ESPV = NPV_{ST} + ROV_{FA} + ROV_{SPB} \tag{1.4.5}$$

where

$ESPV$ – strategic "expanded" net social present value

NPV_{ST} – static NPV of Fusion RDDD programme estimated in a stochastic probabilistic setting

ROV_{FA} – real option value of managerial flexibility actions related to demonstration and deployment of Fusion technology

ROV_{SPB} – real option value of spillover benefits.

In order to estimate in practice the strategic net social present value of Fusion RDDD programme an integrated modelling framework has been developed in this thesis that comprised the following elements: (1) Assessment of the technological potential for deployment of Fusion power plants based on the simulation of multi-regional long term electricity supply scenarios with PLANELEC model; (2) Economic evaluation of Fusion RDDD programme and analysis of different implementation strategies using Real Options model; (3) Estimation of the economic value of spillover benefits from participation in Fusion R&D projects at the level of individual companies with the help of financial evaluation model; (4) Strategic evaluation of Fusion RDDD programme, taking into account both spillover benefits and real options value, and policy recommendations.

Conceptual integrated modelling framework proposed in this thesis is depicted in ***Figure 5***. Next sections provide a more detailed description of the specific elements of this framework.

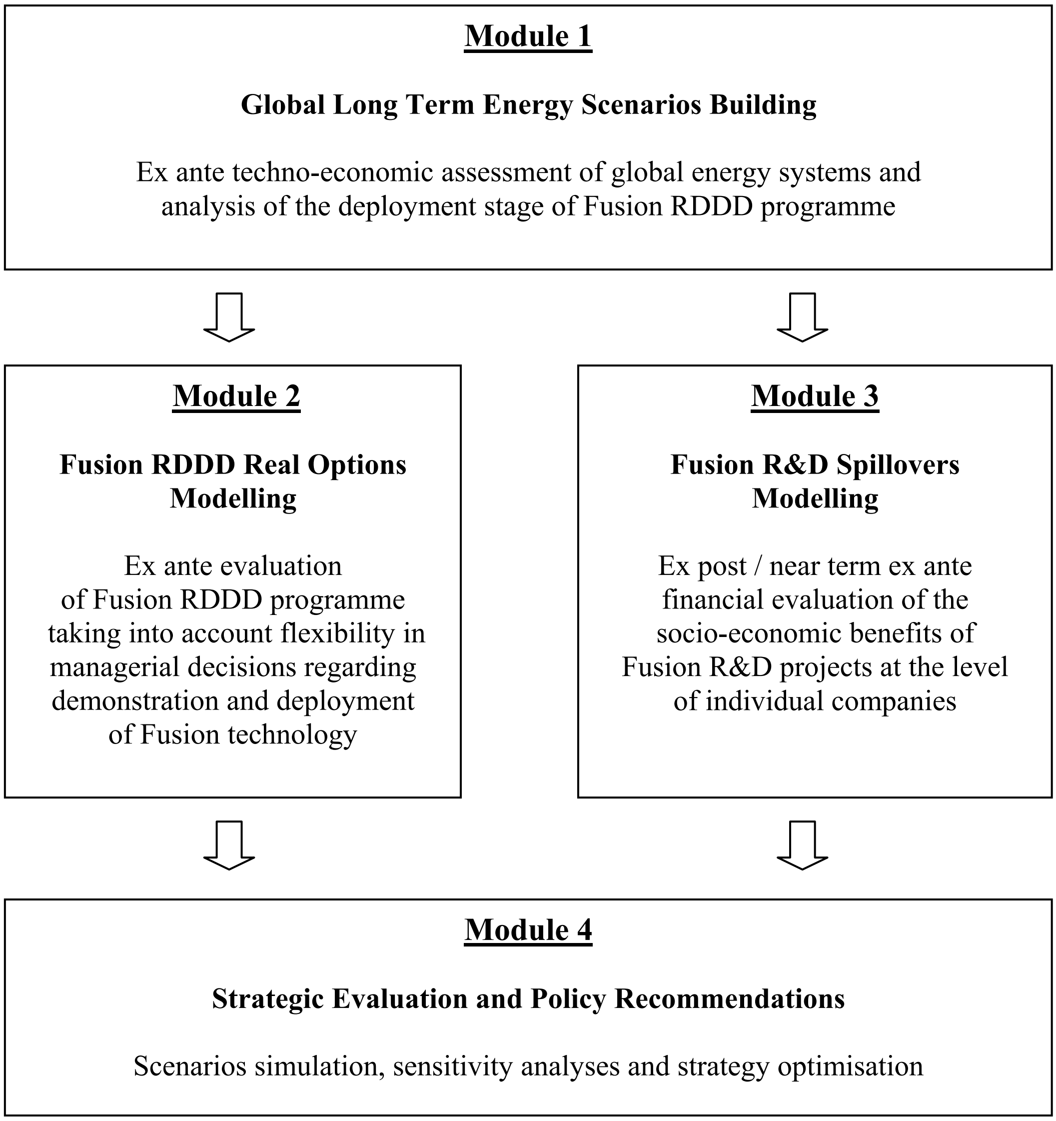

Figure 5. Conceptual Integrated Modelling Framework

<u>Long-term Electricity Supply Scenarios with Fusion</u>

This module aims to explore the potential role of Fusion power in future electricity supply mixes and to quantify its advantages and possible drawbacks. A general assessment of the electricity generation systems in different world regions is carried out at its current and anticipated state through estimating future electricity demand, availability and prices of main energy fuels, generic technical and economical parameters of existing and prospective power generating technologies and building on this basis a set of multi-regional electricity markets scenarios for the time horizon 2100. The methodology makes use of the least cost electricity systems planning model PLANELEC-Pro (Gnansounou, 2003). It determines the expansion plans of the power generation system that adequately meet the electricity demand at minimum cost while respecting the constraints related to the quality of electricity supply and CO_2 emissions. The competitiveness of

Fusion technology is estimated through assessing the impact of various market shares of Fusion power plants on the discounted total cost of the power generation system, levelised electricity cost and cumulative CO_2 emissions.

Real Options Model

The strategic value of Fusion technology is estimated in this module with the help of real options model based on the expected discounted cash flows from construction and operation of Fusion power plants and exogenous assumptions regarding the costs of Fusion RD&D activities alongside with the subjective probabilities of success at each programme stage. The net present value of Fusion RDDD programme, estimated in a probabilistic setting, is taken as benchmark for calculating the real options value attributable to different managerial decisions that may affect the prospective cash-flows. Two different strategies are compared: reference "Baseline" strategy corresponding to the current pace of Fusion RDDD programme vs. "Accelerated" strategy assuming more rapid development and massive deployment of Fusion technology. The later strategy is characterised by the increased spending during demonstration stage that results in a higher probability of success and shorter time to market of Fusion technology. The conclusions are drawn from the model calculations regarding the potential benefits of accelerated development path and the optimal allocation of future public funding.

Spillovers Model

This module contains a conceptual financial evaluation model for estimating spillover benefits of individual Fusion R&D projects embraced in Fusion RDDD programme. Herein, spillover effects are understood as different types of technological, commercial and organisational learning which may be acquired by the companies through their participation in publicly funded Fusion R&D projects. It is assumed that Fusion R&D spillovers may have a positive impact on the key driving factors of the company value in several ways, such as increase in sales revenues, acquisition of new technological competences; building of knowledge stock embodied in company's personnel, patents, manufacturing know-how; development of prototype or ready-to-market innovative products; strengthening of marketing capabilities, etc. Accordingly, the pecuniary value of spillover benefits is calculated based on the estimated increment of the company value due to its participation in the ongoing and future Fusion R&D, demonstration and deployment activities. The economic profit approach is applied in order to estimate the company value under a set of scenarios reflecting different degrees of the company's involvement in Fusion R&D projects and the pace of Fusion RDDD programme. The analysis is based on semi-structured interviews with the managers of private companies and public research centres involved in Wendelstein 7-X Fusion stellarator project, which was chosen as a case study for ground testing of the methodology and collection of empirical data.

Overall socio-economic evaluation of Fusion RDDD programme is made using integrated modelling framework comprising all three models outlined above following the procedure depicted in the methodology flowchart (***Figure 6***). The scenarios elaborated with the first model are taken as inputs for real options analysis of different Fusion demonstration and deployment strategies and estimation of the economic value of spillover benefits at the level of individual companies. Bibliographic analysis and exemplary calculations with spillovers model allow for specifying generic Fusion R&D spillover rate which is used as additional input in real options model for estimating net social present value of Fusion RDDD programme taking into account its internal and external cost and benefits.

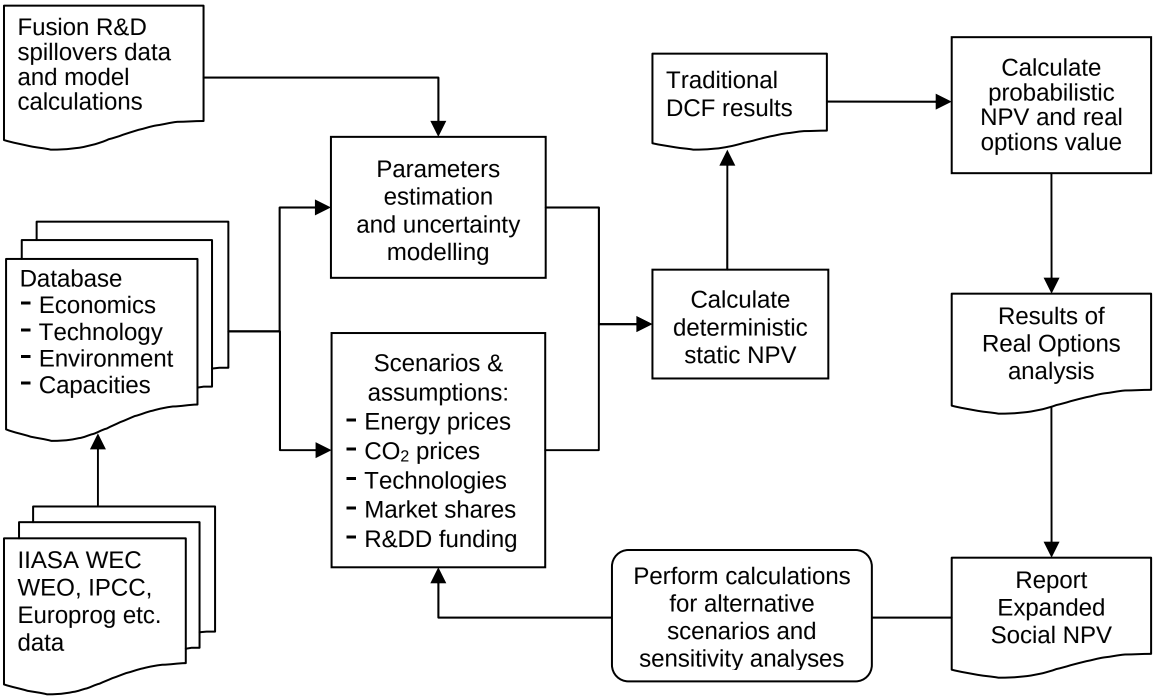

Figure 6. Methodology Flowchart

The analytical framework developed in this thesis can be considered as a decision-aid tool for monitoring the ongoing Fusion R&D activities and optimising future funding subject to the expected net socio-economic return and the underlying uncertainty. It can be also used as a component of the knowledge management system by the private companies interested to secure their strategic position on Fusion technology market.

1.5 Outline of the Thesis

This thesis is structured as follows: next chapter provides the results of extensive literature review, which covers different technological and economical aspects of Fusion technology; theoretical grounds and specific examples of spillover effects; the existing analytical approaches to evaluation of publicly funded R&D programmes; characteristics of risk and uncertainty in the evaluation of long-term energy R&D projects; the theory and application of real options approach. Chapter 3 presents methodology and results of the study emphasised on global long-term electricity supply scenarios. The Fusion RDDD Real Options model with its main data inputs and exemplary calculations is specified in Chapter 4. Development of conceptual Fusion R&D spillovers model and an explicit numerical example of its application is presented in Chapter 5. Chapter 6 is devoted to the case study of Wendelstein 7-X project. The results of integrated analysis are discussed in Chapter 7. Main findings, potential applications, limitations and recommendations for future work are given in the final chapter.

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2. LITERATURE REVIEW

This chapter presents a review of available academic and policy literature dealing with the main topics investigated in this thesis. Section 2.1 covers different technological and economical aspects of thermonuclear Fusion technology. Theoretical grounds and specific examples of spillover effects of large scale R&D programmes, including Fusion, are discussed in section 2.2. The existing analytical approaches to evaluation of publicly funded R&D programmes are further analysed in section 2.3. Main characteristics of risk and uncertainty in the evaluation of long-term R&D programmes are discussed in section 2.4. Finally, section 2.5 introduces the theory and application of real options approach.

2.1 Fusion RDDD Programme

2.1.1 Technology Overview

The idea of extracting energy from nuclear Fusion originates from the famous Einstein's equation ($E = mc^2$) predicting that a small amount of mass could, in principle, be converted into a huge amount of energy. In a typical Fusion reaction, two light nuclei combine to form a fast, heavier nucleus and an even faster nucleon, e.g. neutron or proton (***Figure** 7*). Several Fusion reactions are possible between the lightest nuclei: hydrogen (p) and its isotopes: deuterium (D) and tritium (T), lighter isotope of helium (He^3), boron (B), lithium (Li) and so on (IFRC, 2005).

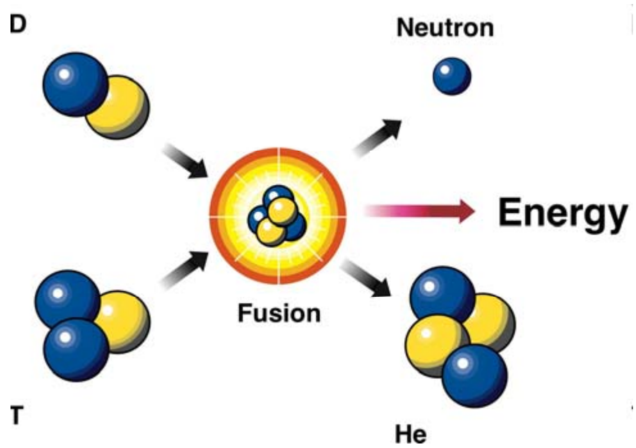

Figure 7. Typical Fusion Reaction *(Source: http://iter.rma.ac.be)*

The least difficult Fusion reaction to initiate on Earth occurs between deuterium and tritium (Ongena & Van Oost, 2006). Deuterium can be extracted in abundance from sea water, while tritium has to be generated from lithium in a tritium breeding blanket. Availability of lithium is considered to be sufficient to cover the production needs for many thousand years (Fasel & Tran, 2005). The Fusion of deuterium and tritium nuclei requires temperatures of 10 - 20 keV (about 100 – 200 million degrees centigrade). At these temperatures the fuel is completely ionised; i.e. becomes plasma – an electrically neutral mixture of nuclear ions (positive) and electrons (negative) with very high thermal kinetic energies.

Fusion between the D – T nuclei emits a neutron with energy of 14MeV and He^4 (alpha particle) of energy of 3.5MeV. The alpha particle, being charged, remains confined in the plasma and loses its energy to the main D – T fuel, thus keeping the matter hot (ignited). The neutron escapes the plasma and is absorbed in the surrounding blankets; the resulting heat in the blankets can be converted into electrical energy through conventional means (IFRC, 2005). About 100 Kg of deuterium and 3 tons of natural lithium will be required to operate 1 GWe Fusion power plant for a whole year, which will generate about 7 million MWh of CO_2 free electricity (EFDA, 2006).

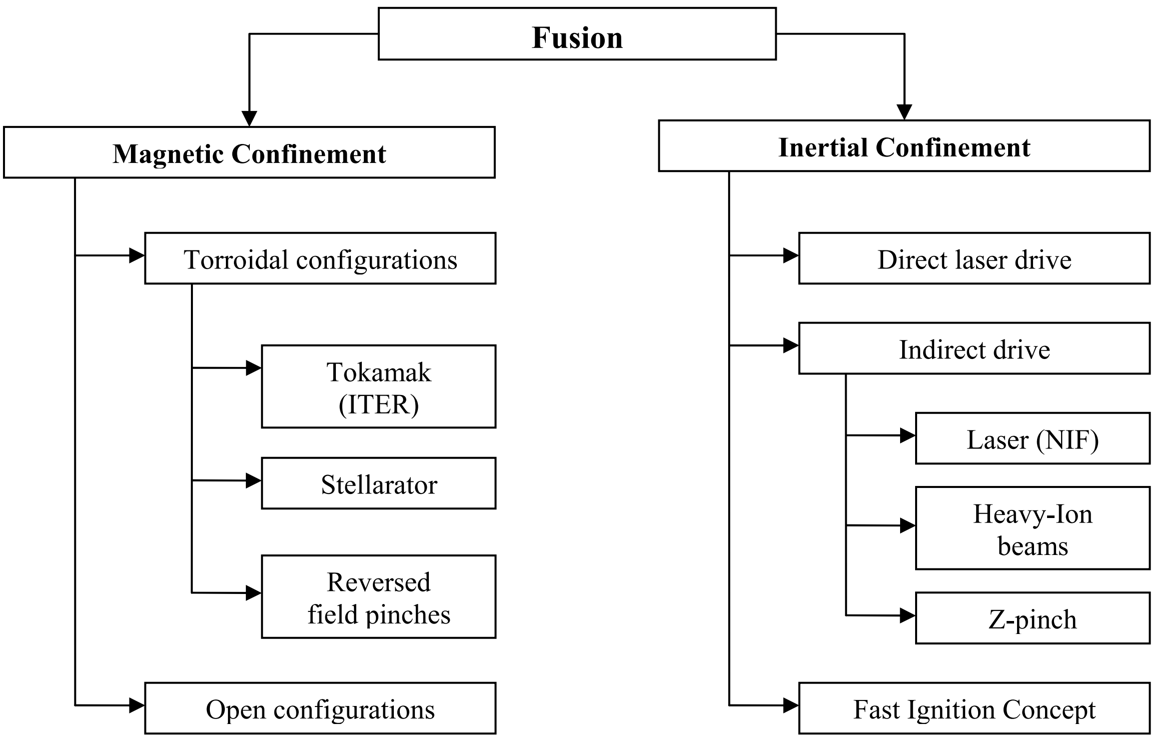

Figure 8. Main Approaches to the Confinement of Fusion Reaction

(Source: FESAC, 2004; IFRC, 2005)

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 as depicted in ***Figure 8*** above**.**

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 project. The analyses presented in this thesis are also emphasised on Tokamak magnetic confinement concept, while Stellarator configuration is considered as alternative design option (see ***Figure 9***). The following section provides a brief overview of both confinement systems.

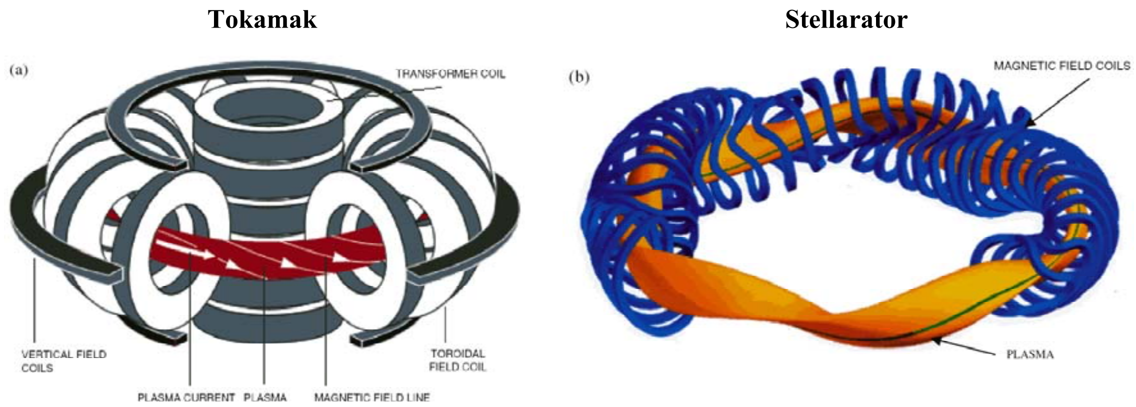

Figure 9. Tokamak (a) and Stellarator (b) Magnetic Confinement Systems

(Source: http://www.ipp.mpg.de)

In a Tokamak reactor[5] the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields. The magnetic fields are created in part by electric currents in the plasma, and in part by currents in coils surrounding the vacuum vessel. The basic components of the Tokamak system include: (1) the toroidal field - which is maintained by magnetic field coils surrounding the vacuum vessel; this is the primary confinement mechanism of the plasma particles; (2) the poloidal field - which pinches the plasma away from the walls and maintains the plasma's shape and stability. The poloidal field is induced both internally, by the current driven in the plasma (one of the plasma heating mechanisms), and externally, by coils that are positioned around the perimeter of the vessel. To minimise dissipation of energy, these coils are superconducting. The main plasma current is induced in the plasma by the action of a large transformer. A changing current in the primary winding (or solenoid) induces a powerful current in the plasma - which acts as the transformer secondary circuit. The resulting total magnetic field is 'helically' twisted around the toroidal direction. Other magnetic field components are generated by additional coils to shape and position the plasma in the reactor.

[5] This overview of Tokamak technology is based on the information from the following web-sites:
http://www.jet.efda.org/pages/Fusion-basics/Fusion3.html
http://www.ipp.mpg.de/ippcms/eng/pr/exptypen/tokamak/index.html
http://ec.europa.eu/research/energy/fu/fu_rt/fu_rt_mc/article_1228_en.htm
A more detailed review of Tokamak and other magnetic and inertial confinement technologies can be found in Rebhan *et al.* (2006)

The blanket surrounding the plasma is also toroidal. The blanket is the component where the energetic neutrons produced by the Fusion process in the burning plasma are slowed down and absorbed by lithium atoms to produce the intermediate fuel, tritium, and deliver their energy in the form of heat. The heat is removed from the blanket by a flow of coolant fluid to steam generator which is used to produce electricity in the conventional way. Between the blanket and the vacuum vessel there is another toroidal structure, the shield. It serves to reduce the neutron flux to the vacuum vessel and the ex-vessel structures. An additional component is the divertor. The divertor is located in the vacuum vessel below the plasma: its function is to evacuate the flow of hot gases (helium, and unburned deuterium and tritium) exhausting from the plasma (Maisonnier *et al.*, 2005).

The plasma current is generated in Tokamaks inductively through the transformer action. Such inductively driven current is inherently transient, making the Tokamak discharge also transient. Thus for achieving steady-state operation, one must be able to drive plasma current by other non-inductive means. This can be achieved in several ways – by injecting high power energetic neutral beams or by injection of radio-frequency waves at characteristic resonant frequencies which selectively impart momentum to the ions or electrons. A significant part of the plasma current (in fact, theoretically 100%) can also be self-generated by the so-called “bootstrap current” effect. According to IFRC (2005) Tokamaks perform reliably only when operated away from certain boundaries in the parameter space (the so-called density limit or current limit). Close to the limits, the plasma current may suddenly disrupt due to internal plasma instabilities leading to large induced currents and undesirable electromagnetic forces on the surrounding hardware. However, many methods have now been found that increase the regime of reliable operation and bring down the current in a benign manner when the plasma disrupts. Overall, Tokamaks form the most advanced toroidal confinement system today and have yielded results, which make them an interesting candidate for the first Fusion demonstration reactor.

According to IFRC (2005) the Stellarator (or one of its variants such as heliotron / torsotron, heliac, helias, etc) is the most viable alternative to the Tokamak among toroidal confinement configurations. These systems are typically toroidally non-axisymmetric (helical) and rely on the concept that closed toroidal magnetic surfaces may be formed in three dimensions by fields entirely produced by externally wound coils. There is thus no requirement of internal plasma currents, current drive, etc; nor is there any danger of macroscopic instabilities like disruptive instabilities. The Stellarator systems are thus excellent candidates for steady-state Fusion power plants. The major shortcomings of these systems are the complex technology of large coils producing 3D magnetic configurations (helical and poloidal as in heliotrons and in earlier Stellarators or the non-planar modular coils as in advanced Stellarators of the Wendelstein type), the large deviations of particle orbits from 3D flux surfaces (and the associated intense neoclassical transport for alpha-particles and the thermal plasma in the weakly collisional regime), and the as yet relatively insufficient data base on the turbulent flux of heat and particles from helical plasma systems (IFRC, 2005).

2.1.2 Programme Timeline

The history of scientific research on thermonuclear Fusion technology accounts already for more than half a century. According to Britannica encyclopaedia the practical R&D works on Fusion have started after the World War II spurred by the technical success of Manhattan project and the need to develop thermonuclear weapons (Britannica, 2009). The strictly classified Fusion research programmes pursued in the USA, Great Britain and Soviet Union were made public during the Second Conference on the Peaceful Uses of Atomic Energy held in Geneva in 1958. This event opened the era of genuine international collaboration in the area of Fusion energy R&D. A real breakthrough was made in 1968 by a group of Russian scientists led by A. Sakharov and I. Tamm who proposed a novel plasma confinement configuration which they called "Tokamak" (toroidal chamber with magnetic coils). Using this device they managed to exceed the previous best values for the triple product[6] of Fusion reaction by a factor of 100, and since that time Tokamak became the internationally leading design concept for Fusion reactors. At this period, it was believed that technical feasibility of Fusion could be demonstrated within around 10 years (Rowberg, 1999).

In the years that followed, considerable progress was made in research into the basic principles, especially as regards understanding the behaviour of hot plasmas (transport phenomena, turbulence, etc.) and in the development of technologies for generating and confining hot plasmas, e.g. different configurations of magnetic fields, methods of heating plasma and diagnostics (Grunwald *et al.,* 2003). Even so, the implementation horizon for the technically possible Fusion energy had to be postponed. In the middle of 1970s it was reported that a demonstration Fusion power reactor could not be ready before the period 2005 - 2010. In the begging of 1980s, the US Department of Energy recognised that it would require another 40-50 years for practical handling of Fusion electricity generation (Rowberg, 1999).

Over the last few decades, a range of major experiments succeeded in advancing the magnetic confinement approach. The triple product was successfully increased by a factor of 10000 over the last 40 years. A further factor of around 6 is still needed for net Fusion energy production (Pellat, 2000). In 1997, the largest European Fusion experimental device Joint European Torus (JET) generated energy output of 16 MW in a pulse lasting around a second, and about 5 MW over 5 seconds. The Fusion research community agrees that this reactor-oriented research programme should be continued to prepare for the construction of the first commercial Fusion reactor in around 2050 (Grunwald *et al.,* 2003). A major step forward will be made with the construction of International Thermonuclear Experimental Reactor (ITER) and International Fusion Materials Irradiation Facility (IFMIF), which should demonstrate 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) after which the deployment of Fusion power could start.

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[6] Criterion which determines the conditions needed for a Fusion reactor to reach ignition, that is, that the heating of plasma by the products of Fusion reaction is sufficient to maintain the temperature of the plasma against all losses without external power input. Calculated as plasma density (particles/m^3) x confinement time (s) x temperature (keV).

The most recent developments in Fusion R&D focus on the "Fast Track" approach and the proposal of a "New Paradigm". In 2001 a group of renowned experts chaired by Prof. Sir David King analysed the Fast Track Fusion development path ("King report") and concluded that the demonstration 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 "King report" however emphasised that practical implementation of this Fast Track approach would depend strongly on the development of adequate materials.

The technological, economical and organisational implications of accelerated development of Fusion were analysed in more details in the report of Cook *et al.* (2005) which 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 (see ***Figure 10***). 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" (EC, 2007a). A recent report of the European Commission (EC, 2007b) recommends the following actions to be considered in the European Strategic Energy Technology Plan:

<u>Option 1 (Strengthened Reference Programme)</u>

- DEMO keeps its ambitious set of objectives: high plasma performance and power densities resulting from full steady state requirements; structural materials with reduced activation tested on IFMIF.
- Detailed DEMO engineering design starts when ITER operation starts, its licensing starts when the first phase of IFMIF experimentation is completed, demonstration of electricity production is achieved in some 30 years, assuming all goes according to plan.

<u>Option 2 (New Paradigm)</u>

- Demonstrate production of electricity as soon as reasonably achievable but on an EDEMO with reduced objectives: moderate plasma performance and power densities; structural materials presently available; ~ 5-10 hour pulse operation during phase 1 of operation.
- EDEMO Conceptual Design starts as early as possible without a negative impact on ITER, and could be followed by construction at the earliest possible date; while results from ITER and IFMIF would not be available in time to influence the design, they would be available in time to support the request for a licence to operate EDEMO.

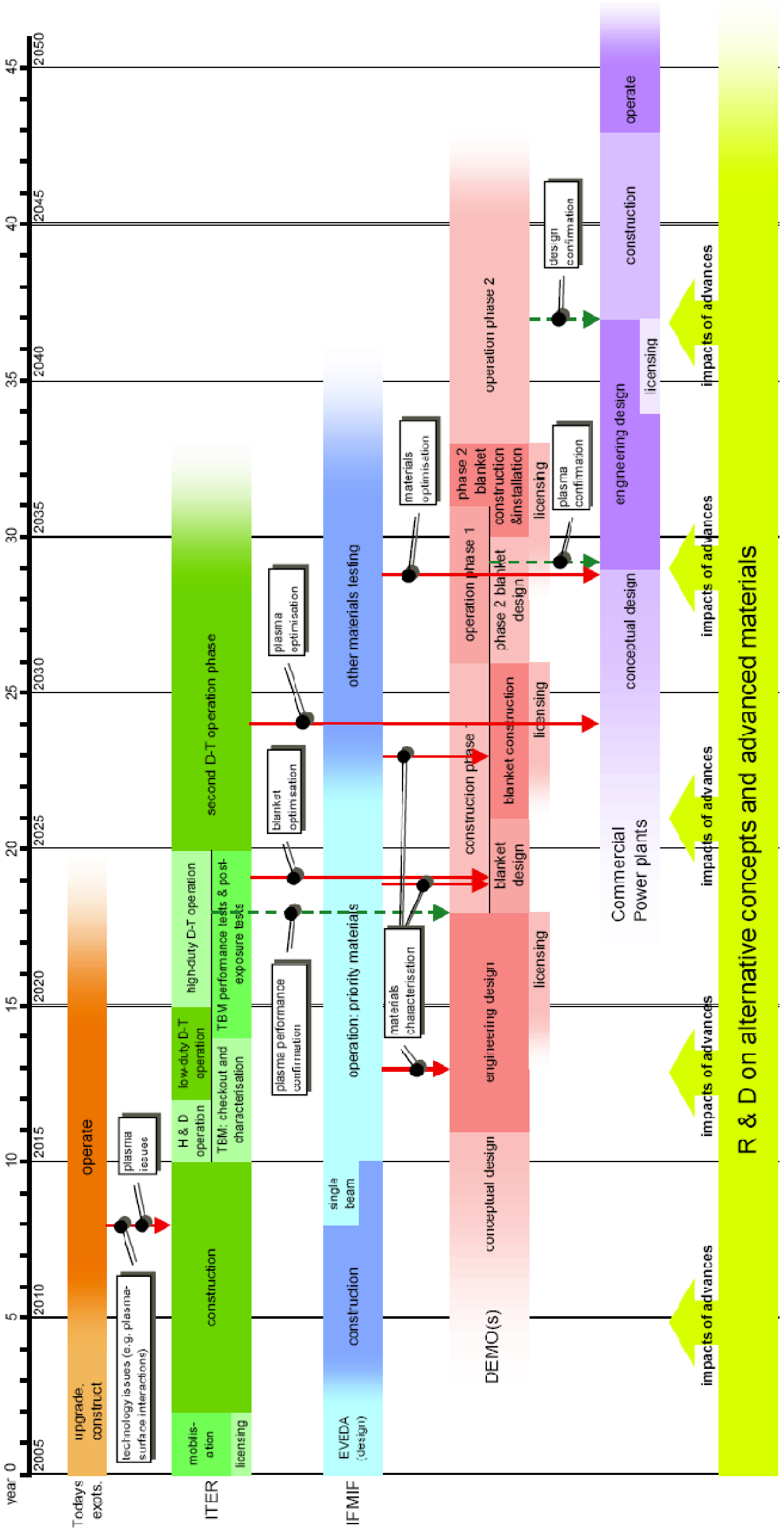

Figure 10. Possible Sequence of Reference Fast Track Programme (Source: Cook et al., 2005)

- Consider constructing a CTF, which would not be available in time to make input to the initial design of EDEMO, but would play a very important role in preparing subsequent power plants.

In both cases it is recommended that the present programme should be reinforced with a view 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. It is also emphasised that close collaboration with industry from the very beginning of the DEMO design phase would be highly desirable.

2.1.3 Costs and Benefits Estimation

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 $0.9 billion per year (IEA, 2003). Some data regarding the total Fusion R&D funding during the earlier stages dating back to the fifties can be found in Rowberg (1999) who estimated total U.S. congressional funding of Magnetic Fusion R&D during the period 1951-1973 at US$ 2.5 billion and during the period 1974 – 2001 at US $13.6 billion (in US$$_{2000}$). Basing 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.

As regards the future cost of Fusion RD&D it can be extrapolated basing 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 (≈ €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 recent 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$$_{2005}$ 107 billion.

Prospective evaluation of potential costs and benefits of Fusion technology extends mainly in three directions. The first one is represented by the studies estimating the direct electricity costs specific to different design configurations. So, the European Fusion Power Plant Conceptual Study - PPCS (Maisonnier *et al.*, 2005) estimated the levelised electricity cost of Fusion technology in a range from €$_{cent}$ 5-9 / kWh for basic design model (A) down to €$_{cent}$ 3-5 / kWh for most advanced concept (model D). In Advanced Reactor Innovation and Evaluation Studies (ARIES) undertaken in the United States the cost of electricity of Tokamak-type Fusion reactors ranges from $\$_{cent}$ 6.5 to $\$_{cent}$ 11.0 per kWh (Delene *et al.* 2001). Another US Study estimated direct electricity cost subject to different unit size in a range from $\$_{cent}$ 8.7 / kWh for smallest 1GWe Fusion power plant down to $\$_{cent}$ 3.7 / kWh for largest 4 GWe configuration (Sheffield *et al.*, 2000).

Another type of evaluation aims to analyse the economic competitiveness of Fusion technology and its potential role in future energy systems. The studies performed within EFDA Socio-Economic Research on Fusion programme (SERF) using MARKAL-based integrated modelling framework (Lechon *et al.*, 2005) indicate that under tight environmental constraints[7] there exists a substantial market window for Fusion which can attain up to 30% of the global electricity production in 2100 (Eherer *et al.*, 2004). Tokimatsu *et al.* (2003) using global energy-environment model LDNE arrives 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-Pro and came to the conclusion that under favourable conditions the market share of Fusion power generation could attain up to 20 % in most developed world regions. Ward *et al*. (2005) using probabilistic decision analysis calculated the total discounted development cost of Fusion technology in the range US $10-20 billion and the total discounted future benefit (with Fusion capturing 10-20% of the electricity market in 50 years time) of US $400-800 billion.

The third type of issues in the evaluation of Fusion RDDD programme relates to the assessment of negative and positive externality effects. One of the major benefits of Fusion technology will reside in the reduction of atmospheric pollution and attenuation of other negative externalities from large-scale power generation as confirmed by several studies, e.g. Goulden *et al.* (2000), Hamacher *et al.* (2001), Ward (2007). The positive externalities of Fusion are represented mainly by spin-off applications, indirect economic effects and different types of technological, organisational, commercial and human learning. The studies on this subject include Dean (1995), Sheffield *et al.* (2000), Konishi *et al.* (2005), Bednyagin & Gnansounou (2007), etc.

The structure of potential costs and benefits of Fusion RDDD programme is shown in ***Figure 11***. The predominantly public funding at the initial stages is expected to be gradually complemented with an increasing amount of private funds invested during applied R&D and demonstration stages. Both public and private R&D expenditures may yield multiple economic and social benefits due to technological spin-offs, knowledge spillovers and other types of indirect effects (R&D spillovers). The macroeconomic impacts of building large scale experimental Fusion facilities may also constitute tangible benefits for regional economies.

Assuming that market conditions are favourable, a successful demonstration of Fusion technology will lead to gradual deployment of Fusion power plants in a world-wide scale. While the main costs of construction and commercialisation of Fusion will be borne by the private sector, a certain amount of public funding will be required during initial deployment stage to

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

allow technology maturing and reducing its upfront investment costs to economically competitive level. At this time, Fusion power plants will start to generate financial revenues (internal benefits) through the sale of energy services (electricity and heat). External benefits are also expected to rapidly increase due to growing importance of market, network and intra-sectoral spillovers as well as macroeconomic effects from technology export and substitution of hydrocarbon fuels. Other types of positive externalities may include: reduction of atmospheric pollution, enhanced energy security and strategic national benefits.

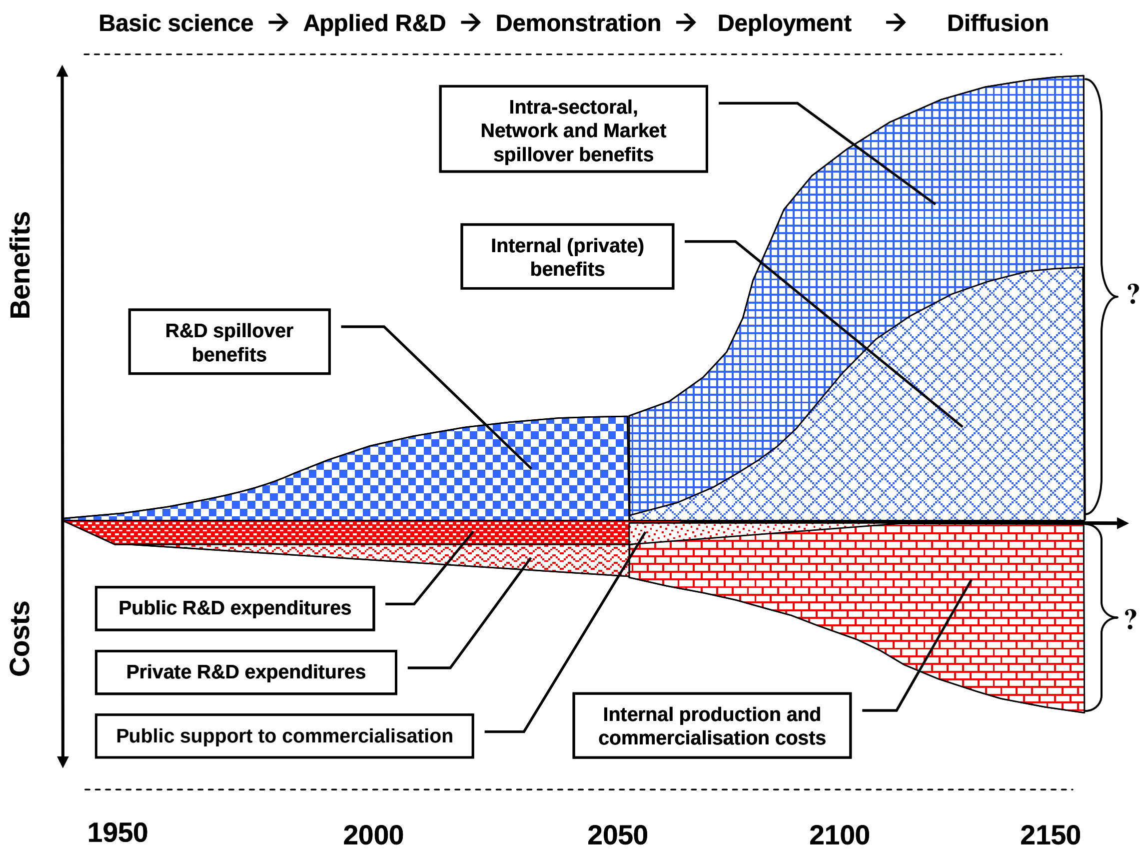

Figure 11. Potential Costs - Benefits Structure of Fusion RDDD Programme

(Source: adapted from Lee, 2002)

The expected net socio-economic benefits from development and deployment of Fusion will depend on the multitude of factors, e.g. 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[8] also has a substantial impact on the estimated present value of Fusion technology. Considering a very long time span of Fusion RDDD programme and extreme variety of technical, economic and structural indicators that have to be taken into account, it should be

[8] e.g. deterministic fixed, decreasing in time due to reduced uncertainty, increasing in time due to substitution of public funding by private capital, stochastic random walk or mean-reverting

recognised that the results of any evaluation would be confronted with a high degree of uncertainty. Accordingly, one of the major challenges in the socio-economic assessment of Fusion technology consists in adequate treatment of the potential risks and various types of uncertainty underlying the modelling assumptions and input data that justifies the need for development of novel analytical methods allowing for more reliable and comprehensive evaluation of Fusion RDDD programme.

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2.2 Spillovers: Definition and Scope

2.2.1 Spillover Effects and Social Rate of Return to R&D

Over past decades, the analysis of spillover effects and estimation of the social rates of return to R&D became an issue of increasing concern in the context of innovation & technology policy research. It is a general observation about R&D that the organization undertaking a research project can not appropriate the integral returns of its investment, because some part of the benefits due to advances in knowledge "spill over" to other firms and consumers without adequate compensation. Accordingly, the total social payoffs of any R&D activity are usually higher than the private returns, especially in the case of basic research, which does not generate immediate patentable products (Nelson, 1959).

This "appropriability" problem creates a significant risk of underinvestment in R&D compared to the socially optimal level. Thus, there is a need for adequate policy regulation to ensure sufficient public funding and to create incentives for private sector to invest in basic science and technological research. From the premises that R&D spillovers are recognised in the "new" endogenous growth theory as fundamental aspect of technological change and economic growth (Aghion & Howitt, 1997), it is important for policy makers to understand the nature and to estimate the magnitude of spillover effects that can be expected from particular R&D programmes.

The notion of spillovers principally concerns an observation of the consequences of innovation. In simple terms, spillover effects can be defined as "*any positive externality that results from purposeful investment in technological innovation or development*" (Weyant & Olavson, 1999). Many empirical studies exist pointing out to some general conclusions: R&D spillovers are present, may be quite large, with social rates of return significantly above the private rates (***Table 2***), see e.g. Mansfield *et al.* (1977); Griliches (1992); Hall (1996). On the other hand, spillovers can manifest in various, very often intangible forms, and for that reason they are extremely difficult to measure in monetary values.

Table 2. Social and Private Rates of Return from Investment in Seventeen Innovations

Innovation	**Rate of Return (%)**	
	Social	**Private**
Primary metal innovation	17	18
Machine tool innovation	83	35
Component for control system	29	7
Construction material	96	9
Drilling material	54	16
Drafting innovation	92	47
Paper innovation	82	42
Thread innovation	307	27
Door control innovation	27	37
New electronic device	(-)	(-)
Chemical product innovation	71	9
Chemical process innovation	32	25
Chemical process innovation	13	4
Major chemical process innovation	56	31
Household cleaning device	209	214
Stain remover	116	4
Dishwashing liquid	45	46
Median	**56**	**25**

Source: Mansfield *et al.* (1977)

Most existing studies make a distinction between the “embodied” and “disembodied” forms of spillovers. The first type of spillovers results in reducing the costs of intermediate inputs or investment goods or release of new, enhanced, or lower-cost technology / product for alternative uses. This increase in consumers’ welfare is called the “market spillover” (Jaffe, 1996). A special form of embodied spillovers can be revealed in the situation when growing market due to major innovation in one sector spurs growth and consequently innovation in the related sector of the economy (Rosenberg, 1994). According to the terminology adopted in Jaffe (1996) this type of spillover can be referred to as “network spillover”.

Disembodied spillovers, also known as “knowledge spillovers”, concern the impact of ideas on the research and development of others (Weyant & Olavson, 1999). The knowledge spillovers are most likely to occur in the result of basic research, but they are also produced by applied R&D, if knowledge created by one actor is used by another without due compensation. The typical examples of knowledge spillovers are: reverse engineering, scientific discoveries with more general applicability than initially intended, or even abandonment of the research line by a firm signalling to others that this research line is unproductive. Jaffe (1996) points out that knowledge spillovers also occur in the case when researchers leave a firm and take a job at another firm or start their own business.

The second set of spillover distinctions concerns the level at which they occur: they can be intra-sectoral or cross-industry, local or international (Weyant & Olavson, 1999, Cincera & van Pottelsberghe, 2001). Intra-sectoral spillovers take place within a particular industry, as the firms receive additional benefit from the innovation and development activities of their direct competitors. Cross-industry spillovers occur between industries, which may borrow products or ideas, or can be stimulated by the developments in related fields. International spillovers work within and between sectors, but also across national boundaries. They can be particularly significant in cases of large collaborative R&D projects involving governmental consortia, such as International Space Station, CERN, etc. International spillovers are also seen as a positive feedback for R&D on environmental control technologies (Sijm *et al.,* 2004).

To estimate the magnitude of spillover effects the researchers normally use one of three methodological approaches, depending on which particular type of spillovers they consider. The first method is based on the specification of standard production function. The presence of spillovers is revealed if the estimated rate of return to R&D expenditures is higher than the return to ordinary capital (see e.g. Jones and Williams, 1998). The second approach consists in defining the external knowledge stock for a specific industry as the sum of all other industries' R&D. Then the impact of knowledge spillovers can be assessed by estimating the level of technological proximity of different industrial sectors. The examples of this approach include Jaffe (1986), Coe & Helpman (1995). The third method explores the impact of spillover effects on the costs or production structure in spillovers receiving firms or industries basing on the cost function estimation. Under this approach, the production costs are related to output, relative factor prices and the quantity of inputs, including the own stock of R&D capital and the R&D stock from other firms or industries (see e.g. Nadiri, 1993).

2.2.2 Spillovers of Large-scale R&D Programmes

In recent years, the evaluation of R&D spillovers became an important research topic especially in the domains of military R&D, space exploration and basic nuclear science. Indeed, the endowments in these areas are immense, while the output of marketable technologies and products is quite limited. Nevertheless, there have been remarkable spin-offs, such as nuclear power plants based on light water reactor concept initially developed for military submarine propulsion, the satellite communication, radiotherapy and many more, which brought about substantial economic and societal benefits and allowed for further advancements in basic and applied R&D.

The term "spin-off" is often used in the literature to designate the way in which a technology or product or even managerial practice developed within one specific R&D programme can be exploited by another organisation in another context (Cohendet, 1997). While analysing the case of high energy physics, Amaldi (1999) distinguished four different types of spin-offs, namely usable knowledge, technologies, methods and people that all together roughly correspond to the generic notion of "knowledge spillovers". Cohendet (1997) in a study focusing on industrial indirect effects of technology programmes implemented under auspices of the European Space Agency proposed the following classification of spin-offs from space-related R&D:

Technological spin-offs

The basic and applied R&D work carried out in the framework of one specific programme gives rise to technological innovations, leading to the emergence of new products and sub-systems, which can be utilised by subsequent R&D programmes or applied in other sectors.

Commercial effects

Increased sales of products or services on new markets that open following the implementation of R&D programmes; quality label associated with specific R&D activities, which is likely to give competitive advantage; closer business ties, etc.

Effects on organisation and methods

Innovations in managerial and production methods that have been inspired by R&D activity, for instance in terms of quality control, production techniques and project management.

Work-factor effects

Formation of human capital - heightened qualifications and skills acquired by the personnel employed in specific R&D programs, which enable them to feed this expertise into other company departments and R&D programmes.

Besides the ***indirect industrial effects*** (spin-offs) Cohendet (1997) examined other forms of economic impacts of space-related R&D programmes, which include: ***direct industrial effects*** (marketable services arising from establishment and operation of industrial infrastructure required for execution of R&D project); ***direct social effects*** (benefits obtained by users of the services provided by R&D program infrastructure); and ***indirect social effects*** (cost and income redistribution effects, possible environmental impact, etc).

Socio-economic benefits of high energy physics were analysed in Bianchi-Streit *et al.* (1984), David *et al.* (1988), Autio *et al.* (2003) basing on the example of “European Organization for Nuclear Research” (CERN). It was found that participation of European suppliers in CERN’s procurement programmes had a four-fold multiplier impact upon the sales revenues of the companies in related product lines (Bianchi-Streit *et al.*, 1984). This fact confirms the idea that large-scale basic science experiments may yield significant network spillovers due to improvements in companies’ capabilities throughout their procurement experience which allow them to tap new markets and to strengthen their market position.

David *et al.* (1998) analysed the overall economic impact of basic research. They found that basic science and R&D can generate valuable “by-products” by means of (1) education of scientists and providing of opportunities for training in experimental techniques; (2) creation of social networks through which unpublished information can be rapidly diffused; (3) elaboration of enhanced standards and novel techniques of scientific research allowing for reducing the costs and increasing the effectiveness of applied R&D; (4) development of new methodologies and instrumentation with a more general applicability in industry and other R&D domains. They concluded that economic returns of basic research reside mainly in the improved performance of complementary R&D activities and technological spillovers which potentially may yield innovations.

1. Knowledge flows from public research centres towards private firms, development of innovative products, process improvements, QMS strengthening, network building, HR training, financial reward, reputational gains
2. Supply of innovative products, or existing / improved products to public R&D facilities
3. Free knowledge flows to other market players (sub-suppliers, competitors)
4. Induced innovation in sub-supplier companies
5. Sales of innovative products by project participants on the market directly intended by R&D project
6. Sales of innovative products on other markets (spin-off applications)
7. Development and sales of innovative products on the main market by the competitors
8. Consumers' surplus

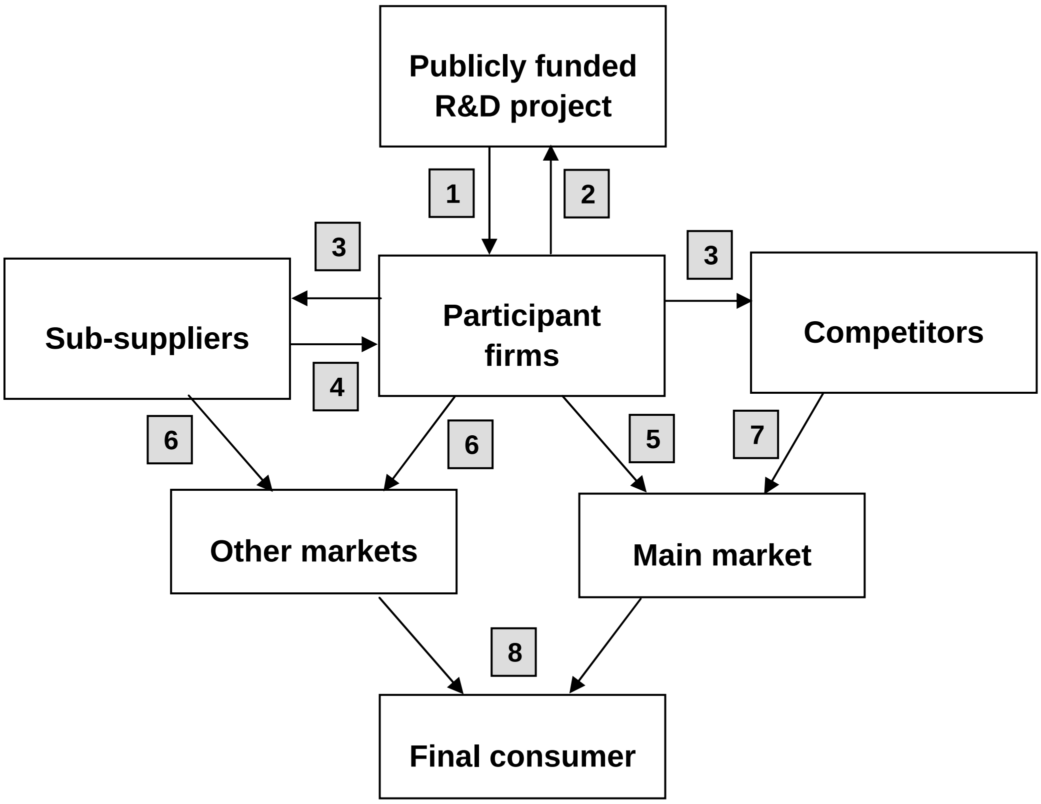

Figure 12. Spillovers' Origin and Transmission Mechanisms

The main spillovers origination and transmission channels are depicted in ***Figure 12***. The following specific types of spillovers can be distinguished in this scheme:

A. Spillovers from public R&D projects towards participating private firms (disembodied knowledge spillovers, channel 1) ;

B. Spillovers through the cooperation networks created by the main Fusion R&D contractors (disembodied knowledge spillovers, channel 3; spillovers embodied in technological innovations, channel 4) ;

C. Spillovers from participating companies to their competitors (disembodied knowledge spillovers, channel 3 - success/failure signals, reverse engineering, headhunting, etc.) ;

D. Intra-sectoral spillovers from equipment manufactures to energy utilities (due to development of new superior technology for power generation and improvement of the existing technologies through borrowing of the technology components, channels 5 and 7);

E. Technology spin-offs (spillovers embodied in technological innovations which can be commercialised in other non-Fusion markets, channel 6);

F. Market spillovers due to economic benefits accruing to the end-users (channel 8).

2.2.3 Spillovers of Fusion RDDD Programme

The main types of spillover effects of Fusion RDDD programme are summarised in ***Table 3***. First of all, the past and ongoing basic research activities emphasised on Fusion technology have already resulted and will continue to supply valuable knowledge in the form of publications, patents, standards, routines, highly trained staff and social networks, that all together fall in to the category of disembodied knowledge spillovers. This knowledge serves as the basis for advancement of applied R&D activities, and it is expected to increase over time with the construction of large scale experimental facilities (such as ITER, IFMIF) and demo / prototype Fusion reactors. The predominantly public nature of Fusion R&D funding, the technological complexity and a significant number of researchers and institutions involved in Fusion R&D programme explain the importance of knowledge spillover effect.

Table 3. Main Types of Spillovers of Fusion RDDD Programme

Form \ Level	**Intra-sectoral**	**Cross-industry**	**Macroeconomic**
Embodied	**Improved performance / lower cost of clustered components** specific to different energy technologies (*due to learning-by-doing*) **Non-electric applications** heat & hydrogen production; nuclear fuel transmutation; spent fuel treatment	**Technology spin-offs** (*non-energy applications of technologies and products developed in the process of Fusion R&D*) **Network spillovers** (*learning and scale economies due to increased demand for subjacent products and services; induced innovation in related sectors*)	**Market spillovers** (*due to supply of competitively priced energy services and non-energy products / services*) **Induced economic activity at regional scale** (*due to economic multiplier effects*) **Improvement of national payment balance** (*due to technology export and reduction of fossil fuel imports*) **Energy security** enhancement **International spillovers**
Disembodied (knowledge spillovers)	**Accumulation of knowledge stock** (*publications, patents*) **Formation of human capital** (*PhDs, experienced researchers, research networks*) **Strengthening of companies' technological and marketing capabilities** **Success / failure signals to industry**		

One of the most remarkable examples of ***cross-industry spillovers*** from Fusion R&D consists in the development of a host of technologies allowing for producing and manipulating low temperature plasmas in various industrial applications. As discussed in Dean (1995) and a recent report of the International Fusion Research Council, the *pervasive influence of plasma technology* can be seen practically everywhere, starting from high efficiency fluorescent lamps and plasma displays to advanced plasma-based systems for manufacturing of computer chips, sterilisation in medicine and food industry, surface and exhaust gas cleaning, etc. (IFRC, 2005).

The ongoing R&D on Fusion energy technology have a significant potential to yield other technological spillovers due to non-electric applications of different substances that can be produced already in the nearest future in low-Q experimental Fusion facilities[9]. According to FESAC report (McCarthy *et al.,* 2002) the scope of these products may include: high-energy neutrons, thermal neutrons, high-energy protons, electromagnetic radiation (microwave to x-rays to gamma rays), high-energy electrons coupled with photons providing ultra-high heat fluxes.

High-energy neutrons can be useful for the following purposes:

- ✓ Production of radioisotopes (for medical applications and research)
- ✓ Detection of specific elements or isotopes in complex environments
- ✓ Radiotherapy
- ✓ Alteration of the electrical, optical, or mechanical properties of solids
- ✓ Destruction of long-lived radioactive waste

Low-energy neutrons can be used in the following processes:

- ✓ Production of radioisotopes (for medical applications and research)
- ✓ Detection of specific elements or isotopes in complex environments
- ✓ Destruction of long-lived radioactive waste
- ✓ Production of tritium for military and civilian applications
- ✓ Production of fissile material
- ✓ Destruction of fissile material for nuclear warheads
- ✓ Production of radioisotopes for portable γ ray sources

High-energy protons can be used for:

- ✓ Production of radioisotopes (for medical applications and research)
- ✓ Detection of specific elements or isotopes in complex environments
- ✓ Destruction of long-lived radioactive waste

Electromagnetic radiation (ER) can be used for:

- ✓ Food sterilization
- ✓ Equipment sterilization
- ✓ Pulsed x-ray sources

Ultra-high heat fluxes from Fusion grade plasmas can be used for the following purposes:

[9] Fusion Energy Gain Factor (Q) = $P_{output} / P_{input} = P_{Fusion} / P_{auxiliary}$; ITER objective → $Q \geq 10$

- ✓ Ionizing waste materials and separating elements
  - o Municipal and medical wastes
  - o Spent reactor fuel elements
  - o Chemical weapons
  - o Extractive metallurgy
- ✓ Production of sources of intense radiation to treat industrial, medical, and municipal wastes.

All these products can be further used in various domains such as medicine, food and equipment sterilisation, detection of specific elements or isotopes in complex environments, etc. In longer-term perspective Fusion may also offer a unique opportunity for high-efficiency propulsion of rocket engines (IFRC, 2005).

Furthermore, there are some important neutron transmutation missions (destruction of long-lived radioisotopes in spent nuclear fuel, "disposal" of surplus weapons-grade plutonium, "breeding" of fissile nuclear fuel) that fall into the category of ***intra-sectoral spillovers.*** Other types of intra-sectoral spillovers may include large-scale production of hydrogen by thermo-chemical water-splitting and low- or high-temperature electrolysis (Sheffield *et al.*, 2000). The supply of high-potential process heat at a vide range of temperatures may be also an important non-electrical application of Fusion, since it can be used in various industries (oil distillation, petrochemical, pulp & paper, coal liquefaction, water desalination, district heating etc.) that may be located in a direct vicinity of Fusion power plants (Konishi, 2001). Eherer & Baumann (2005), Han *et al.* (2006) demonstrated that deployment of Fusion power plants could also lead to the reduction of costs of other electricity generation technologies.

The report of Sheffield *et al.* (2000) presents the results of the study which made an attempt to classify the most prominent products of Fusion R&D with respect to their attractiveness for the market. An assessment methodology was developed with the goal is to estimate the ability of a Fusion power source to provide a needed and useful product to the customer at a reasonable cost. Several critical attributes[10] were selected in order to characterise each Fusion application, and specific weights were assigned to each of the attributes according to the perceived importance to the decision-makers. Then attribute values on a scale from – 5 to + 5 were established for each application basing on expert judgements and literature review.

The results of Fusion products evaluation are presented in ***Figure 13***. The bars of the same colour denote here potentially similar Fusion power plants. Sheffield *et al.* (2000) conclude that all these applications except for Fission-Fusion breeder (not shown on the graph) can be perceived as favourable and valuable. Meanwhile, it was noticed that production of hydrogen scored the highest value among all other Fusion products, and for that reason they performed further in-depth investigation of the economic aspects of combined electricity and hydrogen production at Fusion power plants.

[10] Necessity / Uniqueness / Market Potential / Depletion of Resources / Environmental Impact / Economic Competitiveness / GNP Improvement / Return on Investment / Technology Maturity / Time to Market / National or Company Prestige / Public Support

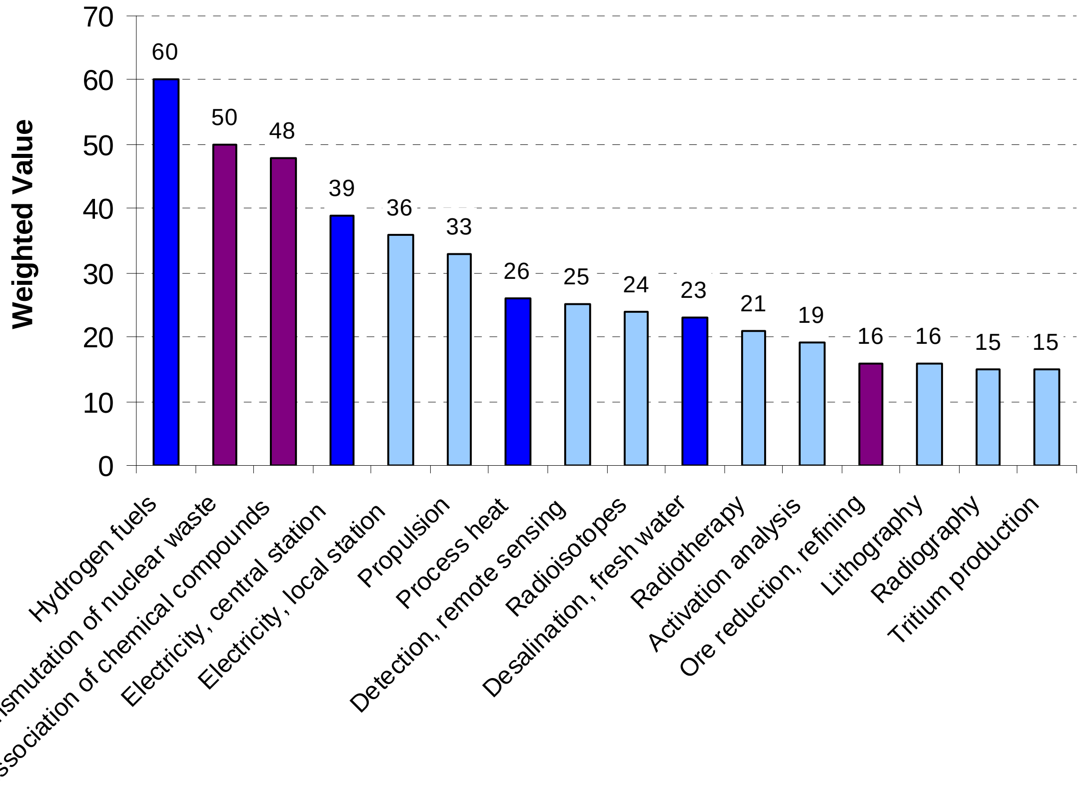

Figure 13. Market Attractiveness of Fusion Products *(Source: Sheffield et al., 2000)*

As discussed in Bogusch *et al*. (2002) and Rey *et al.* (2003) Fusion R&D opens a significant potential for ***network spillovers*** due to industry accession to Fusion - related public procurement contracts. In fact, the progress of Fusion RDDD programme will rely heavily on the development of a set of related technologies in different domains, such as: mechanical, electrical and electronic engineering; computer modelling; plasma technology and diagnostics; electromagnets; cryogenic systems; vacuum vessels and systems; advanced / neutron resistant materials; neutral beam and microwave systems, etc. The investments in Fusion R&D will have a positive impact on the technological progress in these industries. Moreover, if Fusion proves to be economically competitive, accordingly its commercialisation will spur further advancements in related technologies leading to the expansion of their markets and allowing for decreasing overall technology costs.

Finally, the successful demonstration and deployment of Fusion technology may create substantial opportunities for ***market spillovers*** and other types of macroeconomic benefits, including energy security enhancement and international spillovers. It can be expected that deployment of Fusion power plants will lead to gradual reduction of their production costs below system average through exploitation of learning-by-doing opportunities and economies of scale. That will create an economic surplus for energy end-users and will induce additional economic activity at regional scale (EFDA, 2001). The impact on national economy can be much higher if the opportunity for technology export to other regions is envisaged.

One specific issue arises from the fact that Fusion technology is still in its R&D phase which is expected to last for two - three decades from now before the start of demonstration. Considering the predominantly public nature of Fusion R&D funding, it means that the ongoing Fusion R&D activities are most likely to generate disembodied knowledge spillovers rather than pecuniary benefits embodied in specific marketable products and market spillovers.

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2.3 Analytical Approaches to R&D Evaluation

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. Accordingly, in order to define appropriate analytical framework for socio-economic assessment of Fusion RDDD programme it is important to examine, first, the existing evaluation methods and to determine their applicability to the specific case of Fusion.

2.3.1 Programme Evaluation Methods

In recent years a body of literature has emerged aiming to provide an appropriate methodological framework for evaluation of publicly funded research (e.g. Holdsworth, 1999; Georghiou *et al.*, 2002; EC, 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 uncertainty with respect to future technology performance and market conditions. According to Georghiou *et al.* (2002) there is no single methodology, which can address all aspects of socio-economic impacts of international multi-years RTD programmes, such as EU Framework programmes. Therefore, a portfolio of complementary approaches is needed in order to analyse different types of effects revealed through different time and space dimensions.

The basic approach to evaluation of publicly funded programmes, not only in R&D but also in other domains, consists in applying the so-called “Logic Model” which describes logical linkages among programme resources, activities, audiences, outputs, and short-, medium- and long term outcomes related to a specific problem or situation (McCawley, 2001). Logic model represents in a narrative or graphical way the cause-and-effect relationships between the situational context (problem to be resolved), the planned interventions (dedicated resources and activities) and the expected outcomes (programme results). The situation statement allows for communicating the relevance of the programme. It may include social, economic and environmental symptoms of the problem, the description of who is affected by the problem, the likely consequences if nothing is done and identification of main stakeholders. Inputs include the endowments of the programme in terms of appropriated funds, human resources, knowledge base, etc. Outputs represent the specific programme activities and the target audiences, while outcomes correspond to short-to-long term changes in knowledge, behaviour, policies and general social, economical and environmental conditions. Once a programme has been described in terms of "Logic model", then critical measures of performance can be further identified.

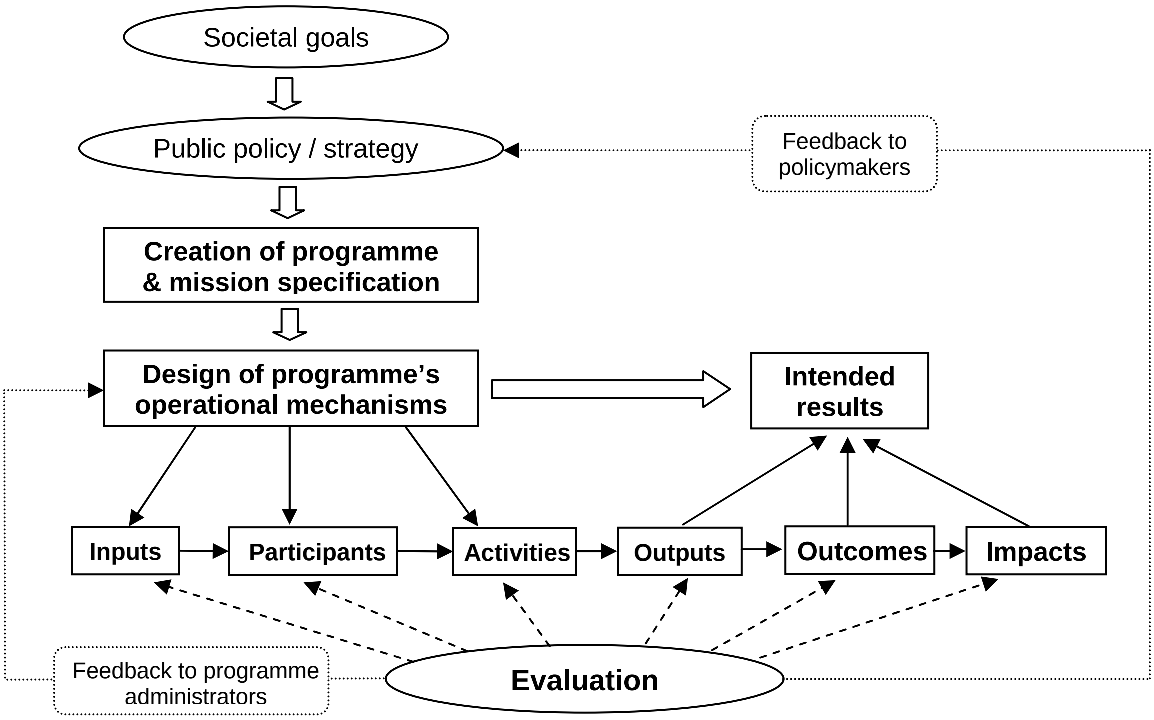

Figure 14. Logic Model of R&D Programme Evaluation

(Source: adapted from Ruegg & Feller, 2003)

Figure 14 represents the "Logic model" of programme evaluation in the context of political decision making process. Considering the specific case of thermonuclear Fusion the "societal goal" can be defined as strengthening long term energy security and overcoming negative effects caused by excessive reliance of fossil fuels. Accordingly, the public strategy consists in developing new clean, safe, resource unconstrained and economically affordable energy technologies, such as Fusion. In line with this strategy, the Fusion R&D programme is being designed and implemented with the support of public funds and other endowments to achieve its mission of bringing to the society a new energy supply option that could also have a significant "insurance" value in case of unforeseen events. The resources, or "inputs", required to carry out the mission convey the programme's costs to the public. The programme's operational mechanisms determine how and by whom the inputs are used and what they produce in terms of programme "outputs". Short-term outputs normally may include advancement in knowledge through construction and operation of series of experimental installations and exchange of this knowledge through publications, presentations, workshops and all sorts of individual / organisational training. Next-stage outputs may include successful demonstration of Fusion technology on a power plant scale via construction and operation of ITER and DEMO facilities, while longer-term outcome may consist in full scale deployment of Fusion power plants. Besides Fusion power generation itself, the long-run programme impacts may include also various 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. All of the programme outputs, outcomes and impacts should be assessed against the programme's mission, operational goals and costs. A final step is to feed the findings of evaluation back to inform programme administrators and policymakers that should allow them to improve the programme structure and operation.

While measurement of direct programme inputs is relatively straightforward with standard indicators such as budget appropriations and headcount of qualified staff, the evaluation of programme outputs, outcomes and impacts is much more difficult because of their different nature (pure knowledge, economic effects, social conditions) and the problem to find the right financial indicators. The typical output metrics correspond to the technical results of the programme activities including but not limited to:

- Development of new or significantly improved products / processes / services
- Development of new tools and production techniques
- Development of demonstrators, prototypes, pilots etc.
- Development of new technical standards, regulations, directives, etc.
- Patent applications and granted patents, licenses issued
- Copyrights, trademarks, registered designs, know-how agreements etc.
- Publications in refereed journals, "grey literature", books, etc.
- Electronic publications (reports, datasets, codes, shareware or other software items made available via Internet, CD-ROMs etc.)
- Public presentations of results (seminars, conferences, TV, radio broadcasts, etc.)
- Qualifications gained by personnel, formation of critical mass.

The distinction between outcomes and impacts is not so evident and sometimes they are listed in the same category of programme results. In general, the outcomes represent the specific changes in attitudes, behaviours, knowledge, skills, status, or level of functioning expected to result from programme activities and which are most often expressed at the individual participants' level (Kellogg Foundation, 2004). Following the terminology adopted in Georghiou *et al.* (2002) the outcomes can be assimilated to the *direct effects*, i.e. the effects which are directly related to the objectives of the R&D projects. For instance, if the objective is to develop a new product (or a new process), the sales of such products (or the economic effects of the use of this new process) are considered as direct effects. This rule is similar in the case of more fundamental research-oriented projects: direct effects are related to the application of the new scientific knowledge or the new technologies in the field foreseen at the beginning of the projects. The typical examples of programme outcomes may include:

- Increased productivity (manufacturing process and R&D)
- Increased sales and market share
- Increased product quality and reliability
- Reduced costs and time to market
- Increased revenues from sales of licences
- Creation of new jobs, formation of new firms
- Decisions taken on further R&D activities
- Improved safety and health
- Reduced energy consumption and atmospheric pollution, etc.

Impacts metrics relate to organizational, community, and / or system level changes expected to result from programme activities (Kellogg Foundation, 2004). The definition of impacts include different types of indirect effects (spillovers) which correspond to the economic valuation of the learning processes experienced during the evaluated programme. They are derived from the use of what has been learned during the execution of the programme in participants' activities which are not directly related to the programme. All types of learning leading to the creation of all types of knowledge are taken into account: technological, organizational, networking, management, industrial, individual / collective, through experience / transfer, from other partners and so on (Georghiou *et al.*, 2002). In more general terms, impact metrics characterise the effects that programme outputs / outcomes might have on the broader socio-economic environment including improved living and economic conditions, increased competitiveness, enhanced security, changes in the policy arena, etc.

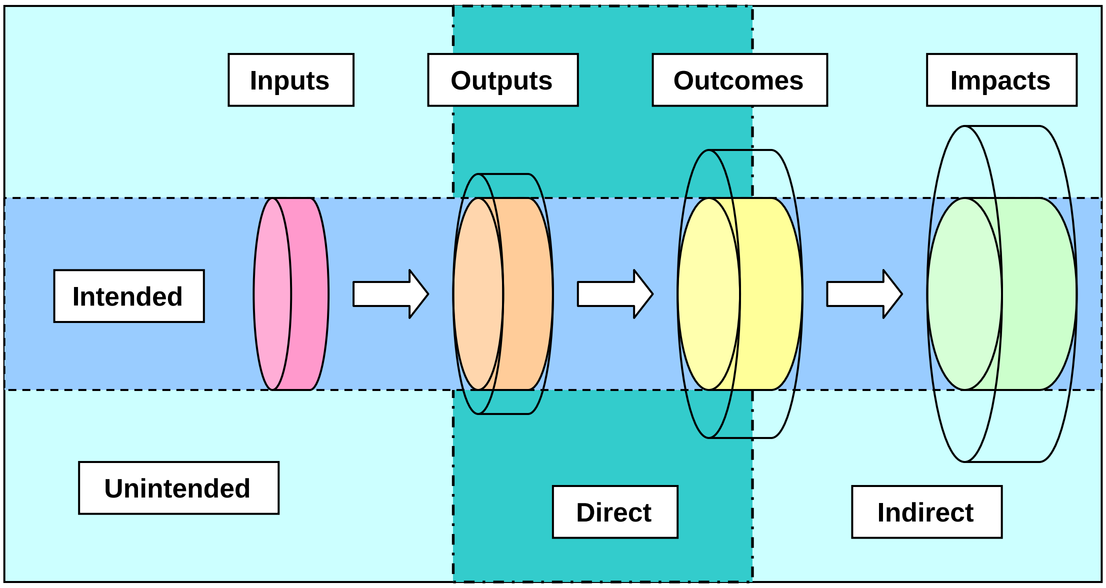

Figure 15. Main Concepts in the Evaluation of R&D Programme Results
(Source: adapted from Hirasawa, 2002)

The relation between programme inputs, outputs, outcomes and impacts is demonstrated in ***Figure 15***. It is evident that a comprehensive ex ante evaluation of the total results of long lasting strategic R&D programmes, such as Fusion, is practically impossible given the time scale, scope of R&D activities and the underlying uncertainty. Therefore, the evaluation efforts are bound to emphasise on intermediate programme results represented by specific types of outputs (e.g.

publications, patents), direct outcomes (e.g. potential market value of Fusion power) and indirect impacts (e.g. spillover benefits to private companies participating in Fusion R&D projects).

Overall programme evaluation is made by comparing the programme inputs and its results in terms of achieved and expected outputs, outcomes and impacts. The effectiveness of a programme is determined by the ratio of achieved results to expected results, while the efficiency is determined by the ratio of achieved results to programme inputs (Arnold & Balazs, 1998). Other more qualitative measures of "relevance" and "usefulness" can be also used in programme evaluation as shows a recent example of evaluation of EU nuclear Fusion research funding for the period 2006-2008 (see ***Table 4*** below).

Table 4. Summary of Evaluation of EU Funding of Research in Nuclear Fusion, 2006-2008

Research Field	Relevance	Effectiveness	Efficiency	Usefulness
Nuclear Fusion	◕ • Potentially very relevant • ITER would solve perceived problems (waste and proliferation) • High opportunity cost • Need to prioritise DEMO development	◑ • Projects funded address real needs, *e.g.* in terms of energy mix • Provides Europe with potential lead time • Need to invest in human capital to avoid skills shortage • Uncertainty as regards technological and commercial viability of ITER • Need for clearer contractual safeguards	◑ • Costs are very high, benefits uncertain • Europe's competitive advantage would materialise only if investments in DEMO occur early enough • Contractual arrangements currently incomplete, increased contract risk • Need to define building codes and streamline procurement rules to avoid cost increases over time	◕ • Potentially very useful, as funded projects meet important needs for EU energy policy • Need to ensure that Europe achieves a competitive advantage and a 'lead time' by prioritising investments in DEMO • Still uncertain whether technologies will be eventually viable, also from a commercial viewpoint

Source: Renda *et al.* (2008)

Practical evaluations may differ in multiple ways – in methods used, in their scale, their scope, and in the extent to which the results are disseminated and used (EC, 2002). Meanwhile, there are four fundamental types of evaluation, which differ in terms of their timing, and which it is particularly important to differentiate:

(1) *Ex-ante evaluation*, conducted before the implementation of the programme, and focusing on the specific objectives of the programme and the ways how they should be achieved;

(2) *Intermediate evaluation*, reviewing the progress of the programme, or its achievements at some point in time during implementation – usually reserved for long-lasting programmes;

(3) *Real-time evaluation*, following the programme in detail throughout its operation;

(4) *Ex-post evaluation*, examining the results of the programme after it has been completed (and possibly several years after completion).

Table 5 and ***Table 6*** extracted from the publication "RTD Evaluation Toolbox" (EC, 2002) summarise the existing methodologies for evaluation of publicly funded R&D programmes stating their areas of applicability, data requirements, potential strengths and limitations.

The main methodologies employed in ex-ante evaluation of R&D programmes include:

- *Foresight studies*: this structured consensus building methodology based on experts judgements permits to anticipate social, economical and technological development opportunities in policy planning and programme implementation;
- *Modelling and simulation*: this quantitative methodology uses scenario modelling to estimate the socio-economic impact of specific programme or policy;
- *Cost-efficiency techniques*: this judgement methodology quantifies the costs and benefits associated with the specific programme or policy intervention;
- *Cost-benefit techniques*: this judgement methodology compares in monetary terms all social and private cost and benefits of a programme to establish whether the benefits exceed the costs. The technique can be adapted to incorporate uncertainty and risk.

The methodologies employed in monitoring and ex-post evaluation of RTD programmes and policies include:

<u>Statistical data analysis</u>

- *Innovation Surveys*: provides basic data to describe the innovation process, summarised using descriptive statistics;
- *Benchmarking* allows to perform comparisons based on a relevant set of indicators across different entities providing a reasoned explanation of their values.

<u>Modelling methodologies</u>

- *Macroeconomic modelling and simulation approaches*: allows to estimate the broader socio-economic impact of selected R&D programme or policy intervention;
- *Microeconometric modelling*: allows to study the effect of programme / policy at the level of individual firms;
- *Productivity analysis*: allows to assess the impact of R&D on productivity growth at different levels of data aggregation. This is particularly relevant to analyse the broader effects of R&D on the economy;
- *Control group approaches*: allows to capture the effect of the programme on participants using sophisticated statistical techniques.

Table 5. Evaluation Methodologies: Applicability and Typology of Socio-economic Effects

Methodology	Data application level	Areas of application	Output	Outcome	Impact
Innovation Surveys	Firm Industry Economy-wide	Innovation IPRs Technology transfer Research collaboration	New products and processes Increase in sales Increase in value added Patent counts IPRs	Creation of new jobs Innovation capacity building	Enhanced competitiveness Institutional and organisational efficiency, Faster diffusion of innovation Employment
Micro Methods	Plant Firm Industry Economy-wide	Sectoral Returns to R&D	Output and value added (collect baseline info for before-after comparisons)	Sectoral productivity Industry sectoral spillovers Additionality Leverage effects	Firms competitiveness
Macro Methods	Firm Industry Economy-wide	Sectoral Regional Economy-wide	Output and value added	Change in R&D Capital, Human capital Social capital International R&D Spillovers	Regional, country productivity Employment Good governance Economic and social cohesion
Productivity Studies	Plant Firm Industry Regional Economy-wide	Sectoral Regional Economy-wide	Output and value added	Knowledge, Geographical and International R&D Spillovers	Regional, country productivity Employment Economic and social cohesion
Control Group Approaches	Firm Industry	Technology implementation Innovation	Output and value added (on supported and non supported firms)	Additionality Rate of return to R&D	Firm, industrial competitiveness
Cost Benefit Analysis	Firm Industry	Health Environment Energy Transport	Value added Benefit-cost ratio IRR Consumer surplus	Health improvements Consumer protection Environmental sustainability	Quality of life Standard of living
Expert Panels/ Peer Review	Firm Industry Economy-wide	Scientific merit Technological capacity	Publication counts Technological output	Scientific and Technological capabilities	R&D performance
Field/ Case Studies	Firm Industry	Science-industry relationships	Detailed inputs and outputs	Firms RTD capabilities On the job-training Educational schemes	Industrial competitiveness Quality of life Organisational efficiency
Network Analysis	Firm Industry Regional	RJVs, Cooperation science industry Clusters	Co-operation linkages	Co-operation in clusters Social embededness	Efficiency of institutional relationships
Foresight/ Technology Assessment	Institution Regional Economy-wide	Technology Trends	Identification of generic technologies Date of implementation	Technological capacities	Technological paradigms shifts
Benchmarking	Firm Industry Economy-wide	Efficiency of technology policy	S&T indicators	Technology capabilities	Industry competitiveness Good governance

Source: EC (2002)

Table 6. Evaluation Methodologies: Type, Data Requirements, Strengths and Limitations

Methodology	Type / *Use*	Data Requirements	Strengths	Limitations
Innovation Surveys	Semi- quantitative Quantitative *Monitoring* *Ex-post*	Micro data Expenditures Profits Patents Innovation	Detect innovation trends and insights on the soft side of innovation Findings from interviewed sample can be generalised to the population Permits to identify size and distribution of impacts Provides groups comparisons and changes over time	High cost and time consuming Processing and analysis of data requires large human resources Some types of information are difficult to obtain Long time series generally not available
Micro Methods	Quantitative Qualitative Categorical data *Monitoring* *Ex-post*	Micro data Expenditures Profits Patents	Results based on explicit formulation of theory based causal relationships R&D Additionality Control for different effects: firm size, expenditures, innovation capacity	Quality of data Persuade participant and non participant entities to disclose information Only private rate of return to R&D
Macro Methods	Quantitative modelling methodology *Ex-ante (simulation)* *Monitoring* *Ex-post*	R&D Expenditures R&D output Macroeconomic data	Social Rate of return to R&D Capture R&D Spillovers Estimate long term policy intervention impact Scenario simulations for policy supported geographical areas	Average returns Robustness of results Time lags for observation of the effects
Productivity Studies	Quantitative modelling methodology *Monitoring* *Ex-post*	Micro data Expenditures Profits R&D Patents	Estimation of effect of R&D on productivity Estimate the rate of return to R&D	Quality of data Deflation of series Required assumptions for measurement of stock variables
Control group approaches	Quantitative *Ex-post*	Micro data Expenditures Profits Patents	Capture the impact of policy intervention on the programme participant entity	Requires high technical capacity High implementation cost Data demanding
Cost Benefit Analysis	Quantitative (with qualitative elements) *Ex-ante (especially)* *Monitoring* *Ex-post*	Micro data Profit & cost estimates	Provides an estimate of socio-economic effect of intervention Good approach to assess the efficiency of an intervention Addresses by making them explicit all the economic assumptions of the impact of the intervention	Requires high technical capacity Some degree of judgement and subjectivity, depends largely on assumptions made Not easily comparable across cases Careful interpretation of results when benefits are not easily quantifiable in monetary terms
Expert Panels /Peer Review	Qualitative Semi- quantitative *Ex-ante* *Monitoring* *Ex-post*	Project programme data	Evaluation of scientific merits Flexibility Wide scope of application Fairness	Peers independence Economic benefits not captured
Field / Case studies	Qualitative Semi- quantitative *Monitoring* *Ex-post*	Project programme data	Observation of the socio-economic impacts of intervention under naturalistic conditions Good as exploratory and descriptive means of investigation Good for understanding how contexts affect and shape impacts	Results not generalisable
Network Analysis	Qualitative Semi- quantitative *Ex-post*	Project programme data	Comprehensive empirical material Compilation for policy purposes Co-operation linkages	Time involved in collecting the survey information Persuasion requirements
Foresight/ Technology Assessment	Qualitative Semi- quantitative *Ex-ante* *Monitoring*	Qualitative data Scenario	Consensus building to reduce uncertainty under different scenarios Combination on public domain and private domain data Articulation and road mapping of development of new technologies	Impossibility to detect major RTD breakthroughs
Benchmarking	Semi- quantitative *Ex-post* *Monitoring*	Science and technology Indicators	Comparison method across different sectors Support to systemic evaluation of institutions and systems	Data detail requirements Non transferable

Source: EC (2002)

Qualitative and semi-quantitative methodologies

- *Interviews and case studies*: uses direct observation of naturally occurring events to investigate behaviours in their indigenous socio-economic setting;
- *Cost-benefit analysis*: allows to establish whether a programme or project is economically efficient by appraising all its economic and social effects;
- *Expert Panels / Peer Review*: measures scientific output relying on the scientists' perception of the scientific contributions made by other peers. Peer review is the most widely used method for evaluation of the output of scientific research;
- *Network Analysis*: allows to analyse the structure of co-operation relationships and the consequences for individual firms decisions' on future actions providing explanations for the observed behaviours by analysing their social connections into networks;
- *Foresight / Technology Assessment*: used to identify potential mismatches in the strategic efficiency of projects and programmes.

Another important R&D programme evaluation technique not mentioned above is represented by bibliometrics studies. Publications and patents constitute major outputs of research programmes, and the large databases created to capture these outputs support the bibliometrics method of evaluation. Bibliometrics encompasses: tracking the quantity of publications and patents, analyzing citations of publications and patents, and extracting content information from documents. Bibliometrics is used to assess the quantity, quality, significance, dissemination and intellectual linkages of research, as well as to measure the progress, dynamics, and evolution of scientific disciplines (Ruegg & Feller, 2003).

Ex-post evaluation uses a combination of qualitative, statistical and econometric techniques to analyse the effects of a given policy or R&D programme. The diversity of methodologies available for performing such evaluation reflects the multiple dimensions in which the programme outcomes and impacts might manifest. For this reason, there is no single best evaluation methodology. Each methodology is fitted to analyse particular dimensions of programme results, but the best evaluation approach would require a combination of various evaluation methodologies possibly applied at various level of data aggregation (EC, 2002).

At the present stage Fusion R&D programme represents a very specific technological domain with a relatively small amount of funding compared to other energy / non-energy sectors. Accordingly, Fusion is unlikely to have a noticeable impact in a macroeconomic scale before the start of massive deployment. Therefore, it was decided to concentrate the analyses in this thesis on a limited number of programme effects and evaluation techniques, which include ex ante social cost-benefits analysis of prospective Fusion demonstration and deployment activities and ex post evaluation of direct / indirect effects at the level of individual companies through a case study of selected Fusion R&D project (namely Wendelstein 7 – X). Next chapters will provide a more detailed explanation of the methodological approaches that may be applied to perform such evaluation.

2.3.2 BETA Method for Measurement of Indirect Effects

The existence of so called "spillover gap" explaining the difference between the private and social rates of return to R&D is broadly recognised as a key argument for public policy intervention to support R&D in strategic domains. Over past decades several studies using different analytical approaches have succeeded in demonstrating the presence of spillover effects and determining the magnitude of the observed phenomenon, see e.g. Jaffe (1986), Griliches (1992), Nadiri (1993), Martins (2002), Adams (2006) to name a few. Meanwhile practical evaluation of spillover effects of big R&D programmes, such as Thermonuclear Fusion, still represent a significant difficulty because of certain methodological lacuna, especially as regards the need to assign correct economic measures to different qualitative variables, and the problem to gather the required data.

The approach developed by Bureau d'Economie Theorique et Appliquée (BETA) at the University of Strasbourg represents one the rare examples of methodologies which allows for broader socio-economic evaluation of publicly funded research and technology development programmes. It was designed for measuring indirect effects of large-scale international R&D programmes, e.g. those administered by CERN, European Space Agency, etc. (see e.g. Cohendet, 1997; Bach *et al.*, 2000; Bach & Matt, 2005). According to BETA method an exhaustive list of possible R&D outputs and impacts is being established (***Table*** *7*). Two main types of effects are distinguished: *direct effects* – directly related to the objectives of the programme and *indirect effects* – those that go beyond the scope of objectives of the programme. Indirect effects are further broken down into four sub-categories[11].

<u>Technological effects</u>

These effects concern the transfer of scientific and technical knowledge acquired or developed during the evaluated project / programme to other activities of the participant firms. Knowledge may be embodied in artefacts (products, systems, materials, processes…), in human or in any codified forms; it may be more or less tacit, individual or collective. What is transferred can therefore be of a very diverse nature, from scientific expertise to workers know-how, including technology laid down as a blue-print, new theories or trade secrets. The transfers lead to the design of new or improved products, processes or services which allow the participants to achieve new sales, to protect existing market shares, to obtain new research contracts, or lead to the granting of new patents.

<u>Commercial effects</u>

These effects include two sub-classes, not necessarily linked to a technological learning process. Network effects refer to the impact of R&D projects on the creation and/or the reinforcement of cooperation with project partners or other entities, which results in other cooperations than the evaluated project itself. Second, by working on behalf of a given public programme, participants sometimes acquire a quality label or a good image, which is afterwards used as a marketing tool.

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[11] description of different types of indirect effects in BETA methodology is cited according to Georghiou *et al.* (2002)

Table 7. Relevance of BETA Methodology for Evaluation of Different Types of Programme Effects

Outputs		**Impacts**			
Intermediate outputs		**Competitiveness**		**Control & care of the**	
- prototypes	*I*	- sales	*I*	**environment**	
- technological sub-systems	*I*	- market share	*I*	- reduced pollution	*IV*
- demonstrations	*I*	- open up markets	*I*	- improved information on	*V*
- models / simulators	*I*	- create new markets	*I*	pollution & hazards	
- integration of technologies	*I*	- lower costs	*I*	- positive impact upon global	*V*
- tools / techniques/methods	*I*	- faster time to market	*I*	climate	
- intellectual property	*I,II*	- licence income	*I*	- reduced raw material use	*I*
- decisions on further RTD	*I*			- reduced energy consumption	*IV*
		Employment			
Products		- jobs created	*II,III*	**Cohesion**	
- new products	*I*	- jobs in regions of high	*II,III*	- employment in less favoured	*IV*
- improved products	*I*	unemployment		regions (LFRs)	
		- jobs secured	*II,III*	- infrastructure in LFRs	*IV*
Processes		- jobs lost	*II,III*	- participation of LFRs	*IV*
- new processes	*I*			- further RTD in LFRs	*IV*
- improved processes	*I*	**Organisation**		- regulation & policy in LFRs	*IV*
		- formation of new firm	*II,III*		
Services		- joint venture to exploit results	*II,III*	**Development of infrastructure**	
- new services	*I*	- new technological networks /	*I*	- transport	*V*
- improved services	*I*	contacts		- telecommunications	*V*
- processes for delivering new	*I*	- new market networks /	*I*		
services		contacts		**Industrial development**	
		- improved capacity to absorb	*I*	- urban development	*V*
Standards		knowledge		- rural development	*V*
- de facto standard	*III*	- core competence	*I*		
- de jure standard	*III*	improvement		**Production & rational use of**	
- reference	*III*	- further RTD	*I*	**energy**	
- conformance	*III*	- reorganisation of firm to	*I*	- energy savings	*IV*
- memoranda of understanding	*III*	exploit results		- renewable sources	*IV*
- common functional	*III*	- change in strategy	*III*	- assurance of future supply	*V*
specification		- increased profile	*III*	- distribution of energy	*V*
- code of practice	*III*			- nuclear safety	*V*
- identified need for regulatory	*III*	**Quality of life**			
change		- healthcare	*IV*	**Regulation & policy**	
		- safety	*IV*	- development of SME sector	*IV*
Knowledge and skills		- social development &	*IV*	- development of large	*IV*
- management & organisation	*I*	services		organisations	
- technical	*I*	- improved border protection &	*IV*	- support for trade	*V*
- training activities	*I*	policing		- EU regulation & policy	*V*
		- support for cultural heritage	*V*	- national regulation & policy	*V*
Dissemination				- world-wide regulation & policy	*V*
- technology transfer activities	*I*			- co-ordination between national	*V*
- knowledge & skills transfer	*I*			& Community RTD programmes	
- publication / documentation	*III*			- development of internal market	*V*
- workshops / seminars /	*III*				
conferences					

I - already evaluated or could be easily derived from the evaluation
II - could be used to characterise an evaluated effect
III - could be collected with very little additional effort
IV - could be evaluated to the extent that it affects the interviewed parties
V - not relevant

Source: Georghiou *et al.* (2002)

Organisation & Methods effects

These effects concern the transfer of organisational or procedural knowledge acquired or developed during the evaluated project to other activities of the participant : they occur when experience gained through the project allows the participant to modify its internal organization and/or to apply new methods in project management, quality management, industrial accounting and so on.

Competence & Training (Work-factor) effects

These effects describe the impact of the R&D project / programme on the "critical mass" relative to the human capital of the participant, i.e. the range of competences related to more or less diversified scientific and technological fields, which are considered to be critical for the future development of the organisation.

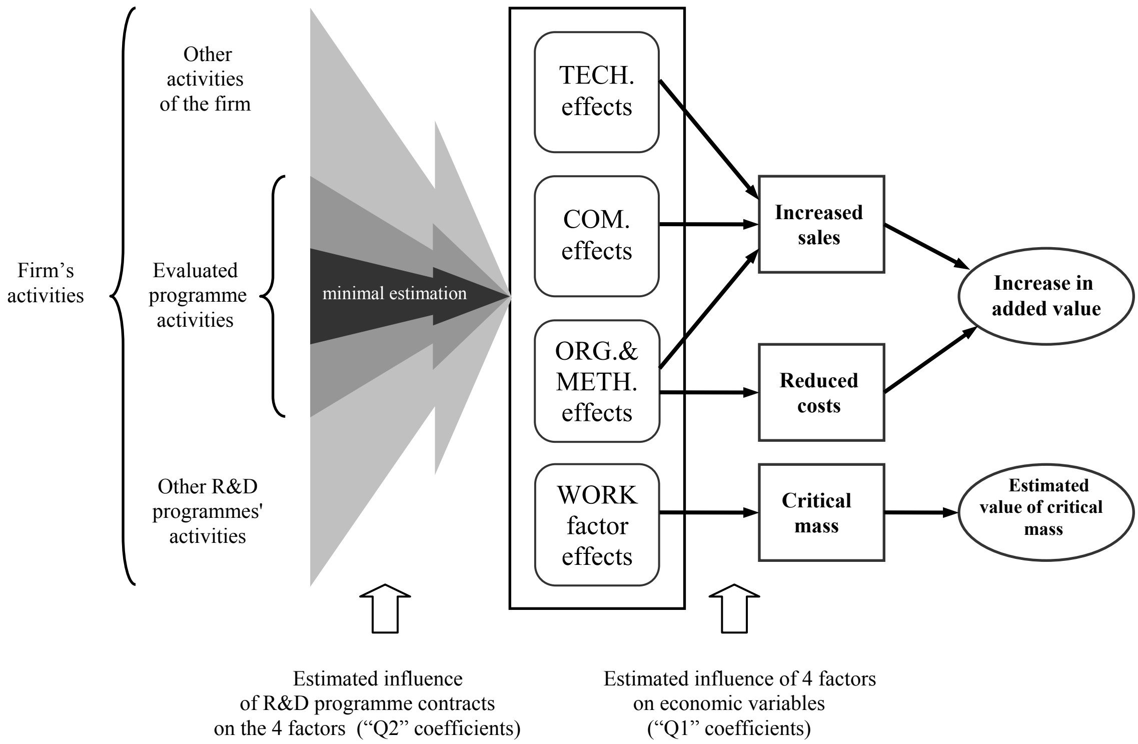
The evaluation with BETA method is limited to the participants of a given R&D programme: what is evaluated is the economic impact (or the economic effects) generated by and affecting the participants (Bach *et al.*, 2000). The methodology is based on microeconomic approach: economic effects are identified, evaluated in monetary terms at participants' level, and then aggregated at the programme level. Information about the effects is gathered through direct interviews with the managers of participant companies. The evaluation has two main goals. On the one hand, it aims to provide a minimal estimation of the economic value of different types of programme effects. On the other hand, it allows for better understanding how these effects are generated, and more generally how innovation processes are spurred by large R&D programmes and how they create economic value.

According to Cohendet (1997) the final unit of measurement used in BETA methodology to express economic value of indirect effects is the ***value added*** (the sum of the firm's wages and profits), together with the estimated value that results from setting up and maintaining highly skilled design and production teams (defined above as the "***critical mass***"). The quantification exercise [12] thus consists in determining how the work carried out for evaluated R&D programmes affects these two parameters; the process is illustrated in the diagram below (see ***Figure 16***). The contracts that firms obtain through participation in publicly funded R&D programmes, like all their other activities, affect the four basic factors corresponding to the four types of effects described earlier (technological, commercial, organisation & methods, competence & training effects). These in turn contribute to increasing the volume of sales and reducing costs and thus, under some circumstances, to increasing the firm's added value. The work factor – related effects also specifically affects the critical mass, which is estimated in a broad fashion on the basis of the payroll of the staff concerned.

In the case of *quantification by sales*, the managers interviewed are asked to estimate, as a percentage, two sets of coefficients:

[12] the following description of the quantification methods applied in BETA methodology is cited according to Cohendet (1997)

- Those (Q1) accounting for the parts played by the three factors, respectively Technology (Q1T), Commercial (Q1C) and Organisation & Methods (Q1OM), in influencing sales; their sum must be equal to 100%. Q1 does not therefore refer exclusively to the evaluated R&D programme activity.
- Those (Q2) accounting for the parts played by evaluated R&D programme work in each of the three factors above (respectively Q2T, Q2C and Q2OM); they must be between 0 and 100 %. They are very often based on objective data such as the share of funding obtained through participation in a given R&D programme in the development of the innovative product in question. The industry representatives also specify the exact nature of the influence of R&D programme activities in each of the three categories.



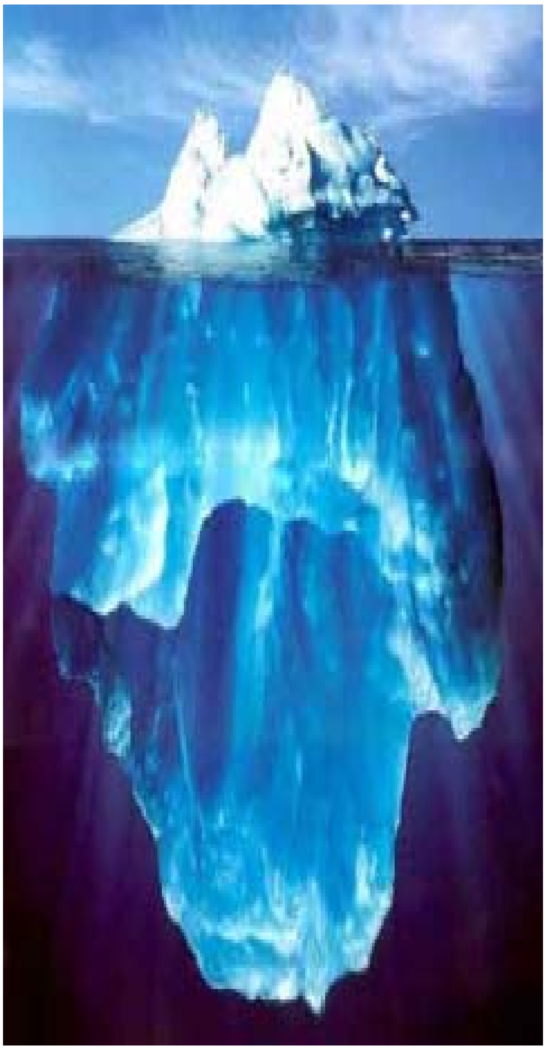
TECHNOLOGICAL EFFECT : Sales x rate of added value x Q1 x Q2T
COMMERCIAL EFFECT : Sales x rate of added value x Q1C x Q2C
ORGANISATION AND METHODS EFFECT : Sales x rate of added value x Q1OM x Q2OM

Figure 16. Quantification of Indirect Effects with BETA Method *(Source: Cohendet, 1997)*

In the case of *quantification by cost reduction*, the data are estimated using savings on inputs, lower reject rates or savings in production time. This is calculated:

- directly, by adding up the savings made thanks to new methods and production techniques acquired through participation in evaluated R&D programme;
- indirectly, by multiplying the following data: amount of savings made thanks to a particular method and percentage of influence of R&D programme experience in implementing that method (Q1).

In the case of *quantification of the critical mass*, for reasons of homogeneity, the quantification is made in monetary terms by taking into account the average cost of an engineer working in the R&D programme related division. The effect thus measures the minimum cost the company would have had to bear in order to qualify for future publicly funded R&D contracts in the same domain if it had not been able to benefit from existing contracts within the framework of the evaluated R&D programme.



Sales of innovative products	
- Good/excellent commercial impact	3*
- Additional annual turnover	3*
- Highly innovative products	1*
Reduced process costs	
- Reduced costs for participant	2*
- Cost savings through more efficient methods	2*
Licence income	1*
Firm Strategy	
- Direct Effect	2*
- Indirect Effect	2*
- Re-orienting Effect	3*
- New Business approaches	2*
- Shift to high tech business	2*
- Regeneration of traditional business	2*
Organisation and method learning	
- Quality control	2*
- Transformation in methods and applications	2*
Use of technology in other parts of business	
- Applications in other areas	4*
- Technology transfer through new competencies	3*
- Follow-on projects	3*
New contacts / networks & prestige	
- Effective use of Programme Label	3*
- New commercial links	4*
Employment, competence and training	
- Status of workforce	4*
- New jobs in non-participants	2*
- New S&E jobs generated	3*
Spill-over to non-participants	
- Competitor spill-over	1*
- Network spill-over	2*
User and social benefits	
- Customer benefits	4*
- Social and environmental benefits	2*
- Economic, safety & product quality	3*
- Combined benefits (health)	2*

Figure 17. Classification and Ratings (Weights) of Effects in "Iceberg Model"

Source: adapted from EUREKA (2006)

According to Bach & Matt (2005) BETA methodology has been recognised as an efficient tool for evaluating broader socio-economic impacts of large scale R&D programmes as show numerous examples of studies implemented in EU (European Space Agency, BRITE-EURAM and ESPRIT programmes, CERN), Japan (National R&D program for Medical and Welfare Apparatus), Brazil (PETROBRAS, CIBERS), etc. Recently BETA methodology has been amended by PREST centre at the University of Manchester and applied in annual 2005/2006 impact study of EUREKA programme. The following "Iceberg model" has been proposed which also includes spillover effects on non-participants and user benefits (***Figure 17***).

Practical application of BETA methodology requires careful definition of both types of "influence rates" (Q1 / Q2). The use of "minimal estimation" on a percentage scale may be a good precautionary principle; meanwhile, it could be useful to complement it with a more accurate quantitative measure. The definition and methods of calculating "value added" also have to be thoroughly explained. This approach can be further improved through implementation of more advanced quantitative analysis techniques, e.g. using plausibility / belief functions and fuzzy sets to treat the questionnaires data.

2.3.3 Company Valuation Methods

Participation in Fusion R&D projects is likely to affect the performance of the involved companies either through the accumulation of knowledge leading to the increased prospects of future gains, or through the accrual of additional income and added value that can be traced through the company's accounts. In both ways a perceptible impact on the company value can be expected. However, the definition of company's value is often a controversial task due to the differences in the valuation methods and limited availability of financial data, especially as regards the privately-held companies. Therefore, it is important to analyse carefully the existing company valuation methods and to choose those methods which could describe in a better way the specifics of Fusion R&D and its participants.

According to Damodaran (2006) there are four basic approaches to company valuation. The first, discounted cash-flow valuation, relates the value of an asset to the present value of expected future cash-flows on that asset. The second, liquidation and accounting valuation, is built around valuing the existing assets of a firm, with accounting estimates of book value often used as a starting point. The third, relative valuation, estimates the value of an asset by looking at the pricing of comparable assets relative to a common variable like earnings, cash-flows, book value or sales. The final approach, contingent claim valuation, uses option pricing models to measure the value of assets that share option characteristics. Fernandez (2007) distinguishes two additional approaches, namely based on value creation and mixed (goodwill) metrics. All six groups of company valuation techniques are summarised in ***Table 8*** below.

Table 8. Main Company Valuation Methods

Approach	**Methods**
Balance Sheet	*Book value, Adjusted book value, Liquidation value, Substantial value*
Income Statement	*Multiples, PER, Sales, P/EBITDA, Other multiples*
Mixed (Goodwill)	*Classic, Union of European Accounting Experts, Abbreviated income, Others*
Cash Flow Discounting	*Free cash flow, Equity cash flow, Dividends, Capital cash flow, APV*
Value Creation	*EVA, Economic profit, Cash value added, CFROI*
Option Pricing	*Black and Scholes, Investment option, Expand the project, Delay the investment, Alternative uses*

Source: adapted from Fernandez (2007)

The following section provides a brief overview drawing on the publication of Fernandez (2007) which analyses in more details the main company evaluation methods cited above.

Balance sheet-based methods (shareholders' equity)

These methods seek to determine the company's value by estimating the value of its assets. They determine the value from a static viewpoint basing on the company's balance sheet. These methods do not take into account the possible evolution of the company's performance over time and ignore other factors, such as industry's current situation, human resources or organizational problems, contracts, etc. that do not appear in the accounting statements. Some of these methods are the following: book value, adjusted book value, liquidation value, and substantial value.

Book value

A company's book value, or net worth, is the value of the shareholders' equity stated in the balance sheet (capital and reserves). This value can be also calculated as the difference between total assets and liabilities, that is, the surplus of the company's total goods and rights over its total debts with third parties.

Adjusted book value

This method seeks to overcome the shortcomings that appear when purely accounting criteria are applied in the valuation. When the values of assets and liabilities match their market value, the adjusted net worth is obtained.

Liquidation value

This is the company's value if it is liquidated, that is, its assets are sold and its debts are paid off. This value is calculated by deducting the business's liquidation expenses (redundancy payments to employees, tax expenses and other typical liquidation expenses) from the adjusted net worth.

Substantial value

The substantial value represents the investment that must be made to form a company having identical conditions as those of the company being valued. It can also be defined as the assets' replacement value, assuming the company continues to operate, as opposed to their liquidation value. Normally, the substantial value does not include those assets that are not used for the company's operations (unused land, holdings in other companies, etc.)

Income statement-based methods

Unlike the balance sheet-based methods, these methods are based on the company's income statement. They seek to determine the company's value through the size of its earnings, sales or other indicators by using some industry specific ratios (multiples).

Value of earnings / PER

According to this method, the equity's value is obtained by multiplying the annual net income of a company by a ratio called PER (price earnings ratio). This ratio represents the relation between the price paid for a share relative to the annual net income or profit earned by the firm per share.

Sales multiples

This valuation method, which is used in some industries, consists of calculating the company's value by multiplying its sales by a certain number, e.g. a pharmacy business is often valued by multiplying its annual sales (in $) by 2 or another number, depending on the market situation.

Other multiples

In addition to the PER and the price/sales ratio, some of the frequently used multiples are:

- Value of the company / earnings before interest and taxes (EBIT)
- Value of the company / earnings before interest, taxes, depreciation and amortization (EBITDA)
- Value of the company / operating cash flow
- Value of the equity / book value.

<u>Goodwill-based methods</u>

Generally speaking, goodwill is the value that a company has above its book value or above the adjusted book value. Goodwill seeks to represent the value of the company's intangible assets, which often do not appear on the balance sheet but which, however, may constitute a considerable competitive advantage with respect to other companies operating in the industry (quality of the customer portfolio, industry leadership, brands, strategic alliances, etc.). The problem arises when one tries to determine its value, as there is no consensus regarding the methodology used to calculate it. These methods apply a mixed approach: on the one hand, they perform a static valuation of the company's assets and, on the other hand, they try to quantify the capital gain resulting from the value of its future earnings.

"Classic" valuation method

This method states that a company's value is equal to the value of its net assets (net substantial value) plus the value of its goodwill. In turn, the goodwill is valued as "n" times the company's net income, or as a certain percentage of the turnover.

Union of European Accounting Experts (UEC) method

According to simplified UEC method, a company's value is computed with the following formula:

$$\boldsymbol{V = A + a_n\,(B - iA)} \tag{2.3.1}$$

where:

$\boldsymbol{A}$ = corrected net assets or net substantial value

$\boldsymbol{a_n}$ = present value, at a rate t, of n annuities, with n between 5 and 8 years

$\boldsymbol{B}$ = net income for the previous year or that forecast for the coming year

$\boldsymbol{i}$ = interest rate obtained by an alternative placement, e.g. the return on equities, bonds or real estate investments (after tax)

$\boldsymbol{a_n\,(B - iA)}$ = goodwill.

<u>Cash flow discounting-based methods</u>

These methods seek to determine the company's value by estimating the cash flows it will generate in the future and then discounting them at a certain discount rate. Cash flow discounting methods are based on the detailed, careful forecast, for each period, of each of the financial items related to the company's operations, such as sales revenues, personnel, raw materials, administrative expenses, loan repayments, etc. In cash flow discounting-based valuations, a suitable discount rate is determined for each type of cash flow. Determining the discount rate is one of the most important tasks and takes into account the risk, historic volatilities, etc. In practice, a minimum "hurdle" discount rate is often used by the evaluators.

Next section provides a formal definition of the "value added" and discusses in more details the Economic Value Added ® approach, while the theory and practical application of Options valuation approach are explained in chapter 2.5.

2.3.4 Definition of Value Added

Traditional Approach

According to DTI (2007) the value added (VA) is defined as the amount of wealth created by a company which is net sales less the cost of bought-in goods and services. Value added can be calculated accurately from company's accounts by adding together operating profit, employee costs, depreciation and amortisation / impairment charges.

Value Added = *Sales less Cost of Bought-in Materials, Components & Services*

and alternatively but equivalently,

= *Operating Profit + Employee Costs + Depreciation + Amortisation & Impairment*

These quantities are defined and calculated as follows:

Operating Profit = *Profit (or loss) before tax plus net interest paid (or minus net interest received) less gains (or plus losses) arising from the sale / disposal of businesses or assets*

Employee Costs = *Total employment costs (wages & salaries, social security & pension costs)*

Depreciation = *Depreciation and impairment charges on owned assets and assets held under finance leases*

Amortisation & Impairment = *Depreciation of capitalised development, impairment of goodwill, amortisation and impairment of other intangibles.*

There are three basic ways in which a company can increase its value added. These are:

- By introducing new products and services that provide even greater value to its customers compared to the cost of the materials, components and services used to make them;
- By selling more existing products and services by improved marketing or by entering markets in new geographies or, in non-competitive markets, by raising prices and hence margins;
- By reducing the cost of bought-in items by more effective procurement and improved design and development.

According to UN System of National Accounts gross value added is the value of output less the value of intermediate consumption; it is a measure of the contribution to GDP made by an individual producer, industry or sector. Net value added is the value of output less the values of both intermediate consumption and consumption of fixed capital (UN, 1993).

Economic Value Added® and Market Value Added Approaches

In the early 1990s Stern Stewart & Co. proposed an enterprise performance measurement approach based on Economic Value Added (EVA®) and Market Value Added indicators (Stewart, 1991). EVA® is measured as company's operating profit less the cost of capital employed to produce the earnings. Its basic formula can be expressed as follows:

$$EVA = NOPAT - (WACC \times IC) \qquad (2.3.2)$$

where

NOPAT = Net Operating Profit After Tax

WACC = Weighted Average Cost of Capital

IC = Invested Capital.

This indicator allows for evaluating the performance of company's management by comparing net operating profit after tax with the total cost of company's capital, both debt and equity (Jalbert & Landry, 2003). Accordingly, if EVA® is positive it means that the company during a given year has earned enough money to remunerate all capital suppliers and to increase its value.

The major difficulty with EVA® resides in the fact that NOPAT and WACC are not reported directly according to generally accepted accounting principles (GAAP). The calculation of NOPAT requires multiple adjustments in financial statements. The cost of capital can only be estimated with subjective assumptions regarding the cost of equity and market risk premium.

In contrast to EVA® which represents an internal evaluation of company's performance, the Market Value Added (MVA) indicator evaluates the company's performance in terms of the market value of debt and equity compared to the invested capital (Reilly & Brown, 2000). It can be calculated as follows:

$$MVA = VD + VE - IC \qquad (2.3.3)$$

where

VD = market Value of Debt

VE = market Value of Equity

IC = book value of Invested Capital.

The problem with MVA indicator is that it is affected by external factors, such as market interest rates and expectations about the future performance, and it is not suitable for privately-held non-listed companies.

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2.4 Risk and Uncertainty in the Evaluation of R&D Programmes

2.4.1 Basic Concepts and Definitions

Implementation of large R&D programmes, such as Fusion, is inevitably confronted with substantial risks and uncertainties. Oftentimes these terms are being confused or not sufficiently delineated that may affect the validity of the analytical findings. Therefore, it is important to define both concepts from the outset that should allow for better framing the programme evaluation process. The notions of risk and uncertainty are highly specific to the context in which they are studied, and accordingly there could be multiple definitions depending on the particular engineering, economical, political and social phenomena faced by the evaluated programmes.

Let's start with the formal definition of risk. The explanations given to this term in various literature sources are most times narrative, highlighting the general idea of risk as some sort of physical or economical burden to an individual, engineering system, firm, society or environment that may occur as a consequence of any underlying variable taking a certain value above or below a predefined benchmark. The most general definition of risk is given by Koller (2005) who defined risk as *a pertinent event for which there is a textual description*. Some typical examples of risks in large scale R&D programmes could be the risks related to the performance levels of completed project, time required to complete the project and the cost to complete the project, see e.g. the discussion of NIF project in Alessandri *et al.* (2004). The examples of risks in construction of large industrial facilities, such as nuclear power plants, are typically represented by the price risk (i.e. the market price of electricity), output risk (power plant's capacity factor), cost risk[13] (fuel and other operating expenses), see e.g. Rothwell (2006).

The notion of risk is inherently related to the uncertainty which is associated according to Koller (2005) with at least two parameters: probability of occurrence of a risky event and the consequence (impact) of its occurrence. Uncertainty is typically, but not always, represented as a range of values (sometimes as a distribution) that encompasses the range of possible outcomes. The definition of uncertainty given by Koller (2005) refers to the concept of probability which considers uncertainty as a random phenomenon, i.e. the underlying factors are modelled as "random variables" which follow certain probability laws (Grabisch *et al.*, 1995). Meanwhile, there exist other sources of uncertainty, e.g. due to incompleteness or imprecision of available information. This type of uncertainty is termed in the literature as epistemic or reducible uncertainty[14] in contrast to the former "variability" type of uncertainty which is also referred to as aleatory, stochastic, irreducible, or objective uncertainty.

Generally speaking, uncertainty is involved in any problem-solving situation as a result of some information deficiency. Information may be incomplete, imprecise, fragementary, not fully reliable, vague, contradictory, or deficient in some other way (Klir & Wierman, 1999). These information deficiencies may result in different types of uncertainty. In an attempt to classify the

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[13] In principle, the investment risk should be included into this category, although it could be mitigated through imposing strict "fixed-price" contractual obligations on equipment suppliers.

[14] Other terms used in the literature to define epistemic uncertainty are subjective or parametric uncertainty.

main types of uncertainty Smithson (1989) proposed the following taxonomy of “unknowns” (***Figure 18***) which starts with the overarching term “ignorance”. Two fundamental types of ignorance are distinguished. One refers to distorted or incomplete knowledge, termed as “error”. The other connotes to overlooking or deliberate inattention, termed as “irrelevance”. Error may arise from “distorted” and/or “incomplete” information. One type of distortion, “confusion”, involves mistaking or wrongful substitution of one attribute for another. The other, “inaccuracy”, refers to distortion in degree or bias. The term “incompleteness” encompasses two types of “unknown”: incompleteness in degree, referred to as “uncertainty”, and incompleteness in kind, referred to as “absence”. In its turn, uncertainty can be further subdivided into “vagueness”, “probability” and “ambiguity” (Bammer & Smithson, 2008).

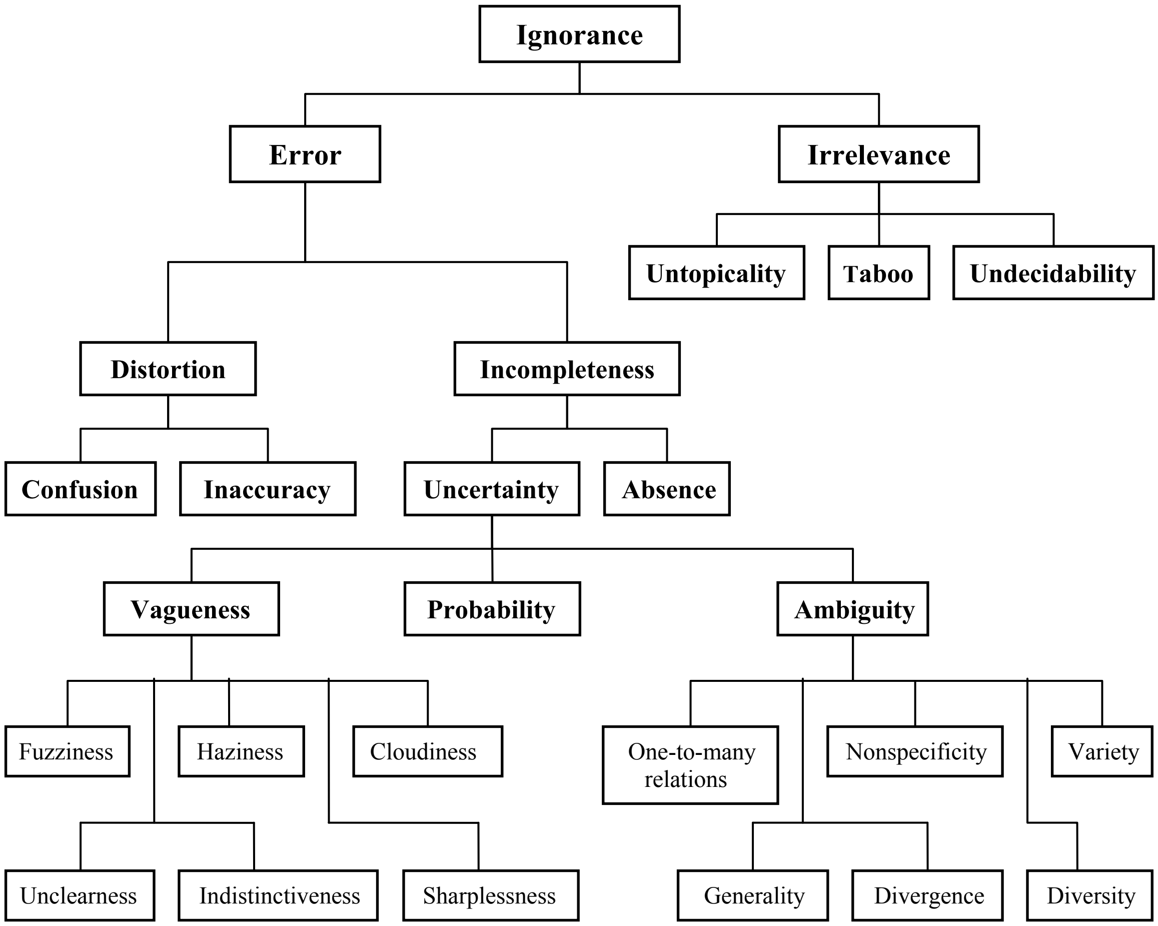

Figure 18. Taxonomy of Different Types of “Unknowns”

Source: adapted from Bammer & Smithson (2008) and Klir & Folger (1998)

According to Klir & Folger (1998) the term vagueness refers to the difficulty of making sharp or precise distinctions, i.e. some domain of interest is vague if it cannot be delimited by sharp boundaries. Some other kindred concepts are connected with vagueness, such as fuzziness, haziness, cloudiness, unclearness, indistinctiveness and sharplessness. Ambiguity is associated with one-to-many relations, i.e. situations in which the choice between two or more alternatives is left unspecified. The other concepts related to ambiguity include nonspecificity, variety, generality, diversity and divergence. The probability, as discussed earlier, refers to the laws of chance, which rely on the concepts of random variables, stochastic processes and events.

An adequate representation of uncertainty in transparent science-engineering & policy-management interface is an important requirement of an efficient model-based policy evaluation and decision support mechanism. However, as pointed out in Walker *et al.* (2003) there is no generally accepted approach to the communication about uncertainty. The main difficulty is that uncertainty propagates throughout the diversity of meanings, dimensions and individual perceptions. In an attempt to harmonise the terminology and typology, the following uncertainty matrix (***Table 9***) was proposed by Walker *et al.* (2003).

Table 9. Uncertainty Matrix

Location		**Level**			**Nature**	
		Statistical uncertainty	Scenario uncertainty	Recognised ignorance	Epistemic uncertainty	Variability uncertainty
Context	Natural, technological, economic, social and political representation					
Model	Model structure					
	Technical model					
Inputs	Driving forces					
	System data					
Parameters						
Model Outcomes						

Source: Walker *et al.* (2003)

In this matrix the uncertainty is classified in three dimensions:

(i) the *location* – where the uncertainty manifests itself within the model complex;

(ii) the *level* – where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance;

(iii) the *nature* – whether the uncertainty is due to the imperfection of our knowledge, or inherent variability of the phenomena.

The approach of Walker *et al.* (2003) was criticised in Norton *et al.* (2006) for not being able to address the diversity of meanings associated with the terms “uncertainty” and “ignorance”, and to explore how these concepts may be assessed and used by different groups of modellers and users. The definition of attribute “level” is problematic, because the uncertainty may be viewed as a state of confidence rather than order from certainty to ignorance. The statistical way to represent quantifiable uncertainty is also imperfect. According to Norton *et al.* (2006) there is a spectrum of well-established methods, not all statistical, for characterising degrees of credibility, ranging from bounds (binary classification as possible / impossible), rough sets (ternary classification as possible / doubtful / impossible), fuzzy sets (graded from possible to impossible), histograms (graded in relative frequency with a probabilistic interpretation available) to probability density functions (taking a Bayesian view), etc.

Many different formal techniques, both quantitative and qualitative, have been elaborated for dealing with uncertain and incomplete information. As pointed out in Klir & Smith (2001) in order to develop a fully operational theory for dealing with uncertainty one has to address a host of issues at four distinct levels which include:

[1] Finding an appropriate mathematical representation of the conceived type of uncertainty;

[2] Developing a calculus by which this type of uncertainty can be properly manipulated;

[3] Finding a meaningful way of measuring relevant uncertainty in any situation formalisable in the theory;

[4] Developing methodological aspects of the theory, including procedures for making the various uncertainty principles operational with the theory.

2.4.2 Overview of Main Uncertainty Theories

Probability Theory

For a long time, the treatment of uncertainty in science, mathematics and engineering relied on the probability theory, initial formalisations of which may be traced back to the works of Gerolamo Cardano in sixteenth century and Blaise Pascal and Pierre de Fermat in seventeenth century. The subsequent works of Huygens, Bernoulli, Bayes and Laplace established a mathematical theory of probability. The foundations of modern probability theory were laid by Kolmogorov in 1933. The probability theory is built on three axioms or laws that define the behaviour of probability measure, which may be used as an estimate of the degree to which an uncertain event is likely to occur (Parsons & Hunter, 1998).

The first law of probability theory is the convexity law which states that the probability measure for an even A given information H is such that:

$$0 \leq \Pr\left(A \middle| H\right) \leq 1 \tag{2.4.1}$$

The second law is the addition law, which relates the probabilities of two events to the probability of their union. For two exclusive events A and B, i.e. two events that cannot both occur at the same time, we have:

$$\Pr\left(A \cup B\right) = \Pr\left(A\right) + \Pr\left(B\right). \tag{2.4.2}$$

If the events are not exclusive we have, instead:

$$\Pr\left(A \cup B\right) = \Pr\left(A\right) + \Pr\left(B\right) - \Pr\left(A \cap B\right). \tag{2.4.3}$$

Furthermore, the sum of the probabilities of a set of mutually exclusive and exhaustive events, the latter meaning that they are the only possible events that may occur, is equal to 1:

$$\Pr\left(A\right) + \Pr\left(\overline{A}\right) = 1 \tag{2.4.4}$$

or, more generally for a set of n such events A_i :

$$\sum_{i=1,\ldots,n} \Pr\left(A_i\right) = 1. \tag{2.4.5}$$

The final law is the multiplication law, which gives the probability of two events occurring together, i.e. the probability of the intersection of A and B :

$$\Pr(A \cap B) = \Pr(A) \times \Pr(B|A). \tag{2.4.6}$$

The probability measure $\Pr(B|A)$ is the conditional probability of B given A, i.e. the probability that B will occur, given that A is known to have occurred[15].

There are many important results in probability theory that have found extensive applications in practical uncertainty analyses. One of them is the law of large numbers. It states that the arithmetic mean of independent, identically distributed random variables converges to the expected value (Gut, 2005). Another one is central limit theorem, which says that the distribution of a sum of independent random variables approaches the normal distribution as the number of variables is increased indefinitely (Prokhorov, 2005).

According to Morgan & Henrion (1990) there exist two different views of the probability. The classical or frequentist approach defines the probability of an event's occurring in a particular trial as the frequency with which it occurs in a long sequence of similar trials. More precisely, the probability can be seen as the value to which the long-run frequency converges as the number of trials increases. Another classical approach relies on "propensity" interpretation according to which probability is thought of as a physical propensity, or disposition, or tendency of a given type of physical situation to yield an outcome of a certain kind, or to yield a long run relative frequency of such an outcome (Hájek, 2007). The frequentist and the propensity views of probability are known as objectivist as they assume that probability is an objective property of the physical world. In the subjectivist, also known as personalist or Bayesian interpretation, probability of an event is the degree of belief that a person has that it will occur, given all the relevant information currently known to that person (Morgan & Henrion, 1990). Thus the probability is a function not only of the event, but also of the state of knowledge. While both approaches rely on the same axioms of the probability theory, the subjectivist view of the probability seems to be more adequate for dealing with epistemic type of uncertainty in real life situations for which empirical sampling data may be inexistent and the analysis should be grounded on expert judgements and Bayesian inferences.

Evidence Theory

The mathematical theory of evidence was developed by Glenn Shafer (1976) who expanded and formalised the earlier works of Arthur Dempster (1996, 1967, 1968). The theory is based on two main ideas: the idea of obtaining degrees of belief for one question from subjective probabilities for a related question, and Dempster's rule for combining such degrees of belief when they are based on independent items of evidence (Shafer, 1990). According to the explanation given in Klir & Wierman (1999), Dempster-Shafer theory of evidence employs a non-additive measure,

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[15] The given above mathematical formulation of the main axioms of the probability theory is cited according to Parsons & Hunter (1998). A good introduction to the probability theory can be found in Grinstead & Snell (1997), Gut (2005), Prokhorov (2005), Bhattacharya & Waymire (2007).

called a *belief measure*. Given a universal set X (usually referred to as the *frame of discernment*) and its power set[16] $P(X)$, a belief measure, *Bel*, is a function

$$Bel: P(X) \rightarrow [0, 1] \tag{2.4.7}$$

such that $Bel(\emptyset) = 0$, $Bel(X) = 1$ and

$$\begin{aligned} Bel(A_1 \cup A_2 \cup ... \cup A_n) \geq \sum_j Bel(A_j) - \sum_{j<k} Bel(A_j \cap A_k) + \\ + \sum_{j<k<l} Bel(A_j \cap A_k \cap A_l) + ... + (-1)^{n+1} Bel(A_1 \cap A_2 \cap ... \cap A_n) \end{aligned} \tag{2.4.8}$$

for all possible families of subsets of X. This property of belief measures implies that they are superadditive in the sense that

$$Bel(A \cup B) \geq Bel(A) + Bel(B) \tag{2.4.9}$$

for any disjoint sets $A, B \in P(X)$.

For any given belief measure *Bel*, a dual measure *Pl*, called *plausibility measure*, is defined by the equation

$$Pl(A) = 1 - Bel(\overline{A}) \tag{2.4.10}$$

for all $A \in P(X)$. Moreover, $Pl(\emptyset) = 0$ and $Pl(X) = 1$. This measure satisfies the inequality

$$\begin{aligned} Pl(A_1 \cap A_2 \cap ... \cap A_n) \leq \sum_j Pl(A_j) - \sum_{j<k} Pl(A_j \cup A_k) + \\ + \sum_{j<k<l} Pl(A_j \cup A_k \cup A_l) + ... + (-1)^{n+1} Pl(A_1 \cup A_2 \cup ... \cup A_n) \end{aligned} \tag{2.4.11}$$

for all possible families of subsets X. This property of plausibility measures implies that they are subadditive in the sense that

$$Pl(A \cup B) \leq Pl(A) + Pl(B) \tag{2.4.12}$$

for any disjoint sets $A, B \in P(X)$.

Either of the two measures is uniquely determined from the other by the equation

$$Pl(A) = 1 - Bel(\overline{A}) \tag{2.4.13}$$

for all $A \in P(X)$, where $\overline{A}$ is the crisp complement of A.

The belief measure *Bel* and its dual plausibility measure *Pl* are characterised by a function

$$m : P(X) \rightarrow [0, 1] , \tag{2.4.14}$$

which is required to satisfy two conditions:

(a) $m(\emptyset) = 0$; (b) $\sum_{A \in P(x)} m(A) = 1$.

[16] The set of all subsets of a given set X is called the *power set* of X and is denoted $P(X)$. If X is finite and its cardinality (the number of elements contained in a set) is $|X| = n$ then the number of subsets of X is 2^n (see Klir & Wierman, 1999).

This function is called *basic probability assignment*, or *mass function*. For each $A \in P(X)$, the value $m(A)$ expresses the degree of support of the evidential claim that the true alternative is in the set A but not in any special subset of A. Any additional evidence supporting the claim that the true alternative is in a subset of A, say $B \subset A$, must be expressed by another nonzero value $m(B)$.

Given a particular basic probability assignment m, the corresponding belief and plausibility measures are determined for all sets $A \in P(X)$ by the formulas:

$$Bel(A) = \sum_{B|B \subseteq A} m(B), \tag{2.4.15}$$

$$Pl(A) = \sum_{B|A \cap B \neq \emptyset} m(B). \tag{2.4.16}$$

The three functions, *Bel*, *Pl* and *m*, are alternative representations of the same evidence. Given anyone of them, the two others are uniquely defined. For example,

$$m(A) = \sum_{B|B \subseteq A} (-1)^{|A-B|} Bel(B) \tag{2.4.17}$$

for all $A \in P(X)$, where $|A - B|$ is the cardinality of the set difference of A and B.

Given a basic probability assignment m, every set $A \in P(X)$ for which $m(A) \neq 0$ is called a *focal element*. The pair $\langle F, m \rangle$, where F denotes the set of all focal elements induced by m is called a *body of evidence.*

The total ignorance is expressed in evidence theory by $m(X) = 1$ and $m(A) = 0$ for all $A \neq X$. Full certainty is expressed by $m(\{x\}) = 1$ for one particular element of x and $m(A) = 0$ for all $A \neq \{x\}$ (Klir & Wierman, 1999).

According to Salicone (2007) evidence obtained in the same frame of discernment from two independent sources and expressed by the two basic probability assignments m_1 and m_2 on the power set $P(X)$ can be properly combined to obtain a joint basic assignment $m_{1,2}$. The standard way to combine evidence is the Dempster's rule of combination, expressed by

$$m_{1,2}(A) = \begin{cases} \dfrac{\sum_{B \cap C = A} m_1(B) m_2(C)}{1 - \sum_{B \cap C = \emptyset} m_1(B) m_2(C)} & \text{if } A \neq \emptyset. \\ 0 \ , & \text{if } A = \emptyset \end{cases} \tag{2.4.18}$$

Based on Dempster's rule of combination, the degree of evidence $m_1(B)$ from the first source, which focuses on set $B \in P(X)$, and the degree of evidence $m_2(C)$ from the second source, which focuses on set $C \in P(X)$, are combined by considering the product $m_1(B)\ m_2(C)$, which focuses on the intersection $B \cap C$ (Salicone, 2007).

According to Liu (2001) the two main advantages of Dempster-Shafer theory consist in its ability to model information in a flexible way, i.e. without requiring a probability to be assigned to each element in a set, and provision of a convenient and simple mechanism (Dempster's combination rule) for combining two or more pieces of evidence. The former allows to describe ignorance because of the lack of information, and the latter allows to narrow the space of possible answers as more evidence is accumulated. The major problem in practical application of this theory is due to computational complexity of Dempster's combination rule which in some cases provides counterintuitive results (see e.g. Pearl, 1990; Möller & Beer, 1998).

Possibility Theory

Possibility theory is another uncertainty theory developed specifically for dealing with incomplete information. It stems from the works of Zadeh (1978), Dubois & Prade (1988) and the earlier works of Shackle (1961), Lewis (1973) and Cohen (1977). Similar to the evidence theory it uses a pair of dual set-functions (*possibility* and *necessity* measures) instead of only one as it is the case in probability theory. The formulation of possibility theory proposed by Zadeh is related to the theory of fuzzy sets to the extent that it defines the concept of a possibility distribution as a fuzzy restriction which acts as an elastic constraint on the values that may be assigned to a variable. This feature is particularly useful for treatment of imprecision of information contained in natural language statements which is mainly possibilistic rather than probabilistic in nature. By employing the concept of a possibility distribution, a proposition, p, in natural language may be translated into a procedure which computes the probability distribution of a set of attributes which are implied by p (Zadeh, 1978).

Formally, possibility theory refers to the study of maxitive and minitive set functions, represented, respectively, by possibility and necessity measures such that the possibility degree of a disjunction (union) of events is the maximum of the possibility degrees of events in the disjunction, and the necessity degree of a conjunction (intersection) of events is the minimum of the necessity degrees of events in the conjunction (Dubois, 2006). Consider a set of alternatives, X. One of these alternatives is true, but it is not known with certainty which one it is, due to limited evidence. Assume that it is also known, according to all available evidence, that the true alternative can not be outside a given subset E, such that $\varnothing \neq E \subseteq X$ .This type of possibility distribution is common in expert judgements stating that a numerical value of a given variable x lies between values a and b, then E is the interval $[a,b]$. This simple evidence can be expressed by a classical possibility measure, Pos_E, defined on X by the formulas:

$$Pos_E(\{x\}) = \begin{cases} 1 \ , & \text{when } x \in E \\ 0 \ , & \text{when } x \in \overline{E} \end{cases} \tag{2.4.19}$$

for all $x \in X$ and

$$Pos_E(A) = \sup_{x \in A} Pos_E(\{x\}) \tag{2.4.20}$$

for all $A \in P(X)$. The necessity measure, Nec_E, can be obtained from possibility measure, Pos_E, using following equation

$$Nec_E(A) = 1 - Pos_E(\overline{A}) \tag{2.4.21}$$

For all $A, B \in P(X)$, possibility measures and necessity measures satisfy the equations

$$Pos(A \cup B) = \max[Pos(A), Pos(B)], \tag{2.4.22}$$

$$Nec(A \cap B) = \min[Nec(A), Nec(B)], \tag{2.4.23}$$

and the inequalities

$$Pos(A \cap B) \leq \min[Pos(A), Pos(B)], \tag{2.4.24}$$

$$Nec(A \cup B) \geq \max[Nec(A), Nec(B)]. \tag{2.4.25}$$

Furthermore, it can be shown that there exists a weak theoretical connection between possibility and probability measures, expressed by the following inequality

$$Nec(A) \leq \Pr(A) \leq Pos(A). \tag{2.4.26}$$

Indeed, if some alternative is impossible, it is likely to be improbable; however, a high degree of possibility does not imply a high degree of probability, nor does a low degree of probability reflect a low degree of possibility (see Parsons & Hunter, 1998). A graphical example of the results that could be obtained using all three uncertainty measures is given in ***Figure 19*** below.

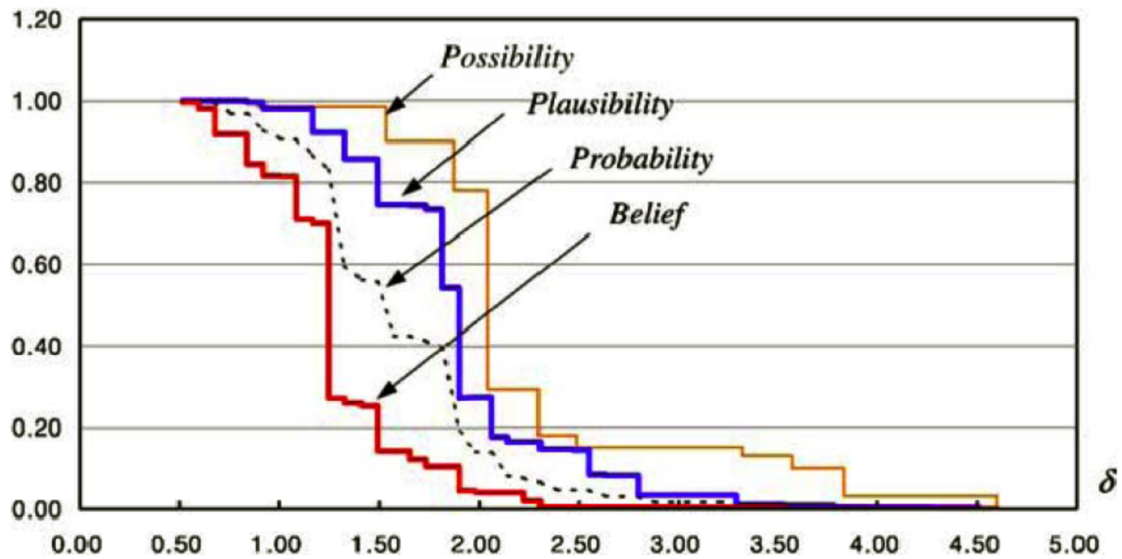

Figure 19. Exemplary Complementary Cumulative Distribution Functions for Measurements Based on Possibility Theory, Probability Theory and Evidence Theory *(Source: Bae et al., 2004)*

According to Dubois & Parade (2003) qualitative possibility measures can be valued on any ordered set (especially finite one). They lead to inconsistency-tolerant extensions of propositional logic such as possibilistic logic, and provide a natural semantic setting for non-monotonic reasoning, whose computational complexity remains close to that of propositional logic. As concerns quantitative possibility measures they can have several applications: a degree of possibility can be viewed as an upper probability bound, a possibility distribution can be viewed as a likelihood function, and it can also be helpful to encode probability distributions with extreme values.

2.4.3 Uncertainty in the Evaluation of Fusion R&D Programme: Need for Integrated Analysis

Having reviewed the main theoretical concepts of risk and uncertainty, we can now proceed with a more detailed analysis of the potential risks in case of Fusion RDDD and investigation of the practical approaches to coping with uncertainty in the evaluation of Fusion RDDD programme. 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 time-to-market as it is advocated by the proponents of New Paradigm / Early DEMO approaches.

The uncertainties underlying the major risks listed 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 which normally follows a mean-reverting stochastic process with jumps and seasonality trends (see e.g. Escribano *et al.*, 2002). 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. the uncertainty regarding contextual assumptions, model structure and its mathematical specification, input data and modelling parameters. Socio-economic evaluation of spillover effects at the level of individual companies involved in Fusion R&D process is facing another type of uncertainty due to inaccuracy and vagueness of human judgements which are required to assess potential impacts of Fusion R&D projects on the firms' economic performance. Finally, some pieces of information required for comprehensive cost – benefit analysis could be simply missing, such as 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 socio-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 social 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. Miller & Waller, 2003; Alessandri *et al.*, 2004; Driouchi *et al.*, 2009). This approach can be supplemented with the methods of robustness analysis introduced by Gupta & Rosenhead (1968) and further developed in Rosenhead (1980a, 1980b).

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 International, 2008). According to Alessandri *et al.* (2004) scenario planning is a mainly qualitative approach to decision-making, used when primary variables are not easily quantifiable, and involves the creation of coherent storylines about possible futures with the goal of identifying and evaluating contingencies, uncertainties, trends and opportunities. 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. The scenarios are based on internally consistent assumptions about the key relationships and driving forces of change that are derived from the current understanding of the historical trends and present situation. Depending on their objectives the scenarios could be either *descriptive*, i.e. exploring possible developments in the absence of significant changes, or *normative* (*prescriptive*), i.e. aiming to investigate the consequences of specific changes in policies, institutions and technologies. Usually scenarios are formulated with the help of formal models, although a more intuitive qualitative approach based on expert opinion is also wide-present[17].

Based on the publications of Shoemaker (1995) and Miller & Waller (2003) the following basic steps can be identified in scenario planning process:

1. Define the objectives and scope of analysis
2. Identify the major stakeholders and solicit inputs
3. Identify basic trends
4. Identify key uncertainties
5. Construct initial scenario themes, i.e. best case and worst case scenarios
6. Check for consistency and plausibility, choose several most relevant scenarios
7. Anticipate interactive dynamics of the various actors
8. Develop quantitative models and identify further research needs
9. Formulate strategies.

As discussed in Miller & Waller (2003) and Driouchi *et al.* (2009) 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 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 that

[17] See Van Notten *et al.* (2003) for more detailed discussion on scenario typology.

will be discussed in consecutive chapter, 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 face of adversity.

The importance of real options approach as a versatile risk and uncertainty management tool was highlighted in the books of Johnathan Mun (2006) who proposed the following integrated risk analysis framework (see ***Figure 20***). The main components of this framework include: (1) Risk identification through qualitative screening; (2) Risk prediction through base case projections; (3) Risk modelling through development of static financial models; (4) Risk analysis based on dynamic Monte Carlo simulation; (5) Risk mitigation through framing the identified problems as real options; (6) Risk hedging based on real options simulation and optimisation; (7) Risk diversification through optimisation of resources allocation; (8) Risk management through visual reporting and analysis updates.

<u>1. Qualitative Screening</u>

Through qualitative screening management has to decide which projects or initiatives are viable for further analysis in accordance with the overall business strategy. At this point the most valuable insights are created as management frames the complete problem to be resolved and the various risks are being identified.

<u>2. Future Projection</u>

At this stage, normally the future sale prices, production volumes and other key revenue and cost drivers are being projected using statistical forecasting techniques or other subjective methods, such as scenarios.

<u>3. Base Case NPV Analysis</u>

For each project / strategy that passes qualitative screening a discounted cash flow model is created. This model serves for calculating deterministic net present value for base case scenario using the forecasted values from the previous step.

<u>4. Monte Carlo Simulation</u>

Because the static discounted cash flow provides only a single point result, there is oftentimes little confidence in its accuracy given the range of underlying uncertainties. Therefore, in order to better estimate the value of particular project, Monte Carlo simulation should be employed next. Such simulation usually starts with sensitivity analysis aiming to determine the key uncertain variables that drive the net present value (critical success drivers). These variables are further used in Monte Carlo simulation which provides a more robust result in terms of stochastic NPV.

<u>5. Real Options Problem Framing</u>

Given the risk and uncertainty metrics obtained through the previous step, the potential risk mitigation strategies are identified at this stage by considering different managerial actions through the prism of real options analysis. These strategic options may include, among others, the options to expand, contract, switch or abandon a project, and so forth.

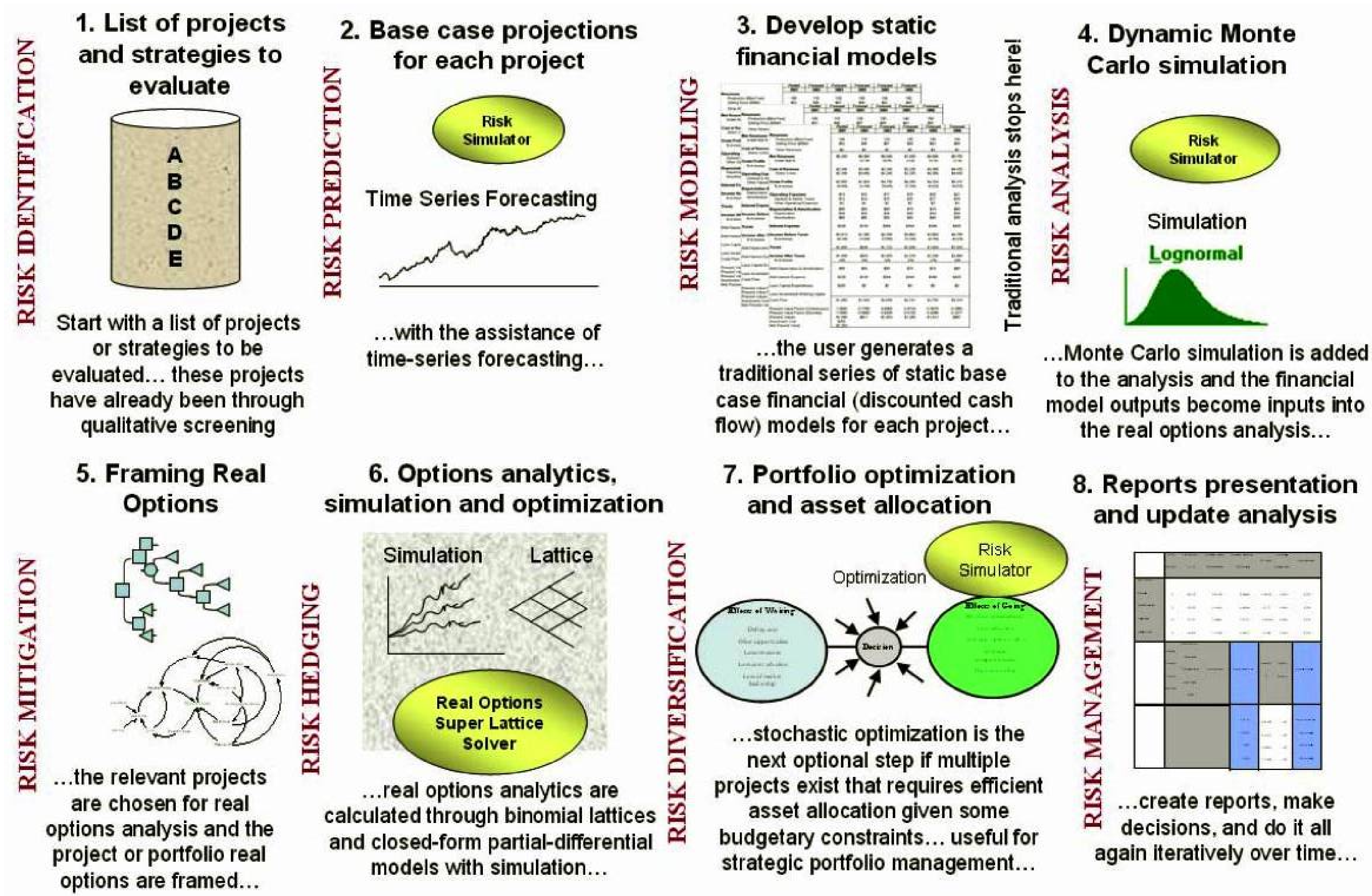

Figure 20. Integrated Risk Analysis Framework *(Source: Mun, 2006)*

6. Real Options Modelling and Analysis

At this stage, the different methods of option pricing are applied in order to obtain an expanded NPV of the project with inclusion of different managerial flexibility options identified at the previous step.

7. Resources Optimisation

This is an optional step in case if several projects are considered under budget constraint. It aims to provide the optimal allocation of investment resources among multiple projects by using portfolio optimisation techniques.

8. Reporting and Update

The final step consists in delivering clear and concise explanations of the results and the procedure how they were obtained to the stakeholders. Considering that the identified uncertainties may be resolved with time, it is also important to revisit the analyses in order to incorporate the decisions made and to update the input assumptions.

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2.5 Real Options Approach

2.5.1 Theoretical Background

In recent years the concept of *real options* has gained particular attention in the economic and business literature dealing with evaluation of long-term investment projects. The origins of term "real options" can be traced back to the work of Myers (1977) who proposed to value corporate assets, and particularly their growth opportunities, as call options. Copeland & Antikarov (2001) emphasised the similarity between real options and traditional financial options and defined real options as the right, but not the obligation, to take an action at a specified cost for a predetermined period of time. Chance & Peterson (2002) describe real options as an approach that applies options-pricing methods to the valuation of capital investments in real assets.

The real options in large investment projects arise due to managerial flexibility, i.e. the possibility to limit the negative effects of an investment while optimising the company's behaviour in order to increase the potential benefits. This flexibility becomes valuable under the conditions of incomplete reversibility (irreversibility) and uncertainty, e.g., if the outcome of an irreversible investment is uncertain, then the possibility to postpone the investment is valuable (Dixit & Pindyck, 1994). The higher the uncertainty about the future and the higher the level of irreversibility of the investment, the more managerial flexibility is worth (Copeland & Keenan, 1998). Value of managerial flexibility is further affected by how much room there is for managerial flexibility.

The basic postulate of the real options theory is that strategic value of an investment extends beyond its value as measured by traditional discounted cash flow (DCF) analysis. So, the strategic net present value (NPV) of a project may be represented as the sum of traditional (static) NPV and additional value identified through option analysis. In fact, a static project valued with a traditional DCF method, without taking in to account the flexibility measures, results in a symmetric risk profile with an expected value, that in some cases can be negative (***Figure 21***). By considering different managerial actions, e.g. the possibility to defer and abandon a low-profile project or to expand a highly profitable project, a company may protect itself against large losses while keeping the chances to increase its profits. Accordingly, in the presence of managerial flexibility the risk profile of an investment project is skewed to the right and the strategic NPV of a project may become positive.

The body of literature on real options has emerged following the seminal book of Dixit & Pindyck (1994) and earlier works of Myers (1977), Margrabe (1978), Cox *et al.* (1979), Geske (1979), Brennan & Schwartz (1985), Carr (1988), etc. More recently, several textbooks on real options theory and its application in different practical domains have been published, e.g. Amram & Kulatilaka (1999), Trigeorgis (2000), Copeland & Antikarov (2001), Brach (2003), Mun (2006) to name a few. In fact, the real options approach relies on the same principles as well-known methods of pricing financial options. Therefore, it is expedient to recall the basic notions and analytical techniques applied in the valuation of options on financial and commodity markets.

In most general terms, an option entitles its holder with a right, but not an obligation, to trade specified quantity of the underlying asset at a fixed price during a certain period of time or on a specific date in the future. A call option provides to its owner the right to buy the underlying asset at a fixed price, called strike or exercise price, prior or exactly on the date of expiration. A put option gives the right to sell the underlying asset again under predefined price and expiration conditions. If the price of the underlying asset is greater than the strike price, the holder of call option will exercise his right, while the holder of put option may choose not to exercise the right and allow the option to expire. If the option is exercised, the net profit from the operation will correspond to the absolute difference between the asset value and strike price multiplied by the quantity of the underlying asset minus the price of buying an option. If the option is left to expire, the owner's losses will be limited to the cost of holding an option.

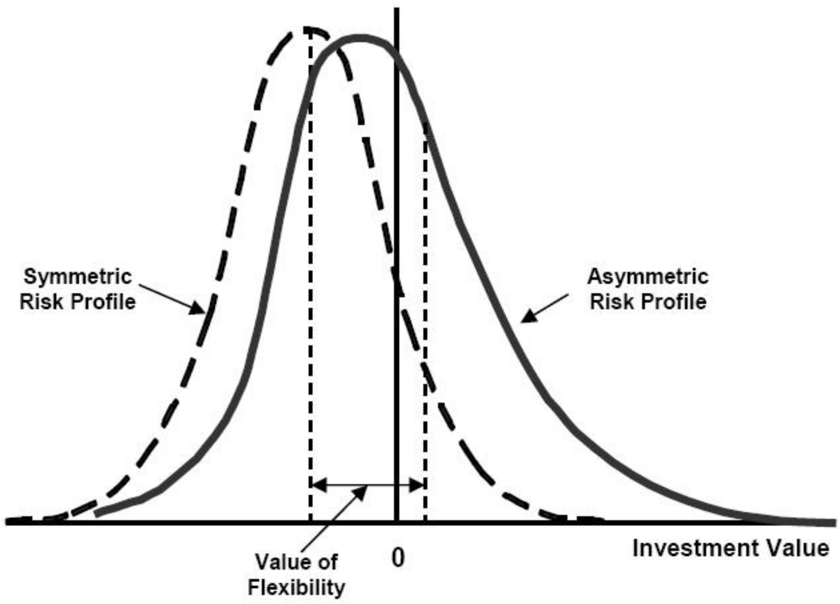

Figure 21. Asymmetric Risk Profile Caused by Managerial Flexibility *(Source: Vollert, 2003)*

Different types of options exist depending on what expiration conditions are being applied. The so-called *American option* can be exercised at any time prior to its expiration, while *European option* can be exercised only at expiration. The American options are more valuable than otherwise similar European options due to possibility of the early exercise. That makes them also more difficult to value (Damodaran, 2005). Besides the widely traded American and European options with standard well-defined properties, also termed as *plain vanilla* products, there exists a whole range of non-standard products, also known as *exotic options*. Hull (2006) distinguished the following types of exotic options: *package* (a portfolio of standard European call and put options plus forward contracts, cash and underlying asset itself); non-standard American options (e.g. *Bermudan* for which early exercise is restricted to certain dates); *forward start options* (e.g. executive stock option which can start at some time in the future); *compound options* (options on options in different combinations - a call on a call, a call on a put, a put on a call, a put on a put); *chooser option* (after a specified period of time, the holder may chose whether the option is a call or a put); *barrier option* (payoff depends on whether the underlying asset price reaches a certain level during a specified period of time); *binary options* (options with discontinuous payoff, e.g. cash-or-nothing, asset-or-nothing); *look-back options* (payoff depends on the maximum or minimum asset price reached during the life of the option); *shout options* (the holder can "shout" to the writer at one time during the life of the option; at the maturity the holder receives either the usual payoff from a European call option or the intrinsic value at the time of the "shout", whichever is greater); *Asian options* (payoff depends on the average price of the underlying asset during at least some part of the life of the option); *exchange options* (options to exchange one asset to another); *rainbow options* (options involving two or more risky assets, e.g. *basket option* where payoff depends on the value of a portfolio of assets) .

2.5.2 Methods of Options Pricing

In Damodaran (2005) the following parameters related to the underlying asset, market conditions and option's characteristics are specified as the main determinants of the option value:

a) <u>Current Value of the Underlying Asset</u>

Increase in the asset value will raise the value of a calls option and, to the contrary, will decrease the value of a put option.

b) <u>Variance in Value of the Underlying Asset</u>

For both call and put options, higher variance in the value of the underlying asset results in a greater value of the option. This is explained by the fact that option holders can never lose more money than they have paid for buying an option; meanwhile, they have a potential to earn significant returns from large price movements.

c) <u>Dividends Paid on the Underlying Asset</u>

The value of a call option is a decreasing function of the size of expected dividend payments, and the value of a put option is an increasing function of expected dividend payments. This is due to the cost of delaying exercise on in-the-money call option: failing to early exercise means that paid out dividends are foregone. To the contrary, the holder of a put option may receive additional value from dividend payments by postponing exercise.

d) <u>Strike Price of Option</u>

The value of a call option declines with the increase of the strike price. In the case of put options, the value will increase as the strike price increases.

e) <u>Time to Expiration</u>

Both call and put options become more valuable as the time to expiration increases, because over longer time horizons the value of the underlying asset may have a higher variance. Additionally, in the case of call, where the buyer has to pay a fixed price at expiration, the present value of this fixed price decreases as the life of the option increases, increasing the value of the call.

f) <u>Risk-free Interest Rate</u>

As the interest rate goes up, the value of call option increases and the value of put option decreases.

The value of any option consists of two parts: intrinsic value and time value. For example, intrinsic value of a call option corresponds to the current market price of the underlying asset net of the exercise price if the current price is larger than exercise price (in-the-money) and zero otherwise (out-of-the-money). The time value represents the difference between the current value of the option and its intrinsic value. The time value is always positive because it reflects the possibility that stochastic movements of the price of the underlying asset may result in a higher intrinsic value at the time of expiration. The typical diagram of a call option value is shown in ***Figure 22***. It is worth noting that the time value decreases with approaching of the expiration date, since the uncertainty about the price of the underlying asset is being resolved, and the option value coincides with its intrinsic value at the time of expiration. It is a very important feature of the real options approach, because traditional DCF methods penalise long-term investment projects with uncertain payoff by choosing relatively high discount rates to account for risk and highly volatile returns.

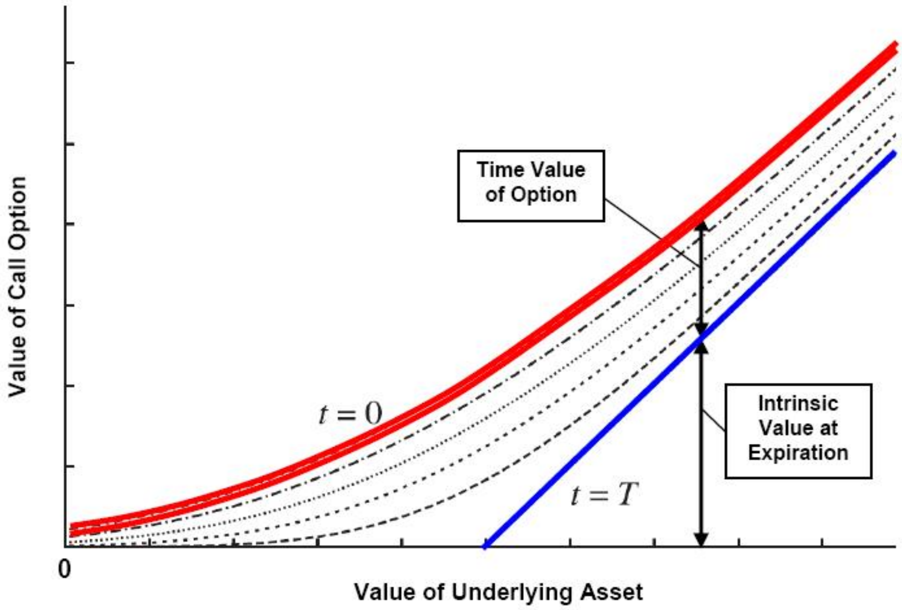

Figure 22. Value of Call Option for Time Range, t = 0 … T *(Source: Newton et al., 2004)*

There exist multiple approaches to calculate the option value ranging from closed-form equations like famous Black-Scholes model and its modifications, Monte-Carlo path dependent simulation methods, lattices (e.g., binomial, trinomial, quadronomial and multinomial lattices), variance reduction and other numerical techniques, to using partial-differential equations and so forth. A general classification of main real option valuation methods is shown in ***Figure 23***. The most widely used methods include closed-form solutions, partial-differential equations and binomial lattices (Mun, 2006).

The basic idea behind most of the option pricing methods consist in constructing a "replicating portfolio", i.e. buying a particular number of shares of the underlying asset and borrowing against them an appropriate amount of money at the risk-free rate, that would provide exactly the same cash flow as the option being valued. Since the option and this equivalent portfolio would generate the same future returns, to avoid risk-free arbitrage profit opportunities they must sell for the same current price. Thus, the value of option can be determined as the cost of constructing this replicating portfolio.

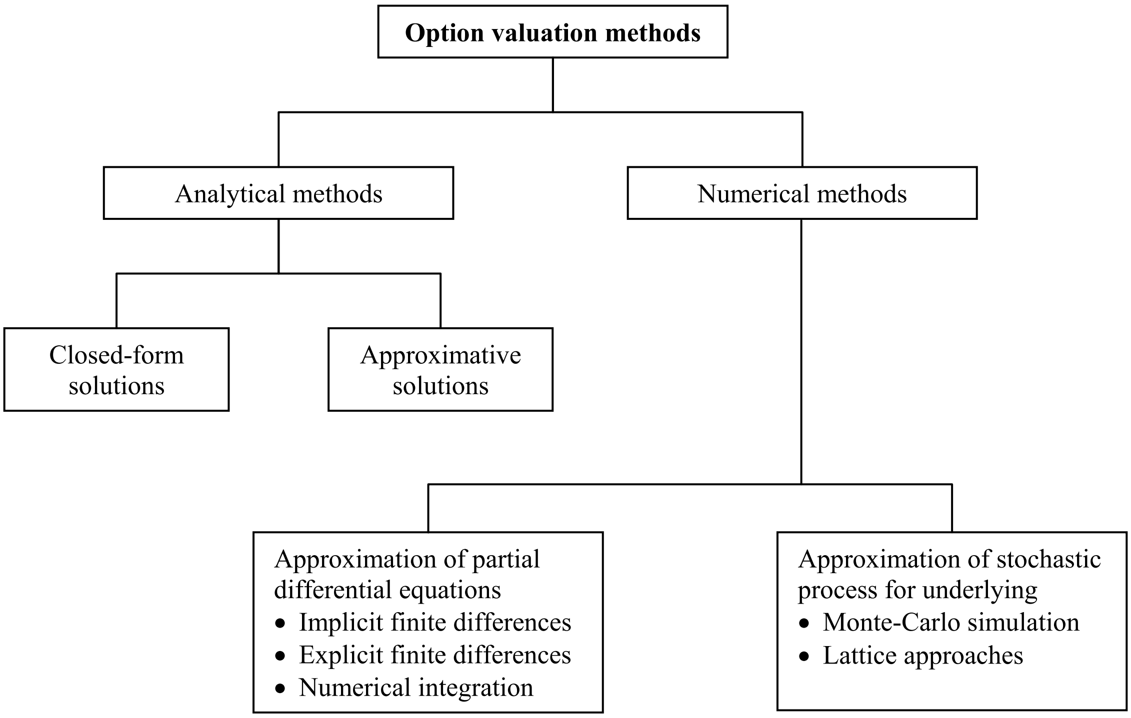

Figure 23. Classification of Real Options Valuation Methods *(Source: Schulmerich., 2005)*

This concept can be illustrated with a simple binomial model where the underlying asset value can move to one of two possible levels reflecting positive (price goes up) and negative (price goes down) trends. Consider a European call option[18] with a strike price of $100, expected to expire in two time periods, on an underlying asset with a current price of $100 which is expected to follow a binomial process (***Figure 24***). The value of option can be calculated with the following formula:

Value of option = current value of the underlying asset * option delta (Δ) –   – borrowing needed to replicate the option payoff (B)

where Δ = number of units (shares) of the underlying asset in replicating portfolio (*hedge ratio*)
B = amount of borrowing in replicating portfolio ($)

In a multi-period binomial process, the valuation has to start from the end nodes and proceed backwards to the current point in time. The replicating portfolios are created and valued at each step.

[18] This illustrative example is adapted from Mauboussin (1999) and Damodaran (2005).

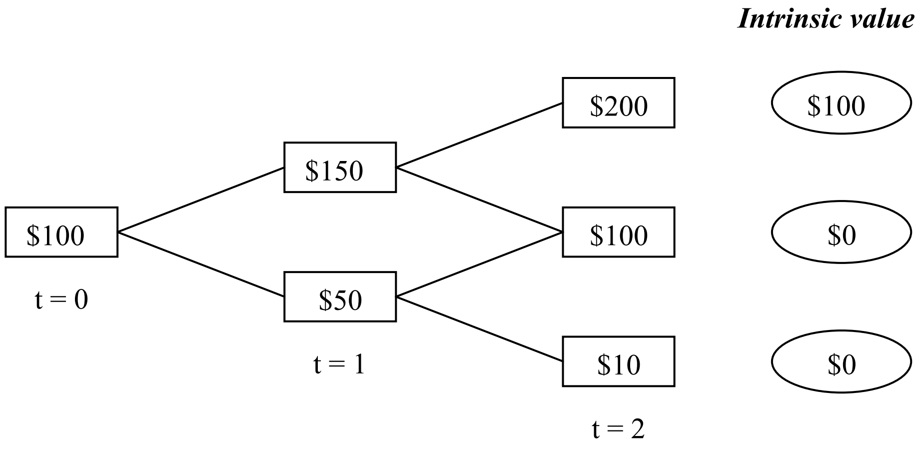

Figure 24. Call Option Valuation with a Binomial Model

Assuming a 5% risk-free interest rate we obtain:

- **End node (upward trend)**

$$\left.\begin{array}{l}(\$200 * \Delta) - (1.05 * B) = \$100 \\ (\$100 * \Delta) - (1.05 * B) = \$0\end{array}\right\} \quad \begin{array}{l}\Delta = 1 \\ B = \$\ 95.2\end{array}$$

Value of call option = ($150 * 1) - $95.2 = $54.2

- **End node (downward trend)**

$$\left.\begin{array}{l}(\$100 * \Delta) - (1.05 * B) = \$0 \\ (\$10 * \Delta) - (1.05 * B) = \$0\end{array}\right\} \quad \begin{array}{l}\Delta = 0 \\ B = \$\ 0\end{array}$$

Value of call option = ($50 * 0) - $0 = $0

- **Starting node**

$$\left.\begin{array}{l}(\$150 * \Delta) - (1.05 * B) = \$54.2 \\ (\$50 * \Delta) - (1.05 * B) = \$0\end{array}\right\} \quad \begin{array}{l}\Delta = 0.54 \\ B = \$\ 25.7\end{array}$$

Value of call option = ($100 * 0.54) - $25.7 = **$28.3**

In other words, borrowing $25.7 and buying 0.54 of a share of the underlying asset will provide the same cash-flow as a call option with a strike price of $100, and the value of this option has to be identical to the value of this position ($28.3).

The same replicating portfolio logic underlies the notorious Black-Scholes option pricing formula developed in the early 1970s in the Nobel prise winning works of Black & Scholes (1973) and Merton (1973). While the discrete time binomial model, described above, provides an intuitive way to determine the option value, it also requires a large number of inputs, e.g. the expected future prices at each node. The Black-Scholes formula is not an alternative to binomial model, but rather it is a limiting case which assumes that the time intervals are shortened approaching to zero and the price process becomes a continuous one with the normal distribution.

The Black-Scholes model belongs to the family of analytical closed-form solutions. It is easier to implement, because it requires only five inputs and one equation to compute the option value. It can be applied for valuation of standard European-type call and put options and with some extensions to calculating the value of more complex options allowing for dividends payments, early exercise etc. The Black-Scholes formulas for the prices at time t_0 of a European call (***c***) and put (***p***) options on a non-divided-paying stock are as follows (see Hall, 1997) :

$$c = S_0 N(d_1) - Ke^{-rT} N(d_2) \tag{2.5.1}$$

$$p = Ke^{-rT} N(-d_2) - S_0 N(-d_1) \tag{2.5.2}$$

where

$$d_1 = \frac{\ln\left(\frac{S_0}{K}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \tag{2.5.3}$$

$$d_2 = \frac{\ln\left(\frac{S_0}{K}\right) + \left(r - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{T} \tag{2.5.4}$$

The function $N(d_i)$ is the cumulative probability distribution function for standardized normal distribution. In other words, it is the probability that a variable with a standard normal distribution will be less than d_i . S_0 is the stock price at time t_0 , K is the strike price, r is the continuously compounded risk-free rate, σ is stock price volatility, and T is the time to maturity of the option. The value of the call option obtained with the help of Black-Scholes formula can be interpreted in terms of hedging portfolio as equivalent to a levered position in the stock where the number of the shares of the stock in the replicating portfolio (option delta) is given by $N(d_i)$ and the amount of borrowing is given by the second term, i.e. $B = Ke^{-rT}N(d_2)$. The Black-Scholes solution for European put option, given above, can be readily obtained from the put-call parity relationship (see Trigeorgis, 2000).

The major breakthrough made in the works of Black, Scholes and Merton and acknowledged by the Nobel Prize committee consists in the demonstration of the fact that it is not necessary to use any risk premium when valuing an option (KVA, 1997). This does not mean that the risk premium disappears; instead it is already included in the stock price. Accordingly it is possible to obtain a correct value of the option from its expected future values (using risk-neutral probability) discounted at the risk-free rate (Trigeorgis, 2000).

2.5.3 Taxonomy of Real Options

In order to properly estimate the real options value of the investment projects it is important to specify the flexibility options that may occur in real life situations and to analyse their implication for managerial practice. Looking from management perspective Vollert (2003) proposed the following classification: (1) *strategic real options* – understood as the flexibility to create and exploit future business opportunities; (2) *operational real options* – related to managerial flexibility in already undertaken investment projects; and (3) *financial real options* – flexibility in structuring company's capital. ***Table 10*** summarises the main types of real options most often cited in the dedicated literature (e.g., Dixit & Pindyck, 1994; Trigeorgis, 1998; Copeland & Antikarov, 2001; Brach, 2003).

Table 10. Common Types of Real Options

Category	***Option Type***	***Description***
Strategic	Option to defer investment (*American call option*)	If potential revenues of the project (e.g. future market price) are highly uncertain there is an option to delay the investment until the time when it becomes more profitable
	Growth option (*Compound option*)	Early investment in a smaller project (e.g. R&D, Joint Venture, purchase of licence, etc.) may open up opportunities for implementing further investment projects and capitalising on their results
	Staged investment option (*Compound option*)	Breaking up investment into incremental conditional steps creates opportunity to freeze or abandon the project in midstream if market conditions are unfavourable
	Abandonment option (*American put option*)	If the project has an unsatisfactory financial performance (e.g. due to deteriorating market conditions), there is an option to stop the use of this asset and to collect its liquidation value
Operational	Option to adjust production (*American call and put options*)	Subject to market conditions a company may have a possibility to choose the scale of production (options to expand or contract), the scope of activities (options to increase / decrease scope, to shut down and restart), the lifetime (options to extend or shorten)
	Option to switch (*portfolio of American call and put options*)	Depending on the market conditions (prices and demand) company may change its output mix (product flexibility), or alternatively the same output can be produced using different inputs (process flexibility)
Financial	Option to change capital structure (*American call and put options*)	During the course of a project, the company may issue new stocks, repurchase outstanding stocks, increase debt financing, change the debt maturity, or default on debt payments

It should be noted that most real-life investment projects often involve a collection of various options. These options can be also driven by multiple sources of uncertainty. The combined value of options may differ from the sum of their separate values, i.e. they interact (Trigeorgis, 2000). Accordingly, the real options in such multifaceted projects should be evaluated as *compound rainbow options* (Copeland & Antikarov, 2001).

2.5.4 Real R&D Options

The evaluation of R&D investments is one of the areas where real options approach could in principle provide the most tangible results. Any R&D activity is inherently characterised by rather substantial lead-time and the uncertainty about the final outcome. Furthermore, a company may capitalise on its R&D works only if additional investments are made in order to start the production. Generally speaking, it is the uncertainty about the future returns and the possibility to actively manage the product commercialisation (e.g. to postpone if market conditions are unfavourable) that gives value to real R&D option.

Vonortas & Desai (2007) identified the following analogies between undertaking a R&D project and buying a stock option:

(i) The cost of the initial R&D project is analogous to the price of a financial call option.

(ii) The cost of the follow-up investment needed to capitalize on the results of the initial R&D project is analogous to the exercise price of a financial call option.

(iii) The stream of returns to this follow-up investment is analogous to the value of the underlying stock for a financial call option.

(iv) The downside risk of the initial R&D investment is that the invested resources will be lost if, for whatever reason, the follow-up investment is not made. This is analogous to the downside risk of a financial call option which, in case that the option is not exercised, will be the price of the option.

(v) Increased volatility (uncertainty) decreases the value of an investment for risk-averse investors. It, consequently, increases the value of an option to this investment. Similarly, increased uncertainty (for the whole required R&D investment) raises the value of an initial R&D project if it is considered an option to a potentially valuable technology.

(vi) A longer time framework decreases the present discounted value of an investment. It, consequently, increases the value of an option to that investment. Similarly, time length may well increase the value of an initial R&D project if it is considered an option to longer-term, high-opportunity investments.

Schneider *et al.* (2008) proposed a generic valuation framework for the appraisal of R&D projects based on real option theory (***Figure 25***). Their model represents the structure of the real world R&D project with its investments, expected results and decisions that need to be taken conditionally on the outcomes of research activities. By creating multidimensional trees, they calculate the real option value of starting an R&D project, i.e., the value of undertaking the first investment and thus acquiring the subsequent decision opportunities given by the completion of the first research effort. Furthermore, they derive the optimal exercise strategy that gives the manager the possibility to have an a priori overview of where an R&D project may lead to, which decisions need to be taken in which circumstances, and when the project needs to be stopped in order not to generate losses.

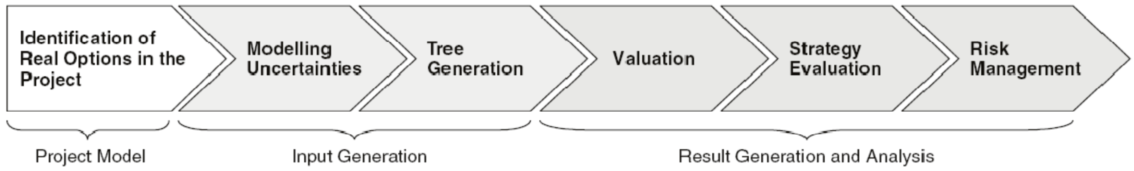

Figure 25. General Procedure for Real Option Valuation of R&D Projects
(Source: Schneider et al., 2008)

Huchzermeier & Loch (2001) analysed in more details different sources of uncertainty in the evaluation of R&D projects, namely market payoffs, project budgets, product performance, market requirements and project schedules. In addition to the traditional option to abandon they introduced the option for corrective action that management can take during the project. They demonstrated that there is an option value of additional information. So, the managers should be willing to pay for flexibility after new information becomes available and before major costs or revenues occur, if the probability of that flexibility being exercised is significant. Their analyses also confirm that “improvement” represents an extra source of option value, in addition to continuation, abandonment, expansion, contraction, or switching.

Childs & Triantis (1999) examined dynamic R&D investment policies and the valuation of R&D programmes in a contingent claims framework. They incorporated the following characteristics of R&D programmes into their model: learning-by-doing, collateral learning between different projects in the programme, interaction between project cash flows, periodic re-evaluations of the programme, different intensities of investment, capital rationing constraints and competition. They showed that a firm may invest in multiple projects even if only one can be implemented after development is complete. Furthermore, the firm may significantly alter its funding policy over time. For example, it may simultaneously develop multiple projects for a period of time, then focus on a lead project, and potentially resume funding of a "backup" project if the lead project fails to deliver on its early promise. In considering whether to accelerate development of a project, a firm should balance the adverse effects of increased costs and the loss of investment flexibility against the positive effects of rapid uncertainty resolution and accelerated cash flows. In the presence of a budget constraint that prevents the firm from simultaneously accelerating projects and developing projects in parallel. They found that, if one project significantly dominates another early in the development stage, the option to accelerate the lead project is likely to be more valuable than the option to exchange projects.

Ran *et al.* (2004) applied fuzzy sets theory to evaluate compound option in a R&D project. They argue that fuzzy form of the inputs and outputs of the model describes in a better way the actual situation faced by R&D intensive firms. Wang & Hwang (2007) developed a fuzzy real options valuation model for R&D portfolio selection that can handle both uncertain and flexible parameters to determine the optimal project portfolio. A more general discussion on the application of fuzzy set approach to real option valuation is given in Carlsson et Fuller (2003). They 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. They determined further the optimal exercise time for investment option with the help of possibilistic mean value and variance of fuzzy numbers.

2.5.5 Real Options Valuation of Energy R&D Projects

Some of the papers in real options literature deal specifically with 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.

Siddiqui *et al.* (2005) proposed a binomial lattice compound real options model for evaluating 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 RDDD process; and the possibility for adjustment of RDDD 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 RDDD effort. The option value of RDDD 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 based on data for the Turkish electricity supply industry 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 technologies in the longer run.

Finally, some authors advocated the use of real options approach in the evaluation of Fusion RDDD programme as well. The doctoral thesis of Ott (1992) proposes 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 papers 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.

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3. LONG-TERM ELECTRICITY SUPPLY SCENARIOS WITH FUSION

This chapter examines the global potential for deployment of Fusion power through elaboration of multi-regional long-term electricity market scenarios for the time horizon 2100. The probabilistic simulation dynamic programming model PLANELEC-Pro was applied in order to determine the expansion plans of the power generation systems in different world regions that adequately meet the projected electricity demand at minimum cost given the quality-of-service and CO_2 emissions constraints. It was found that under reasonable assumptions the total Fusion power generation capacity by 2100 could reach 330 GWe in moderate "Fusion Introduction" scenario and 950 GWe in a more optimistic "Massive Deployment" scenario, with Fusion share in regional electricity supply mixes in optimistic scenario varying from 1.5 to 23% depending on the region. This amount of Fusion power could allow for reducing global CO_2 emissions from electricity generation by 1.8 - 4.3 % while entailing a slight increase of the levelized system electricity cost.

3.1 Introduction

Estimating direct economic benefits of Fusion power generation requires in-depth prospective analysis of global energy systems for the period extending beyond 2050 as well as explicit techno-economic assessment of main electricity supply options with which Fusion technology will have to compete on the market. Considering a very long time span of such analysis and the range of uncertainties affecting most of the underlying factors, it is practically impossible to make a single reliable forecast for the period of fifty to one hundred years. Hence, most of the existing studies advocate the scenarios approach which allows to perform the analysis on "if…then…" basis as it was discussed in Chapter 2.4.

During the last decades several renowned studies investigated the possible development paths of global energy systems in the context of international policy debate on the issue of greenhouse gas emissions and climate change. The scenario storylines and numerical projections developed in such studies as IIASA / WEC "Global Energy Perspectives" (Nakicenovic *et al.*, 1998), IPCC "Special Report on Emissions Scenarios" (Nakicenovic & Swart, 2000) constitute a sound basis for further analyses. However, thermonuclear Fusion as potential electricity supply option was practically neglected in these works. Therefore, it is important to complement the existing scenario studies with a numerical assessment of the potential role of Fusion power in future electricity systems of different world regions.

The main objective pursued in this section of the dissertation consists in building a set of long-term multi-regional energy scenarios consistent with the findings of internationally renowned studies, estimating the possible market share of Fusion in future electricity supply mixes and evaluating its advantages and possible drawbacks. More specifically, the regional power generation systems are analyzed from economic and environmental points of view subject to a varying share of Fusion power and competing base-load electricity supply options represented by advanced nuclear fission reactors, combined cycle natural gas and advanced coal-fired power plants, including those with CO_2 capture & sequestration functionality.

The following world regions[19] were considered: North America (NAM); Latin America and the Caribbean (LAM); Sub-Saharan Africa (AFR); Middle East and North Africa (MEA); Western Europe (WEU); Central and Eastern Europe (CEE); Russia and other CIS countries (CIS); China and other Centrally Planned Asia, (CPA); South Asia (SAS); Pacific OECD (PAO); and Other Pacific Asia (PAS). The exhaustive list of countries and their regional groupings is given in "Appendix A" at the end of this chapter.

3.2 Methodology

Projection of future development paths of global energy systems requires elaboration of a robust analytical framework that could allow for analysing multiple socio-economic and technical phenomena in their interaction. The typical approach consists in merging within one integrated assessment framework (***Figure 26***) a global general equilibrium model, which can provide a general pattern of main socio-economic development trends, and a technology explicit bottom-up engineering-economic model emphasised on energy sector. Some additional inputs from energy end-use models and prospective studies are normally used to complement the picture.

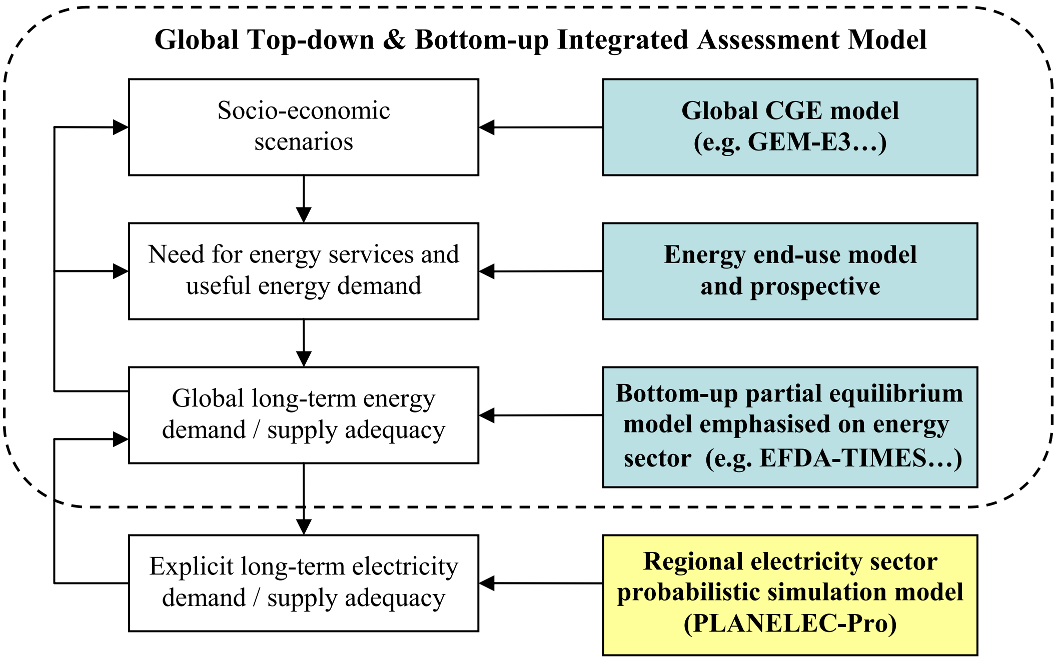

Figure 26. Analytical Framework for Projection and Analysis of Long-term Energy Scenarios

Present study aims to expand this analytical framework by performing explicit analysis of the regional power generation systems. Basing on the comprehensive statistics of installed power

[19] The regional groupings adopted here slightly differ from the region definition in IIASA/WEC study (Nakicenovic *et al.*, 1998). So, Estonia, Latvia and Lithuania are included in the CEE region, while in IIASA/WEC study they belong to the FSU region; the Republic of Korea is included in the "Pacific OECD" region, while it belongs to "Other Pacific Asia" in IIASA/WEC study.

generation capacities and a consistent set of regional energy demand / supply scenarios, the electricity sector expansion planning model PLANELEC-Pro allows in this extended framework for estimating prospective market shares of each specific technology, while taking into account the operational modes of the whole electricity generation system.

The model applied in the study is PLANELEC-Pro, which is a least cost probabilistic simulation and dynamic programming model (Gnansounou & Rodriguez, 1998; Gnansounou, 2003). Given the assumptions about electrical load, technology performance, fuel prices, electricity supply quality constraints (loss-of-load probability; reserve margin) and CO_2 penalty or emission cap, the candidate technology options are selected by the model to satisfy the projected electricity demand together with the existing power plants. The objective function to be minimized is the total discounted cost of the power generation system including investment, operating and maintenance, fuel costs and the cost of unserved energy. The outputs of the model are optimal expansion plans concerning the number, the time and the type of power plants to be installed, total discounted cost of the expansion plan, levelised system electricity cost, CO_2 emissions of each year, etc. The overall structure of PLANELEC-Pro model is shown in ***Figure 27***.

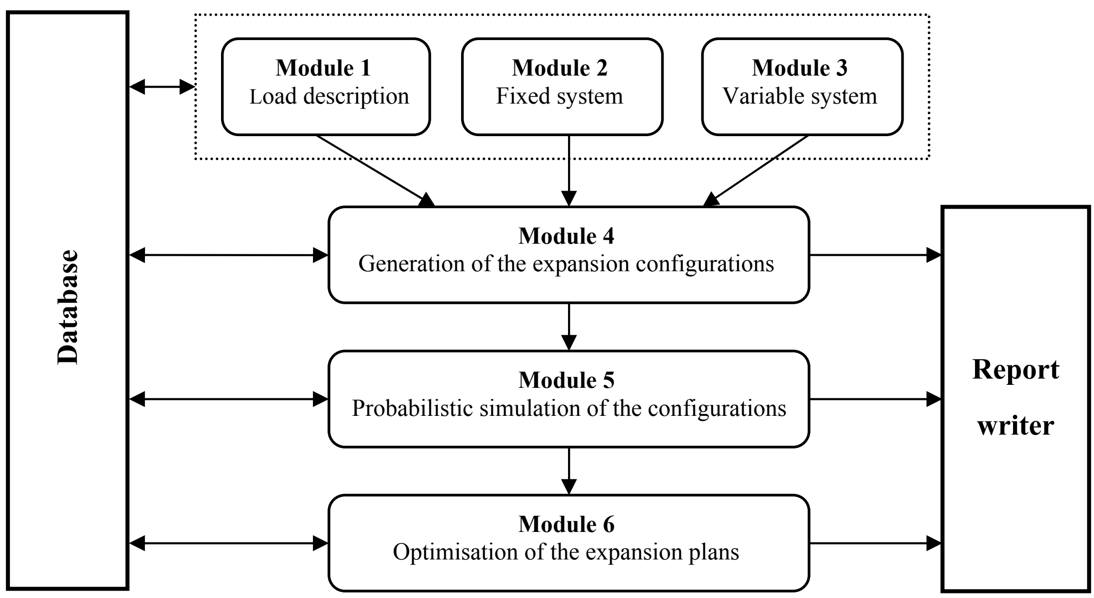

Figure 27. Structure of the PLANELEC-Pro model

The methodological approach is based on the probabilistic simulation of selected expansion plans of the existing power generation systems in different world regions. The study includes the following core elements:

- General assessment of the existing electricity technology mixes and prospective technical and economical evaluation of future power generation technologies;
- Elaboration of long term electricity demand and supply scenarios worldwide;
- Computation of possible expansion configurations of the existing electricity systems with additions of the power plants of prospective technologies;

- Economical & environmental (in terms of CO_2 emission reduction) evaluation of selected expansion plans.

An overview of the methodology is given in flowchart (***Figure 28***) stating its main logical components and analysis sequence.

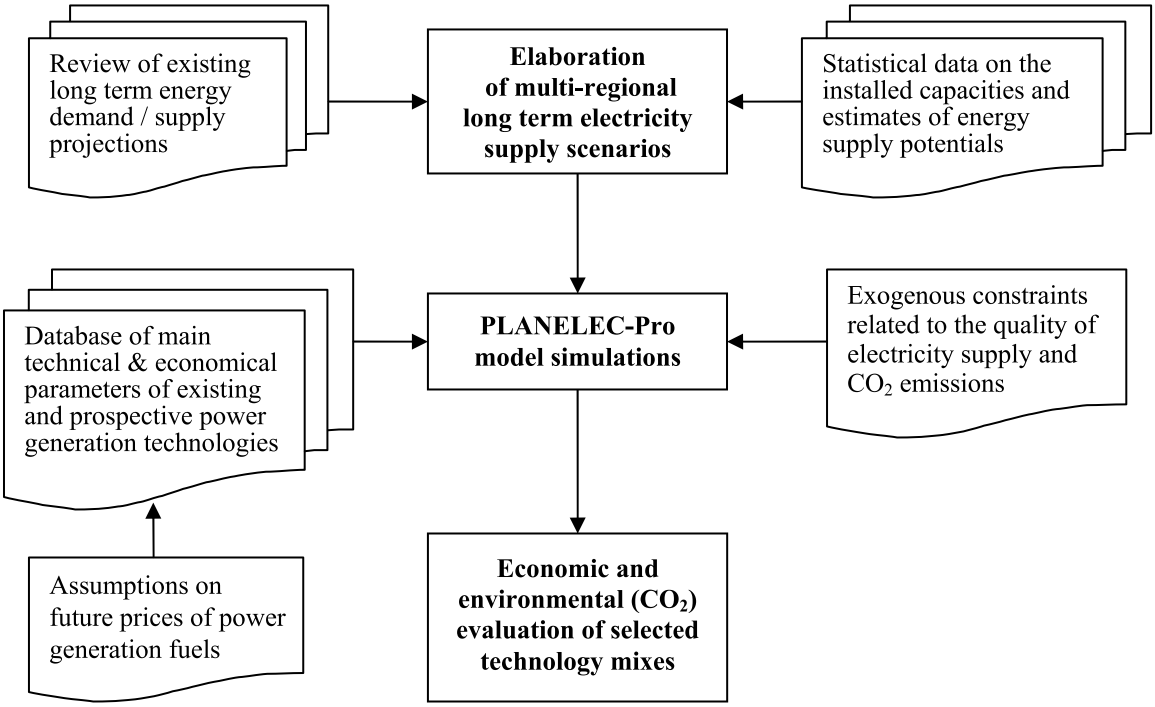

Figure 28. Methodology of Long-term Electricity Supply Scenarios Study with PLANELEC-Pro Model

First and foremost, the proposed methodology required elaboration of credible scenarios of future energy markets until 2100 – the time horizon of the study. For that purpose, the dominant trends and key determinant factors of global energy systems development in the past had to be identified and their extrapolation in the future had to be made. Such analysis was carried out through an extensive review of available datasets describing the existing power generation systems in different world regions (e.g. IEA annual publications "Electricity Information" and "World Energy Outlook", US DoE / EIA publication "International Energy Annual"), the scenario projections of internationally renowned studies (e.g. IIASA/WEC "Global Energy Perspectives", various modelling studies implemented within the framework of IPCC "Special Report on Emission Scenarios"), as well as on the basis of expert judgements.

Once the scenarios of future energy consumption and corresponding electricity demand were made and given the assumptions regarding technological development patterns as well as the availability and prices of main power generation fuels, the least cost expansion planning model PLANELEC-Pro allowed for determining the electricity supply mixes that could meet the projected demand under fuel resource and quality of service constraints. The scenario presuming maximum share of coal-based power generation (without CO_2 capture) was chosen as baseline for making the reference CO_2 emissions projection and estimating the benchmark system expansion cost. The alternative scenarios assume substitution of the fixed amount of coal-fired power plants by an equivalent capacity of Fusion, advanced nuclear fission and coal with CO_2 capture & sequestration technologies.

The time frame of the study (2000-2100) was divided into five 20-years periods. The “reference” case of system expansion without Fusion and its different variants were simulated with PLANELEC-Pro model for each period and each region. The results of simulations were compared with those of the reference case. The main model outputs further analyzed in the study are total discounted cost of the power generation system, levelized system electricity cost and annual CO_2 emissions. Based on the simulation of different scenarios two additional indicators were derived such as total CO_2 emissions reduction throughout the study period and incremental CO_2 abatement cost.

3.3 Input Assumptions and Projections

3.3.1 Regional Electricity Demand

The starting point in the formulation of multi-regional long-term electricity supply scenarios consisted in in-depth review of internationally renowned studies such as IIASA / WEC “Global Energy Perspectives” (Nakicenovic *et al.*, 1998) and various modelling works implemented within the framework of IPCC “Special Report on Emissions Scenarios” (Nakicenovic & Swart, 2000) with the objective to determine some reasonable estimates of the future electricity demand for each world region. All these studies develop their own sets of scenarios, which differentiate essentially on the underlying assumptions regarding population, economic growth, availability of primary energy resources, technology development patterns and other factors. As a result, the future levels of energy consumption and electricity generation significantly differ across various studies and scenarios.

The IIASA / WEC study describes three alternative cases that diverge into six scenarios of future economic development and energy consumption trends, and quantifies their implications for 11 world regions. Case “A” is characterised by remarkable technological improvements which entail rapid economic growth resulting in a highest energy demand. Case “B” is considered as less ambitious, though perhaps more realistic, with a moderate pace of technology improvements, and consequently slower economic growth and lower energy consumption. Case “C” corresponds to the projection of an ecologically driven future. It allows for significant technological progress, especially as concerns non-fossil energy technologies, and favours extensive international cooperation centred on environmental protection and equitable economic growth. The projected energy consumption in case “C” is the lowest one among all scenarios. The projections of world final energy consumption for all alternative cases and scenarios are shown in ***Figure 29***.

The IPCC “Special Report on Emission Scenarios” (SRES) has a larger number of scenarios and, hence, a broader range of energy demand projections, because several models developed by different research institutions were applied. The SRES scenarios are built on the basis of four general storylines, which can be characterised by the following excerpt from Nakicenovic & Swart (2000):

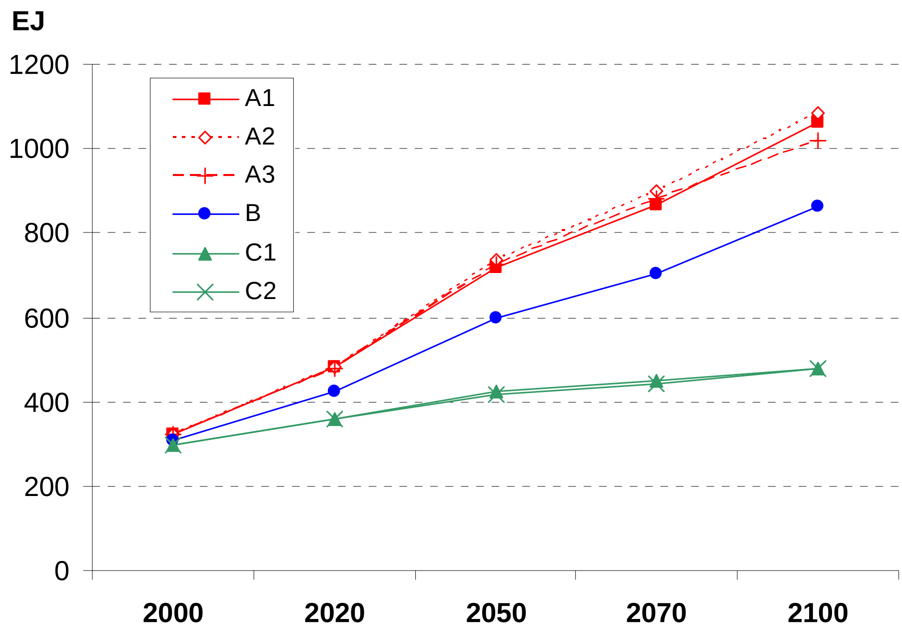

Figure 29. World Final Energy Consumption in IIASA / WEC Study "Global Energy Perspectives"

(Source: Nakicenovic et al., 1998)

- *The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.*

- *The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.*

- *The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.*

- *The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 and A1 storylines.*

The possible evolution of world final energy consumption according to different scenarios as projected by the models applied in SRES studies is shown in ***Figure 30***. It was observed that IIASA / WEC projections fall into the range of SRES estimates, and the IIASA / WEC case "B" scenario of future energy consumption is relatively close to SRES "B2" storyline scenarios.

Therefore, the projection of final energy demand of IIASA / WEC middle-course scenario "B" was chosen in this study as the baseline for further elaboration of long-term multi-regional electricity demand and supply scenarios.

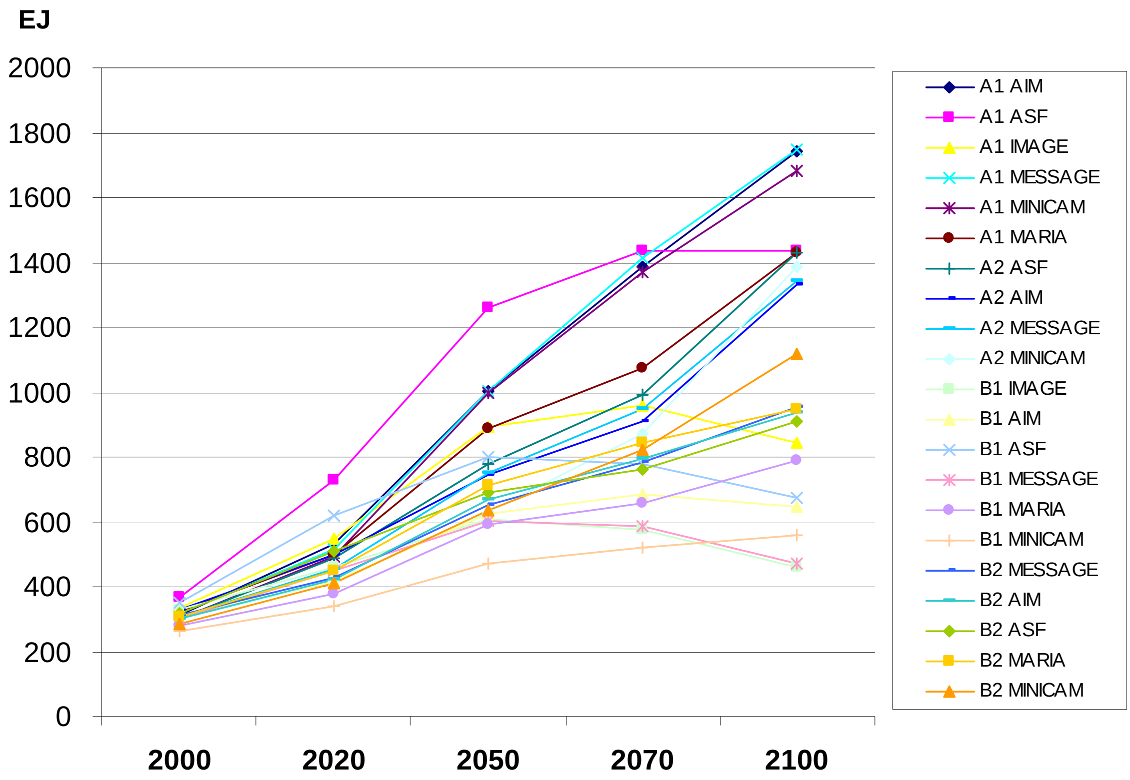

Figure 30. World Final Energy Consumption in IPCC SRES Studies

(Source: Nakicenovic & Swart, 2000)

Next, the existing regional scenarios of future final energy and electricity consumption were analysed. Considering that electricity consumption represents a portion of the total final energy consumption, the total demand for electricity could be estimated as the sum of electricity production needed to satisfy the end-use demand and the additional production to meet specific requirements of the electricity system, including the own use of power plants, electricity use by heat pumps, electric boilers and pumping storage, as well as the transmission and distribution network losses.

According to the IIASA/WEC scenario "B", the total final energy consumption in the industrialised countries increases moderately in the first half of the century, and then it is expected to steadily go down. In Central & Eastern European countries and Former Soviet Union, the final energy consumption is projected to rise until the time horizon 2070, and then it may slightly decrease. The greatest increase in final energy consumption with an impressive pace is supposed to occur in developing Asian and African countries. Moreover, it is expected that by the end of century the final energy consumption in these developing countries will be more than three times higher compared to the industrialised OECD and Former Soviet Union countries.

The share of electricity in world total final energy consumption in IIASA / WEC scenario “B” is expected to increase from actual 13.3% up to 16.2% in 2050 and up to 24.2% in 2100. Meanwhile, there is a significant deviation from world average figures across the regional data. As it is specified in ***Table 11***, the industrialised countries actually record higher values of electricity share in final energy consumption than developing and transitional economy countries. The prospects for the end of century indicate that this difference is likely to remain. This fact can be explained by a remarkable increase of the electricity share in final energy consumption in industrialised countries (up to 45%), while the countries of MEA, AFR and CPA regions are expected to stay considerably below the average values.

Table 11. Electricity Share (%) in Total Final Energy Consumption (IIASA / WEC – Scenario “B“)

	2000	**2020**	**2050**	**2070**	**2100**
North America	*18.4*	*23.8*	*30.7*	*36.0*	*45.6*
Latin America & Caribbean	*9.2*	*9.1*	*11.1*	*13.8*	*24.9*
Western Europe	*19.0*	*24.2*	*33.5*	*38.1*	*45.8*
Central & Eastern Europe	*13.3*	*14.8*	*17.2*	*20.4*	*28.5*
Former Soviet Union	*12.3*	*12.2*	*14.0*	*16.5*	*24.3*
Middle East & North Africa	*7.5*	*7.9*	*8.7*	*10.6*	*17.3*
Sub-Saharan Africa	*9.4*	*7.9*	*10.3*	*12.1*	*17.4*
South Asia	*6.3*	*7.6*	*10.8*	*15.9*	*23.1*
Pacific OECD	*22.2*	*25.8*	*33.2*	*36.9*	*39.0*
Centrally Planned Asia	*7.2*	*7.2*	*9.6*	*12.5*	*17.7*
Other Pacific Asia	*8.7*	*10.2*	*14.4*	*19.8*	*28.4*
World average	***13.3***	***14.3***	***16.2***	***18.5***	***24.2***

Source: Nakicenovic *et al.* (1998)

Based on the estimations of final energy consumption in global / regional perspective and the projected share of electricity in total regional energy consumption, the evolution of regional electricity demand was assessed for the whole study period up to 2100. In near-term perspective (up to 2030) the projections relied mainly on the available statistics of electricity sector such as IEA “Electricity Information” yearbook (IEA, 2005a) and the prospective data from IEA “World Energy Outlook” (IEA, 2004), US DoE / EIA “International Energy Outlook” (EIA, 2006a) and EURPROG (Eurelectric, 2006) publications. The assumptions of scenario “B” developed in IIASA / WEC study were used for the period 2030 - 2100. The resulting estimates of future electricity demand for each world region are shown in ***Figure 31***. The regional electricity demand projections supplemented with additional assumptions regarding system load factors and load duration curves were further used for estimating maximum and minimum load to be assured by the regional electricity systems[20].

[20] Detailed assumptions can be found in LASEN-EPFL report for EFDA-SERF programme (see Gnansounou & Bednyagin, 2006)

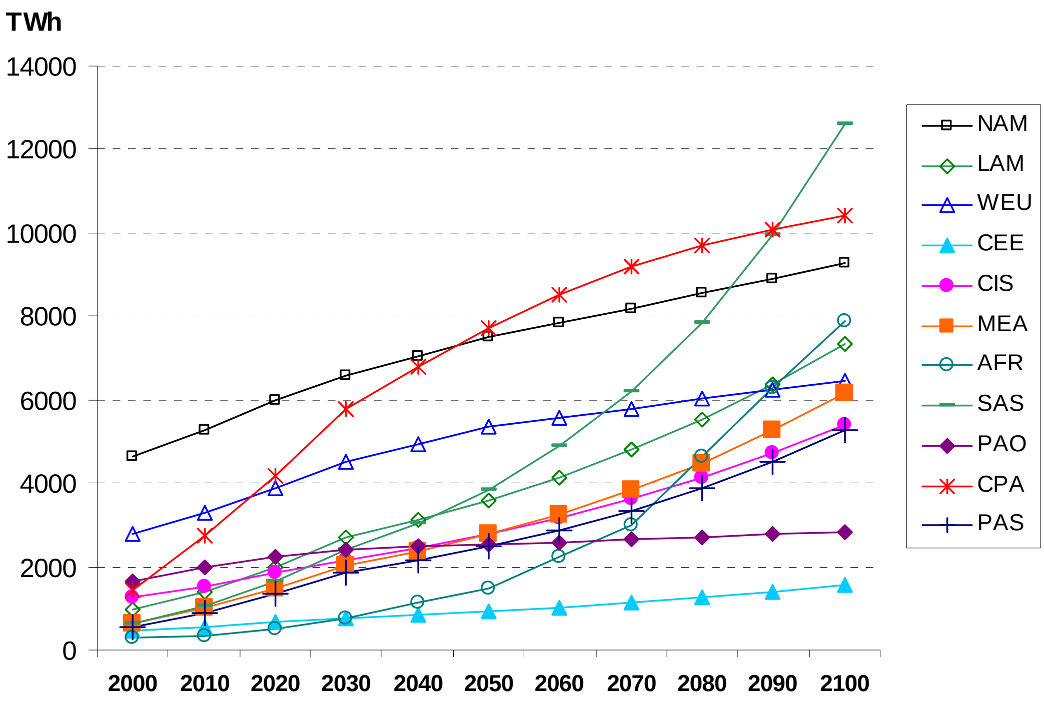

Figure 31. Evolution of Regional Electricity Demand *(source: author's calculation)*

3.3.2 Current Structure of Electricity Generation and Near-term Prospects

Because of the considerable life time of most types of power generating facilities, extending over several decades, and a relatively slow pace of technological change in the domain of energy infrastructures, an in-depth review of the installed electricity generation capacities, the capacities committed to be built and the analysis of the current electricity generation structure constituted an important step in the elaboration of long-term electricity supply scenarios.

The regional structure of installed power generating capacities and net electricity production in 2000 was assessed basing on US DoE / EIA "International Energy Annual" data (EIA, 2005). The regional statistics of gross and net electricity production was taken also from IEA "Electricity Information" publication (IEA, 2005a) which provided additional data regarding the structure of thermal power generation (in repartition by main type of primary energy fuels: hard coal, brown coal, natural gas, oil) and electricity production from renewable sources (geo-thermal, solar, wind, biomass & wastes). The historical data on the installed power generation capacities were available only for OECD countries (NAM, WEU, PAO regions). For other world regions some approximations had to be made in order to build a consistent database of the existing capacities which was further used for simulations with PLANELEC model.

In Western Europe the present structure of installed power generating capacities by fuel and technology type and its near-term development prospects (up to 2020) were analysed basing on "EURPROG" report (Eurelectric, 2006). ***Figure 32*** represents the projected technological structure of electricity generating capacities in WEU region for the period 2000 - 2020. It clearly shows the growing importance in electricity mix of the power plants based on natural gas combined cycle and renewable energy technologies, while the relative shares of oil-fired, coal-fired and nuclear power plants are projected to decline over twenty years period.

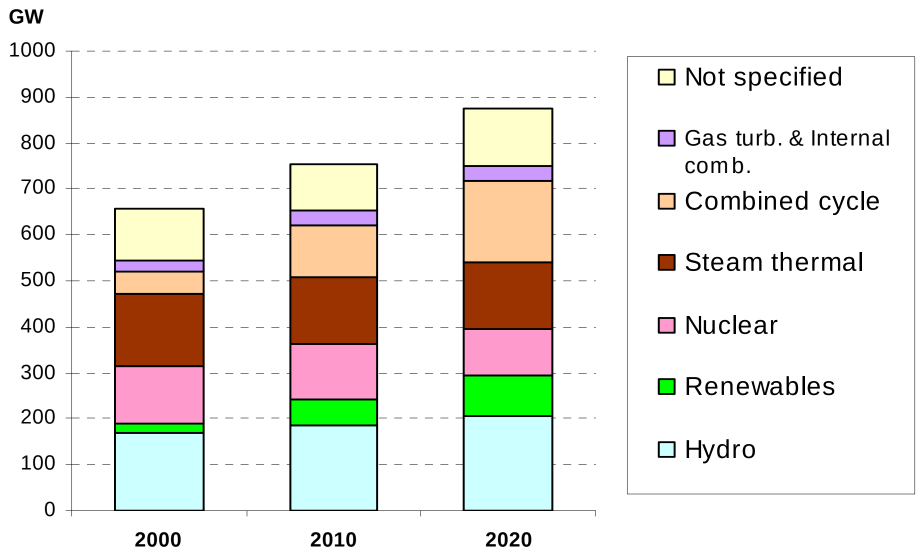

Figure 32. Projected Structure of Electricity Generating Capacities in Western Europe

(Source: Eurelectric, 2006)

The near term projection (up to 2030) of the evolution of power generation system in USA was taken from DoE / EIA publication "Annual Energy Outlook" (EIA, 2006b). ***Figure 33*** represents the structure of electricity generating capacities in repartition by main technology types for the period 2005 – 2030 in "Reference case". Contrary to the situation in Western Europe, the share and total capacity of coal-fired power generation are expected to increase in USA over 25-years period, while the capacity of nuclear power plants is expected to remain relatively stable, the share and capacity of conventional thermal oil and natural gas – fired power generation are projected to decline and the capacity of combined cycle power plants is expected to grow. The increase in total capacity of power generating technologies using renewable energy sources is projected to be much more moderate than in WEU region.

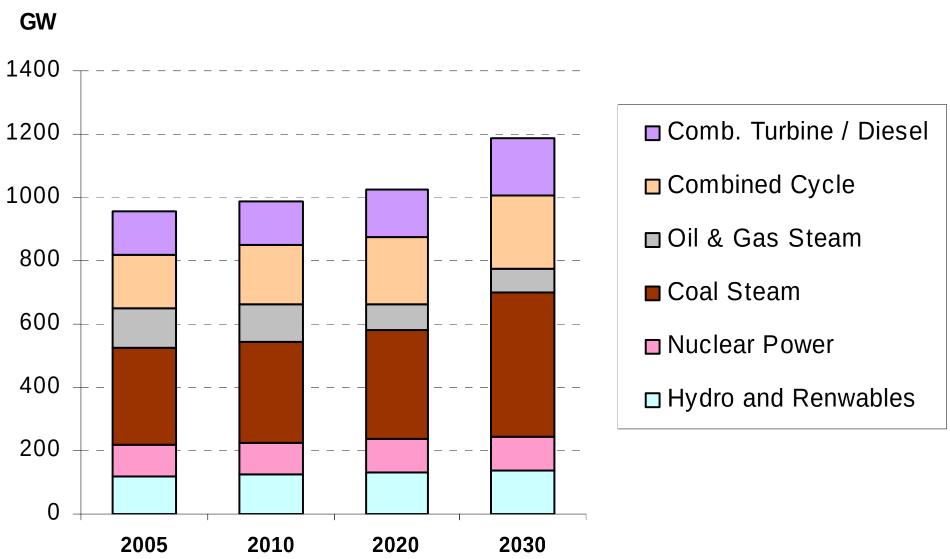

Figure 33. Projected Structure of Electricity Generating Capacities in the USA *(Source: EIA, 2006b)*

The depicted above near term prospects for development of power generation systems in WEU and NAM regions were compared with the projections of other long term energy scenario studies and served as the basis for elaboration of regional electricity supply scenarios. For other world regions, where detailed near-term projections of electricity supply mixes were not available, mainly the data from the existing long-term energy scenarios and "World Energy Outlook" (IEA, 2004) were used.

3.3.3 Maximum Electricity Supply Potentials of Main Technological Options

In order to determine the upper bounds for market penetration of different power generation technologies, the long-term electricity supply potentials in repartition by main types of primary energy were analyzed. ***Table 12*** summarizes the estimated amounts of available energy resources and the selected values of maximum global electricity supply potentials for main technological options considered in the study. Based on the review of available energy resource assessments, it was assumed that existing conventional and non-conventional resources of fossil fuels, except for oil, would suffice to cover the electricity generation needs in the 21st century, and hence the market deployment of respective technologies would be subject to economical and environmental considerations.

Table 12. Energy and Electricity Supply Potentials

Energy type	Estimated available energy resource*, EJ	Maximum global electricity supply in 2100**, TWh/yr
Thermonuclear Fusion	[a]	*7000*
Nuclear Fission[b]	*227400*	*40000*
Coal[c]	*132000*	[d]
Natural Gas[c]	*31500*	[d]
Oil[c]	*45000*	[e]
Hydro	*62* *(per year)*	*10000*
Wind	*600* *(per year)*	*10000*
Photovoltaic	*1600* *(per year)*	*15000*
Biomass	*250* *(per year)*	*5000*
Geothermal	*5000* *(per year)*	*800*
Marine / Ocean	*7* *(per year)*	[f]

Source: (*) IPCC AR4 (Sims *et al.*, 2007) and (**) author's estimation

[a] almost inexhaustible (the resources are sufficient for many thousand years)
[b] uranium reprocessing is included
[c] both conventional and unconventional resources are included
[d] there are no specific limits on electricity supply from coal and natural gas technologies in the study
[e] oil – based electricity generation is assumed to be phased out, except for oil-exporting regions
[f] marine / ocean technologies are not considered in this study as electricity supply option

The hypotheses underlying these estimates are explained hereunder.

Thermonuclear Fusion

One of the main factors that drives the research & development of Fusion technology is the availability of practically inexhaustible and universally accessible fuel resources, namely deuterium and tritium. As discussed in Chapter 2.1, deuterium is found naturally in sea water in abundant amounts (1 part in 6000), and tritium may be readily bred from the vast deposits of lithium which exist in the earth's crust and the oceans (IFRC, 02005). A more comprehensive assessment of the resources required for construction and operation of Fusion energy facilities is given in Tokimatsu *et al.* (2003) confirming the idea that there are no major limitations for Fusion at least for several thousand years.

According to the current estimates, commercially viable production of Fusion power can be started in the second half of this century or even earlier if a more ambitious accelerated Fusion development programme with EDEMO concept is followed (see e.g. Cook *et al.*, 2005a and EC, 2007). As regards the total capacity of Fusion power that can be deployed over the time horizon of the study, it will depend mainly on the pace of technological progress and the resulting economic performance of Fusion power plants. The evaluation given in Cook *et al.*, (2005b) assumes that under favourable conditions Fusion power generation can tap 20% of the global market that can be translated into electricity production of ≈ 15000 TWh in 2100 and ≈ 2000 GW of installed Fusion power generating capacities in case of IIASA / WEC scenario "B" projection. In the study of Tokimatsu *et al.* (2002) the range of estimates of global Fusion capacities in 2100 corresponds to ≈ 1700 GW in IIC case (with *Initial Introduction Constraints*) and ≈ 3500 GW in MCS case (assuming *Maximum Construction Speed* for Fusion).

Based on the existing studies and experts' recommendations the following figures were chosen to describe the maximum regional potentials for deployment of Fusion power plants:

- **Western Europe**

Lako *et al.* (1999) in their study of long term energy scenarios for Western Europe estimate the maximum capacity of Fusion power that can be installed in 2100 under tight CO_2 emission constraints (450 - 500 ppm) at 157.5 GWe. In the present study maximum capacity of Fusion power plants to be deployed in WEU region in most optimistic scenario is assumed to not exceed 10 GW in 2060, 60 GW in 2080 and 200 GW in 2100 [21].

- **North America**

In the paper of Schmidt *et al.* (2000) two Fusion implementation scenarios have been investigated assuming growth rates of 1 and 2 % per year starting from 2070, normalised to the total North American electricity production. These growth rates translate in to annual construction of about 10 and 20 GWe of Fusion capacities. Accordingly, the total installed capacity of Fusion power plants in 2100 can achieve 300 GWe in the first scenario and 600 GWe

[21] according to the recommendations of EFDA SERF programme experts (conclusions of the meeting held in Garching, EFDA/CSU, October 13, 2003)

in the second scenario. In order to preserve coherence with the assumptions made for the case of Western Europe and considering the projected electricity demand and the size of power generation system in NAM region, which are roughly 1.5 times bigger than in WEU region, the first "more moderate" scenario was chosen for estimating the potential of Fusion deployment. The resulting maximum values of Fusion power generating capacities to be installed in North America are: 15 GWe in 2060, 100 GWe in 2080 and 300 GWe in 2100.

- **Japan**

According to the paper of Tokimatsu *et al.* (2000) the construction of Fusion power plants can start in Japan simultaneously with Western Europe, North America and Former Soviet Union, i.e. in 2050, reaching the total capacity of ≈ 100 GWe in 2100. Considering that this estimate corresponds to the optimistic projection of world total installed Fusion power generation capacity of ≈ 3500 GW in 2100, and that a more realistic scenario presumes nearly half of that figure (see Tokimatsu et al., 2002), it was decided to set the maximum potential for deployment of Fusion in Japan equal to 3 GWe in 2060, 20 GWe in 2080 and 60 GWe in 2100.

- **China, India**

The projections of maximum Fusion power generating capacities that can be installed in developing countries, such as China and India, are based on the report of Hamacher & Sheffield (2004). In the case of China the national target is to have 10% of electricity production from Fusion by 2100. Assuming that deployment of Fusion will begin in China starting from 2070 and considering the electricity demand projection for China according to IIASA-WEC scenario "B" (≈ 10000 TWh in 2100), the maximum potential for construction of Fusion power plants in China was estimated at 30 GWe in 2080 and 140 GWe in 2100. The projection for deployment of Fusion power in India assumes the maximum capacity of 70 GWe (7% of total capacity) in 2100 and 100 GWe for the whole SAS region.

- **Other regions**

It was further assumed that in other regions the potential for deployment of Fusion power could reach ≈ 200 GWe in 2100, and the maximum worldwide electricity supply potential of Fusion power plants could attain in most optimistic case ≈ 1000 GWe (≈ 7000 TWh) that roughly corresponds to 9.5 % of global electricity market.

The exact values of the projected Fusion power generation capacities in each world region according to different scenarios obtained through the simulations with PLANELEC model are presented in Chapter 3.4.

Nuclear Fission

The power generation based on nuclear fission technology is seen in the IIASA-WEC scenario "B" projection as the main source of future electricity supply. Its share in total world electricity production is assumed to increase steadily from 17% in 2000 to 38% in 2050 and reaching substantial 47 % (35600 TWh) in 2100 (Nakicenovic *et al.*, 1998). Meanwhile, the analysis of recent trends and near-term prospects for development of regional power generation systems leads to significant revision of these estimates. So, in "Reference scenario" of IEA "World

Energy Outlook" the share of nuclear power in world electricity production is expected to decrease from 15% (2790 TWh) in 2006 to 10% (3460 TWh) in 2030 (IEA, 2008). These values roughly correspond to the "low estimate" projections of International Atomic Energy Agency (IAEA, 2008).

As regards the longer term prospects for development of nuclear power (from 2030 up to 2100) the following issues have to be taken into account. First, the extensive growth of nuclear power capacities based on open fuel cycle, such as thermal light water reactors, will face the problems of exhaustion of uranium resources and handling of spent nuclear fuel. As discussed in Gagarinskii *et al.* (2005) closure of the fuel cycle with separation of plutonium from thermal reactors and using of this plutonium in fast reactors with expanded breeding will allow for increasing the nuclear power capacity in 2100 to about 5000 GWe without exceeding the limits of supply of natural uranium. This solution, however, will be confronted with the problem of proliferation of radioactive materials and general public acceptance. Another option consists in using thorium as a fuel for nuclear fission reactors.

On the other hand, the need for curbing the emissions of greenhouse gases and a relatively good economic performance of nuclear power plants compared to other base-load electricity generation options using fossil fuels can play in favour of nuclear power. Considering these facts, the maximum global potential for deployment of nuclear power in 2100 was assumed to not exceed 3200 GWe (25000 TWh) that is in line with "Business-as-Usual / Basic Option" scenario considered in Bennett & Zaleski (2001) and nearly double of the maximum nuclear capacity assumed in Tokimatsu *et al.* (2002) for once-through reactor concepts.

Coal

The current estimates of coal reserves-to-production ratio fall in to the range of 133 – 150 years (BP, 2008; WEC, 2007). That makes of coal the power generation fuel of primary choice, especially for less developed countries, because of its abundance, more or less uniform distribution across world regions, relatively stable price and the accumulated experience in handling coal-fired electricity generation technology. The major factors, which limit further expansion of coal power generation, relate to the emission of greenhouse gases blamed for their contribution to the global climate change, and the release in to the atmosphere of other pollutants (such as SOx, NOx and particulate matters) that mostly exercise a local impact.

The local pollution can be reduced through adoption of many practically proved measures, such as retrofitting power plants with flue gas cleaning equipment (e.g. electrostatic precipitators, filters, scrubbers etc.) and pre-treatment of coal. The possible solutions for curbing greenhouse gases emissions from coal combustion consists in increasing the efficiency of coal-fired power plants by applying innovative thermodynamic cycles, such as integrated coal gasification – combined cycle technology, and equipping the power plants with CO_2 capture functionality allowing for its further sequestration in earth crust and/or deep ocean.

While the former solution may lead to reduction of CO_2 emissions by several percentage points (6 to 8 % of power plants reference emissions according to different estimates) without significant increase of the electricity cost, the latter type of technology, which is still in demonstration phase, potentially may allow for substantial CO_2 emission abatement (up to 90%), however at the expense of nearly doubled electricity production cost. Furthermore, the most affordable sites for geological sequestration of CO_2 will be used first and foremost, and that will attenuate the potential for electricity cost reduction due to technological learning.

Considering the given above facts and taking into account the necessity for ever increasing global efforts aimed at reducing the greenhouse gases emissions, it was decided to limit the worldwide power generation from coal to 25000 TWh in 2100 and to investigate more thoroughly the possible market share and the potential for CO_2 emissions abatement of the coal-fired technologies with CO_2 capture and sequestration.

Natural Gas and Oil

The current prospects for availability of oil and natural gas fuels are less promising than those for coal resources. The ranges of reserves and reserves-to-production estimates in WEC and BP statistics are: 160 – 168 Gt / 41 – 41.6 years for oil and 176 – 177 tcm (trillion cubic metres) / 56.5 – 60.3 years for natural gas (WEC, 2007; BP, 2008). These figures can be criticised as too pessimistic, since they don't account for so-called "non-conventional" resources which may be extracted at higher cost. On the other hand, they can give an idea, when the peak in production of conventional oil and gas will be attained giving the place to massive exploitation of more costly non-conventional resources.

A recent IEA study draws a more comprehensive picture of global conventional and non-conventional reserves of oil and natural gas that can be summarised as follows:

Oil

- ***Some 7 to 8 $\times 10^{12}$ barrels of conventional oil.*** *Of these, 3.3 $\times 10^{12}$ barrels are considered technically (or ultimately) recoverable; 1.0 $\times 10^{12}$ have already been produced.*
- ***7 $\times 10^{12}$ barrels of non-conventional oil*** *(heavy oil, bitumen, oil sands, and oil shales). Estimated technically recoverable quantities vary from 1 to 3 $\times 10^{12}$ barrels.*

Natural Gas

- ***450 $\times 10^{12}$ cubic metres of technically recoverable conventional gas****, or 2.8 $\times 10^{12}$ barrels of oil equivalent (boe), of which about 80 $\times 10^{12}$ cubic metres have already been produced (0.5 $\times 10^{12}$ boe).*
- ***At least 250 $\times 10^{12}$ cubic metres of non-conventional gas****, or 1.5 $\times 10^{12}$ boe (coal bed methane, tight gas, gas shales), although there is no reliable estimate worldwide and there could be two or three times more.*
- ***Between 1 000 and 10 000 000 $\times 10^{12}$ cubic metres of gas locked in the form of hydrates*** *at seabed level or in permafrost (between 6 and 60 000 $\times 10^{12}$ boe). The recoverability status of these resources is unknown.*

Source: IEA (2005b)

Given the above figures it can be assumed that the existing oil and natural gas resources will suffice to cover the electricity generation needs. Hence, the major factor limiting the deployment of oil and gas – fired power generation facilities will be the future market price of these fuels.

Hydropower

The hydropower potential was assessed basing on WEC "Survey of Energy Resources" (WEC, 2007). ***Table 13*** summarises the estimations of gross theoretical, technical and economical capabilities for exploitation of hydropower resources in different world regions. It was observed that the value of total world economically exploitable hydropower potential roughly corresponds to the upper estimate given in IPCC Third Assessment Report: 8700 TWh / yr (Metz *et al.*, 2001). In IIASA/WEC scenario "B" projection the total world hydropower production in 2100 attains 7400 TWh (Nakicenovic *et al.*, 1998). In the present study the maximum potential for hydropower production in 2100 was fixed at 10000 TWh/yr assuming that economical potential can be fully exploited and additional 1000 TWh/yr of technically exploitable potential can become economically viable.

Table 13. Hydropower Exploitation Capability (TWh/yr)

	Gross theoretical capability	**Technically exploitable capability**	**Economically exploitable capability**
North America	*7501*	*2853*	*1037*
Latin America & Caribbean	*7674*	*3195*	*1703*
Western Europe	*2725*	*1085*	*774*
Central & Eastern Europe	*362*	*171*	*117*
Former Soviet Union (CIS)	*3568*	*2258*	*1287*
Middle East & North Africa	*704*	*249*	*177*
Sub-Saharan Africa	*3686*	*1799*	*954*
South Asia	*4136*	*1138*	*809*
Pacific OECD	*1081*	*299*	*187*
Centrally Planned Asia	*6863*	*2732*	*1890*
Other Pacific Asia	*2991*	*743*	*88*
World Total	***41291***	***16522***	***9023***

Source: WEC (2007)

Other Renewable Energy

The global potential electricity supply from renewable energy sources, other than hydropower, was assessed basing on the data provided in IPCC Third Assessment Report (Metz *et al.*, 2001).

So, the worldwide potential of wind power generation is estimated at 20000 TWh/yr which is about 2.5 times lower than other estimates that can be found in the literature [22]. The range of estimates of solar energy potential is 1575 to 49837 EJ/yr. Assuming the conversion efficiency of photovoltaic modules equal to 15%, that gives the electricity production potential of ≈ 65000 – 2000000 TWh/yr which may substantially exceed the global electricity demand projected in IIASA / WEC Scenarios. The total biomass energy potential is estimated at 396 EJ/yr in 2050, that assuming 40% efficiency of biomass-fired power plants gives the total electricity production potential of ≈ 44000 TWh/yr. The global long-term potential of geo-thermal energy according to IPCC SRES can be estimated at 20 EJ/yr corresponding to ≈ 800 TWh/yr with 15% conversion efficiency (Nakicenovic & Swart, 2000). The marine energy can also represent a significant potential estimated at 7 EJ/yr in most recent IPCC Fourth Assessment Report (Sims *et al.*, 2007), but it was difficult to find any reliable technical-economical characteristics of the technology itself, and hence it was omitted from the analyses.

While renewable energy resources appear to be immense and practically inexhaustible, several factors hinder their utilisation for electricity generation purposes. As regards wind and solar power, the main limiting factors are related to their low energy density, uneven geographical distribution and intermittent character. In order to overcome these problems and to exploit fully this type of energy resources, the deployment of a global interconnected electricity grid has to be envisaged, as discussed in Biberacher *et al.* (2004). Another major obstacle is due to higher economic cost compared to other electricity supply options, especially in the case of photovoltaic technology. This problem can be overcome through intensification of R&D efforts and proliferation of public policy measures supporting the deployment of renewable energy technologies that should lead to gradual reduction of their costs through exploitation of different learning opportunities. The main difficulty with biomass energy arises from the competition for arable land with food and feedstock production required to meet the alimentary needs. This problem is expected to become more and more acute in the second half of the 21st century, especially in developing countries, given the projected pace of world population growth. Considering these issues, some reasonable limits on the global renewable energy supply potentials had to be imposed. The resulting estimates of the maximum worldwide electricity production by main types of renewable energy technologies are given in ***Table 12*** above.

3.3.4 Assumptions on Fuel Prices

Availability and prices of power generation fuels are among the key drivers that will determine the future structure of regional electricity systems. The maximum electricity supply potentials of main energy resources have been discussed above. In the simulations with PLANELEC model this issue was taken into account through limiting the shares of specific technologies in total electricity capacities to be installed. Meanwhile, several assumptions had to be made regarding the evolution of fuel prices for the whole study period of one hundred years.

For that purpose, the historical and actual prices of main power generation fuels (fuel oil, natural gas and steam coal) were analysed according to IEA statistical data (IEA, 2004a, 2004b, 2004c,

[22] The assessment of Grubb and Meyer (1993) citied in IPCC TAR corresponds to 53000 TWh/yr

2005a). The future prices of main hydrocarbon fuels were estimated based on the "Reference scenario" assumptions of IEA "World Energy Outlook" (IEA, 2005c) and long-term projections of marginal costs (shadow prices) calculated with IIASA - MESSAGE model (Nakicenovic & Riahai, 2002). The price of lignite was assumed to be ≈ 20 % lower than the price of anthracite grade coal due to its inferior calorific value.

The price of fuel for nuclear fission reactors was estimated based on the actual data from "Ux Consulting Company" (UxC, 2006) with the provision of nearly two-fold increase in long term perspective considering the use of breeding technologies and taking into account the costs of nuclear waste management in accordance with the data of WISE Uranium Project (2006). The cost of fuel for thermonuclear Fusion was assessed basing on the publications of Varandas (2003) and Hamacher & Bradshaw (2001). Finally, the future price of biomass fuel was estimated on the basis of actual data from EUBIONET (Alakangas *et al.*, 2007) and assuming a relatively moderate cost increase with the annual factor of 0.6 – 0.8 %.

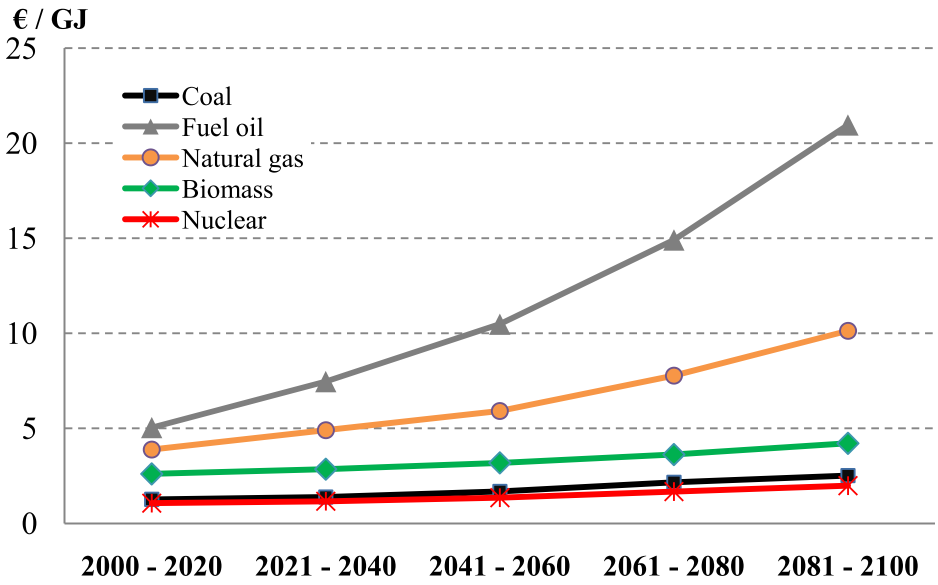

Figure 34. Projected Average Fuel Prices in PLANELEC Model

Considering the increasing tendency towards globalisation of international energy markets, the uncertainty in prediction of future fluctuations of energy prices and a very-long time horizon of the study, it was assumed that single fuel prices could be applied for all world regions to perform scenario analyses, although it is a very rough approximation. ***Figure 34*** indicates the resulting global projections of the average fuels prices for each of the 20-years sub-periods. The explicit numerical assumptions on future fuel prices can be found in Gnansounou & Bednyagin (2006). The price of fuel for thermonuclear Fusion reactors is not shown above because of its very low expected value (0.004 – 0.005 €/GJ) compared to other power generation fuels.

It is worth noting that in 2008 the oil prices have already exceeded the value of 100 $/bbl (12.5 €/GJ), that constitutes nearly 3-fold increase from their level in 2000. Although the economic downturn has reduced the pressure on oil prices, in 2010 they remain at relatively high level of 70-80 $/bbl. The natural gas prices have exhibited the same dynamics during the first decade of this century, with 2010 prices being close to 4 €/GJ.

3.3.5 Technology Characteristics

The standard procedure followed in the electricity sector studies based on least cost expansion planning models involves a detailed representation of the technical and economical parameters of the existing power plants and definition of generic characteristics of prospective technological options. Considering a global magnitude of the analyses performed in this study and a lack of comprehensive data describing the regional electricity generation systems at the individual power plants' level, it was decided to aggregate the existing power plants into cohorts of larger capacity and to apply averaged values as proxy estimates of theirs technical and economical performance.

The existing power plants were classified according to the following main types of electricity generation technologies and fuels:

- Open cycle gas turbine
- Gas turbine operated in combined cycle with steam turbine
- Natural gas fired thermal power plant
- Diesel engine
- Fuel oil fired thermal power plant
- Multifuel thermal power plant (coal, fuel oil, natural gas)
- Nuclear power plant
- Anthracite coal fired thermal power plant
- Lignite coal fired thermal power plant
- Municipal wastes and biomass residues incinerator equipped with steam turbine
- Run-of-the-river hydro power plant
- Reservoir accumulation hydro power plant
- Pumping and storage hydro power plant
- On-shore / off-shore wind power plant

The detailed assumptions on each power generation technology of the existing system can be found in Gnansounou & Bednyagin (2006). The candidate electricity generation technologies considered in the study include the following options:

Natural gas - based technologies

Four different types of natural gas fuelled technologies were considered as potential candidates for expansion of the existing electricity generation systems. They include: [1] open cycle gas turbine (GT); [2] gas turbine equipped with heat recovery steam generator and operated in combined cycle with steam turbine (NGCC); [3] combined cycle gas turbine with the possibility of CO_2 capture and storage (NGCC-CCS); [4] fuel cell.

Fuel oil technologies

Two types of fuel oil fired power generation technologies were considered in the study including: [1] advanced thermal power plant (only for the period 2000 – 2020) and [2] fuel oil gasification combined cycle power plant.

Coal – based technologies

The coal – fuelled power generation technologies are divided in the PLANELEC model into two main categories depending on the type of coal used: anthracite or lignite. The technologies considered in the study include: [1] anthracite-fuelled advanced thermal power plant based on pulverised coal (PC) combustion; [2] lignite-fuelled advanced thermal power plant based on coal fluidised bed combustion; [3] anthracite and lignite - fuelled integrated coal gasification power plant based on combined cycle technology (IGCC); [4] anthracite-fuelled IGCC power plant equipped with CO_2 capture and storage functionality; [5] anthracite-fuelled integrated coal gasification power plant based on fuel cell technology and operated in combined cycle with steam turbine (IGFCCC); [6] anthracite-fuelled IGFCCC power plant with CO_2 capture and storage functionality.

Nuclear technologies

The candidate nuclear fission and Fusion power generation technologies considered in the study included: [1] conventional light water nuclear fission reactor (only for the period 2000 – 2020), [2] advanced fission reactor of generic concept as envisaged by Generation IV International Forum initiative [23], including those allowing for “breeding” of nuclear fuel (for the period 2020 – 2100), [3] thermonuclear Fusion reactor based on magnetic confinement concept (from 2050 onwards).

Hydropower, other renewable energy and waste incineration technologies

The power generation technologies based on renewable energy sources include: [1] biomass – fired thermal power plant; [2] geothermal power plant; [3] solar energy plant based on photovoltaic technology; [4] on-shore and [5] off-shore wind power plant (wind-farm). The hydropower technologies considered as potential candidates include: [6] run-of-the-river hydropower plant; [7] accumulation hydro plant with reservoir and [8] pumping and storage hydropower plant. The power plants based on incineration of municipal wastes [9] are also considered as special type of electricity generation technology.

The explicit assumptions on each candidate power generating technology for the final period of the study (2080 – 2100) are given in ***Table 14*** below. The assumptions for other periods can be found in Gnansounou & Bednyagin (2006). All economical indicators are given in $€_{2005}$. The discount rate applied in the calculation of annuity payments on capital investment is 5%. The learning factors which normally explain the reduction of capital and O&M costs of new technologies subject to the total capacity installed were defined exogenously basing on the assumptions made in similar studies (see e.g. IEA, 2000; Hamacher & Bradshaw, 2001; Eherer & Baumann, 2005).

The reference values, presented in ***Table 14***, are based on the case of Western Europe. According to the assumptions of “Energy Technology Perspectives” (ETP) model applied in recent IEA studies (see e.g. IEA, 2004e) the region specific cost multipliers were derived in order to define generic economic parameters of the power plants in other world regions. It was further assumed

[23] www.gen-4.org

in the study that the costs related to electricity grid connection and grid extension in the future regionally, or even globally, interconnected systems would not have a decisive impact on the choice of candidate power generation technologies, and hence they were omitted from the analyses.

***Table 14. Assumed Technical & Economical Parameters of Candidate Power Generation Technologies** (Average Values for the Period 2080 – 2100)*

	Efficiency	O&M fixed	O&M variable	Investment cost	Lifetime	Forced outage	Scheduled mainte-nance
	%	€/kW *month	€/MWh	€ / kW	yrs	%	days
NGCC	*66*	*1.70*	*0.50*	*368*	*25*	*5*	*20*
NGCC-CCS	*58*	*2.22*	*4.52*	*637*	*25*	*5*	*36*
GT	*46*	*1.02*	*0.59*	*321*	*25*	*5*	*164*
NG Fuel Cell	*70*	*0.19*	*19.06*	*1081*	*25*	*3*	*20*
Oil IGCC	*56*	*1.88*	*0.52*	*991*	*25*	*5*	*30*
Nuc. Fission “Gen. IV”	*48*	*3.64*	*0.30*	*1595*	*40*	*3*	*20*
Fusion (Intro)	*50*	*12.40*	*0.26*	*4089*	*40*	*4*	*54*
Fusion (+)	*60*	*10.40*	*0.23*	*3100*	*40*	*4*	*54*
Anthracite Thermal Adv.	*55*	*2.21*	*1.53*	*855*	*30*	*4*	*20*
Anthracite IGCC	*60*	*3.13*	*1.63*	*920*	*25*	*5*	*20*
Anthracite IGCC-CCS	*54*	*3.13*	*9.65*	*1183*	*25*	*6*	*30*
Anthracite IGFCCC	*66*	*3.29*	*2.55*	*1169*	*25*	*7*	*40*
Anthracite IGFCCC-CCS	*58*	*3.48*	*9.77*	*1318*	*25*	*8*	*40*
Lignite FBC	*50*	*2.12*	*1.81*	*910*	*30*	*4*	*20*
Lignite IGCC	*60*	*3.47*	*2.00*	*936*	*25*	*5*	*20*
Waste Thermal	*32*	*5.23*	*3.40*	*4893*	*30*	*10*	*55*
Biomass	*52*	*2.30*	*2.54*	*1108*	*30*	*6*	*28*
Geothermal	*15*	*4.94*	*0.30*	*1268*	*30*	*3*	*20*
Hydro-Run-of-the-River	-	*1.40*	*0.20*	*1800*	*50*	-	-
Hydro-Accumulation	-	*1.10*	*0.20*	*2400*	*50*	-	-
Hydro-Pumping & Storage	-	*1.80*	*1.20*	*2600*	*50*	-	-
Wind on-shore	-	*1.40*	-	*525*	*30*	-	-
Wind off-shore	-	*2.94*	-	*751*	*40*	-	-
Solar PV	-	*0.58*	-	*1104*	*30*	-	-

The main data sources used in the formulation of technology assumptions included: EFDA report “Socio-Economic Research on Fusion / Summary of EU Research 1997 – 2000” (Borelli *et al.* 2001), ECN report “Characterisation of Power Generation Options for the 21st Century” (Lako & Seebregts, 1998), MIT study “The Future of Nuclear Power” (Ansolabehere *et al.*, 2003), ORNL study “An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion” (Delene *et al.*, 1999), EFDA report on the European Fusion Power Plant Conceptual Study (Maisonnier et al., 2005), ECN studies “Coal-fired Power Technologies” (Lako, 2004) and “Potentials and Costs for Renewable Electricity Generation” (de Noord *et al.*, 2004), IEA study “Prospects for CO_2 Capture and Storage” (IEA, 2004d), NEA/IEA publication “Projected Costs of Generating Electricity” (NEA, 2005), US DoE / EIA publication “Assumptions to the Annual Energy Outlook” (EIA, 2005), etc.

Before proceeding to the analysis of specific scenarios developed with the help of PLANELEC model it is interesting to compare the economic performance of thermonuclear Fusion with the competing technology options. For that purpose the levelized unit electricity generation cost methodology (NEA, 2005) can be applied which uses the following formula:

$$LUEC = \frac{\sum[(I_t + OMF_t + OMV_t + F_t)(1+r)^{-t}]}{\sum[E_t\ (1+r)^{-t}]} \qquad (3.1)$$

$LUEC$ = Average lifetime levelised unit electricity generation cost
I_t = Investment expenditures in the year t
OMF_t = Fixed operations and maintenance costs in the year t
OMV_t = Variable operations and maintenance costs in the year t
F_t = Fuel expenditures in the year t
E_t = Electricity generation in the year t
r = Discount rate.

Under the assumptions adopted in this study the levelized electricity cost of Fusion technology is expected to steadily go down from ≈ 0.10 € / kWh in 2050 to 0.055 € / kWh by the end of the century in moderate “Fusion Introduction” scenario, and even lower to 0.043 € / kWh in more aggressive “Massive Deployment of Fusion” scenario. The cost of Fusion electricity is estimated in the same order of magnitude (0.03 – 0.09 € / kWh) in the study of Ward et al. (2005) which utilised a technology explicit “PROCESS” code[24] to determine the cost characteristics of four main configurations of Fusion power plants considered in European PPCS studies (Maisonnier et al., 2005). A more recent study of Han & Ward (2009) explored the economics of *early* (10th of kind) and *mature* (100th of kind) generations of Fusion power plants in both basic and advanced configurations. They compiled an updated data set of the economic parameters of future Fusion power plants and concluded that the lower cost projections (0.03 – 0.05 € / kWh) are justified for mature Fusion technology.

The presented above LUEC characteristics of Fusion power plants allow to assess their economic competitiveness compared to other technological options (see ***Figure 35***). So, in the absence of CO_2 taxation the economic prospects of coal-based power generation appear to be more lucrative. This assessment, however, does not account for the price of CO_2 emission permits or CO_2 tax that may radically deteriorate the economic performance of coal power plants under stringent policies aiming to curb global CO_2 emissions. If such policies are enacted in a world-wide scale, then coal-based power generation should rely on more costly technologies allowing for carbon capture and storage which would have similar cost characteristics as Fusion. As concerns the natural gas technologies which have become in recent years the primary choice for environmentally friendly power generation, their economic prospects are not so appealing in the second half of the century due to the expected rise of natural gas prices. The same refers to oil-based power generation, even to a much greater extent, which will be facing the problem of

[24] The code PROCESS allows for calculating the cost of Fusion electricity (*CoE*) as a function of the key parameters of plasma, the heat conversion cycle and the reactor availability according to the following formula: $CoE \approx \left(\frac{rF}{A}\right)^{0.6} \frac{1}{\eta_{th}{}^{0.5}} \frac{1}{P_e{}^{0.4}\,\beta_N{}^{0.4}\,N^{0.3}}$ where r is the discount rate, F is the learning factor, A is the plant availability, η_{th} is the thermodynamic efficiency, P_e is the net electric power, β_N is the normalised plasma pressure and $N = n/n_G$ is the Greenwald normalised plasma density.

steadily decreasing reserves after the peak in oil production that may occur by the middle of this century. Nevertheless, natural gas and oil – based power generation can be expected to remain an important electricity supply option in certain world region which possess the highest share of global hydrocarbon reserves.

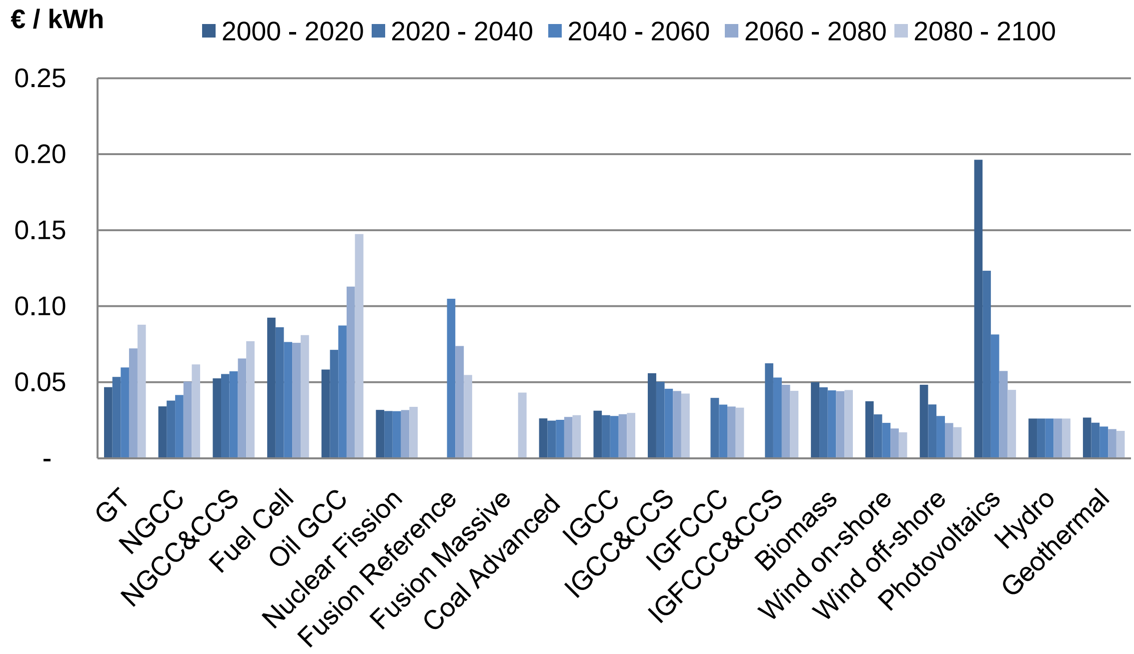

Figure 35. Estimated Levelized Unit Electricity Cost of Main Power Generation Technologies

Among the other power generation options, the advanced concepts of nuclear fission reactors may represent the highest interest due to their low electricity production cost, however as practice shows their deployment may be substantially hindered by general public distrust induced by the fears of major accidents, the risk of proliferation of fissile matters and the problem of long term storage of nuclear wastes. The renewable energy technologies, although currently characterised by relatively high production cost, may also represent an important potential for large scale electricity generation in longer term perspective as far as their cost will be gradually reduced due to continuous learning and scale economies. Meanwhile, their intermittent nature, low energy density and dependence on local conditions make them more suitable for distributed power applications rather than centralised electricity generation.

3.4 Regional Electricity Supply Scenarios with Fusion

Based on the dataset of installed power generation capacities, the near-term prospects (up to 2030) for expansion of electricity systems in different world regions according to the existing studies, and given the assumptions on future electrical load, fuel prices and technologies' characteristics, the long term "Baseline" scenarios of future electricity supply mixes were elaborated for each world region with the help of PLANELEC model. These scenarios did not include Fusion, and they were considered as reference for assessment of different scenario variants presuming "moderate" and "massive" introduction of Fusion, as well as "massive" deployment of nuclear fission and coal with CO_2 capture & sequestration technologies. The main details of "Baseline" scenarios and its main variants are explained below. Hereinafter, only the aggregated data referring to the global power generation system are being discussed, while the explicit details of regional electricity supply scenarios can be found in the main study report (Gnansounou & Bednyagin, 2006).

Baseline Scenario

According to the reference "Baseline" scenario, in the first half of the century, the major contributors to the expansion of electricity generating capacities worldwide will be natural gas and coal based technologies. Natural gas is expected to reach its maximum share (≈ 35%) by 2030 and maximum capacity (≈ 2780 GWe) by 2040. Starting from 2040 it will gradually decline, mainly due to the increase of natural gas prices. The coal-fired technologies are expected to attain their maximum share (≈ 32%) by 2060, while their total capacity will steadily grow throughout the whole period of the study, reaching ≈ 4830 GWe in 2100.

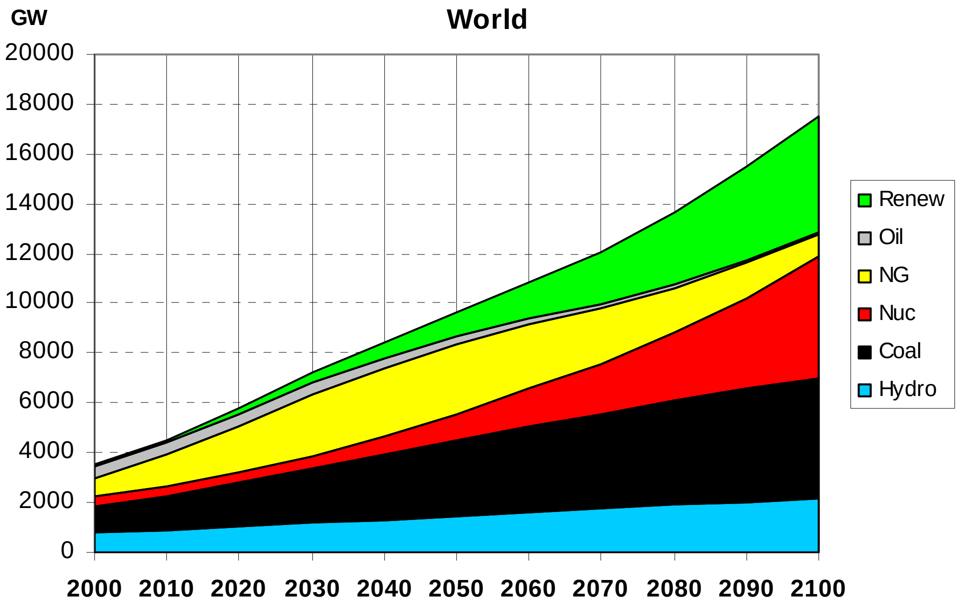

Figure 36. Projected Structure of Global Power Generation Capacities in "Baseline" Scenario

It is projected that in the second half of the century further expansion of the global electricity generation system will be assured by advanced nuclear fission power plants (4870 GWe, 28% of total capacity in 2100) and renewable energy technologies (4690 GW, 27% of total capacity in 2100). As regards the hydropower generation, it is projected to increase at moderate pace (from 770 GWe in 2000 to 2170 GWe in 2100), and the fuel oil-fired power plants are expected to be practically phased out (only 40 GWe in 2100). The projected overall structure of global electricity generating capacities in "Baseline" scenario is depicted in ***Figure 36*** above.

Alternative Scenarios

In addition to the "Baseline" scenario, the following alternative scenarios were analyzed:

<u>Moderate Introduction of Fusion</u>

The case of "moderate" deployment of Fusion has been simulated through the introduction of a fixed amount of Fusion power into the electricity system replacing an equal capacity of coal-based electricity generation. The installed capacities of other technologies were assumed to remain the same as in the "Baseline" case. According to this scenario, it is assumed that during the period 2040 – 2060, about 10 Fusion power plants of 1500 MWe capacity each can be put in operation in NAM, WEU and PAO regions (see ***Table 15***). During the next period (2060 – 2080) the total capacity of fusion power will be increased up to 126 GWe, corresponding to the total 84 Fusion power plants being in operation in six world regions, countries from which participate in ITER initiative. By the end of the century, the total capacity of Fusion power is expected to reach 330 GWe taking into account the decommissioning of Fusion power plants of the first generation. This amount of Fusion power corresponds to about 2% of the total projected electricity generating capacities installed in 2100.

Table 15. Fusion Power Capacities in the "Fusion Intro" and "Fusion Massive" Scenarios (GWe)

Region	**2060**		**2070**		**2080**		**2090**		**2100**	
	Intro	Mass	Intro	Mass	Intro	Mass	Intro	Mass	Intro	Mass
NAM	6	15	24	58	48	100	81	200	120	300
LAM	-	-	-	-	-	3	-	12	-	30
WEU	6	9	24	35	42	60	66	123	90	186
CEE	-	-	-	-	-	-	-	6	-	18
CIS	-	-	-	3	3	9	9	24	15	42
MEA	-	-	-	-	-	3	-	12	-	30
AFR	-	-	-	-	-	-	-	6	-	15
SAS	-	-	3	6	9	30	18	60	30	99
PAO	3	3	6	9	12	21	21	36	33	60
CPA	-	-	3	9	12	30	24	75	42	140
PAS	-	-	-	-	-	3	-	12	-	30
Total	**15**	**27**	**60**	**120**	**126**	**259**	**219**	**566**	**330**	**950**

Massive Deployment of Fusion

This is an alternative case presuming that increased R&D funding and active industry involvement will allow for bringing down the costs of Fusion technology. It will also require improvement of the technical characteristics of Fusion power plants and build-up of the required manufacturing facilities. According to this scenario, in 2060 the capacity of Fusion power will reach 27 GWe, and during the period 2060-2080 it will be increased up to 259 GWe (see ***Table 15***). Assuming an optimistic Fusion cost estimate, corresponding to the model "D" of European PPCS study (Maisonnier *et al*., 2005), it is expected that total 950 GWe of Fusion capacities can be installed by the end of the 21st century. This amount of Fusion represents about 5.4% of the total projected worldwide capacities in 2100. Similarly to the previous case, in this scenario Fusion power plants will be displacing the same amount of coal-based electricity generating capacities.

Massive Deployment of Coal with Carbon Capture & Sequestration (Coal CCS)

This case is analogous to "Fusion Massive" scenario with the only difference that Fusion power is substituted here by the same amount of coal-fired power generation technologies with carbon capture & sequestration (27 GWe by 2060; 259 GWe by 2080; 950 GWe, about 5.4% of total capacity in 2100).

Extra Nuclear Fission

This scenario is characterized by the increased amount of nuclear fission electricity generating capacities. Similarly to the “Fusion Massive” and “Coal CCS” scenarios, the additional capacity of nuclear fission power plants (27 GWe by 2060; 259 GWe by 2080; 950 GWe by 2100) displaces here the same amount of coal-fired power generation (without carbon capture).

CO2 Tax

In addition to the set of basic scenario variants, the case of Western Europe region was chosen in order to demonstrate the effect of more stringent environmental policy regime. For that purpose, the same technology mixes, as described above, were simulated with the application of CO_2 tax (€ 20 - € 50 / tCO_2).

3.5 Results of Scenarios Simulation with PLANELEC Model

The results of the simulations of two Fusion deployment scenarios for all world regions are given in ***Table 16***. These results show that a substantial amount of Fusion power can be deployed in the second half of this century without substantial increase of the levelized system electricity cost. So, in most developed regions (NAM, WEU, PAO) Fusion power can reach a market share of about 20% in terms of electricity generation entailing only a modest increase of the levelized system electricity cost (by $€_{cent}$ 0.3 - 0.4 per kWh). In less developed world regions with lower deployment rates of Fusion the increase of levelized electricity cost is practically insignificant (less than 0.1 $€_{cent}$ / kWh).

Table 16. Fusion Share in Total Regional Electricity Generation (2100) and Increment of Levelized System Electricity Cost (2080-2100)

	Fusion share (%)		**Electricity cost increment ($€_{cent}$ / kWh)**	
	Fusion Intro	Fusion Massive	Fusion Intro	Fusion Massive
NAM	9.2	22.9	0.20	0.28
LAM	-	2.9	-	0.02
WEU	9.9	20.4	0.26	0.38
CEE	-	8.3	-	0.04
CIS	2.0	5.6	0.04	0.06
MEA	-	3.5	-	0.04
AFR	-	1.4	-	0.01
SAS	1.7	5.6	0.03	0.04
PAO	8.3	15.1	0.21	0.30
CPA	2.9	6.8	0.04	0.06
PAS	-	4.1	-	0.03

The expected levels of CO_2 emission reductions in different scenarios compared to “Baseline” case and the corresponding estimates of regional CO_2 abatement costs are given in ***Table 17***. The presented values correspond to the reduction of total CO_2 emissions of the electricity generation systems in different world regions throughout the whole study period. The incremental CO_2

abatement cost was calculated as the difference of discounted total system costs in the "Baseline" case and the respective scenario divided by the difference in total CO_2 emissions.

Table 17. Cumulative CO_2 Emission Reductions and CO_2 Abatement Cost

	CO_2 emission reductions (million t CO_2)				**CO_2 abatement cost (€ / t CO_2)**			
	Fusion Intro	**Fusion Mass.**	**Coal CCS**	**Fission Extra**	**Fusion Intro**	**Fusion Mass.**	**Coal CCS**	**Fission Extra**
NAM	8307	18519	5025	19535	40.3	27.0	19.3	3.2
LAM	-	1268	138	1401	-	15.2	64.2	2.3
WEU	7807	13558	8002	14326	40.0	32.3	16.8	9.6
CEE	-	434	197	462	-	18.0	24.2	3.7
CIS	790	2141	871	2287	32.7	18.3	15.0	2.4
MEA	-	981	675	1047	-	25.6	19.2	4.1
AFR	-	597	31	665	-	15.8	167.4	2.5
SAS	1554	5240	280	5887	26.9	12.1	71.0	1.8
PAO	2349	4117	1648	4319	48.6	37.0	22.8	3.9
CPA	2267	6832	2157	7525	25.3	12.5	15.4	1.5
PAS	-	718	154	702	-	25.8	34.2	5.5
Total	**23074**	**54405**	**19178**	**58156**	**-**	**-**	**-**	**-**

In general, the advanced nuclear fission technology offers the highest potential for reducing CO_2 emissions at lowest cost, followed by thermonuclear Fusion and coal-based technologies with carbon capture and sequestration. The higher level of CO_2 abatement cost in NAM, WEU, and PAO regions in both Fusion scenarios can be explained by the fact that here the deployment of Fusion starts earlier. Accordingly, at the end of the study period the electricity systems in these regions contain a greater number of more expensive Fusion power plants of the first generation, while other world regions benefit of the decreasing costs due to technological learning.

A relatively low level of achievable CO_2 emission reductions and higher regional variance of CO_2 abatement cost in the "Coal CCS" scenario are explained by the fact that in certain regions (LAM, AFR, SAS) the coal-fired power plants with carbon capture and sequestration are classified in the lower range of the economic loading order that prohibits them from being exploited at full capacity rates.

The results of the simulation of two environmental policy regimes presuming introduction of CO_2 taxes (€20 and €50 per tCO_2) in case of WEU region are given in ***Table 18***. These results demonstrate that a higher level of CO_2 taxation may favour the introduction of Fusion power, which can be massively deployed in the situation with €50/tCO_2 tax practically without increase of the levelized system electricity cost and ensure a substantial reduction in CO_2 emissions (about 13500 mln tCO_2).

Table 18. Evolution of Levelized System Electricity Cost (€cent / kWh) in the WEU Region at Different Levels of CO_2 Tax

	Baseline	Fusion Intro	Fusion Massive	Coal CCS	Fission Extra
€ 20 / tCO2					
2040 - 2060	4.6	4.7	4.7	4.7	4.6
2060 - 2080	4.5	4.6	4.6	4.5	4.4
2080 - 2100	4.4	4.6	4.6	4.4	4.4
€ 50 / tCO2					
2040 - 2060	5.4	5.4	5.4	5.4	5.3
2060 - 2080	5.2	5.3	5.2	5.2	5.1
2080 - 2100	5.0	5.1	5.0	4.9	4.8

The more explicit results of the scenario simulations for other world regions can be found in Gnansounou & Bednyagin (2006).

3.6 Conclusions and Implications for Other Analyses

According to the results of the simulations of multi-regional electricity market scenarios elaborated in the present study, controlled thermonuclear Fusion can become an important electricity supply option attaining the maximum share in total regional electricity production in case of the NAM region (22.9%) and providing the maximum contribution to CO_2 emissions abatement in case of the WEU region (16.7%). The potential contribution of Fusion to the reduction of global CO_2 emissions from power generation during the study period is estimated at about 1.8% in the moderate "Fusion Introduction" scenario and at about 4.3% in the "Fusion Massive" scenario.

In all world regions the deployment of Fusion power entails a slight increase of levelized system electricity cost. In general, higher deployment rates result in a higher increment of levelized electricity cost, which is in the range $€_{cent}$ 0.3 - 0.4 per kWh in WEU, NAM and PAO regions, and it does not exceed $€_{cent}$ 0.1 per kWh in less developed world regions. Meanwhile, the case of the WEU region demonstrates that introduction of a stringent CO_2 tax (€50/tCO_2) allows Fusion power to be massively deployed practically without any change of levelized electricity cost compared to the "Baseline" scenario.

As regards the economic performance of Fusion, it was found that in the second half of the century Fusion power could become competitive compared to natural gas - fired technologies, mainly due to a significant increase of natural gas prices. Furthermore, during the period 2080 – 2100 it can equalize the production cost of coal-based technologies with carbon capture & sequestration, which will be gradually facing the problem of exhaustion of most affordable sites for geological sequestration. While Fusion technology is expected to remain more costly than advanced nuclear fission power plants, its deployment may be favoured by the public distrust in nuclear fission, the necessity for reliable storage of long-lived radioactive waste and the risk of proliferation of fissile materials from breeder reactors.

Compared to other studies investigating the economic potential for market penetration of Fusion technology the results obtained in this work can be considered as rather conservative. So, in the paper of Vaillancourt *et al.* (2008) the total Fusion power generation capacity in 2100 under most stringent 450-ppm GHG stabilisation scenario is estimated at 1500 GW corresponding to 23 % of the global market. According to the analyses performed with EFDA-TIMES model the potential contribution of Fusion is expected to be about 20% in less stringent 550-ppm scenario and much higher approaching to 50% under the same 450-ppm scenario (see Muehlich & Hamacher, 2009). This difference can be explained mainly by the lower value of Fusion capacity growth constraint in PLANELEC model and the effect of public policy measures aimed at limitation of global GHG emissions that are assumed to be enacted in a world-wide scale.

Based on the results of regional scenarios simulation with PLANELEC model it can be concluded that economic viability of Fusion power will depend mainly on the advancements in R&D and practical handling of Fusion technology that should allow for bringing down its future costs. During the current stage of Fusion development process the technological progress will be subject to the amount of public funding and the potential contributions of the involved industries. Also it should not be neglected that market penetration of Fusion will be facing the problem of relatively high upfront capital cost which may reduce the enthusiasm of private investors in liberalised electricity markets concerned with pay-back-time considerations. Furthermore, the feasibility of very stringent world-wide GHG emissions abatement policies may be questioned considering their economic downside which is too hard to accept for decision-makers, especially in developing countries.

Overall, the scenarios elaborated in the present study can be considered as more realistic since they take into account the regional specifics, compared to other purely global studies, and the dynamics of the technology diffusion process in electricity sector. Accordingly, these scenarios may constitute a sound basis for further analyses that should be emphasised on the optimization of the public expenditures supporting further development, demonstration and deployment of Fusion technology.

APPENDIX A. List of Regions and Countries Considered in PLANELEC Scenarios

Code	Region	Countries
NAM	**North America**	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
LAM	**Latin America and the Caribbean**	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, St. Lucia, St. Vincent and Grenadines, Suriname, Trinidad-Tobago, Uruguay, Venezuela
WEU	**Western Europe**	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
CEE	**Central and Eastern Europe**	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, The former Yugoslav Republic of Macedonia, Poland, Romania, Serbia and Montenegro, Slovakia, Slovenia
CIS	**Commonwealth of Independent States**	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MEA	**Middle East and North Africa**	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, Yemen
AFR	**Sub-Saharan Africa**	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo, Congo (DR), Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe
SAS	**South Asia**	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
PAO	**Pacific OECD**	Australia, Japan, New Zealand, Republic of Korea
CPA	**Centrally Planned Asia**	Cambodia, China, Korea (DPR), Lao (PDR), Mongolia, Viet Nam
PAS	**Other Pacific Asia**	Brunei, Fiji, French Polynesia, Indonesia, Kiribati, Malaysia, Myanmar, New Caledonia, Papua-New-Guinea, Philippines, Samoa, Singapore, Solomon Islands, Thailand, Tonga, Vanuatu.

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4. FUSION RDDD REAL OPTIONS MODEL

The strategic value of Fusion technology is estimated in this chapter with the help of real options approach. Estimation is based on the expected discounted cash flows from construction and operation of Fusion power plants, exogenous assumptions regarding the costs and duration of Fusion RD&D activities, and subjective probabilities of success at each programme stage. The expected net present value of Fusion RDDD programme estimated in a stochastic probabilistic setting represents the benchmark for calculating real option value attributable to different managerial decisions that may affect the prospective cash-flows. Two different strategies are compared: "Baseline" corresponding to the current relatively moderate pace of Fusion RDDD programme vs. "Accelerated" strategy which assumes rapid development and massive deployment of Fusion. The calculations are made using different specifications of real option model: simple vs compound; crisp vs fuzzy. The conclusions are drawn from the model calculations regarding the potential net benefits of Fusion RDDD programme and the attractiveness of "Accelerated" strategy.

4.1 Real Options Analysis in the Context of Fusion RDDD Programme

In recent decades, the real options approach (ROA) has gained an increasing attention in academic literature and business practice as a versatile capital budgeting technique which allows for evaluation of large investment projects characterised by a high degree of uncertainty and multiple risks. The main advantage of ROA consists in the possibility to capture the strategic value of investments arising due to flexibility in the managerial decisions that can be taken throughout the lifecycle of a project, i.e. specific actions aimed at reducing the downside losses if the market situation is unfavourable and increasing potential project upside in the opposite case. Meanwhile, practical implementation of ROA is not straightforward, since it relies on numerous exogenous assumptions and different computational algorithms that should be adapted to the needs of each individual project under evaluation.

For large scale multi-stage projects or R&D programmes, such as Fusion, exhibiting both "technical" project uncertainty and "economic" market uncertainty it is important to use a combination of traditional evaluation methods, namely DCF and decision tree analysis (DTA), with a real options approach. Indeed, the economic performance of any project may depend on both exogenous factors, e.g. future market prices, competition, regulation, etc., and project-specific technical parameters, e.g. product costs, production volume, efficiency, etc., which can be also uncertain at the beginning of the project. While uncertainty about exogenous factors is beyond control of the investor, as it can be resolved only with time, the "technical" uncertainty can be reduced by undertaking some actions and progressing through the project implementation stages. Accordingly, the choice of most appropriate evaluation technique will depend on the degree of both "technical" and "economic" uncertainty, considering that traditional DCF method is more suitable for the situations with low uncertainty, while its combination with ROA and DTA is preferred for evaluation of projects characterised by higher "technical" and "economic" uncertainty and the possibility to actively manage project pay-offs (see e.g. Piesse *et al*., 2005).

In the evaluation of Fusion RDDD programme "technical" uncertainty (which can be also referred to as epistemic or reducible uncertainty) principally relates to technical & economical parameters of future Fusion power plants (investment and O&M costs, thermodynamic efficiency, capacity factor, etc). "Economic" (aleatory or irreducible) uncertainty concerns mainly the future market conditions, e.g. fuel, electricity and carbon prices, availability of economically and socially acceptable alternative power supply options, environmental policy regime, etc. Finally, the probability of moving from one programme implementation stage to another, duration of each stage and as well as the total amount of Fusion power generation capacities to be built exhibit elements of both "technical" and "economic" types of uncertainty.

The typical managerial decisions (flexibility actions) through the pace of Fusion RDDD programme can be described as follows:

1. Once the practical feasibility of Fusion technology is successfully proved during R&D and demonstration stages, the programme managers will have the possibility either to invest in the construction of Fusion power plants in order to rip economic benefits from electricity sale on the market or to postpone the investment if market conditions turn out to be unfavourable. This type of managerial decision corresponds to the **"option to invest"** or **"option to defer"** (equivalent to financial *American call option*) which quantifies a trade-off between the higher expected revenues from immediate investment and the potential losses that can be avoided by waiting until the uncertainty about the future value driving factors is being resolved.

2. In practice, many investment opportunities have a sequential nature, meaning that progress towards an ulterior stage depends on the successful completion of the previous stages. This type of real options, known as **"compound option"**, is equivalent to a set of financial *European call options*. The Fusion RDDD process may be viewed as such sequential compound option, because at each stage the managers will have to decide whether to move on with further investments or to stop the programme. On the one hand, the decision to invest will depend on the expected net present value of all future stages; on the other hand, the opportunity to invest in the next phase will emerge only if the previous phase was successful. The value of compound option is significant, especially in the case of long lasting multi-stage projects involving significant R&D and other learning investments which *per se* are characterised by high level of technical uncertainty and negative NPV, but which potentially are capable to generate important positive cash flows through the ulterior market deployment stages.

3. Another type of real options consists in the possibility to abandon a project if the expected value of future cash flows is not sufficient to cover the total (present and future) project costs. By deciding to permanently close a project, the investor may "save" its follow-up expenditures and to recover, at least partially, the salvage value of the incurred investments. This **"abandonment option"** is equivalent to financial *American put*

option. Although in the case of Fusion RDDD programme it is hard to envisage that Fusion research infrastructure or reactor equipment could be used for other purposes than performing experiments on confinement of Fusion plasma, nevertheless it may represent a significant economic value due to "spillover" benefits, i.e. alternative applications in other non-Fusion domains of different types of knowledge, materials, processes and products developed for specific Fusion RD&D needs.

4. A successful implementation of Fusion RD&D programme resulting in practical handling of Fusion technology for electricity generation purposes will open opportunity for development of other applications of Fusion reaction, such as large scale production of hydrogen, desalination of water, outer space propulsion, etc (see e.g. Sheffield *et al.*, 2000). Commercialisation of these additional products may enhance the overall economic prospects of Fusion, because the potential demand for these products / services could, in principle, be very high given a restrained range and significant cost of alternative solutions. These additional market opportunities can be considered as **"expansion (growth) options"** (equivalent to financial *American call option*) and they also have to be taken properly in to account in the evaluation and management of Fusion RDDD programme.

5. One additional managerial flexibility option can be embedded in the demonstration stage of Fusion RDDD programme if the decision is made to proceed with the construction of two or more Fusion "Demo" installations relying on alternative technological concepts. As discussed in chapter 2.1.1 the "mainstream" design configuration based on Tokamak-type Fusion reactor is being currently developed in parallel with several other configurations stemming from both "Inertial" and "Magnetic" confinement concepts. So, in the event if Tokamak design will be facing insurmountable technical problem (e.g. failure to assure the required level of stability of Fusion plasma), the programme managers may have the possibility to switch to alternative configuration (e.g. Stellarator-type Fusion reactor, which has superior technological characteristics in respect of plasma stability). Such a flexibility option corresponds to the real **"option to switch"** which is analogous to a *portfolio of American call and put options*. It is also not excluded that future Fusion power plant could be designed in such a way that would allow them for switching production from electricity to hydrogen. This flexibility can be also valued using real options approach as discussed in Botterud et al. (2008) based on the example of advanced "Generation IV" nuclear power plants.

Several other types of real options have been also considered in the literature (e.g. option to adjust production volume, option to shut down and restart operation, option to change capital structure, simultaneous compound option, etc.), which are more relevant for the operational stage of Fusion RDDD programme, i.e. when Fusion will become technologically and commercially proved technology. Given the time frame and the underlying uncertainty, the evaluation of these options will hardly add any substantial insight regarding the potential socio-economic value of Fusion RDDD programme, and hence they will not be further investigated in this thesis. Meanwhile, considering the described above taxonomy of real options, the consecutive analyses will concentrate on determining the strategic "expanded" net present value of Fusion RDDD programme, which according Trigeorgis (2000) can be determined as the sum of traditional (static) NPV of expected cash flows plus the value of strategic options arising due to active management of Fusion RD&D process and interactions thereof (option premium).

4.2 Expected NPV of Fusion RDDD programme

In order to estimate the strategic value of Fusion RDDD programme one has to proceed first with 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 probabilistic setting which allows for random fluctuation of the key parameters within predefined value ranges while assuming a specific probability of success for each programme implementation stage.

4.2.1 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 “Demonstration” 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 37***. Subsequent sections provide a detailed analysis of each of the main factors which 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 with the help of PLANELEC model and presented in Chapter 3 above. The third ***optimistic*** scenario (“**C”**) reflects the main hypotheses adopted in the UKAEA study[25].

Initial public RD&D costs

The current estimates of the total costs related to the construction and experimental operation of major Fusion RD&D facilities such as ITER, IFMIF, Demo alongside with the costs of other supporting RD&D activities were presented in Chapter 2.1 above. In summary, it is expected that the total public investments in Fusion RD&D will be in the range € 60 - 100 billion. Assuming that these works will be finished by 2050, these figures correspond to the annual expenditures of €1.4 billion in less ambitious scenario and €2.4 billion in most optimistic scenario envisaging construction of several Demo reactors of alternative concept (see ***Table 19***).

[25] “The value of Fusion as a Possible Future Energy Source: Model and Example Calculations” (see Ward *et al*., 2002)

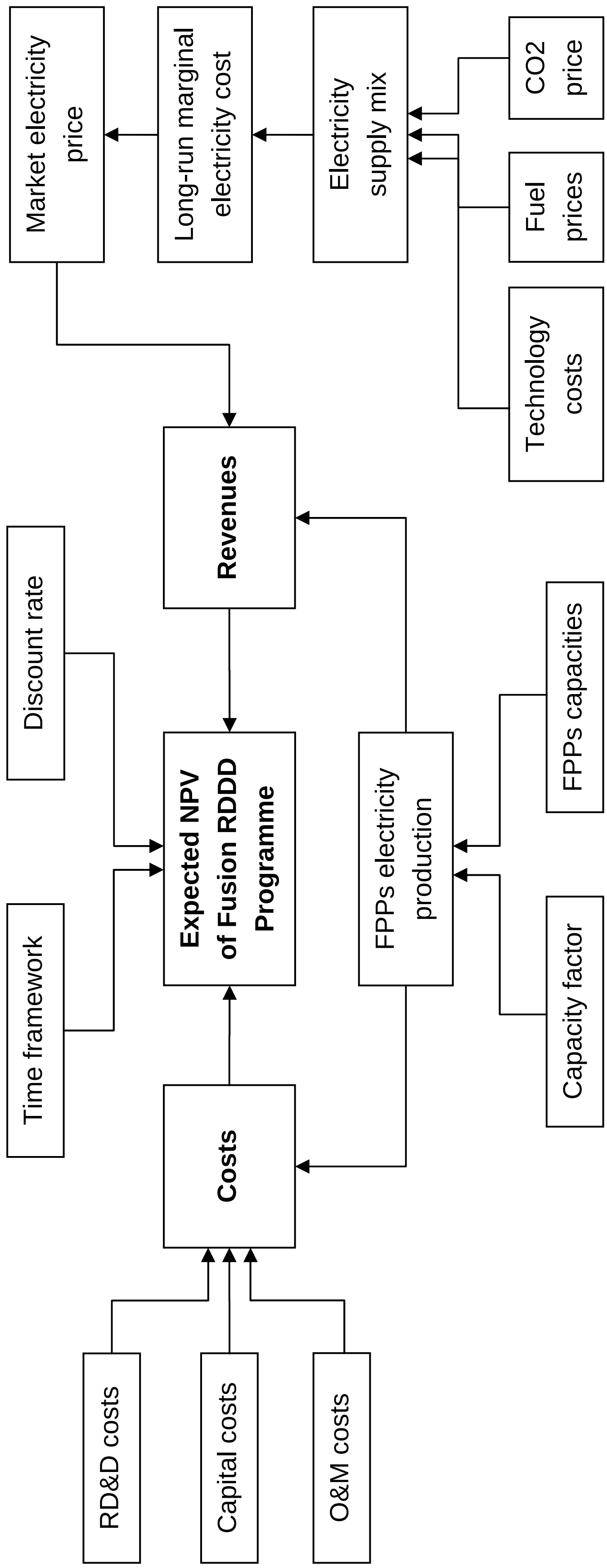


Figure 37. Fusion ENPV Influence Diagramme

Table 19. Assumed Values of Future Public Investments in Fusion RD&D

	Scenario A	Scenario B	Scenario C
Annual costs (€ billion)	1.4	1.9	2.4
Duration (yrs)	42	42	42
Total cost for 2009-2050 (€ billion)*	60	80	100

* undiscounted

In the present deterministic case, the time frame 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 of Fusion technology. This issue will be investigated more thoroughly in the next chapter performing ENPV calculations in a probabilistic setting.

Further 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 may also fall into this category. It is also assumed that the total amount of public funds invested in these activities will be gradually reduced from initial relatively high values, corresponding to the annual expenditures during RD&D stages, to nearly "zero" value meaning that Fusion technology became mature and fully assimilated be the private sector (see ***Table 20***).

Table 20. Assumed Costs of Fusion RD&D and Other Public Support 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 throughout 2051-2100	*Linear reduction to "zero" value by 2100*		
Total cost for 2051-2100 (€ billion)	30	40	50

Again, like with RD&D expenses the time frame for "Deployment" stage is assumed to be the same for all three scenario cases, i.e. 50 years from 2051 until 2100.

Fusion power plants' construction & operation costs

In order to estimate the total costs due to construction and operation of Fusion power plants 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 that can be expressed as follows:

$$COE \approx \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}{}^{0.5}} \frac{1}{P_e{}^{0.4}\beta_N{}^{0.4}N^{0.3}} \tag{4.1}$$

where *COE* is the cost of electricity, *A* is the availability, η_{th} is the thermodynamic efficiency, P_e is the net electric power, β_N is the normalised plasma pressure, and $N=n/n_G$ is the 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%).

Using the PROCESS model the electricity cost of four main Fusion design concepts considered in European PPCS study (Maisonnier *et al*., 2005) was estimated in the range of 50 to 90 €/MWh. A recent review of the economics of Fusion power made by Han & Ward (2009) provides the following estimates of capital, fixed O&M and variable O&M costs for different generations of Fusion reactors (***Table 21***).

Table 21. Specific Costs of Fusion Power Plants

	Capital	FIXOM	VAROM
Basic plant	3940 $/kW (*early*)	65.8 M$/GWa	2.16 M$/PJ (*early*)
	2950 $/kW (*mature*)	65.8 M$/GWa	1.64 M$/PJ (*mature*)
Advanced plant	2820 $/kW (*early*)	65.3 M$/GWa	2.14 M$/PJ (*early*)
	2170 $/kW (*mature*)	65.3 M$/GWa	1.64 M$/PJ (*mature*)

Source: Han & Ward (2009)

In these estimates the fuel costs associated mainly with a regular replacement of lithium blanket and decommissioning costs are included in fixed O&M costs, while waste disposal is included in variable O&M costs. "Early" technology corresponds to 10^{th} of a kind Fusion power plant (FPP) and "mature" technology to 100^{th} of a kind. Based on the values presented in *Table 21* above 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.

As discussed in IEA (2000) practically in all fields of industrial activities, including production of power generation equipment, there is a steady quantitative relationship between the cost and cumulative production or use of a technology. This relationship, called "experience curve", describes how the cost declines with cumulative production, where cumulative production is used as an approximation for the accumulated knowledge and experience in producing and employing a technology. A specific characteristic of experience curves is that cost is reduced by a constant percentage with each doubling of the total number of units produced (Neij *et al*., 2003).

Usually, the experience curve is defined by the following equation:

$$C_X = C_1 X^{-E} \tag{4.2}$$

where C_X is the specific cost as a function of cumulative output (X), C_1 is the cost of first unit produced and E is the experience parameter. The value (2^{-E}), which is called the progress ratio, is used to express the progress of cost reduction. Accordingly, the relative cost reduction (learning rate) for each doubling of cumulative production can be expressed as ($1-2^{-E}$), i.e. a progress ratio of 85%, for example, means that costs are reduced by 15% each time cumulative capacity is doubled. The typical values of progress ratios for Fusion reactors found in the literature vary from conservative 90% (e.g. Eherer & Baumann, 2005; Han & Ward, 2009) to relatively optimistic 80% (e.g. Hamacher & Bradshaw, 2001).

Given the estimates of specific investment and O&M cost of 1st of a kind FPP and assuming some reasonable progress ratio for Fusion reactor equipment, the total costs due to construction and operation of Fusion power plants can be determined for each scenario variant subject to the scenario-specific annual Fusion build-up rates. According to the findings of PLANELEC study described in Chapter 3, the total Fusion power generation capacity in 2100 can be estimated at 330 GW in pessimistic "Scenario A" and 950 GW in intermediate "Scenario B". The total Fusion capacity in most optimistic "Scenario C" is projected to reach 1950 GW that roughly corresponds to the mean value[26] in UKAEA study of Ward *et al*. (2002).

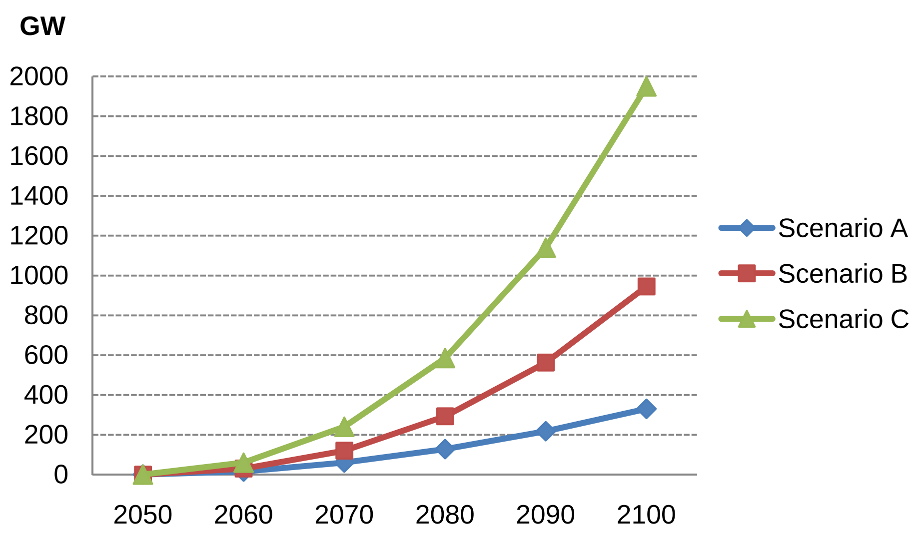


Figure 38. Projected Fusion Power Capacities in Three Scenarios *(Source: author's estimation)*

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 38*** above. Based on the

[26] min 1500 GW, mid 2000 GW, max 2500 GW after 40 years from the start of FPPs construction

corresponding annual build-up rates and assuming a conservative 90% progress ratio, the specific costs can be estimated for Fusion power plants of different vintages as shown in ***Figure 39***. It is worth noting that during the initial deployment period (2050-2070) the FPPs costs decline steeply from relatively high values for 1st of a kind FPP to 10th of a kind FPP, while during the consecutive period 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 demonstration stages.

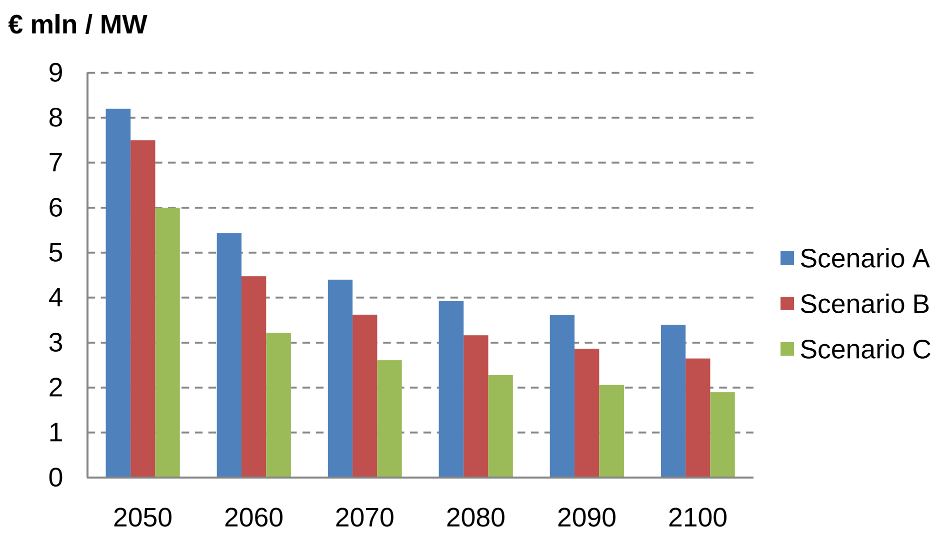


Figure 39. Estimated Specific Capital Costs of Fusion Power Plants *(Source: author's estimation)*

Taking into account the projections of Fusion technology costs made in PLANELEC study 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 (see ***Table 22***). These costs represent 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 Fusion COE and annual Fusion electricity production subject to scenario-specific Fusion build-up rates and FPPs capacity factor.

Table 22. Assumptions on Average Investment and O&M 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[27] (mln €)	350	270	190
Annual O&M costs[28] (mln €/MW)	0.15	0.12	0.11
Fusion COE[29] (€ / MWh)	55	43	34

27 assuming 5% interest rate, 40 years lifetime and 1500 MW unit capacity

28 include both fixed and variable O&M costs

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 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 (see *Figure 38*) 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; Heng & Li, 2007). In order to estimate LRMC one needs to elaborate two optimized expansion plans of a given power generation system over a substantial period of time ($\approx$ 30 years), one of them representing the current load forecast and another one under the forecast which has a predefined load increment. Then LRMC can be calculated as the difference in the NPV of two optimized expansion plans divided by the change in NPV of load (IES, 2004).

The specifics of this approach is that it determines the marginal electricity cost based on existing and new power generation capacities taking into account both operating and capital costs required for new capacity. Depending on the state of the system, e.g. if there exist an excess capacity, additional electricity can be supplied at prices close to short run marginal cost of electricity, i.e. excluding the capital costs of capacity expansion. Considering that in very long-term energy scenario planning, extending over 100 years, the future state of the electricity system, including the structure of installed power generation capacities and the reserve margins, is highly uncertain, the estimation of LRMC using the presented above method can be significantly biased by the subjective assumptions.

Another simplified approach to the estimation of future electricity prices consists in the calculation of 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. According to the analyses performed in the previous chapter, conventional power generation technologies such as nuclear power, advanced coal and combined cycle natural gas may suit well for representing such a marginal electricity supply option for the time horizon 2050 when Fusion technology is expected to enter the market.

The main factors which should be considered in the computation of LRMC include: (i) technology – specific technical & economical parameters (i.e. capital costs, fixed and variable

[29] assuming 80% capacity factor

O&M costs, efficiency, lifetime and capacity factor); (ii) fuel prices; and (iii) CO_2 prices (for technologies using hydrocarbon fuels, such as coal and natural gas). While technical-economical parameters can be estimated based on the existing data and assuming some prudent hypothesis about the technological learning rates, the fuel and CO_2 prices are by far more difficult to forecast, since they are subject to multiple market forces and political regulations. Hence, the projection of LRMC should also rely on scenario approach.

Table 23 below represents the cost assumptions for four main power generation technologies, namely natural gas combined cycle power plant (NGCC), nuclear power plant (NUC), coal-based integrated gasification combined cycle power plant (IGCC) and IGCC power plant with CO_2 capture and sequestration (IGCC-CCS), which can be considered as most technically and economically viable options for expansion of electricity generation systems by the middle of this century. These values correspond to the reference technology assumptions for the time period 2060-2080 and indicative fuel prices scenario adopted in PLANELEC study (see Chapter 3), and they are also in line with the projections given in OECD (2005) and EIA (2009).

Table 23. Long-run Marginal Cost Assumptions for Coal, Natural Gas and Nuclear Power Plants

	Unit	IGCC	IGCC-CSS	NGCC	NUC
Power plant capacity	*MW*	900	900	600	1500
Lifetime	*years*	30	30	25	40
Thermal efficiency	*%*	58	52	64	45
Capacity factor	*%*	87	82	88	90
CO_2 emission rate	*t/MWh*	0.61	0.07[30]	0.32	0.0
Investment costs	*€/MW*	960	1300	400	1650
Fuel price	*€/GJ*	2.2	2.2	7.8	1.7
CO_2 price	*€/t*	20	20	20	20
Cost of capital	*€/MWh*	11.2	16.1	4.8	17.5
Fuel costs	*€/MWh*	13.4	14.9	43.7	13.3
Variable O&M costs	*€/MWh*	3.2	8.9[31]	1.5	0.5
Fixed O&M costs	*€/MWh*	5.0	6.4	2.7	8.5
CO_2 costs	*€/MWh*	12.2	1.4	6.3	0.0
LRMC	*€/MWh*	**45.0**	**47.7**	**59.0**	**39.9**

As stated above, the estimation of LRMC for each individual technology over very long period of time (i.e. beyond 2050) depends greatly on the assumptions regarding fuels' and CO_2 prices. Indeed, while technological progress is supposed to drive the electricity cost down and this movement can be reasonably assessed based on the current estimates of technologies' costs and their historical learning rates; at the same time, the unexpected upward price movements, especially in the case of natural gas, may inflate substantially the cost of electricity generation. In order to grasp the effect of fuels and CO_2 price fluctuation on LMRC, the sensitivity analyses

[30] assuming 90% carbon capture & sequestration efficiency (v/v)

[31] including the costs of CO_2 transportation and geological sequestration

have been performed for all four technologies. The fuel prices were allowed to vary within diapason -50% / + 100% compared to the reference values given in *Table 23*, and the considered levels of CO_2 price were 0; 10;...50 € / t CO_2.

As shown in ***Figure 40*** below, the full cost of electricity (i.e. LRMC) that can be produced by these representative technologies falls in to the range of €26 to €112 per MWh under different assumptions regarding fuels' and CO_2 prices. 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/tCO_2 price. By excluding the nuclear power which is facing severe political risks of complete phase-out, such as in the case of Germany, and the variants envisaging doubled fuels' prices and CO_2 price below €20/t which corresponds to the current price (2008) in EU emission trading scheme, the LRMC range is narrowed to €45 to €90 per MWh.

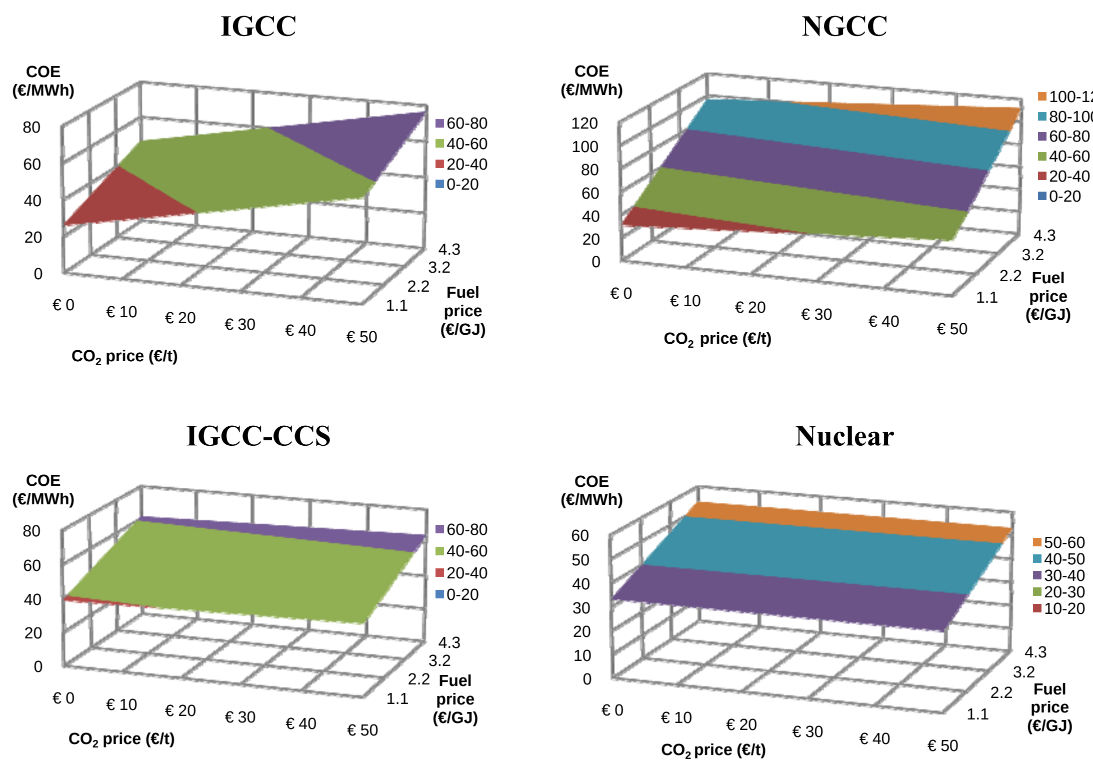


Figure 40. LRMC Sensitivity to Fuel and CO_2 Prices *(Source: author's estimation)*

It is interesting to note that this price range (€45 - 90 per MWh) 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 (€70 - 130 per MWh). Accordingly, it was decided to perform further evaluation of Fusion RDDD programme based on the future electricity price diapason of €50 - 100 per MWh.

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. As regards the timeframe, the length of publically supported Fusion "deployment" stage is limited in this study to 50 years (i.e. up to the time horizon of 2100) assuming that afterwards Fusion technology can be fully uptaken 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 higher discount rate during RD&D stage and lower discount rate during deployment stage reflecting the higher degree of risk during initial programme stages. This approach coincides with the proposal made in the seminal paper 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). Finally, Newell & Pizer (2004) proposed the concept of uncertain discount rates which may follow mean-reverting or random walk stochastic process and 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.

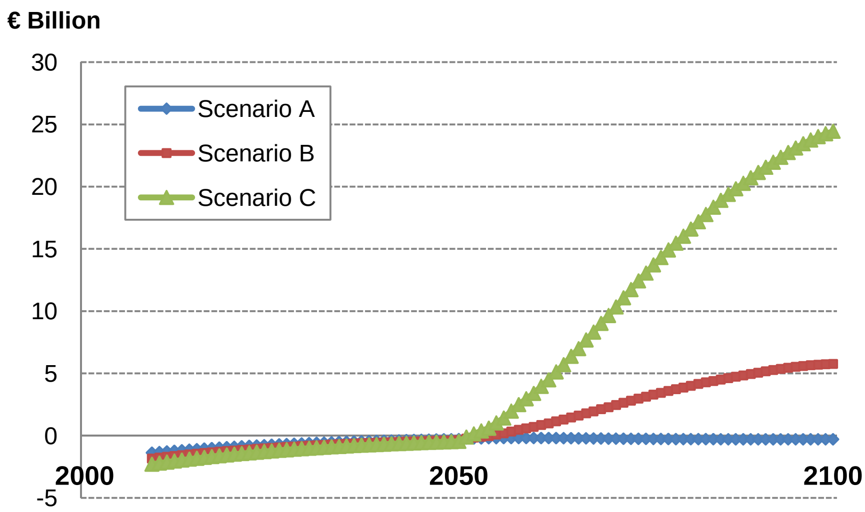


Figure 41. Projected Cash-flows of Fusion RDDD Programme in Deterministic Case

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; Hansen, 2006) it was chosen to set up a constant discount rate of 4% for all scenarios in the present deterministic case (with consecutive sensitivity analyses) and to perform evaluation using uncertain stochastic discount rates varying in the range of 3% to 5% in the probabilistic case.

Results

The projected discounted cash-flow patterns of Fusion RDDD programme in all three scenarios are shown in ***Figure 41*** above. 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 the Fusion production cost further down.

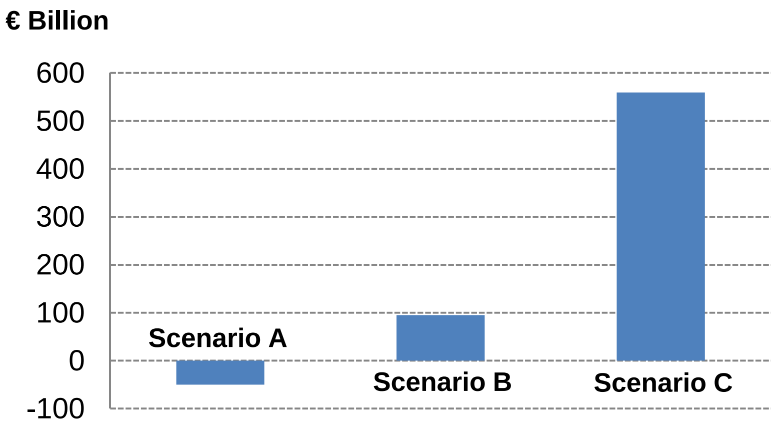


Figure 42. NPV of Fusion RDDD Programme in Deterministic Case

Two other scenarios indicate a substantially positive net present value of Fusion RDDD programme, namely €95 billion and €559 billion (see ***Figure 42***) confirming the idea that under reasonable assumptions, development and deployment of Fusion technology may bring about important net socio-economic benefits due to creation of a novel environmentally friendly and economically competitive electricity supply option.

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% as suggested by Weitzman (2001) for medium term analyses, results in more than five-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 stills positive in two out of three scenarios (see ***Table 24***).

Table 24. Fusion RDDD Programme NPV Subject to Different Discount Rates (€ billion)

	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

Another relevant sensitivity analysis reflects the possibility of choosing different discount rates for RD&D and Deployment stages as it was done in UKAEA study. As shown in ***Figure 43*** the choice of lower discount rate during RD&D stage and higher discount rate during Deployment decreases NPV of the Fusion RDDD programme due to relative devaluation of the prospective economic benefits and increase of the present value of incurred RD&D costs.

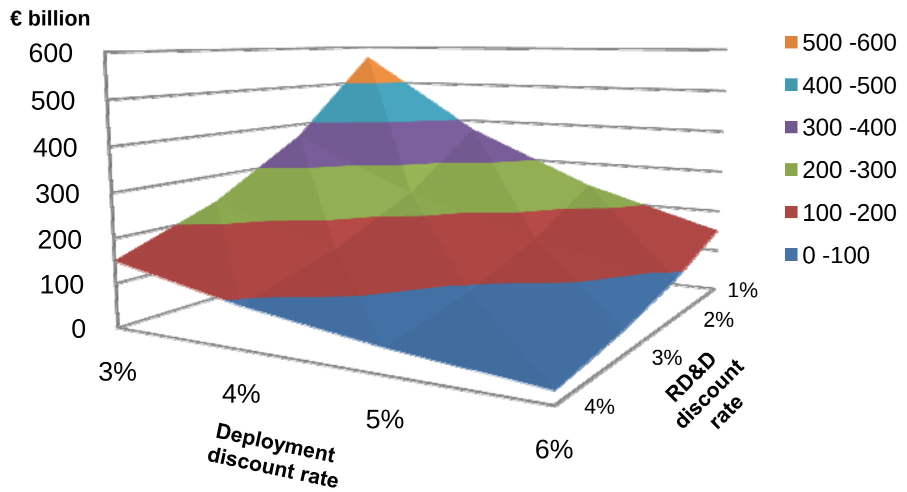


Figure 43. Sensitivity of Fusion RDDD Programme NPV to Different Discount Rates During RD&D and Deployment Stages (Scenario B)

The results of scenario analyses elaborated in a 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 probabilistic simulation technique.

4.2.2 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 probabilistic setting in which specific probabilities of success are assigned for each programme stage, and the main model variables (such as duration, costs, revenues, discount rate) are allowed to vary stochastically according to certain probability functions. On top of this, the possible effects of different managerial actions can be also evaluated through a combination of probabilistic simulation and scenario analyses.

The main assumptions and hypotheses underlying the probabilistic simulation of the basic case, which is derived from the middle course “Scenario B” elaborated in a deterministic setting, are presented in ***Table 25*** below.

Table 25. Main Assumptions for Probabilistic Simulation of Fusion RDDD Programme

	Unit	Minimum Value	Likely Value	Maximum Value	Distribution Form
R&D stage					
Total costs	€ billion	-	35	-	
Duration	yrs	-	22	-	
Probability of success	%		90		Bermoulli
Demo stage					
Total costs	€ billion	30	45	60	Triangular
Duration	yrs	15	20	25	Triangular
Probability of success	%	70	80	85	Bermoulli + Triangular
Deployment stage					
R&D support costs	€ billion	30	40	50	Triangular
Duration	yrs	-	50	-	
Average annual Fusion electricity production					
2051 - 2060	TWh	45	90	181	Triangular
2061 - 2070	TWh	256	515	1030	Triangular
2071 - 2080	TWh	668	1461	2922	Triangular
2081 - 2090	TWh	1218	3023	6117	Triangular
2091 - 2100	TWh	1945	5382	10975	Triangular
Fusion Cost of Electricity					
2051 - 2060	€/MWh	51.3	64.5	78.4	Triangular
2061 - 2070	€/MWh	43.6	54.8	66.7	Triangular
2071 - 2080	€/MWh	39.4	49.3	61.1	Triangular
2081 - 2090	€/MWh	36.4	45.6	57.3	Triangular
2091 - 2100	€/MWh	34.3	42.9	54.6	Triangular
Market electricity price	€/MWh	50	75	100	Uniform / Triangular / Lognormal
Discount rate	%	3	4	5	Uniform / Trinagular

Compared to the previous deterministic case which used specific annual cost of Fusion electricity and installed capacity figures, in the probabilistic setting Fusion power plans are distinguished according to different vintages corresponding to five 10-years time 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 25*** should be considered as weighted average values for each specific 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*" stage which will be entirely taken on charge be the private sector.

The software employed for probabilistic analysis of Fusion RDDD programme is "*Risk Simulator*", version 5.3, developed by Johnathan Mun at Real Options Valuation, Inc. 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 (see Mun, 2009a). In all simulations the number of trials was fixed at 2000 with a unique seed sequence.

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 either *uniform* probability distribution (e.g. to model future discount rates) or *triangular* distribution 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 knowledge of the minimum and maximum values and an "inspired guess" as to what the modal value could be (see ***Figure 44***).

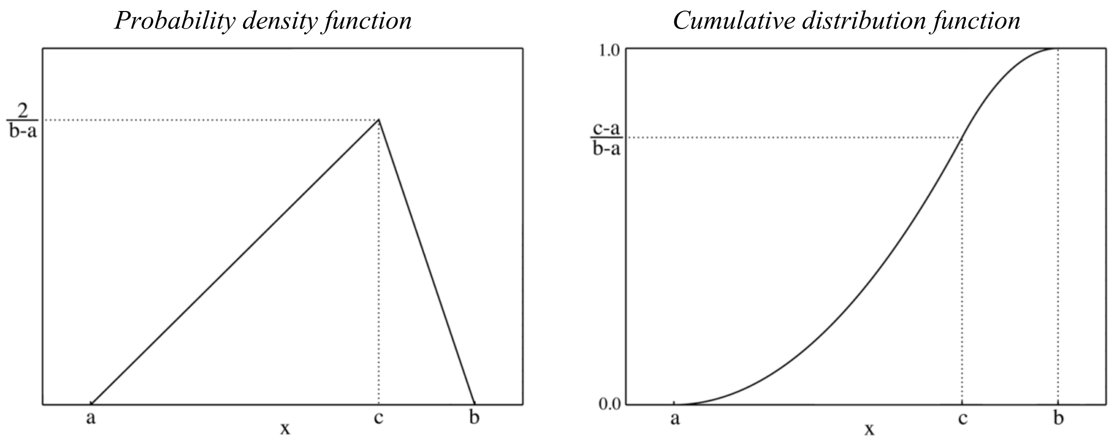


Figure 44. Triangular Distribution

The triangular distribution belongs to the family of continuous distributions. It is defined on the range $x \in [a,b]$ with probability density function

$$P(x) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & for \;\; a \le x \le c \\ \frac{2(b-x)}{(b-a)(b-c)} & for \;\; c < x \le b \end{cases} \tag{4.3}$$

and cumulative distribution function

$$D(x) = \begin{cases} \frac{(x-a)^2}{(b-a)(c-a)} & for \;\; a \le x \le c \\ 1 - \frac{(b-x)^2}{(b-a)(b-c)} & for \;\; c < x \le b \end{cases} \tag{4.4}$$

where $c \in [a,b]$ is the mode, and $\mu = \frac{1}{3}(a+b+c)$ is the mean (see e.g. Evans *et al.*, 2000).

Accordingly, minimum value (*a*), mode or most likely value (*c*) and maximum value (*b*) constitute the distributional parameters.

Simulation # 1

The simple fact of introducing probabilities of success for each programme stage, i.e. R&D and Demonstration, while using "most likely" values exhibited in *Table 25* above, reduces significantly the expected NPV compared to the results of deterministic scenario analyses. As shown in ***Figure 45*** the probabilistic simulation allows for taking into account the 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 mean value or in other terms 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 scenario "B" that roughly corresponds to the alone positive outcome).

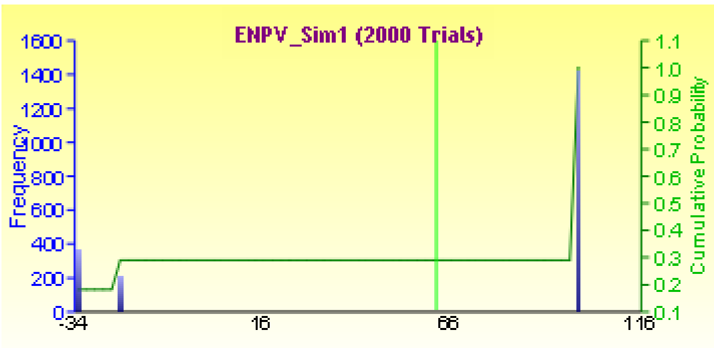


Figure 45. Expected NPV of Fusion RDDD Programme *(Simulation # 1)*

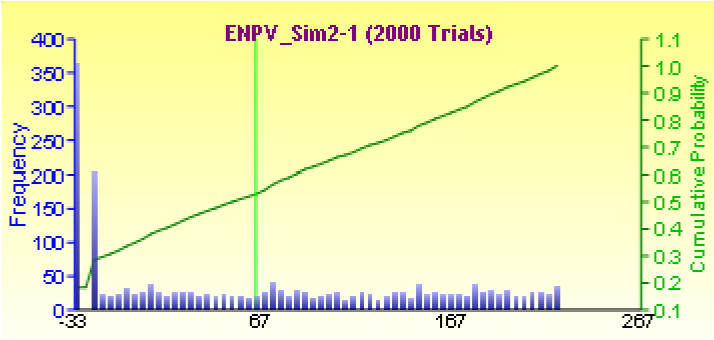
Evidently the results of deterministic and probabilistic analyses may diverge even to a greater extent, as far as the number of successive stages may be increased and the specific probabilities of success at each stage are lowered.

Simulation # 2

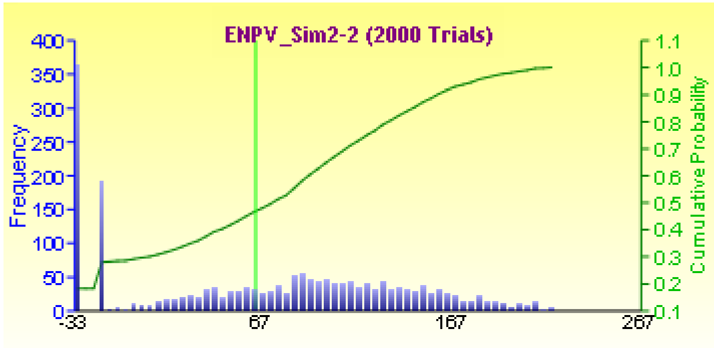
The second simulation explores the effects of stochastic variation of future electricity price, while all other variables are still assigned with their most likely values. The electricity price is modelled in three different ways. In Simulation # 2.1 it follows a uniform distribution meaning that any level of electricity price is equally possible within predefined diapason (i.e. €50 to €100 per MWh). Considering the historical dynamics of European wholesale electricity prices which normally exhibit a mean-reverting tendency with seasonal drifts and occasional spikes, such an assumption could be considered as less realistic compared to triangular distribution (Simulation # 2.2) or lognormal distribution (Simulation # 2.3).

The results of all three simulations are shown in ***Figure 46***. In fact, the expected NPV of Fusion RDDD programme increases due to uncertainty about the future electricity prices. In the first case it is equal to €62.7 billion (with volatility of 136%). In the second case ENPV is practically the same: €62.8 billion, while volatility (117%) is lower. In the third case ENPV is a little bit higher: €65.9 billion, while volatility (264%) is practically doubled.

Uniform electricity price distribution



Triangular electricity price distribution



Lognormal electricity price distribution

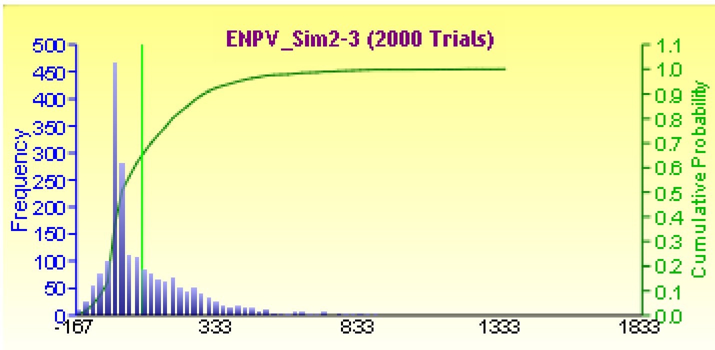


Figure 46. Expected NPV of Fusion RDDD Programme *(Simulation # 2.1, 2.2 and 2.3)*

In principle, the use of lognormal distribution in modelling of future electricity prices is advocated in numerous studies. However, in the context of the present Monte Carlo simulation it results in excessive volatility. This can be explained by the fact that here single electricity price is assigned to all years of the study period, while in practice extreme price levels embraced in lognormal distribution may occur only during short periods of time. Hence, the choice of triangular distribution with some reasonable bounds appears to provide a more realistic estimate.

<u>Simulation # 3</u>

This simulation explores the effect of introducing positive correlations between future electricity price and the amount of Fusion power generation. The intuition behind this assumption is that higher market electricity prices may booster deployment of Fusion power plants and hence their absolute production volumes and vice versa. Accordingly, in this case the future Fusion electricity production is also allowed to vary stochastically with positive correlation between annual production volumes of each 10 years sub-period. Meanwhile, Fusion COE is kept constant at the level of its most likely value. As shown in ***Figure 47*** in this case ENPV of Fusion RDDD programme is significantly higher compared to the previous simulations with mean value of €79.6 billion and volatility of 128%.

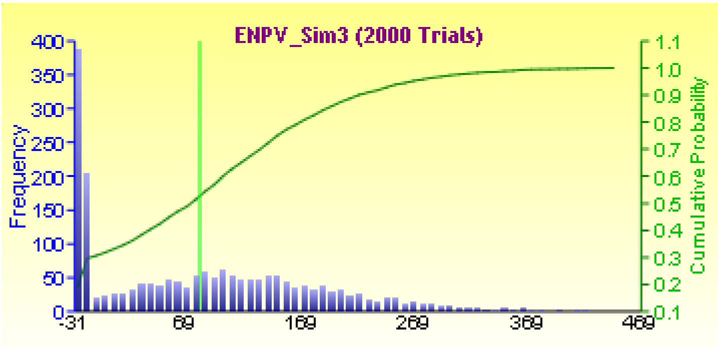


Figure 47. Expected NPV of Fusion RDDD Programme *(Simulation # 3)*

<u>Simulation # 4</u>

This simulation goes one step further by allowing a stochastic variation of Fusion cost of electricity parameter and assuming a negative correlation between future Fusion electricity production and Fusion COE specific for each 10 years sub-period. Such a set up can be considered as more adequate for representing the learning process of Fusion technology which naturally implies a gradual cost reduction subject to the increasing capacity and production volumes. Future market electricity prices are also allowed to vary stochastically in this simulation. However, there is no correlation between them and Fusion electricity production as in previous simulation.

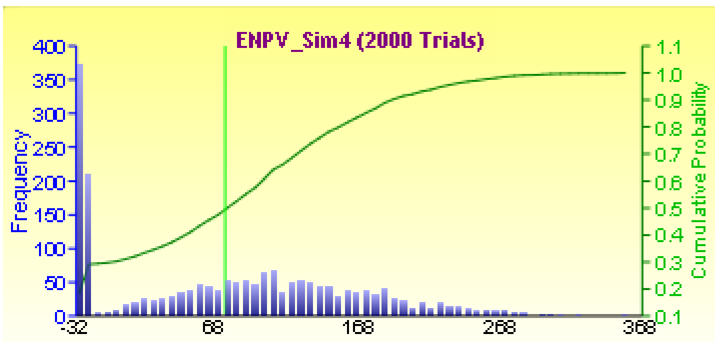


Figure 48. Expected NPV of Fusion RDDD Programme *(Simulation # 4)*

As shown in ***Figure 48*** above in this case ENPV of Fusion RDDD programme is lower compared to the previous Simulation # 3 and higher compared to Simulations # 1 and 2 with mean value of €73.7 billion and volatility of 120%.

Simulation # 5

In this simulation like in the previous one the future electricity prices, Fusion production volumes and Fusion cost of electricity are allowed to vary stochastically conforming to a triangular probability distribution function. The difference compared to the simulations # 3 and # 4 is that 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. The results of the simulation demonstrate an increasing ENPV (79.7 billion) and volatility of 125% .

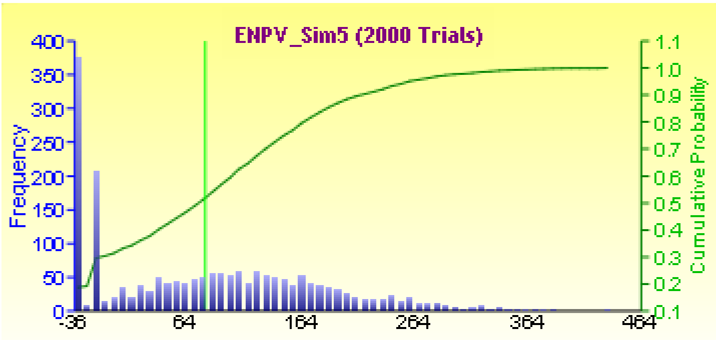


***Figure 49. Expected NPV of Fusion RDDD Programme** (Simulation # 5)*

Simulation # 6

This simulation represents the most general case. The main assumption here is that probability of success and duration of the DEMO stage are allowed to vary stochastically subject to the amount of endowed funding, which also varies stochastically according to a triangular distribution function. Negative correlation is implied between duration of the stage and its funding, while positive correlation is assumed between funding and the probability of success. The funding of the DEMO stage is positively correlated with the further R&D and support funding during deployment stage and negatively correlated with Fusion cost of electricity 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 other assumptions are in line with those of the previous simulation # 5.

Table 26. Correlation Matrix for Probabilistic Simulation # 6

		I	II	II	IV	V	VI	VII
I	DEMO stage funding	1.00						
II	DEMO stage duration	**-0.99**	1.00					
III	DEMO probability of success	**0.72**	0.00	1.00				
IV	Deployment support funding	**0.51**	0.00	0.00	1.00			
V	Fusion COE	**-0.51**	0.00	0.00	**-0.26**	1.00		
VI	Fusion electricity production	0.00	0.00	0.00	0.00	**-0.10**	1.00	
VII	Electricity price	0.00	0.00	0.00	0.00	0.00	**0.10**	1.00

The adjusted correlation matrix is given in ***Table 26***. Compared to the previous case the expected NPV of Fusion RDDD programme becomes slightly lower (€73 billion) with practically the same volatility (124%). The decrease in ENPV can be explained by the distribution assumptions regarding the DEMO stage probability of success, which is skewed to the left, i.e. with most likely value 80%, the minimum value is 10% lower, while maximum value is only 5% higher.

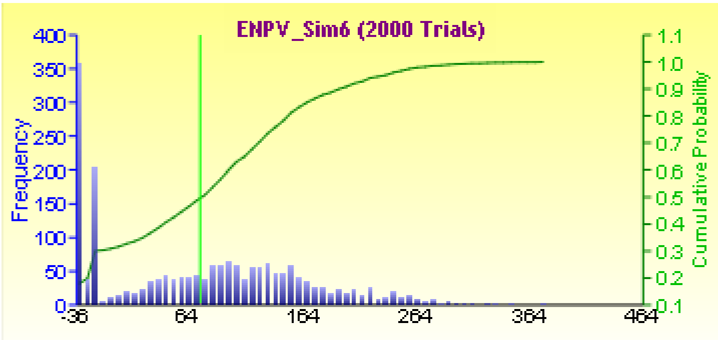
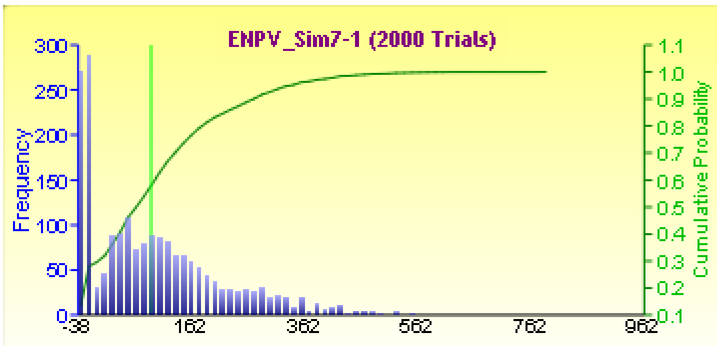


Figure 50. Expected NPV of Fusion RDDD Programme *(Simulation # 6)*

<u>Simulation # 7</u>

The last two simulations investigate the impact of random discount rates on the ENPV calculation. Uniform distribution is applied in simulation # 7.1 and triangular distribution in simulation # 7.2. All other assumptions are the same as in previous simulation # 6. Both simulations result in higher ENPV: €90.8 billion at 136% volatility with uniform distribution and €85.0 billion at 129% volatility with triangular distribution.

Uniform distribution



Triangular distribution

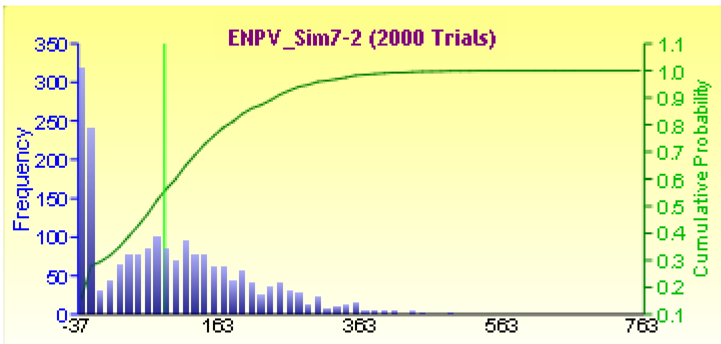


Figure 51. Expected NPV of Fusion RDDD Programme *(Simulations # 7.1 and # 7.2)*

4.3 Specification of the Real Options Model

4.3.1 Investment Option Model

In order to develop a real options model of Fusion RDDD programme, we need to define first the managerial flexibility actions that can give rise to the strategic real options. Next, we have to specify the main assumptions and data inputs. For that purpose, a schematic view of Fusion RDDD programme is elaborated, as shown *Figure 52*, 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 R&D and DEMO facilities; K_i – investment and O&M costs of commercial Fusion power plants (FPPs); R_i – revenues from Fusion electricity sales; and S_i – potential spillover benefits at each stage.

Two general strategies are considered. According to the "Baseline" strategy 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 DEMO 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.

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 energy sales, R, and potential value of spillover benefits, S. 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.

$$V = XN(d_1) - Ke^{-rT}N(d_2) \quad (4.3.1)$$

where

$$d_1 = \frac{\ln\left(\frac{X}{K}\right)+\left(r+\frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \quad (4.3.2)$$

$$d_2 = \frac{\ln\left(\frac{X}{K}\right)+\left(r-\frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{T} \quad (4.3.3)$$

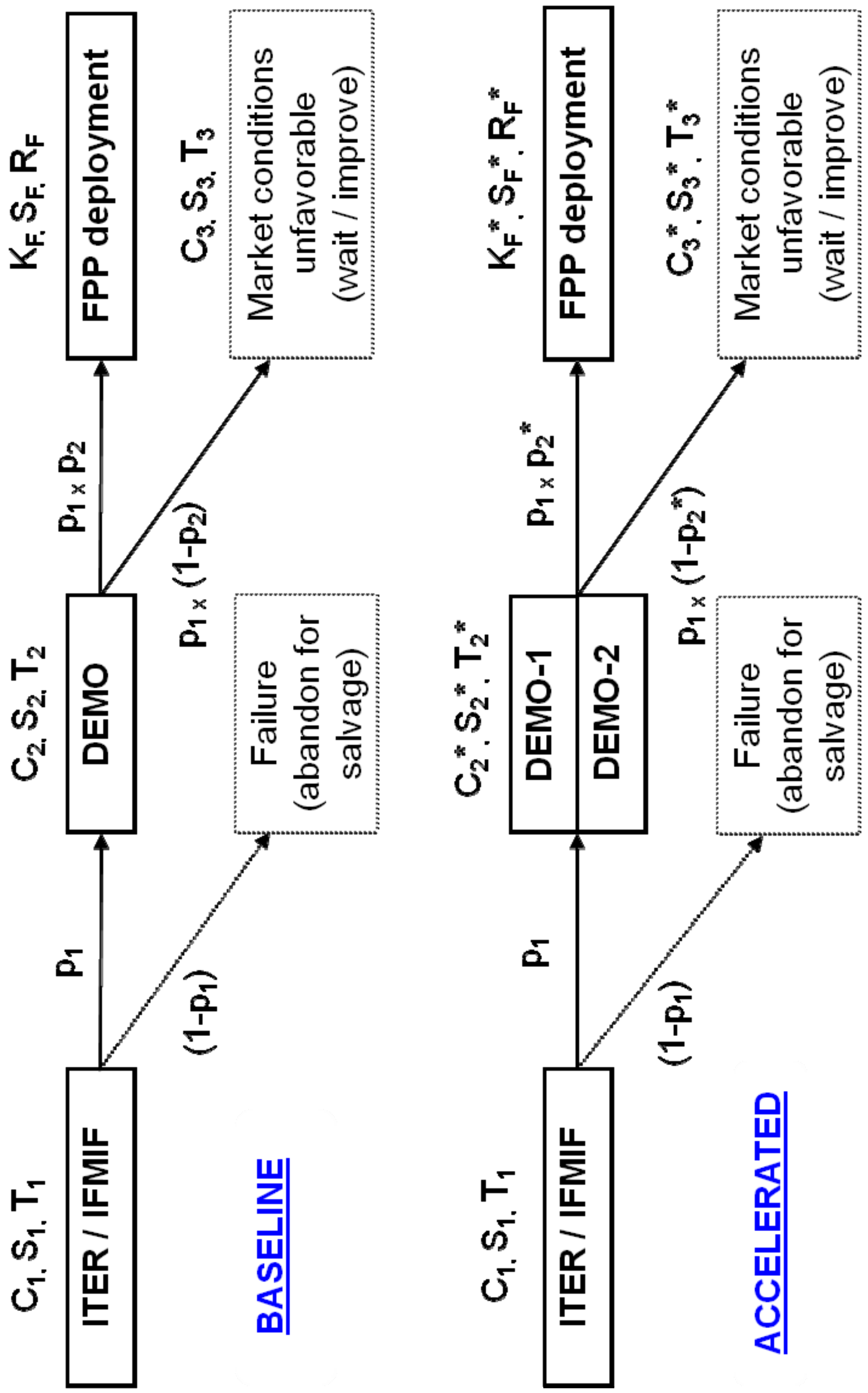


Figure 52. Alternative Strategies to Realisation of Fusion RDDD Programme

Surely, the results that can be obtained with such a model will essentially depend 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 value of the real option. Nevertheless, the model can provide useful insights regarding the strategic value of Fusion RDDD programme as an investment option, and it can be particularly helpful to perform sensitivity analyses to all of its input parameters (see Chapter 4.5). As regards the computational algorithms, both analytic approximations and closed form numerical methods may be equally used, although the latter are usually preferred to value multi-staged projects exceeding two or three stages.

To verify the solutions obtained with the help of Black – Scholes model it is worthwhile to calculate the value of the real option using alternative methods, e.g. binominal or multinomial lattices. Following the explanations given in Mun (2006) in order to solve a binomial lattice equation one needs to specify first the up step size, u, down step size, d, and risk-neutral probability, $\bar{p}$, with the help of the following formulae:

$$u = e^{\sigma\sqrt{\delta t}} \tag{4.3.4}$$

$$d = e^{-\sigma\sqrt{\delta t}} \tag{4.3.5}$$

$$\bar{p} = \frac{e^{r(\delta t)} - d}{u - d} \tag{4.3.6}$$

The time step, δt, is calculated as the total time to expiration in years, T, divided by the number of steps in the lattice. The risk neutral probability value is a mathematical intermediate and by itself has no economical or financial meaning.

The nodal values in the first lattice, describing possible evolution of the underlying asset, are obtained by multiplying the present value of the expected returns, X_0, by the up and down factors, u and d. The terminal nodes in the second option valuation lattice are calculated through the maximisation between executing the option and letting the option to expire worthless if the costs, K, exceed the benefits of execution, X_T. The intermediate nodes are calculated using risk-neutral probability through backward induction according to the following formula:

$$V_i = \left[pV_{i+1}^{u} + (1-p)V_{i+1}^{d}\right]e^{r(\delta t)} \tag{4.3.7}$$

where

V_{i+1}^{u} - is the value of the upper node next to the intermediate node (i) and

V_{i+1}^{d} - is the value of the lower node next to the intermediate node (i).

By performing this backward induction calculation all the way back from terminal nodes to the starting period, the option value at the time "zero" can be finally estimated.

4.3.2 Compound Option Model

Another approach that may reflect in a better way the multi-staged nature of Fusion RDDD programme consists in modelling Fusion RDDD 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 Demo) 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 the 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 proposed by Carr (1988) based on the earlier works of Margrabe (1978) and Geske (1979) according to which the value of a compound option, W, can be calculated with the following formulae:

$$W[V(X,K,T),C,t] = XN_2(h_1,d_1;\rho) - Ke^{-rT}N_2(h_2,d_2;\rho) - Ce^{-rt}N_1(h_2) \quad (4.3.8)$$

$$h_1 = \frac{\ln\left(\frac{X}{Q}\right)+\left(r+\frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \quad (4.3.9)$$

$$h_2 = h_1 - \sigma\sqrt{t} \quad (4.3.10)$$

$$d_1 = \frac{\ln\left(\frac{X}{K}\right)+\left(r+\frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \quad (4.3.11)$$

$$d_2 = d_1 - \sigma\sqrt{T} \quad (4.3.12)$$

$$\rho = \sqrt{\frac{t}{T}} \quad (4.3.13)$$

subject to the boundary conditions:

$$V(X,K,T) \geq W(V,C,t) \geq 0 \quad (4.3.14)$$

and terminal condition:

$$W(V,C,0) = max\left[0, XN_1\left(d_1\left(\frac{X}{K},T-t\right)\right) - Ke^{-r(T-t)}N_2\left(d_1\left(\frac{X}{K},T-t\right)\right) - C\right], \quad (4.3.15)$$

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:

$$C = QN_1\left(\frac{\ln\left(\frac{Q}{K}\right)+\left(r+\frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right) - Ke^{-r(T-t)}N_1\left(\frac{\ln\left(\frac{Q}{K}\right)+\left(r-\frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right) \qquad (4.3.16)$$

Naturally, the proposed solution to the valuation of compound sequential exchange option is quite difficult to solve and interpret. Therefore, it is always recommendable to cross check the results by using both closed-form solutions based on differential equations together with analytical approximations based on binomial or multinomial lattices as it will be shown in Chapter 4.5 below. In practice different methodological approaches can be implemented using commercially available solver software packages, e.g. "Multiple Assets Super Lattice Solver" designed and developed by "Real Options Valuations Inc." (Mun, 2009b). The use of "ready-made" real options solvers allows also for valuing more complex multi-stage "rainbow" options characterised by multiple sources of uncertainty and several underlying assets.

4.3.3 Fuzzy Real Option Model

In recent decades 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 range of project parameter and the most plausible value within that range 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. Ran *et al.* (2004) proposed a fuzzy pattern for evaluation of compound R&D option. Tolga & Kahraman (2008) performed fuzzy multi-attribute evaluation of R&D projects using a real options model. 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, $A = \{(x, \mu_A(x), x \epsilon X)\}$ 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, $A^\lambda = \{x \epsilon X, \mu_A(x) \geq \lambda\}$ is the set of elements x such that their membership function is greater or equal to the threshold $\lambda \in [0,1]$.

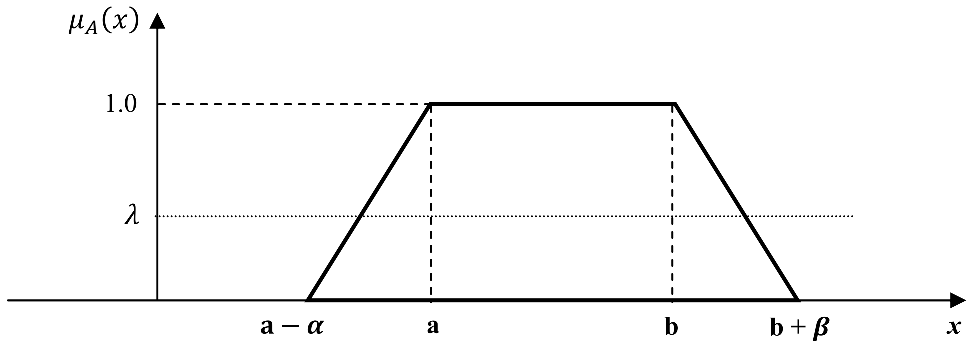


Figure 53. Representation of Uncertain Value with Trapezoidal Fuzzy Number

A trapezoidal fuzzy number (***Figure 53***) is a normal and convex fuzzy set that can be defined by a quadruple $A = (\mathrm{a}, \mathrm{b}, \alpha, \beta)$, where α and β are respectively the lower and the upper bounds of the fuzzy number, and $[\mathrm{a}, \mathrm{b}]$ is the core. A trapezoidal fuzzy number is defined by the following membership function:

$$A(x) = \begin{cases} 1 - \frac{\mathrm{a}-x}{\alpha} & if\ \ \mathrm{a} - \alpha \leq x < \mathrm{a} \\ 1 & if\ \ a \leq x < b \\ 1 - \frac{x-\mathrm{b}}{\beta} & if\ \ \mathrm{b} \leq x < \mathrm{b} + \beta \\ 0 & otherwise \end{cases} \qquad (4.3.17)$$

A triangular fuzzy number is a special case of trapezoidal fuzzy number with a = b. The trapezoidal fuzzy number can be defined in terms of its λ-cut as:

$$[A]^\lambda = [\mathrm{a} - (1-\lambda)\alpha, \mathrm{b} + (1-\lambda)\beta], \quad \forall\lambda \in [0,1]\,. \qquad (4.3.18)$$

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

$$E(A) = \frac{\mathrm{a}+\mathrm{b}}{2} + \frac{\beta-\alpha}{6} \qquad (4.3.19)$$

and the possibilistic variance as

$$Var(A) = \frac{(\mathrm{b}-\mathrm{a})^2}{4} + \frac{(\mathrm{b}-\mathrm{a})(\alpha+\beta)}{6} + \frac{(\alpha+\beta)^2}{24}\,. \qquad (4.3.20)$$

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:

$$FV = \tilde{X}N(d_1) - \tilde{K}e^{-rT}N(d_2) \tag{4.3.21}$$

$$d_1 = \frac{\ln\left(\frac{E(\tilde{X})}{E(\tilde{K})}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \tag{4.3.22}$$

$$d_2 = d_1 - \sigma\sqrt{T} \tag{4.3.23}$$

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 (4.3.21) in fuzzy numbers:

$$\begin{aligned} FV = (x_1, x_2, \alpha, \beta)N(d_1) - \left(k_1, k_2, \alpha', \beta'\right)e^{-rT}N(d_2) = \\ (\ x_1\, N(d_1) - k_2 e^{-rT}N(d_2),\ x_2\, N(d_1) - k_1 e^{-rT}N(d_2), \\ \alpha\, N(d_1) + \beta'^{e^{-rT}}N(d_2),\quad \beta\, N(d_1) + \alpha' e^{-rT}N(d_2)\ )\quad . \end{aligned} \tag{4.3.24}$$

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:

$$FW = \tilde{X}N_2(h_1, d_1; \rho) - \tilde{K}e^{-rT}N_2(h_2, d_2; \rho) - \tilde{C}e^{-rt}N_1(h_2) \tag{4.3.25}$$

$$h_1 = \frac{\ln\left(\frac{E(\tilde{X})}{Q}\right) + \left(r + \frac{\sigma^2}{2}\right)t}{\sigma\sqrt{t}} \quad ; \quad h_2 = h_1 - \sigma\sqrt{t} \tag{4.3.26}$$

$$d_1 = \frac{\ln\left(\frac{E(\tilde{X})}{E(\tilde{K})}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \quad ; \quad d_2 = d_1 - \sigma\sqrt{T} \tag{4.3.27}$$

$$\rho = \sqrt{\frac{t}{T}} \tag{4.3.28}$$

$$\sigma = \frac{\sqrt{Var(\tilde{X})}}{E(\tilde{X})} \tag{4.3.29}$$

The first term of the eq. (4.3.25) 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

$$QN_1\left(\frac{\ln\left(\frac{Q}{E(\tilde{K})}\right)+\left(r+\frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right)-E(\tilde{K})e^{-r(T-t)}N_1\left(\frac{\ln\left(\frac{Q}{E(\tilde{K})}\right)+\left(r-\frac{\sigma^2}{2}\right)(T-t)}{\sigma\sqrt{(T-t)}}\right)-E(\tilde{C})=0\,. \qquad (4.3.30)$$

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:

$$\begin{aligned} FW &= (x_1,x_2,\alpha,\beta)N_2(h_1,d_1;\rho)-(k_1,k_2,\alpha',\beta')e^{-rT}N_2(h_2,d_2;\rho)-(c_1,c_2,\alpha'',\beta'')e^{-rt}N_1(h_2) = \\ &= (\; x_1N_2(h_1,d_1;\rho)-k_2e^{-rT}N_2(h_2,d_2;\rho)-c_2e^{-rt}N_1(h_2), \\ &\quad x_2N_2(h_1,d_1;\rho)-k_1e^{-rT}N_2(h_2,d_2;\rho)-c_1e^{-rt}N_1(h_2), \\ &\quad \alpha N_2(h_1,d_1;\rho)+\beta'e^{-rT}N_2(h_2,d_2;\rho)+\beta''e^{-rt}N_1(h_2), \\ &\quad \beta N_2(h_1,d_1;\rho)+\alpha'e^{-rT}N_2(h_2,d_2;\rho)+\alpha''e^{-rt}N_1(h_2)\;). \end{aligned} \qquad (4.3.31)$$

Thus, the fuzzy pattern of the value of compound R&D option is also a trapezoidal fuzzy number. Recently, Collan *et al.* (2009) proposed a new method for estimating fuzzy real option value according to which it can be calculated as the fuzzy mean value of the positive NPV outcomes according to the following formula:

$$FV=\frac{\int_0^{\infty}A(x)dx}{\int_{-\infty}^{\infty}A(x)dx}\times E(A_+) \qquad (4.3.32)$$

where A stands for the fuzzy NPV, $E(A+)$ denotes the fuzzy mean value of the positive side of the NPV, and $\int_{-\infty}^{\infty}A(x)dx$ computes the area below the whole fuzzy number A, while $\int_0^{\infty}A(x)dx$ computes the area below the positive part of A.

4.4 Data Inputs

Numerical data for each variable of the real option model, i.e. duration and costs of ITER / DEMO stages, the costs and revenues of Fusion power plants, their total capacity and annual production generally correspond to the assumptions of the less constrained *Simulation # 7.2* specified in *Chapter 4.2.2* above. Estimations of the transitional probabilities of success are based on the hypotheses describing “Reference” and “Accelerated” cases in Ward *et al.* (2002). Annualized volatility of expected returns was estimated using the following formula:

$$\sigma=\frac{\sigma^*}{\sqrt{T}} \qquad (4.4.1)$$

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.

The reference risk free rate (2.25%) is taken as a mean value of the daily US real long-term borrowing rates for TIPS[32] with remaining maturities of more than 10 years calculated for the period from January 2003 to September 2009 based on the data published by the US Department of Treasury[33]. ***Table 27*** below summarises the main assumptions and data inputs underlying the calculation of the real option value of Fusion RDDD programme.

Table 27. 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
Total costs[(a)]	€ billion	35	35
Demo stage			
Duration	yrs	20	15* - 19
Probability of success	%	80	81 – 85*
Total costs[(a)]	€ billion	45	60
Deployment stage			
Duration	yrs	50	50
Expected costs[(b)]	€ billion	203	214 – 261*
Expected revenues[(b)]	€ billion	324	341 – 417*
Volatility	%	6.6%	6.7 – 6.9* %
Risk free rate	%	2.25	2.25

(a) undiscounted values
(b) discounted values

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 the increase of 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.

4.5 Results and Sensitivity Analyses

According to the results of the computations using both Black-Scholes differential equation and binomial lattice methods (see ***Table 28*** and ***Figure 55*** below) the strategic real option value

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

33 http://www.ustreas.gov/offices/domestic-finance/debt-management/interest-rate/real_ltcompositeindex_historical.shtml

which may be created through undertaking Fusion R&D and demonstration activities amounts to €245 billion in the case of "Baseline" srtategy. This value substantially exceeds the projected costs of Fusion RD&D estimated over period 2009 – 2050 at €80 billion in undiscounted terms or €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.

Table 28. Option Valuation Audit Sheet (Baseline Strategy)

Assumptions		***Intermediate Computations***	
PV Asset Value (€ billion)	324.0	*Stepping Time (dt)*	4.20
Implementation Cost (€ billion)	203.0	*Up Step Size (up)*	1.1448
Maturity (Years)	42.0	*Down Step Size (down)*	0.8735
Risk-free Rate (%)	2.25%	*Risk-neutral Probability*	0.8315
Volatility (%)	6.60%	***Results***	
Lattice Steps	10	*Black-Scholes Result (€ billion)*	245.11
Option Type	European	*Super Lattice Results (€ billion)*	245.10

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 shown in ***Figure 54*** below.

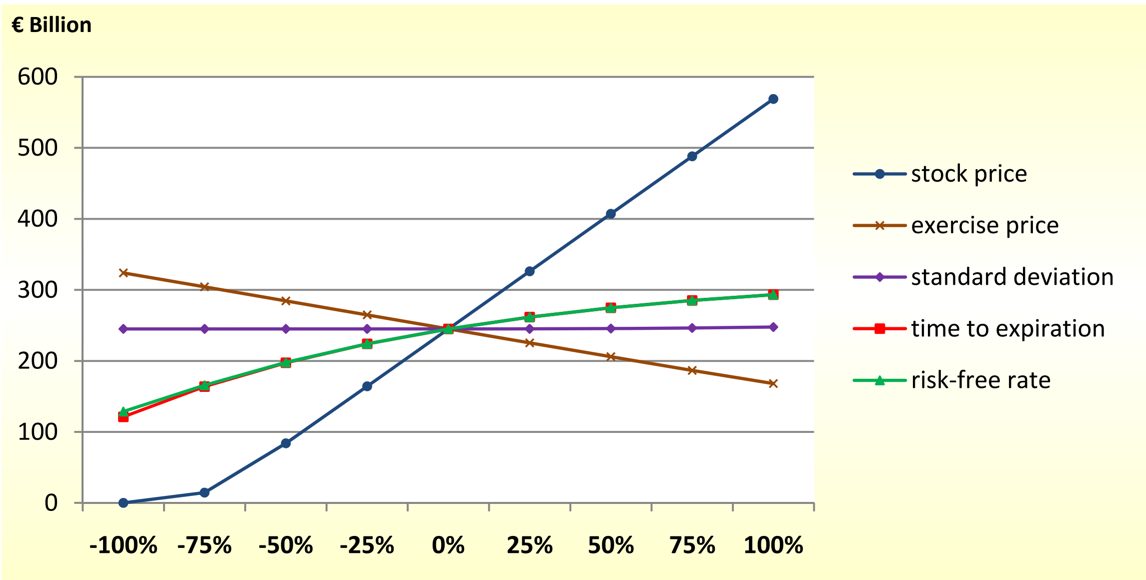


Figure 54. Sensitivity of Real Option Value to Input Parameters in Black-Scholes Formula (Baseline Strategy)

As it can be seen on the above "spider" diagram, the real option value of Fusion RDDD programme is driven mainly by the expected revenues. The relative impact of other factors such as expected costs (negative) as well as time to expiration and risk-free rate (both positive) is much lower, while the impact of the volatility is practically negligible.

Underlying Asset Lattice
(€ billion)

										1253
									1095	
								956		956
							835		835	
						729		729		729
					637		637		637	
				557		557		557		557
			486		486		486		486	
		425		425		425		425		425
	371		371		371		371		371	
324		324		324		324		324		324
	283		283		283		283		283	
		247		247		247		247		247
			216		216		216		216	
				189		189		189		189
					165		165		165	
						144		144		144
							126		126	
								110		110
									96	
										84

Option Valuation Lattice
(€ billion)

										1050
									910	
								788		753
							682		650	
						590		561		526
					511		484		452	
				441		417		389		354
			381		360		333		301	
		329		310		286		257		222
	284		266		244		218		186	
245		229		209		185		156		121
	196		178		156		130		98	
		152		132		108		80		44
			111		90		64		33	
				74		51		25		0
					41		19		0	
						14		0		0
							0		0	
								0		0
									0	
										0

Figure 55. Analytical Approximation of European Call Real Option Value Using Binomial Lattice Method (Baseline Strategy)

It is 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 comparable with 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.

The analysis of the alternative "Accelerated" strategy characterised by the higher costs during Demonstation 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 €15 billion funding of Fusion demonstration activities[34] 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 as shown in ***Figure 56*** below.

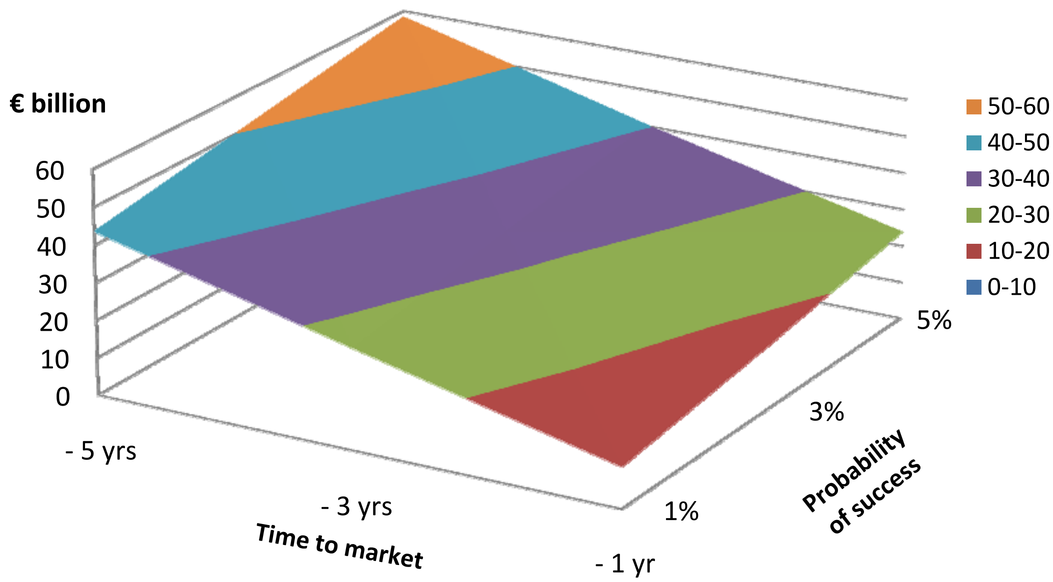


Figure 56. Increment of the Real Option Value Subject to Different Assumptions Regarding Increase of the Probability of Success and Shortening of the Time to Market

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 option value increases by €11 billion compared to Baseline strategy that is below the incremental cost of Fusion demonstration activities. 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 the potential downsides.

[34] As discussed in Chapter 2.1 this incremental funding roughly corresponds to the construction of one additional Fusion Demo reactor of alternative concept alongside with the general intensification of Fusion demonstration activities.

A more precise estimation of the real option 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 outlined in section 4.3.2 above. Let us consider first the most simple two-stage option comprising RD&D and deployment stages. 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 optimistic "Accelerated" strategy.

In order to obtain these values with the most simple binomial lattice method one needs to construct first the evaluation lattice of the underlying asset. Next, the real options values of initial and consecutive phases can be calculated using backward induction process. If the number of steps in the lattices is remained unchanged, then calculation of the underlying asset's and the last stage "Deployment" option's lattices yields exactly the same result as for European call option. The valuation lattice of the initial RD&D stage can be finally calculated as shown in ***Figure 57*** below taking the final stage lattice as the underlying asset and using the same terminal and intermediate nodes equations.

RD&D Option Valuation Lattice
(€ billion)

										1014
									877	
								758		717
							655		618	
						566		532		490
					488		457		420	
				421		393		359		318
			363		337		306		269	
		312		289		261		227		186
	269		248		222		191		153	
231		212		188		160		126		85
	181		160		134		103		66	
		135		112		84		51		8
			93		68		39		6	
				55		30		5		0
					23		4		0	
						3		0		0
							0		0	
								0		0
									0	
										0

Figure 57. Valuation Lattice of Compound Real Option (Baseline Scenario)

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. The solution for such a multi-phase compound option can be easily obtained using Real Options "Multiple Super Lattice Solver" (Mun, 2009b) or by performing series of lattice calculations as described above. In this case the strategic real option value of the initial R&D stage can be assessed more precisely.

As shown on ***Figure 58*** below the real option value of the initial R&D stage (€ 226 billion in "Baseline" strategy) can be calculated through backward induction based on the valuation lattice of the consecutive "Demo" stage, which in turn is calculated based on the valuation lattices of the underlying asset (FPPs revenues) and final "Deployment" stage option which both will have the same terminal and intermediate nodes' values as in the case of standard European call option.

Valuation Lattice for Demo Stage
(€ billion)

										1037
									898	
								777		740
							672		639	
						581		551		513
					503		474		441	
				434		409		378		341
			375		**351**		323		290	
		323		302		277		246		209
	279		259		**236**		208		174	
240		223		201		176		145		108
	191		172		**148**		120		86	
		146		125		100		69		31
			105		**82**		55		24	
				67		44		18		0
					35		14		0	
						10		0		0
							0		0	
								0		0
									0	
										0

Valuation Lattice for R&D Stage
(€ billion)

					480
				413	
			356		328
		306		281	
	263		240		213
226		205		181	
	175		153		125
		129		104	
			86		59
				46	
					12

Figure 58. Valuation Lattices for Multi-stage Compound Real Option (Baseline Scenario)

It is worth noting that terminal nodes values in the "R&D" stage lattice are calculated based on the intermediate nodes values of the subsequent "Demo" stage lattice instead of the terminal nodes due to the fact that maturity of "R&D" option is shorter compared to the maturity of the underlying "Demo" stage option (roughly two times: 22 yrs / 42 yrs). Naturally, increasing the number of steps in the lattices may help in obtaining even more accurate option valuation results.

In order to cross-check the results obtained with the help of lattice valuation method additional calculations have been performed using compound option valuation formulae (4.3.8 – 4.3.16). In case of “Baseline” strategy the value of Fusion R&D option is estimated at €222 billion and in case of “Accelerated” strategy the option value increases to €273 billion. Basically these results are in line with those obtained using the lattice valuation method. A slight difference (≈ 2%) can be explained by the lack of accuracy of the calculation using the R&D lattice which has only 5 time steps each lasting 4.2 yrs (same as other lattices) in the presented Baseline calculation.

The results of fuzzy real options analysis are outlined below. Based on the three deterministic scenario calculations, discussed in chapter 4.2.1, 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 real option value with basic “Black – Scholes” type of model of the European call investment option we have to compute first the possibilistic mean and variance according to equations (4.3.19) and (4.3.20) 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 (4.3.22), (4.3.23) and (4.3.29):

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

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

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

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.

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 (4.3.24) we obtain the real option value of Fusion RDDD programme in the format of a trapezoidal fuzzy number as illustrated in ***Figure 59***.

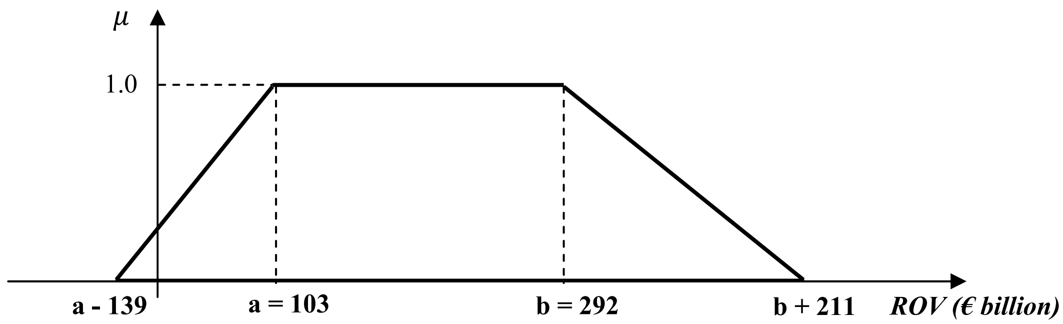


Figure 59. Fuzzy Real Option Value of Fusion RDDD Programme

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 option 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 (4.3.25 – 4.3.31) 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 (4.3.19) 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.

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" based on the most pessimistic assumptions, and hence it is worthwhile to pursue further R&D and demonstration activities.
- The real options analysis suggests that substantial strategic value of Fusion RDDD programme is being ignored by the traditional NPV approach. This value is created due to the uncertainty about future energy markets (e.g. there is a potential of high upward swings because of exhaustion of fossil energy reserves and introduction of more stringent environmental regulation). The programme managers are also able to limit potential losses and increase 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 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 corresponding increase of the programme costs. This result is confirmed by the calculations using both simple Black-Scholes investment option valuation model and a more complex compound option model.
- Compared to the deterministic scenarios, the evaluation of the expected NPV of Fusion RDDD programme made 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.
- 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 evaluation on the ongoing and next-step stages (i.e. R&D and Demonstration) 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.

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5. FUSION R&D SPILLOVERS MODEL

Conceptual model for evaluation of Fusion R&D spillovers at the microeconomic (company) level is outlined in this chapter. Pecuniary value of spillover benefits is calculated basing on the estimated increment of the company value due to its participation in Fusion R&D, demonstration and deployment activities. Financial model is implemented based on the "Economic profit" approach. It is assumed that Fusion R&D spillovers may have a positive impact on the key driving factors of the company value in multiple ways, such as increase in sales revenues, building of knowledge stock, development of prototype innovative products, etc. Viability of the proposed analytical approach is demonstrated with a numerical example which aims to estimate potential impact of Fusion R&D spillovers on the value of a hypothetical company participating in a given Fusion R&D project.

5.1 Introduction and Conceptual Model

In recent decades, as it was discussed in Chapter 2.2, the analysis of spillover effects became a topic of increasing concern in the context of the evaluation of publicly funded R&D programmes. The main postulate is that social rate of return of any R&D activity, in most cases, may be higher than its internal (private) rate of return due to the spillovers of knowledge and other types of socio-economic benefits to other market players. The magnitude of spillover effects is usually much bigger in the case of basic science and research infrastructures sponsored by the public agencies, because of the "open" nature of the research collaborations between all involved institutions and a relative difficulty to apply in this context traditional appropriation mechanisms, such as patents and other legal and corporate structures.

The Fusion RDDD programme represents *per se* a perfect example of such a public – private research collaboration, which potentially may yield a significant amount of spillover benefits. The key aspects that support this idea can be summarized as follows:

- Global character: involvement of public research institutions and private companies from all leading nations of the world (EU, USA, Japan, Russia, China, India, Korean Republic are partners of the ITER project, and many researchers from other countries participate in this and other Fusion R&D initiatives);
- Very long timescale: the programme started back in 1950s and it will be pursued for another 40 years or so, before the viability of Fusion technology can be proved in practice;
- Pluridisciplinary nature: the research on Fusion technology required major advancements in many scientific and engineering fields, such as high energy / plasma physics, mechanical, electrical and electronic engineering, material science, computer modelling, electromagnet and cryogenic systems, etc.

- Technologically challenging: considering the highly demanding specifications of plasma confinement installations, the Fusion RDDD programme is constantly pushing forward the limits of knowledge within the involved public and private institutions.

Given the fact that construction of next-step Fusion experimental devices, such as ITER and IFMIF, will be only possible with the important contributions from the industry sector, it is expedient to investigate how participation in Fusion R&D projects may impact the economic performance of the involved companies and try to estimate the potential spillover benefits of Fusion DDDD programme.

A conceptual model for evaluation of Fusion R&D spillovers at microeconomic (company) level is outlined in ***Figure 60*** below. The methodological approach consists in estimating the increase of the company value due to its participation in Fusion R&D activities. It is assumed that different types of Fusion R&D spillovers may impact the key driving factors of the company value, namely return on the invested capital, projected growth rates and their underlying drivers, such as the amount of invested capital per unit of production, manufacturing cost and revenues per unit, production volume, etc.

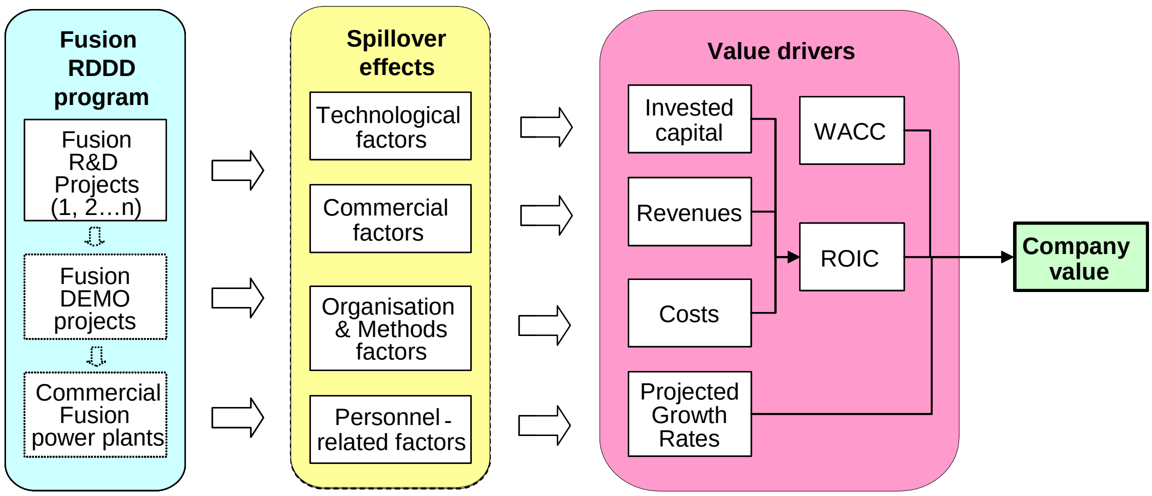


Figure 60. Fusion R&D Spillovers Model

The typical examples of spillover effects considered in the study include: development of innovative products / processes / services; increase in the revenues from sales of the company's products / services to Fusion R&D market and other non-Fusion markets; accumulation of the stock of knowledge embodied in IPR, manufacturing know-how, experience of management and production personnel; improved capacity to absorb and exploit knowledge due to increased number of qualified R&D, engineering and technical staff; formation of new technological cooperation networks; strengthening of the company's reputation that can be used as marketing tool; etc. A more detailed specification of spillover effects is given in Section 5.3 below.

The model assumes that spillover effects of Fusion R&D activities may reveal in two distinct forms. On the one hand, they can increase the tangible assets of the company. This can be achieved e.g. through the development and commercialisation of innovative products leading to the expansion of the company's production capacity and the increase of sales. On the other hand, participation in Fusion R&D may boost the intangible assets of the company and create future profit opportunities, e.g. due to build up of the knowledge stock and strengthening of the market reputation. While the first type of spillover benefits may have a direct pecuniary equivalent in terms of the increased added value and economic profit, the second type of benefits is more difficult to estimate in monetary terms. Alternative *ex ante* evaluation methods based on scenarios and option pricing approaches may be required.

The model can be applied at the level of individual companies, and also at the level of selected Fusion R&D projects, such as construction of Wendelstein X-7 installation. In a later case, a comprehensive survey has to be carried out among all the participating companies, and their accounting data have to be accessed. Accordingly, the pecuniary value of spillover benefits of a given Fusion R&D project will correspond to the total sum of the value increments of all companies participating in this particular project.

Given this indicative timeline of Fusion RDDD programme (see Chapter 2.1.2) the following scenarios have been elaborated for further investigation with spillovers model:

"Baseline" (BL) - reference scenario corresponding to the current situation (present level of involvement in the ongoing Fusion R&D projects) and a conventional pace of Fusion RDDD programme;

"No Fusion" (NF) - indicative scenario assuming no participation in Fusion R&D projects in the past and a lower probability of accession to future Fusion RDDD projects;

"Accelerated" (AC) - alternative scenario assuming accelerated implementation of Fusion RDDD programme (increased funding, several DEMOs, reduced time, higher deployment rate of FPPs compared to Baseline scenario).

It is worth noting that Wendelstein 7-X stellarator project (W7-X) is the last superconducting experimental device currently under construction in Europe before the ITER, and as such it deserves a more close attention for investigation of its realised and potential spillover benefits.

5.2 Mathematical Formulation

The model follows "Economic Profit" valuation approach which is a variant of well-established "Discounted Cash Flow" method (see Copeland *et al.*, 2000). This approach can be considered as a complement to the traditional "Value Added" approach, e.g. implemented in the studies of indirect effects using B.E.T.A. methodology (see Cohendet, 1997) with the advantage that it allows for taking into account the projections of future profit opportunities.

The company value is defined as the sum of the invested capital plus the present value of projected economic profit (5.2.1).

$$CV = IC + PEP + CEP \quad \text{where} \tag{5.2.1}$$

CV = total company value;
IC = invested capital at the beginning of forecast;
PEP = present value of projected economic profit during explicit forecast period;
CEP = continuing value of projected economic profit after explicit forecast period.

Invested capital is represented by the amount of funds invested in the operations of the business including operating working capital (operating current assets minus non-interest-bearing current liabilities); net property, plant and equipment (book value of the company's fixed assets), and other operating assets, net of other liabilities (***Table 29***).

Table 29. Invested Capital Calculation[35]

€ million	**200Y**
Operating current assets	
Cash	783
Accounts receivables	1502
Inventories	394
Non-interest-bearing current liabilities	
Accounts payable	(2,041)
Tax payable	(72)
Other current liabilities	(425)
Operating working capital	**141**
Net property, plant and equipment	607
Other operating assets, net of other liabilities	(67)
Operating invested capital (excl. goodwill & intangibles)	**681**
Goodwill & Intangibles	738
Operating invested capital (incl. goodwill & intangibles)	**1419**

Economic profit measures the value created in a company in a single period. It is defined as follows:

$$EP = IC \times \left(ROIC - WACC\right) \tag{5.2.2}$$

[35] The data in this numerical example are taken from the publicly available annual report of Bilfinger Berger Group (see Chapter 6 for details of the case study).

where

EP = economic profit in a single period;

$ROIC$ = rate of return on invested capital;

$WACC$ = weighted average cost of capital.

The rate of return on invested capital is computed as follows:

$$ROIC = \frac{NOPLAT}{IC} \quad \text{where} \tag{5.2.3}$$

$NOPLAT$ = net operating profit less adjusted taxes.

NOPLAT represents the after-tax operating profits of the company after adjusting taxes to a cash basis. ***Table 30*** shows the details of NOPLAT calculation.

Table 30. Calculation of Net Operating Profit Less Adjusted Taxes (NOPLAT)

€ million	**200Y**
Sales revenues	7509
Other operating income	193
Cost of goods sold	(4738)
Personnel expenses	(2027)
Depreciation	(99)
Other operating expenses	(657)
Earnings before interest, taxes and amortisation (EBITA)	**180**
Taxes on EBITA	(77)
Changes in differed taxes	-
NOPLAT	**103**

Weighted average cost of capital can be estimated as weighted average cost of each source of the company's capital according to the following formula:

$$WACC = k_d\left(1 - TX_c\right)\left(\frac{D}{MV}\right) + k_s\left(\frac{S}{MV}\right) \quad \text{where} \tag{5.2.4}$$

k_d = cost of debt (%);

k_S = market-determined opportunity cost of equity capital (%);

TX_c = corporate tax rate (%);

D = market value of interest-bearing debt;

S = market value of equity;

MV = market value of the company being valued ($MV = D + S$).

Depending on the company's situation, WACC formula may also take into account the cost of capital gathered in the form of non-callable nonconvertible preferred stock. ***Table 31*** gives an example of WACC calculation.

Table 31. Cost of Capital Calculation

%	200Y
Risk-free interest rate	5.0
Market-risk premium	4.5
Beta factor	0.9
Cost of equity capital after taxes	**9.1**
Cost of borrowed capital before taxes	5.5
Tax-reducing effect of interest on borrowed capital (tax shield)	-1.9
Cost of borrowed capital after taxes	**3.6**
Proportion of equity capital	60.0
Proportion of borrowed capital	40.0
Cost of capital after taxes	**6.9**
Income tax rate	35.0
Cost of capital before taxes (WACC)	**10.5**

It is worth noting that the given above equations for calculation of a single period economic profit provide exactly the same result as the Economic Value Added ® formula proposed in Stewart (1991).

The present value of projected economic profit corresponds to the discounted total sum of future annual values of the economic profit. It can be decoupled into two parts: present value of projected economic profit ***during*** explicit forecast period (PEP) and the continuing value of projected economic profit ***after*** explicit forecast period (CEP).

$$PEP = \sum_{t=0}^{T} \frac{EP_t}{(1+WACC)^t} \quad \text{where} \tag{5.2.5}$$

EP_t = economic profit during explicit forecast period (t= 0…T).

$$CEP = \frac{EP_{T+1}}{WACC} + \frac{NOPLAT_{T+1}\left(\frac{g}{RONIC}\right)(RONIC - WACC)}{WACC(WACC-g)} \quad \text{where} \tag{5.2.6}$$

EP_{T+1} = normalized economic profit in the first year after explicit forecast period;

$NOPLAT_{T+1}$ = normalized NOPLAT in the first year after explicit forecast period;

g = expected growth rate in NOPLAT in perpetuity;

$RONIC$ = expected rate of return on net new investment.

According to the formula (5.2.6) the continuing value equals the present value of economic profit in the first year after explicit forecast period in perpetuity plus any incremental economic profit created by additional growth at returns exceeding the cost of capital.

The calculation of CEP can be further detailed by breaking up the continuing value period into two periods with different growth and RONIC assumptions (see Koller et al., 2005). The corresponding two-stage CEP formula is the following:

$$CEP = \frac{EP_{T+1}}{WACC} + \left[\frac{NOPLAT_{T+1}\left(\frac{g_A}{RONIC_A}\right)(RONIC_A - WACC)}{WACC(WACC - g_A)} \right] \times \left[1 - \left(\frac{1+g_A}{1+WACC} \right)^n \right]$$

$$+ \frac{NOPLAT_{T+1}(1+g_A)^n \left(\frac{g_B}{RONIC_B}\right)(RONIC_B - WACC)}{WACC(WACC - g_B)(1+WACC)^n} \quad \text{where} \qquad (5.2.7)$$

n = number of years in the first stage of the CV period;

$g_{A,B}$ = expected growth rate in the first stage (A) and the second stage (B) of the CV period;

$RONIC_{A,B}$ = expected incremental rate of return on net new investment during the first stage (A) and the second stage (B) of the CV period.

The standard procedure for estimating the value of company includes the following steps:

1. Analyse the company's historical performance and estimate its cost of capital
2. Develop a strategic perspective on future company's performance taking in to account both the industry characteristics and the company's competitive position
3. Translate the strategic perspective into financial forecasts: income statement, balance sheet and key value drivers (ROIC and growth ratios)
4. Develop alternative performance scenarios
5. Check the overall forecasts for internal consistency.

The whole valuation process can be implemented using well-established spreadsheet models, such as McKinsey Valuation Model (see Copeland et al., 2000; Jennergren, 2007).

The mechanism of value creation due to spillover effects can be described in the following way. We assume that participation in Fusion R&D project may have increased the company value compared to an indicative scenario (*no participation in Fusion R&D*). Accordingly, the Fusion R&D spillover benefit is represented by the increment of the company value attributable to a given Fusion R&D project (*j*).

$$SPB_i^j = \Delta CV_i = \Delta IC_i + \Delta PEP_i + \Delta CEP_i \quad \text{where} \qquad (5.2.8)$$

SPB_i^j = spillover benefit due to participation of company (*i*) in publicly funded Fusion R&D project (*j*);

ΔCV_i = increase in the company value due to participation in Fusion R&D project;

ΔIC_i = increase in the company's operating invested capital;

ΔPEP_i = increase in present value of projected economic profit during explicit forecast period;

ΔCEP_i = increase in continuing value of projected economic profit after explicit forecast period.

The spillover rate at the level of the whole Fusion R&D project involving (N) companies can be calculated as the total sum of spillover benefits of all companies participating in a given project (j) divided by the amount of public investments in this project:

$$SPR_j = \frac{\sum_i^N SPB_i^j}{IP_j} \quad \text{where} \tag{2.5.9}$$

SPR_j = spillover rate of Fusion R&D project;

IP_j = amount of public funds invested in Fusion R&D project (j).

The spillover rate at the level of individual company (i) is represented by the increment of the company value divided by the company's investment in a given R&D project:

$$SPR_i^j = \frac{\Delta IC_i + \Delta PEP_i + \Delta CEP_i}{IF_i^j} \quad \text{where} \tag{2.5.10}$$

IF_i^j = company's investments in Fusion R&D project.

The increase in each component of the company value due to company's participation in Fusion R&D project can be defined as follows:

$$\Delta IC_i = IC_{BL} - IC_{NF} = IC_{BL} \times \sum_k \left(\frac{Q_k^{IC}}{IC_{BL}} \times \sum_m R_m^k \right) \quad \text{where} \tag{2.5.11}$$

$IC_{BL,NF}$ = amount of operating invested capital at the time of evaluation (t=0) in "Baseline scenario" (BL) and indicative "No Fusion" scenario (NF);

Q_k^{IC} = total contribution (in monetary terms) of each value driving factor (k) to the company's operating invested capital;

R_m^k = rate of contribution (%) of Fusion R&D spillover effect of type (m) to k-th value driving factor.

$$\Delta PEP_i = PEP_{BL} - PEP_{NF} \quad \text{where} \tag{2.5.12}$$

$PEP_{BL,NF}$ = present value of the projected economic profit during explicit forecast period in "Baseline" scenario and "No Fusion" scenario.

Based on the equations (2.5.2), (2.5.3) and (2.5.5) the present value of projected economic profit during explicit forecast period in "Baseline" scenario can be computed as follows:

$$PEP_{BL} = \sum_{t=0}^{T} \frac{NOPLAT_t^{BL} - IC_t^{BL} \times WACC}{(1+WACC)^t} \quad \text{where} \tag{2.5.13}$$

$NOPLAT_t^{BL}$ = net operating profit less adjusted taxes in each year during explicit forecast period in "Baseline" scenario;

IC_t^{BL} = operating invested capital in each year during explicit forecast period in "Baseline" scenario.

Accordingly, the company's projected economic profit during explicit forecast period in indicative "No Fusion" scenario can be defined as follows:

$$PEP_{NF} = \sum_{t=0}^{T} \frac{NOPLAT_t^{BL} \times \left[1 - \sum_k \left(\frac{Q_k^{NOPLAT}}{NOPLAT_t^{BL}} \times \sum_m R_m \right)\right] - IC_t^{BL} \times \left[1 - \left(\frac{Q_k^{IC}}{IC_t^{BL}} \times \sum_m R_m \right)\right] \times WACC}{(1+WACC)^t}$$

where (2.5.14)

$Q_k^{NOPLAT,IC}$ = total contribution of each value driving factor (k) to the company's NOPLAT and operating invested capital;

R_m = rate of contribution (%) of Fusion R&D spillover effect of type (m) to k-th value driving factor.

The alternative approach to estimate the present value of projected economic profit during explicit forecast period in "No Fusion" scenario may consists in the definition of specific influence rates of Fusion R&D project for NOPLAT and operating invested capital respectively. The computation formula in this case will be the following:

$$PEP_{NF} = \sum_{t=0}^{T} \frac{\frac{NOPLAT_t^{BL}}{F_t^{NOPLAT}} - \frac{IC_t^{BL}}{F_t^{IC}} \times WACC}{(1+WACC)^t} \quad \text{where} \tag{2.5.15}$$

F_t^{NOPLAT} = rate of influence of Fusion R&D project activities on NOPLAT during explicit forecast period;

F_t^{IC} = rate of influence of Fusion R&D project activities on operating invested capital (IC) during explicit forecast period.

The influence rates determine the potential impact of Fusion R&D spillover effects on the key driving factors which enter into calculation of the projected economic profit. The influence rate can be specified as a multiplicative function following the algorithm proposed by Wei & Malik (2005) :

$$F_k = (F_{TEC})^{\beta_1} \times (F_{COM})^{\beta_2} \times (F_{ORM})^{\beta_3} \times (F_{WRK})^{\beta_4} \quad \text{where} \tag{2.5.16}$$

F_k = rate of influence of Fusion R&D project activities on the respective driver (*k*) of the projected economic profit;

$F_{TEC,COM,ORM,WRK}$ = influence index of each category of Fusion R&D spillover effects (*technological, commercial, organisation & methods, work-factor* effects, see Section 5.3 for detailed classification);

$\beta_{1,2,3,4}$ = intensity of contribution of each category of spillover effects.

The sum of all "intensity of contribution" coefficients is equal to unity ($\beta_1 + \beta_2 + \beta_3 + \beta_4 = 1$) and the value of each individual coefficient is $0 \le \beta \le 1$.

The value of each influence index is determined basing on the assigned values of assessment indicators (v_m) and weights (w_m) of its constituent components, i.e. spillover effects:

$$F_{TEC,COM,ORM,WRK} = \sum_m w_m v_m \,. \tag{2.5.17}$$

The sum of the weights of all assessment indicators of spillover effects belonging to the same category is also equal to unity ($\sum_m w_m = 1$).

The value of each assessment indicator is determined by comparing the state of the underlying variable in reference "Baseline" scenario with the hypothetical state of the same variable in indicative "No Fusion" scenario. So, if the company's headcount of highly qualified S&E staff would be 20% lower in the case if it did not participate in Fusion R&D project, then the assigned value of respective assessment indicator is equal to 1 / 0.8 = 1.25.

The increase in the continuing value of the projected economic profit after explicit forecast period can be defined in a similar way using the Fusion R&D influence rates specific to each type of the involved driving factors. Based on the equation (2.5.6) we can determine the continuing value of the economic profit in "Baseline" scenario. The continuing value in hypothetical "No Fusion" scenario can be estimated with the following formula:

$$CEP_{NF} = \frac{EP_{T+1}^{NF}}{WACC} + \frac{NOPLAT_{T+1}^{NF}\left(\frac{g}{F^g} \times \frac{F^{RONIC}}{RONIC}\right)\left(\frac{RONIC}{F^{RONIC}} - WACC\right)}{WACC\left(WACC - \frac{g}{F^g}\right)}. \quad (2.5.18)$$

Numerical estimates of the economic profit and NOPLAT in the first year after explicit forecast period (EP_{T+1}^{NF} and $NOPLAT_{T+1}^{NF}$) can be obtained either by extrapolation of respective values for the final year of explicit forecast period (EP_{T}^{NF} and $NOPLAT_{T}^{NF}$) or by applying specific Fusion R&D influence rates to the respective values in "Baseline" scenario according to the following equations:

$$NOPLAT_{T+1}^{NF} = \frac{NOPLAT_{T+1}^{BL}}{F_{T+1}^{NOPLAT}} \quad (2.5.19)$$

$$EP_{T+1}^{NF} = NOPLAT_{T+1}^{NF} - \frac{IC_{T+1}^{BL}}{F_{T+1}^{IC}} \times WACC \quad (2.5.20)$$

The continuing value of the projected economic profit in a more optimistic "Accelerated" scenario can be calculated using two-stage CEP formula (5.2.7) assuming that the rate of return on new invested capital (RONIC) and growth rate in NOPLAT (g) in the second stage (*B*) would be higher with coefficients (γ^g, γ^{RONIC}) compared to the respective values during the initial period (*A*):

$$g_B = \gamma^g g_A \ , \quad (2.5.21)$$

$$RONIC_B = \gamma^{RONIC} RONIC_A \ . \quad (2.5.22)$$

The resulting increment of continuing value of the projected economic profit after explicit forecast period due to participation in Fusion R&D project can be estimated according to the following formula, where coefficient α represents the assumed probability (%) of "Baseline" scenario.

$$\Delta CEP_i = \alpha \times (CEP_{BL} - CEP_{NF}) + (1 - \alpha) \times (CEP_{AC} - CEP_{NF}). \quad (2.5.23)$$

5.3 Taxonomy of Spillover Effects

Specific types of spillover effects considered in the study are listed in ***Table 32***. Four main categories are distinguished: *technological*, *commercial*, *organisation & methods*, *work-factor*. Each effect can be relevant for one or several value driving factors. Influence rates of Fusion R&D spillovers on respective value drivers are determined using computational algorithm of Analytical Hierarchy Process basing on the data gathered through face-to-face interviews with the company managers.

Table 32. Spillover Effects of Fusion R&D Projects

	Spillover Effects	Designation	Relevance
Technological effects	Development of innovative (new / improved) products / services with potential application in future Fusion experiments	TEC1	RONIC, g
	Development of innovative products / services with potential applications in other non-Fusion domains	TEC2	RONIC, g
	Core competence improvement	TEC3	RONIC, g
	Advancements in company's R&D (new theories, prototypes, demonstrations, models, simulators; decisions on further RTD)	TEC4	RONIC, g
	Registration of Intellectual Property Rights	TEC5	IC, RONIC, g
	Acquisition of new fixed assets (production equipment and other infrastructure)	TEC6	IC, NOPLAT
	Acquisition of licences	TEC7	IC, NOPLAT
Commercial effects	Sales of existing products / services to Fusion R&D project	COM1	IC, NOPLAT
	Sales of innovative products / services to Fusion R&D project	COM2	IC, NOPLAT
	Sales of innovative products / services developed for Fusion R&D project in non-Fusion markets	COM3	IC, NOPLAT
	Additional revenues from sale of licences	COM4	IC, NOPLAT
	Cost reduction due to improvement of manufacturing processes through participation in Fusion R&D project	COM5	IC, NOPLAT
	New commercial links	COM6	g
	Increased profile / possibility to use programme label as marketing tool	COM7	g
Organisation & Method effects	Improved quality system	ORM1	RONIC
	Adoption of new production techniques	ORM2	RONIC, g
	Improved R&D process (new R&D tools / techniques / methods, integration of technologies)	ORM3	RONIC
	Improved project management capability	ORM4	RONIC, g
	New technological networks / contacts	ORM5	RONIC
	Formation of new firm / joint venture to exploit results	ORM6	IC, RONIC, g
Work-factor effects	New S&E jobs created within the company	WRK1	NOPLAT, g
	Learning through experience & training	WRK2	RONIC, g
	Improved capacity to absorb & exploit knowledge	WRK3	RONIC, g

5.4 Value Driver Trees

Considering the different nature of spillover effects and their potential impacts (e.g., direct impact from increased sales of products / services developed in the result of Fusion R&D project vs. indirect impact on potential future income due to accumulation of knowledge and enhanced technological / marketing capability) the "value driver trees" are constructed in order to trace the relationship between specific types of spillovers and each component of the company value.

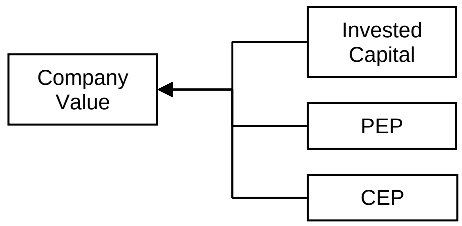


Figure 61. General Value Driver Tree for Company Value

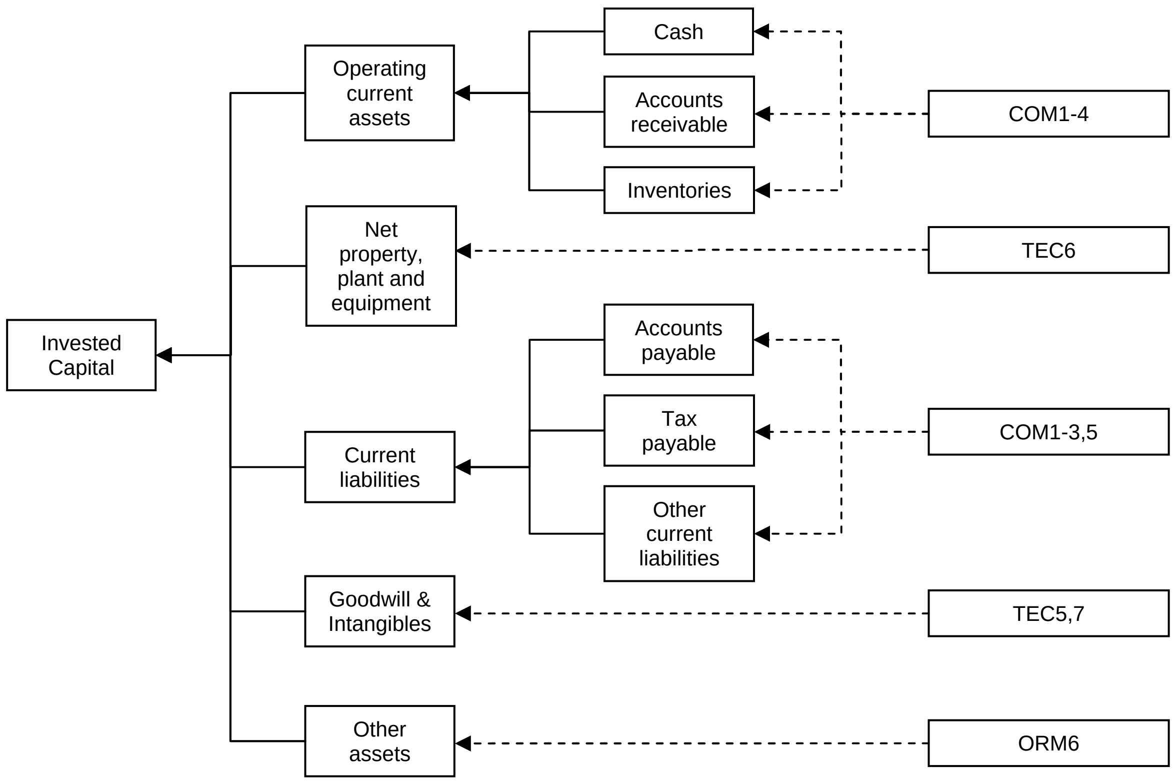


Figure 62. Value Driver Tree for Invested Capital

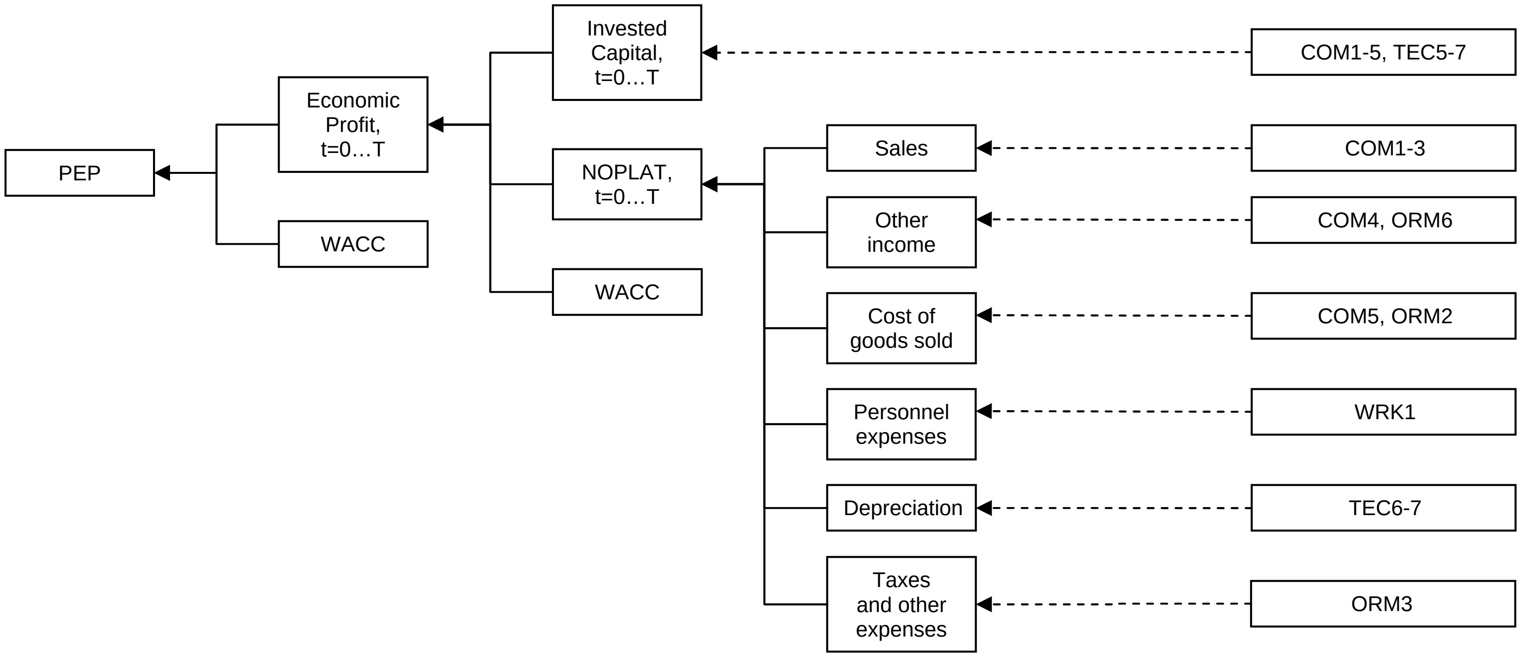


Figure 63. Value Driver Tree for Projected Economic Profit during Explicit Forecast Period

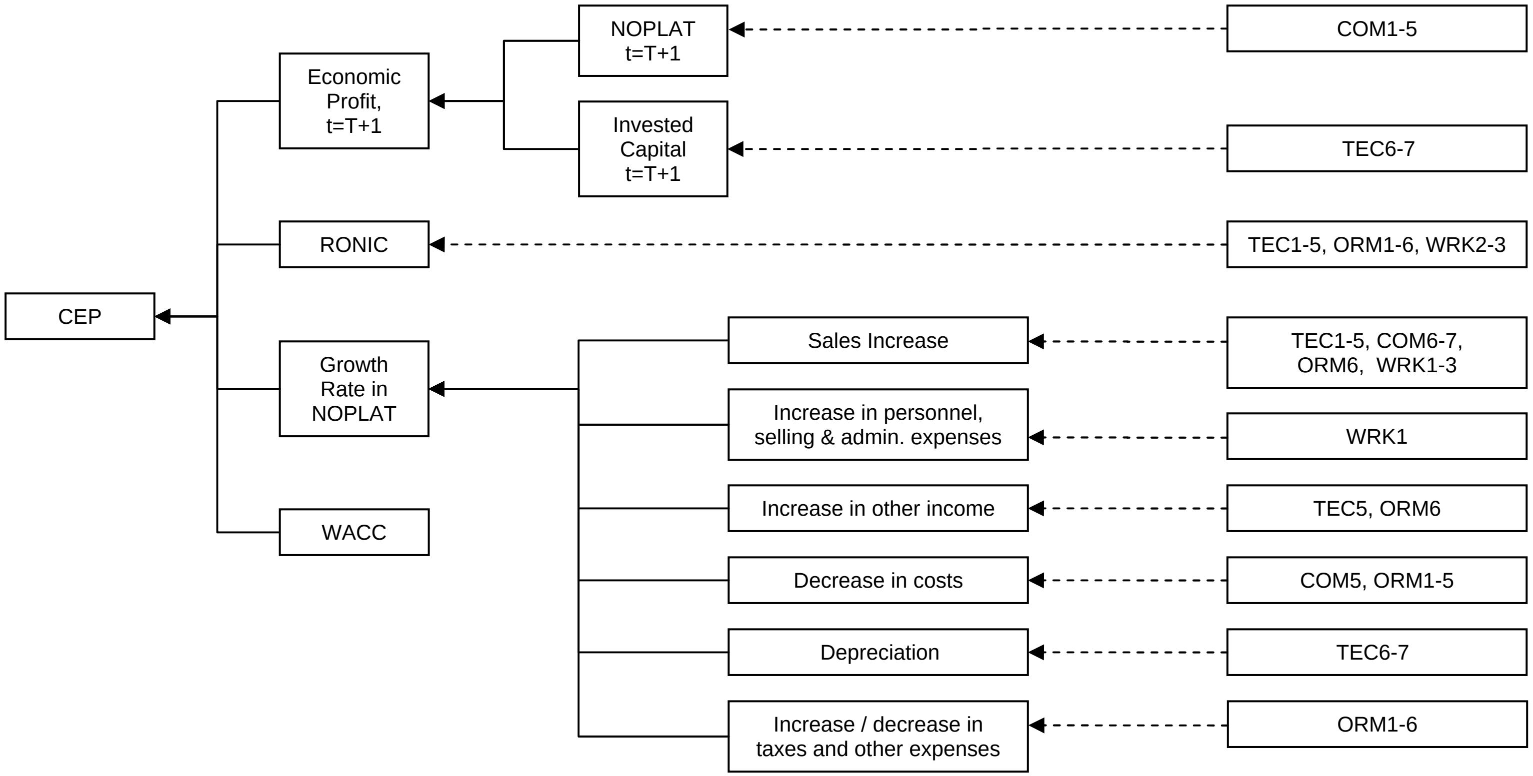


Figure 64. Value Driver Tree for Continuing Value of the Economic Profit after Explicit Forecast Period

5.5 Numerical Example

A case study demonstrating application of the proposed methodology to evaluation of spillover effects is implemented based on the example of Babcock Noell Gmbh company (BNG), a member of Bilfinger Berger Group. The core activities of BNG include nuclear service, nuclear technology, magnet technology and environmental technology. Position of BNG within Bilfinger Berger Group is shown in ***Figure 65***.

In the early 90s BNG launched the area of magnet technology with the development of large superconductor magnet systems for high-energy physics (CERN) and nuclear Fusion. A unique coil production technology was developed and an assembly plant was established for these purposes [36]. BNG in consortium with Italian group ANSALDO is responsible for supply of 50 super-conducting non-planar modular field coils for Wendelstein 7 – X project. It has also good prospects for supplying equipment components for ITER project.

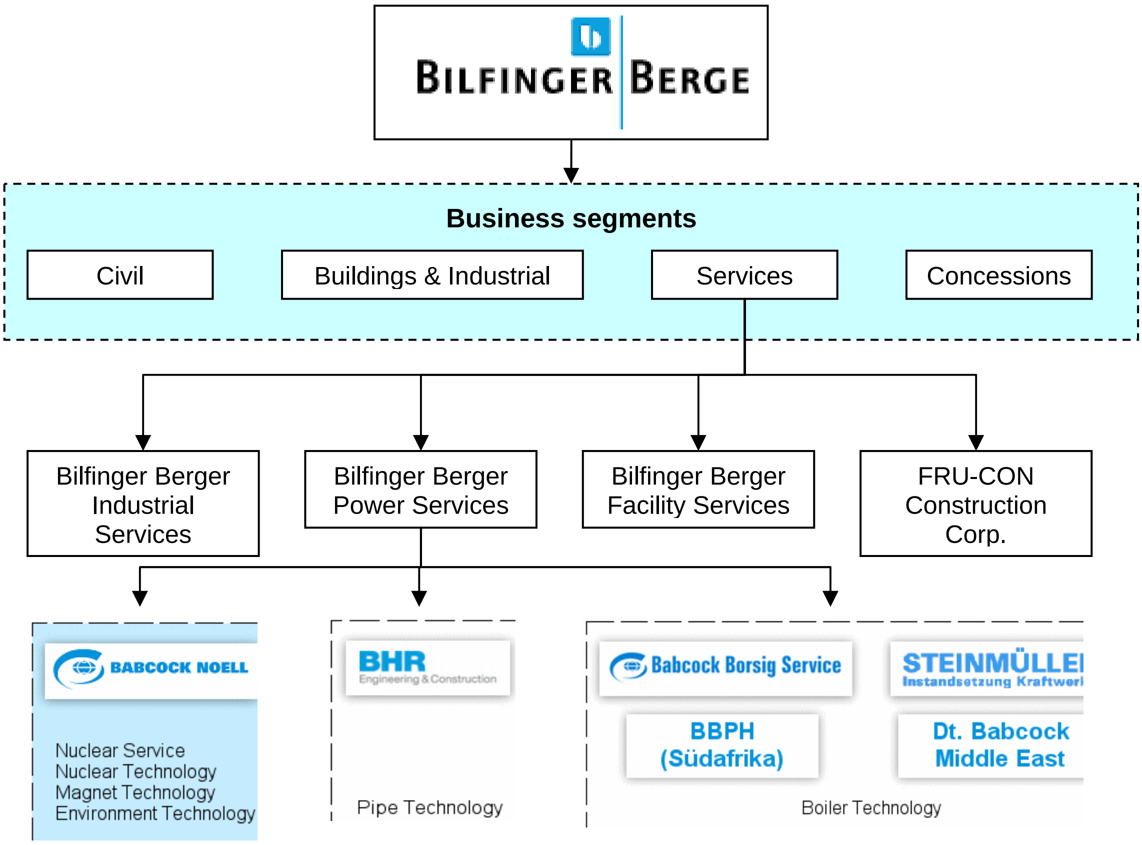


Figure 65. Organisational structure of Bilfinger Berger Group

[36] http://www.babcocknoell.de/en/babcock-noell-gmbh.139.html

The company value and Fusion R&D spillover benefits calculations provided below are based on the consolidated public accounting data of Bilfinger Berger Group. Considering that superconducting magnets represent only a modest part in the total business portfolio of Bilfinger Berger Group, accounting for about 1% in the total turnover of its “Services” division, the original data were scaled down by the factor of 100 in order to derive plausible data inputs. Accordingly, all results should be considered only as illustrative example of Fusion R&D spillovers model application without any direct relevance to BNG company.

The evaluation of Fusion R&D spillover benefits with the proposed model, at the company level, involves the following steps:

1. Collection of historical financial data, reorganisation of income statement and balance sheet to the required format.
2. Deriving of historical ratios from the available financial data and forecasting of future ratios.
3. Forecasting of future values of invested capital and economic profit according to the selected scenarios; calculation of the company value and Fusion R&D spillover benefits.

Historical balance sheet

€ mln	2000	2001	2002	2003	2004	2005	2006	2007
Cash and marketable securities	8.8	8.0	7.7	9.0	9.1	8.1	7.8	8.0
Inventories, receivables, other assets	13.5	16.1	16.0	14.7	14.4	15.7	19.0	22.0
Current liabilities	16.6	16.7	20.6	19.1	21.2	22.7	26.0	29.8
Net property, plant and equipment	4.8	5.0	5.5	5.4	4.8	5.1	6.1	5.8
Operating invested capital (excl. goodwill & intangibles)	10.5	12.5	8.7	9.9	7.1	6.3	6.8	6.0
Goodwill & Intangibles	0.8	0.8	2.1	3.0	3.5	5.9	7.4	7.9
Operating invested capital (incl. goodwill & intangibles)	11.3	13.3	10.8	12.9	10.6	12.2	14.2	13.8

Historical income statement

€ mln	2000	2001	2002	2003	2004	2005	2006	2007
Sales revenues	44.4	46.1	49.1	55.9	61.1	70.6	79.4	92.2
Cost of goods sold, personnel and other expenses	42.8	44.4	47.3	53.9	59.1	68.5	77.1	89.8
EBITA	1.6	1.7	1.9	2.0	2.0	2.2	2.3	2.4
Taxes on EBITA	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9
NOPLAT	1.0	1.1	1.2	1.3	1.3	1.4	1.5	1.6
ROIC (%)	9.2	8.3	11.0	9.8	12.2	11.4	10.5	11.3

Historical ratios

%	2000	2001	2002	2003	2004	2005	2006	2007
Revenue growth		3.8	6.6	13.7	9.4	15.5	12.4	16.2
Cash / Revenue	19.8	17.4	15.7	16.1	14.9	11.5	9.9	8.6
Inventories & receivables / Revenue	30.5	34.9	32.6	26.2	23.6	22.3	23.9	23.8
Current liabilities / COGSPOE	38.7	37.5	43.5	35.4	35.8	33.1	33.8	33.2
Net PP&E / Revenue	10.7	10.9	11.3	9.6	7.8	7.3	7.6	6.3
Goodwill / Acquired revenue	49.4	69.5	44.4	66.5	62.3	84.3	61.1	49.4
COGSPOE / Revenue	96.3	96.3	96.2	96.7	96.7	97.0	97.0	97.4
EBITA / Revenue	3.7	3.7	3.8	3.53	3.3	3.0	2.9	2.6

Explicit forecast for "Baseline" scenario

€ mln	Ratio*	2008	2009	2010	2011	2012	2013	2014	2015	2016
Sales revenues	11.1	102.5	113.8	126.5	140.5	156.1	173.4	192.7	214.1	237.9
COGSPOE	97.4	99.8	110.8	123.2	136.8	152.0	168.9	187.6	208.5	231.6
EBITA		2.7	3.0	3.3	3.7	4.1	4.6	5.1	5.6	6.2
Taxes on EBITA	35.5	0.95	1.06	1.18	1.31	1.45	1.62	1.80	1.99	2.22
NOPLAT		1.73	1.93	2.14	2.38	2.64	2.94	3.26	3.62	4.03
Cash and marketable securities	8.6	8.8	9.8	10.9	12.1	13.5	15.0	16.6	18.5	20.5
Inventories, receivables, other	23.8	24.4	27.1	30.2	33.5	37.2	41.4	45.9	51.1	56.7
Current liabilities	33.2	33.1	36.8	40.8	45.4	50.4	56.0	62.2	69.1	76.8
Net PP&E	8.7	8.9	9.9	11.0	12.2	13.6	15.1	16.7	18.6	20.7
Goodwill & Intangibles	62.5	6.4	7.1	7.9	8.8	9.8	10.8	12.0	13.4	14.9
Operating invested capital		15.5	17.2	19.1	21.2	23.6	26.2	29.1	32.4	35.9
ROIC (%)		11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2

* Historical ratio (%) applied to perform evaluation during explicit forecast period

Projected economic profit during explicit forecast period in "Baseline" scenario

€ mln	2008	2009	2010	2011	2012	2013	2014	2015	2016
Annual economic profit	0.34	0.38	0.42	0.47	0.52	0.58	0.64	0.71	0.79
Discount factor (at WACC = 9%)	1	1.09	1.19	1.30	1.41	1.54	1.68	1.83	1.99
Present value of annual economic profit	0.34	0.35	0.35	0.36	0.37	0.37	0.38	0.39	0.40
PEP	3.31								

Assumptions for calculation of continuing value in "Baseline" scenario

WACC : 9.0 %

Economic profit $_{2017}$: € 0.88 mln

NOPLAT $_{2017}$: € 4.47 mln

RONIC : 11.2 %

Growth rate in NOPLAT : 6 %

Continuing value of economic profit in "Baseline" scenario

$$CEP = \frac{EP_{2017}}{WACC} + \frac{NOPLAT_{2017}\left(\frac{g}{RONIC}\right)(RONIC - WACC)}{WACC(WACC - g)} = € \, 29.30 \text{ mln}$$

Total company value in "Baseline" scenario

$CV = IC_{2008} + PEP + CEP$ = 15.5 + 3.3 + 29.3 = € 48.1 mln

Increment of operating invested capital: "Baseline" vs. "No Fusion" scenario in 2008

Value driving factor	Total contribution (Q_k, € mln)	Spillover effect	Contribution Rate (R_m)
Operating current assets	33.3		
		COM1	2.0%
		COM2	10.0%
		COM3	1.0%
NPPE	8.9		
		TEC6	5.0%
Goodwill & Intagibles	6.4		
		TEC5	2.0%
		TEC7	1.0%
Current liabilities	33.1		
		COM1	2.0%
		COM2	10.0%
		COM3	1.0%
		COM5	0.5%
Invested Capital 2008 (BL)	15.48		
ΔIC (IC_{BL} - IC_{NF})	0.83 (5.3%)		

Fusion R&D project influence rate for NOPLAT

Category of spillover effect	**Intensity of contribution (β)**	**Spillover effect**	**Weight of assessment indicator (w)**	**Value of assessment indicator (v)**	**Influence Index (F)**
Technological	0.3				1.26
		TEC6	0.8	1.2	
		TEC7	0.2	1.5	
Commercial	0.6				1.20
		COM1	0.22	1.6	
		COM2	0.22	1.5	
		COM3	0.22	1.2	
		COM4	0.22	1.1	
		COM5	0.12	1.2	
Organisation & Methods	0.05				1.19
		ORM2	0.5	1.2	
		ORM3	0.3	1.3	
		ORM6	0.2	1	
Work - factor	0.05				1.1
		WRK1	1.0	1.1	
Influence rate (F^{NOPLAT})					**1.2119**

Fusion R&D project influence rate for Invested Capital

Category of spillover effect	**Intensity of contribution (β)**	**Spillover effect**	**Weight of assessment indicator (w)**	**Value of assessment indicator (v)**	**Influence Index (F)**
Technological	0.6				1.33
		TEC5	0.4	1.3	
		TEC6	0.3	1.2	
		TEC7	0.3	1.5	
Commercial	0.4				1.17
		COM1	0.4	1.2	
		COM2	0.2	1.2	
		COM3	0.2	1.1	
		COM4	0.1	1.2	
		COM5	0.1	1.1	
Influence rate (F^{IC})					**1.2635**

Increment of projected economic profit during explicit forecast period: “Baseline” vs. “No Fusion” scenarios

€ mln	2008	2009	2010	2011	2012	2013	2014	2015	2016
$NOPLAT^{BL}$	1.73	1.93	2.14	2.38	2.64	2.94	3.26	3.62	4.03
$NOPLAT^{BL} / F^{NOPLAT}$	1.43	1.59	1.77	1.96	2.18	2.42	2.69	2.99	3.32
IC^{BL}	15.5	17.2	19.1	21.2	23.6	26.2	29.1	32.4	35.9
IC^{BL} / F^{IC}	12.3	13.6	15.1	16.8	18.7	20.7	23.0	25.6	28.4
Present value of annual economic profit in NF scenario	0.33	0.33	0.34	0.35	0.35	0.36	0.37	0.37	0.38
PEP_{NF}	3.19								
ΔPEP (PEP_{BL} - PEP_{NF})	0.12 (4%)								

Fusion R&D programme influence rate for growth rate in NOPLAT (after explicit forecast period)

Category of spillover effect	Intensity of contribution (β)	Spillover effect	Weight of assessment indicator (w)	Value of assessment indicator (v)	Influence Index (F)
Technological	0.6				1.31
		TEC1	0.4	1.4	
		TEC2	0.2	1.2	
		TEC3	0.2	1.4	
		TEC4	0.1	1.2	
		TEC5	0.1	1.1	
Commercial	0.2				1.28
		COM6	0.4	1.4	
		COM7	0.6	1.2	
Organisation & Methods	0.1				1.03
		ORM2	0.2	1	
		ORM4	0.3	1.1	
		ORM6	0.5	1	
Work - factor	0.1				1.26
		WRK1	0.4	1.2	
		WRK2	0.3	1.5	
		WRK3	0.3	1.1	
Influence rate (F^{g})					**1.2680**

Fusion R&D programme influence rate for RONIC (after explicit forecast period)

Category of spillover effect	Intensity of contribution (β)	Spillover effect	Weight of assessment indicator (w)	Value of assessment indicator (v)	Influence Index (F)
Technological	0.6				1.31
		TEC1	0.4	1.4	
		TEC2	0.2	1.2	
		TEC3	0.2	1.4	
		TEC4	0.1	1.2	
		TEC5	0.1	1.1	
Organisation & Methods	0.3				1.10
		ORM1	0.2	1.2	
		ORM2	0.3	1	
		ORM3	0.1	1.1	
		ORM4	0.1	1.1	
		ORM5	0.2	1.2	
		ORM6	0.1	1	
Work - factor	0.1				1.38
		WRK2	0.6	1.5	
		WRK3	0.4	1.2	
Influence rate (F^{g})					**1.2496**

Continuing value of the projected economic profit in "No Fusion" scenario

$$NOPLAT_{2017}^{NF} = \frac{NOPLAT_{2017}^{BL}}{F^{NOPLAT}} = 4.47 / 1.2119 = € 3.69 \text{ mln}$$

$$EP_{2017}^{NF} = NOPLAT_{2017}^{NF} - \frac{IC_{2017}^{BL}}{F^{IC}} \times WACC = 3.69 - \frac{39.94}{1.2635} \times 9\% = € 0.85 \text{ mln}$$

$$CEP_{NF} = \frac{EP_{2017}^{NF}}{WACC} + \frac{NOPLAT_{2017}^{NF}\left(\frac{g}{F^{g}} \times \frac{F^{RONIC}}{RONIC}\right)\left(\frac{RONIC}{F^{RONIC}} - WACC\right)}{WACC\left(WACC - \frac{g}{F^{g}}\right)} =$$

$$= \frac{0.85}{0.09} + \frac{3.69\left(\frac{0.06}{1.268} \times \frac{1.2496}{0.112}\right)\left(\frac{0.112}{1.2496} - 0.09\right)}{0.09\left(0.09 - \frac{0.06}{1.268}\right)} = € 9.21 \text{ mln}$$

Assumptions for calculation of continuing value in "Accelerated" scenario

$\gamma^{g} = 1.1$

$\gamma^{RONIC} = 1.05$

$g_B = \gamma^{g} g_A = 1.1 \times 6\% = 6.6\%$

$RONIC_B = \gamma^{RONIC} RONIC_A = 1.05 \times 11.2\% = 11.8\%$

$n = 2046 - 2017 + 1 = 30$ yrs.

$\alpha = 80\%$

Continuing value of the projected economic profit in "Accelerated" scenario

$$CEP_{AC} = \frac{EP_{2017}^{BL}}{WACC} + \left[\frac{NOPLAT_{2017}^{BL}\left(\frac{g_A}{RONIC_A}\right)(RONIC_A - WACC)}{WACC(WACC - g_A)} \right] \times \left[1 - \left(\frac{1+g_A}{1+WACC} \right)^{30} \right]$$

$$+ \frac{NOPLAT_{2017}^{BL}(1+g_A)^{30}\left(\frac{g_B}{RONIC_B}\right)(RONIC_B - WACC)}{WACC(WACC - g_B)(1+WACC)^{30}} = € \ 34.74 \text{ mln}$$

Increment of continuing value of projected economic profit after explicit forecast period

$$\Delta CEP_i = \alpha \times (CEP_{BL} - CEP_{NF}) + (1 - \alpha) \times (CEP_{AC} - CEP_{NF}) =$$

$$= 0.8 \times (29.30 - 9.21) + 0.2 \times (34.74 - 9.21) = € \ 21.18 \text{ mln.}$$

Total spillover benefit

$SPB_i^j = \Delta CV_i = \Delta IC_i + \Delta PEP_i + \Delta CEP_i = 0.83 + 0.12 + 21.18 =$ € 22.1 mln.

5.6 Discussion of the Results

The results of numerical analysis of hypothetical company data with the proposed "Fusion R&D Spillovers Model" demonstrate that a substantial part of the company value resides in the estimated continuing value of the projected economic profit after explicit forecast period followed by the amount of operating invested capital at the date of evaluation and the present value of the projected economic profit during explicit forecast period.

The spillover effects of the ongoing Fusion R&D projects and future demonstration and deployment activities are most likely to affect the continuing value of the projected economic profit. This is not surprising considering the timescale and the magnitude of future profit opportunities that may be created through a successful completion of Fusion RD&D programme. It is also important to take into account the fact that current Fusion R&D projects mostly contribute to the build up of intangible assets which may increase company revenues in a longer term perspective rather than generate immediately additional sales with high commercial margin.

The next step involves carrying out face-to-face interviews with the managers of public research centres and private companies involved in Fusion R&D projects (in the present case - Wendelstein 7-X Fusion stellarator project). The main objectives of these interviews consist in determining the specific types of spillover effects occurred throughout the projects and estimating their influence rates on the key driving factors of the company value. The discussions are structured according to a questionnaire given in Annex II.

An algorithm based on the approach of Analytic Hierarchy Process (AHP) has been developed in order to convert qualitative linguistic variables of the questionnaire into numerical data suitable for quantitative assessment (see Annex III).

6. CASE STUDY OF WENDELSTEIN 7-X PROJECT

This chapter is emphasised on the evaluation of Fusion R&D spillovers through a case study of the companies participating in the construction of Wendelstein 7-X stellarator experimental device. The spillovers are understood here as direct and indirect effects of publicly funded Fusion R&D activities in terms of their influence on tangible value and strategic value of the involved companies. These effects principally concern the different types of technological, commercial, organisational and other types of learning, which allow firms to strengthen their market position and to achieve new sales and / or cost reductions.

6.1 Background and Objectives

In order to perform ground testing of the spillovers evaluation methodology and to gather initial data for quantitative analysis, an in-depth case study of Wendelstein 7-X project was carried out. The study involved semi-structured interviews with the managers of participant private companies and public research centres. The main objectives of the study were as follows:

- to get a better understanding of the main technological and organisational aspects of W7-X project;
- to identify the technological areas and the companies among the suppliers of W7-X project that represent the highest interest for further investigation;
- to quantify spillover benefits basing on the data and information obtained through the interviews with project directorate and managers of the involved private companies.

6.2 General Information about W7-X Project

6.2.1 Project Overview, Objectives and Time Framework

The Wendelstein 7-X experiment comprises the stellarator device (magnet coils, cryostat, plasma vessel, and divertor), the plasma heating systems (using microwaves and fast neutral particles), the supply facilities (electric power and cooling), machine control, and diagnostics (IPP, 2010). According to EFDA (2010) the main objective of W7-X is to prove the power plant relevance of advanced Fusion stellarators. Energy and particle confinement will be investigated in an optimized magnetic configuration and the stationary operation of a power plant relevant divertor system will be demonstrated.

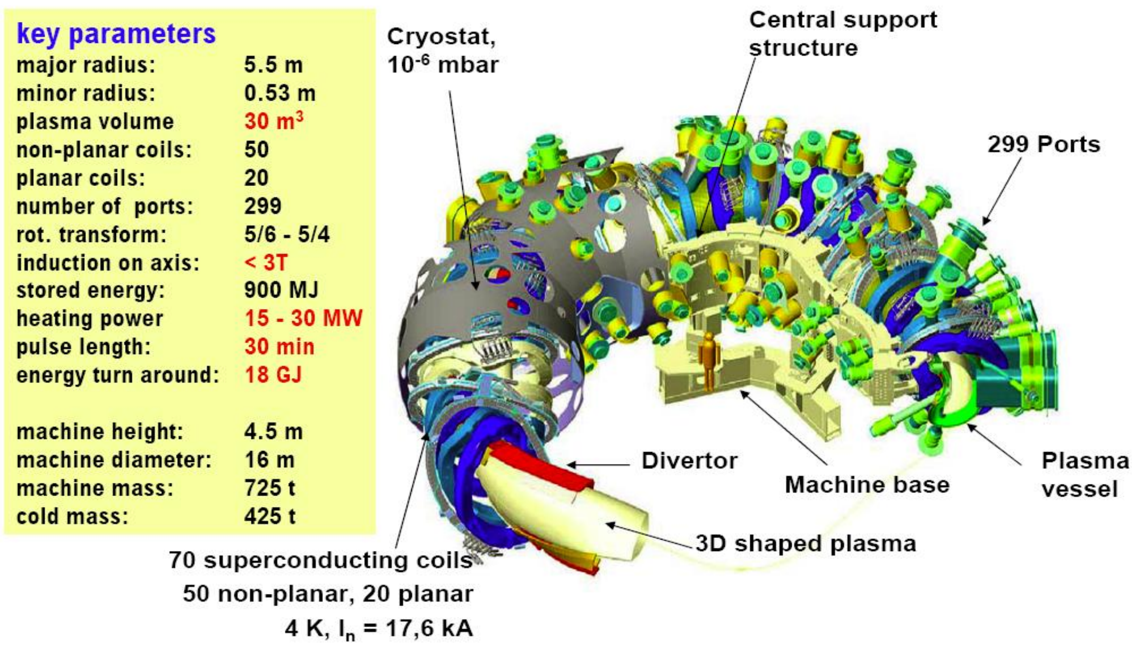
The centrepiece of the experiment is the coil system composed of 50 non-planar, superconducting magnetic field coils. They will allow W7-X to demonstrate the essential stellarator property, steady-state operation. The magnetic field cage produced will confine a plasma with temperatures up to 100 million degrees. W7-X should thus be capable of yielding convincing proof of the power plant properties of stellarators, without actually producing an energy-yielding plasma. As the properties of ignited plasma in tokamaks can be largely extended to stellarators, the experiment can dispense with the use of the radioactive fusion fuel, tritium, at great saving.

The construction of W7-X project has started in 1996 (Bünde *et al*., 2001). After an intensive R&D programme the project is in the phase of procurement and field assembly of the main components - magnet system, the cryostat, power supplies, and various tools. The latest information on the status of W7-X construction can be found in Wegener (2009). Estimated completion date is 2014. The start of plasma operation is due in 2015. The operation stage can last for another 50 years.

6.2.2 Funding and Procurement Structure

According to project management, the total cost of W7-X device is estimated at ≈ 1 billion Euro. Nearly 40% of this amount is invested in engineering, construction, assembly and testing of the stellarator device, 10% is spent on infrastructure incl. buildings. The remaining 50% are split between overhead and personnel costs. A more detailed structure of the project costs is given in Apendix I. The future costs during the operation stage can be estimated at 40-50 M€ per year.

The project funding mainly comes from German sources: Federal Ministry of Education and Research (BMBF) – 72%, Länder / local government – 8%. The contribution of Euratom was reduced from initial 45% to the present 20%. For the moment, approx. 400 M€ have been invested in the project design and construction.



Source: IPP, 2006

Figure 66. General Design and Parameters of W7-X Device

The main design parameters and structural components of W7-X stellarator device are shown in ***Figure 66***. Specific product / work packages were allotted through the organisational structure comprising six technical divisions (Magnet System; CryoSystems; in-Vessel Components; Heating Systems; Plant Control & Operation Planning; Integration & Test) and two functional divisions (Project Control; Quality Management). See details in Appendix II and III.

Detailed specifications of the procurement packages were provided by the project directorate. Private companies were not involved in the preparation of the specifications and were invited to participate in open tenders. Most part of the project contracts were signed on a fixed cost basis. However, some contracts contained fixed price and open price components (e.g. fabrication and assembly of plasma vessel). The list of major industrial companies supplying components to W7-X project is given in Appendix IV.

6.2.3 Selected Suppliers

The following companies participating in the construction of Wendelstein 7-X project can be considered as reference examples that may be interesting for further investigation:

MAN DWE

MAN DWE GmbH is a 100 % subsidiary company of MAN Group SE (München, Germany). In 2006 MAN DWE was integrated into MAN Turbo Group. In March 2010 Man Turbo AG was merged with MAN Diesel SE to form MAN Diesel & Turbo SE - a company with about 12500 employees present in 150 countries.

The main product range of MAN DWE includes tubular reactors and pressure vessels for chemical and petrochemical industry. Furthermore, vacuum vessels and heavy and large components, up to 1500 metric tons unit weight, for physical research facilities. Main contributions to W7-X project include: Main support structure; Thermal insulation; First wall cooling panels; Outer vessel; Plasma vessel.

http://www.mandieselturbo.com/0000852/products/reactors-and-apparatus.html

Babcock Noell

BABCOCK NOELL GmbH (BNN / BNG) is the centre of competence for Nuclear, Magnet and Environment Technology with world-wide responsibility inside the Babcock Borsig Service, a member of Bilfinger Berge Group (Germany). With approx. 200 employees, mainly in the field of engineering, the company covers a wide range of areas from development and design to operation of the supplied equipment.

Babcock Noell started with the development of large super-conducting magnetic systems for high-energy physics and Fusion experiments in the early ‘90s. Currently work is being performed on contracts for the series of magnets for W7-X Fusion experiment, other EFDA projects and the Large Hadron Collider at CERN.

http://www.babcocknoell.de/en/references-Fusion-technology.101.html

PLANSEE

The Plansee Group is one of the world’s leading suppliers of powder metallurgical products and components. With its 8500 employees at 62 companies worldwide, the divisions of Plansee

Group are valued partners in many industrial sectors, owing to its expertise in design, engineering, material and process know-how and application knowledge, which are steadily updated by tight collaborations with universities and research institutes. This attitude reflects that innovation is a major driver of the Group's success. In the fiscal year 2005, approximately 30% of the Group's total sales were generated by products developed within the last five years. In this period, 11% of sales were invested in product and process development as well as in new installations.

Currently PLANSEE HPM is manufacturing the target elements for the divertor of W7-X project. Over the last 5 years PLANSEE has been working on more than 10 contracts related to the manufacture of prototypes of high heat flux components envisaged for the divertor of ITER. Experience in materials, joining, coating, machining, and non-destructive examination of materials and components complete a successful basis to manufacture these demanding components.

http://www.plansee.com/power-engineering-nuclear-fusion.htm

Romabau-Gerinox AG

Romabau-Gerinox pursues the tradition of successful Swiss small and medium sized enterprises. The company is known for its first-class production of complex apparatus, construction parts, high vacuum technology and pressure vessels. The core competence lies in the top quality processing of metallic material. For W7-X project Romabau-Gerinox produced 299 ports to provide connection between outer and plasma vessel for diagnostics, heating systems, power supply lines and maintenance.

http://www.romabau-gerinox.ch/index_e.htm

P&S Vorspannsysteme AG

P&S Vorspannsysteme AG is a rapidly growing small-to-medium size Swiss engineering company with about 50 employees. The flagship product of the company is a tensioning system, called SUPERBOLT®, which is designed as a direct replacement for hex nuts. These SUPERBOLT® devices can be threaded onto a new or existing bolt, stud, threaded rod or shaft. The main thread serves to position the tensioner on the bolt or stud against the hardened washer and the load bearing surface. Once it is positioned, actual tensioning of the bolt or stud is accomplished with simple hand tools by torquing the jackbolts which encircle the main thread.

The SUPERBOLT systems supplied to W7-X project used silver coated nuts and washers and special 2-layer coated jackbolts that allowed to decrease the friction coefficient to approx. 0.06. Both coating processes were improved by the manufacturer especially for W7-X (Vilbrandt *et al.*, 2009). Consequently, a new tightening procedure of nuts was developed. The required bolt preload could be achieved using reduced torque and in shorter time (Dudek, 2009).

http://p-s.ch/gb/index.htm

6.3 Socio-Economic Evaluation of W7-X Project

W7-X is the last large superconducting Fusion experimental device in Europe before ITER. It is facing important technological challenges, because

- superconducting coils have to be built to sustain energy turnover of 18GJ at pulse length of 30 min;
- components subject to forces of 450 t have to be placed with mm accuracy and to remain there during operation;
- 3-D shapes have to be constructed, produced, welded and measured;
- some components are heated up to 1200 K, others - close to - are cooled down to 3.5 K;
- components are subject to pressures of 170 bar at a quench, whereas the vicinity remains at high vacuum;
- components carry 3 V during regular operation and are subject to 6 kV at a quench;
- there are about 1 Mill pieces of 20000 different types mounted inside the vessel, about 100 000 pieces are custom-made;
- DC-power supplies with [130 kV, 50 A] or [30 V, 20 kA] (IPP, 2006).

Accordingly, the project yielded a significant number of technological innovations in the areas of structural analysis, production technology, process engineering, electronic control, material technology, cryo-technology, electrical engineering, superconductor, vacuum and assembly technology (see detailed list in Appendix V).

6.3.1 Strategic Value

The main goal of W7-X project is to build a novel scientific device according to the highest academic standards which meets specific needs of Fusion R&D programme and creates an option for achieving disruption free operation and steady-state capability of Fusion reactor through implementation of alternative plasma confinement concept.

Many technological solutions developed for specific W7-X project needs have a direct relevance to ITER, e.g. superconducting coils, steady-state heating, energy handling techniques, steady-state operation, steady-state diagnostics (see Appendix VI for details).

The project represents also an excellent opportunity for training of engineers and physicists, training of industry (technologies, documentation, quality assurance) and network building.

6.3.2 Spillover Benefits to Industry

It was observed that for most part of the companies their participation in W7-X construction represented rather a minor activity compared to their core business. The interest of industrial community to participate was justified mainly by the opportunities to develop internal know-how relevant to Fusion technology and the expectation to grasp new market to be opened through the future Fusion RD&D projects, such as construction of ITER. Some companies also see in W7-X project an opportunity to improve the existing products in their business portfolio, to enhance their production techniques, and the possibility of some profit-taking. The main types of technological, managerial and work-factor learning effects are depicted in more details in Appendix VII. The reputation gains and network building also constitute important attraction factors for industry.

Questionnaire

See Annex II. Page 241.

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Appendix I.

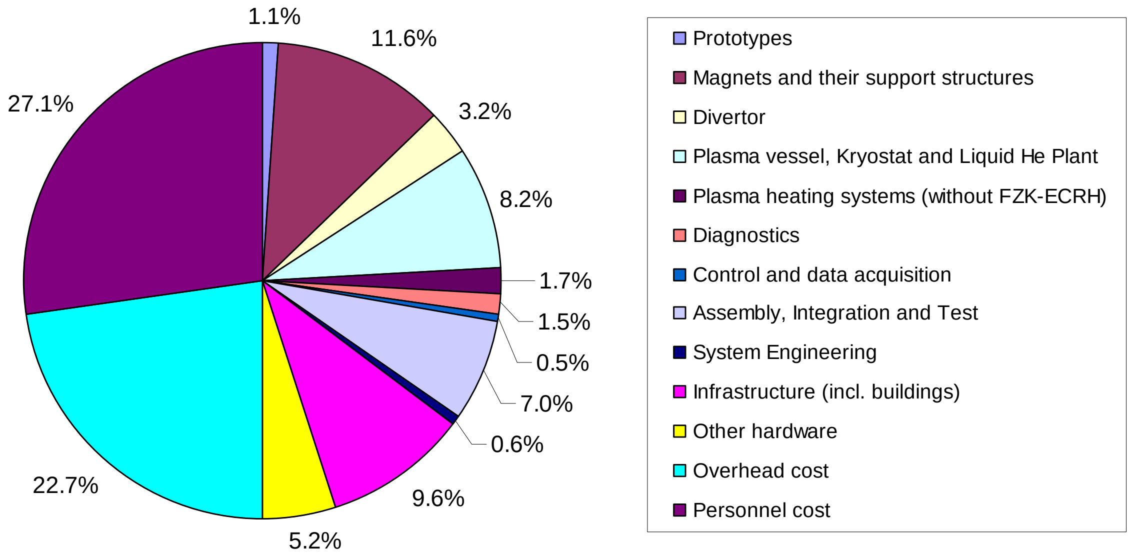

***Figure 67. Cost Structure of Wendelstein 7-X Project** (Source: IPP, 2006)*

Appendix II.

Table 33. Aggregated Product / Work Procurement Packages of W7-X Project

A	TORUS SYSTEM	TORUS SYSTEM
AA	MAGNETSYSTEM	MAGNET SYSTEM
AAA	Abteilungsleitung	Head of Department
AAB	Nichtplanare Spulen	Non-planar coils
AAC	Planare Spulen	Planar coils
AAD	Stütz- und Tragstruktur	Support structure
AAE	Stromversorgung Spulen	Coils current supply
AAF	Spulentests	Coil tests
AAG	Kühlung der Stromversorgung	Cooling of the power supply
AAH	Spulenstromverbindungen	Coil current leads
AB	KRYOSTAT	CRYOSTAT
ABA	Allgemein	General
ABB	Plasmagefäß	Plasma vessel
ABC	Außengefäß	Outer Vessel
ABD	Thermische Isolation	Thermal Insulation
ABE	Komponentenkühlung	Component Cooling
ABF	Stromzuführungen	Power supply
ABG	Kryostat-Vakuumsystem	Cryostat vacuum system
ABH	Kryostat-Abstützung	Cryostat support
ABI	MSR-Technik	Control & Instrumentation (C&I)
AC	KOMPONENTEN IM PLASMAGEFÄSS	IN-VESSEL COMPONENTS
ACA	Abteilungsleitung	Head of Department
ACB	Divertor-Entwicklung	Divertor Development
ACC	Divertor-Betriebsdiagnostik	Divertor operating diagnostics
ACD	Targetflächen	Target plates
ACE	Baffleflächen	Baffles
ACF	Kryopumpen	Cryo pumps
ACG	Regelspulen	Control coils
ACH	Wandauskleidung	Wall protection
ACI	Divertor-Gaseinlass	Divertor Gas Inlet

ACK	Divertor-Heizung / Kühlung	Divertor heating / cooling
ACL	MSR-Technik	C&I
ACM	Stromversorgung Regelspulen	Current supply control coils
AD	VAKUUMTECHNIK	VACUUM TECHNOLOGY
ADA	Abteilung Vakuumtechnik	Vacuum Technology Division
ADB	Vakuumsystem (mech.)	Vacuum System (mech.)
ADC	Vakuumtechnik	Vacuum Technology
ADD	Lecksuche	Leak
ADE	Unterstützung Diagnostik	Diagnostic support
AE		PORTS
AF	STUTZEN	SUPPORT STRUCTURE
B	KRYOSYSTEME	CRYO-SYSTEMS
BA	ABTEILUNGSLEITUNG	HEAD OF DEPARTMENT
BC	KÄLTEVERSORGUNG	CRYOGENIC SUPPLY SYSTEM
BCA	Allgemein	General
BCB	Helium-Kälteanlage	Helium refrigeration plant
BCC	Unterkühlsystem	Under cooling system
BCD	Helium-Reinigungssystem	Helium-cleaning system
BCE	Hilfseinrichtungen	Auxiliary Facilities
BCF	Kältemittelverteilung	Refrigerant distribution
BCG	Kühlmittel-Speichersystem	Coolant-storage system
BCH	Energieversorgung	Energy supply
BCI	MSR-Technik	C&I
C		HEATING SYSTEMS
D		CONTROL SYSTEM
F		PROTOTYPES
E		INTEGRATION & TEST
Q,R		PLASMA DIAGNOSTICS
S		ENERGY SUPPLY
T		MEDIA / COOLING
U		BUILDINGS

Source: W7-X internal document “Aufgabenstruktur” complemented with information from (IPP, 2006)

Annex III.

Organisational Breakdown Structure of W7-X Project

Project Director (L)

Project Control (M) • Organisation • Planning • Controlling Quality Management (N) • System Coordination • Documentation • Quality Planning • Quality Assurance • Change Control Plant Control / Operation Planning (D) • Central Control • Auxiliary Systems • Control Room / Communication • Components Control • Operation Planning • Vacuum Valves Integration & Test (E) • Installation Layout • Utilities / Cooling • Tools / Facilities • Plant Assembly • Electrical Connections	Magnet system (AA, F) • Non-planar Coils (NPC) • Planar Coils (PLC). • Control Coils • Support Structure • Coils Power supply • Coil Tests • DEMO-Coil Cryosystems (AB, AE, B, F) • Cryostat Vessels • Components Cooling • Cryo-Vacuum System • Cryogenic Supply System • DEMO-Cryostat In-Vessel Components (AC, AD) • Divertor Development • Divertor Diagnostics • Target elements • Baffle Elements • Cryopumps • Wall protection • Divertor Gas Inlet • Heating / Cooling • Vacuum System Heating Systems (C) • ECRH • ICRH • NBI • Gyrotron Development • Cooling of Heating System • HV Power Supply

Appendix IV.

Major Industrial Companies Involved in Components Supply

High-heatflux-divertor components:	SNECMA (F), Plansee (A), MAN DWE (G)
Plasma vessel:	MAN DWE (G)
Thermal insulation:	MAN-DWE (G) and Linde (G)
Non-planar coils:	BNN (G), Ansaldo (I), ABB (G) and sub-contractors
Planar coils:	Tesla (GB)
Outer vessel:	MAN DWE (G)
Ports:	Romabau-Gerinox (CH)
Experimental platform:	MAN DWE (G)
Machine base:	MAN DWE (G)
Cryosystem:	Linde (G)
Power supplies:	JEMA (E), ABB (CH), Siemens (G), Thales (CH)
ECRH gyrotrons:	Thales (F)
Building:	Henn (G)

Source: IPP (2006)

Appendix V.

Technological Innovations due to W7-X Project

- Structural analysis
    - Stress and deformation calculations of complex formed compound structures subject to mechanical and electromechanical forces (with Efremov, TUWarshow, CEA, ENEA…)
    - Eddy-current calculations of complex components
- Production technology
    - Plasma vessel: welding construction of a complex formed container at minimal welding distortions
    - Precision water-jet cutting of openings in 3-d shaped structures
    - Air-pressure technique to produce freely shaped water-cooled panels for wall protection
- Process engineering
    - Calculations of heat transmission at thermal loads up to 20 MW/m² for the target plates
- Control/Electronic
    - Development of a trigger time event system for fast synchronisation of control processes
- Material technology
    - Development of an Al-alloy as jacket for the SC conductor which hardens at elevated temperatures and is suitable for low temperatures.
    - Development of bonding techniques (with CEA) of
        - CuCrZr with CFC
        - Cu with steel
        - CuCrZr with steel
        - B4C coatings of steel surfaces
- Cryo-technology
    - Development of a novel radiation shield from fibre-glass re-enforced epoxy material with integrated copper mesh
- Electrical engineering
    - Manufacturing of large superconducting non-planar coils
    - Casting technology of coil casings under stringent accuracy conditions
    - LINAC radiation testing of massive steal structures
    - Continuous wall-thickness measurement during SC cable production
- Electrical engineering /SC technology
    - Development of a high-current power supply (20 kA/30 V) with low ripple
    - Development of a Ni-resistor as safety system for energy absorption at a rapid discharge of the coil system
    - Development of a fast and reliable quench detection system based on 500 signals at mV voltage level in a noisy environment (with FZK)
    - Development of current leads for 20 kA to minimise refrigeration power under stand-by conditions
    - Development of a low-resistance electrical joints for high currents (1nΩ/18 kA) (with FZJ)

- Assembly technology
  - o Development of a system for precise assembly of heavy components
  - o Development of combined systems for rapid and precise measurement of complex 3-d shaped components
- Vacuum technology
  - o Tests of turbo-molecular pumps suitable for operation in magnetic fields.
  - o Development of leak tests on the basis of SF6 (with FZK)
  - o Development of leak testing techniques for complex shaped test bodies

Source: IPP (2006)

Appendix VI.

The 17 Technologies Specific to Fusion and Essential for the Next Step

Plasma engineering	Contribution from W7-X
High power, high frequency sources (in the range 5-8 and 120-180 GHz)	major
Neutral Beam Power Supplies and High Voltage Components (of the order of 1MV)	partially (HV)
Plasma Facing Components	
Tiles and Coatings	major
Plasma Facing Component Models	input
Vessel, Shield and Blanket	
Vacuum Vessel, segments of Neutron Shields and of Tritium Breeding Blankets	partly / no
Superconducting Magnets	
Strands	partly
Conductors	partly
Model Coil Windings	partly
High Power Electrical Amplifiers	partly
Remote Handling Equipment	
Qualification of Standards and Tools	partly
Remote handling devices (transporters and ectuators)	
Fuel Cycle	
Tritium Compatible Vacuum Cryopumps and Mechanical Pumps	no
Tritium Compatible Vacuum Valves	no
Components for Tritium Handling and Atmosphere Detritiation	no
Materials for fusion specific applications	
Low activation structural materials for in-vessel components of a fusion reactor	no 92
Material for tritium breeding blankets icluding ceramic breeder and beryllium pebbles and permeation barriers	no

Source: IPP (2006)

Appendix VII.

Learning Benefits of W7-X Project

Technologies, technical solutions

- Superconductivity, cable-in-conduit technology, quench-detection, coil testing, instrumentation
- FE calculations
- cryo-technology and thermal insulation
- design of 3-d elements
- leak detection, lubrication at low temperature
- metrology tools (laser tracker and scanner, photogrammetry, back office).

Management:

- preparation of technical specifications for non-standard components
- contract management of large and complex contracts
- exercise management tools like handling of non-conformities, change-notes
- experience in quality management
- experience in project documentation systems
- qualification of materials and processes (e.g. low temperature properties, compound structures, joining of dissimilar materials)
- experience in working with interlinked work breakdown structures (WBS) to follow the schedule of tasks within the departments and the project globally
- contacts to several institutions which can support the design and construction of the machine (metrology, material science, test labs)
- back office (measurement of as built configuration, comparison with design geometry).

Source: IPP (2006)

7. RESULTS OF INTEGRATED ANALYSIS

This chapter describes the methodology and results of integrated analysis. A customised compound real options model was developed which allowed to estimate the strategic value of Fusion RDDD programme taking in to account the value of flexibility in managerial decisions and different spillover benefits. The value of the existing knowledge and infrastructure is modelled as salvage value in the abandonment option, while prospective spillover benefits are represented by the value of the expansion option. It was found that the value created due to spillover effects through the expansion option may represent a significant proportion of the strategic socio-economic value of Fusion RDDD programme (nearly 50%).

Integrated analysis is performed using a customized sequential compound option model, which assumes that at every stage of Fusion RDDD programme there may be different combinations of options, including the possibility to (i) accelerate and expand the programme; (ii) continue to the next stage as planned; (iii) contract the scope of activities resulting in some savings; or (iv) abandon the accomplished works in return for its salvage value (see ***Figure 68***). The value of potential embodied spillovers (e.g. spin-off applications) is represented in this model by the value of the expansion option, while the value of existing infrastructures and knowledge spillovers is equivalent to salvage value in the abandonment option.

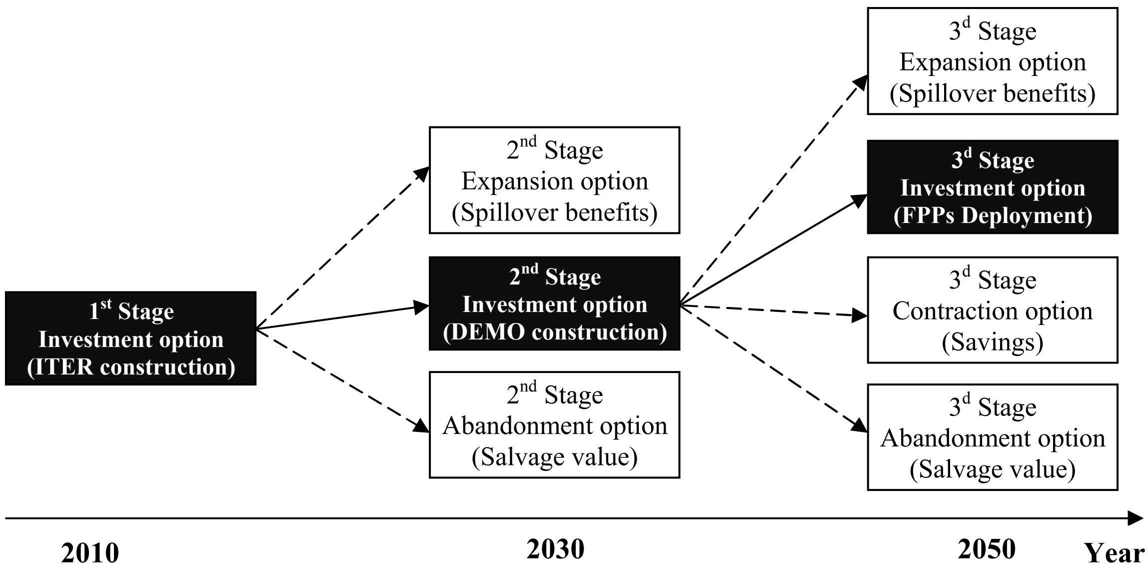

Figure 68. Integrated Sequential Compound Option Model of Fusion RDDD Programme

The traditional NPV method ignores the value of these strategic options arising due to possibility to take appropriate managerial decisions when the uncertainty becomes resolved. Therefore, the proposed real options approach may provide a more accurate evaluation of Fusion RDDD programme taking into account both its strategic value due to flexibility and the value of spillover / spin-off benefits. The mathematical algorithm allowing to obtain a numerical solution for such a complex compound option is based on the backward induction process and includes the following steps:

Stage 3:	Terminal	Max(Underlying*Expansion-ExpCost-Cost,Underlying-Cost, Underlying*Contract+Savings-Cost,Salvage,0)
	Intermediate	Max(Underlying*Expansion-ExpCost-Cost, Underlying*Contract+Savings-Cost,Salvage,OptionOpen)
Stage 2:	Terminal	Max(Stage3*Expansion-ExpCost-Cost,Stage3-Cost,Salvage,0)
	Intermediate	Max(Stage3*Expansion-ExpCost-Cost,Salvage,OptionOpen)
Stage 1:	Terminal	Max(Stage2-Cost,Salvage,0)
	Intermediate	Max(Salvage1,OptionOpen)

The following verbal interpretation can be given to the proposed integrated real options model. At the current stage, the decision makers have the possibility to pursue Fusion RDDD programme according to the reference "Baseline" scenario that means to proceed with the construction of ITER / IFMIF and to continue other R&D activities as needed. This possibility represents a "compound" option that gives the right either to invest in the demonstration stage (construction of DEMO reactor), or to stop the programme in the case of insurmountable technical problem and to save further investment outlays ("abandonment" option). The "expansion" option consists in the possibility to develop and market other products capitalising on the knowledge spillovers and technology spin-offs from the ongoing and future R&D works.

Upon completion of the demonstration stage, the decision makers will have the right either to invest in the deployment of Fusion power plants or to abandon the programme if the market conditions turn out to be unfavourable, and there is no more sense to continue. Two additional simultaneous options at this stage are represented either by the possibility (i) to reduce the scope of deployment activities ("contraction" option) that would allow to make some investment savings or (ii) to increase the scope of commercial activities (including the sales of Fusion non-electrical by-products and all sorts of other spin-offs) that will entail some additional costs but will also generate supplementary revenues.

With such a set up, the value of the underlying asset is represented by the expected revenues from Fusion electricity sales according to a "Baseline" scenario. The other model parameters such as costs of staged investments, time framework, risk-free rate and annualised volatility are the same as in the case of simple compound option. Specific parameters of the model (salvage values, expansion rates / costs, contraction rate, savings) are summarised in ***Table 34***. Some additional sensitivity analyses were performed by varying the knowledge spillover rate, which determines the salvage value subject to the endowed funding at the preceding programme stages, and the "expansion" rate, which reflects the future potential gains subject to the expected revenues from sales of Fusion electricity and spin-off products.

The model was implemented in practice using "Real Options SLS" software (Mun, 2009b) and its Multiple Asset Super Lattice Solver (MSLS).

Table 34. Main Assumptions in Integrated Compound Real Options Model

	Unit	**Baseline Scenario**	**Sensitivity Analysis Range**
R&D stage			
Undiscounted costs	€ billion	35	-
Discounted costs	€ billion	23	-
Salvage value[(a)]	€ billion	50	0 – 50
Demo stage			
Undiscounted costs	€ billion	45	-
Discounted costs	€ billion	13	-
Salvage value[(a)]	€ billion	73	0 – 73
Expansion rate	x	1.1	1.0 – 1.5
Expansion cost [(a)]	€ billion	1.3	0 – 6.5
Deployment stage			
Expected revenues / Underlying[(a)]	€ billion	324	-
Expected costs[(a)]	€ billion	203	-
Salvage value[(a)]	€ billion	86	0 – 86
Expansion rate	x	1.1	1.0 – 1.5
Contraction rate	x	0.5	0.5 – 1.0
Expansion cost[(a)]	€ billion	20	0 – 100
Savings[(a)]	€ billion	100	0 – 100
Volatility	%	6.6	-
Risk free rate	%	2.25	-

(a) discounted values

The first indicative computation with the proposed integrated real options model was performed using the same numerical assumptions as in the case of simple compound option model, i.e. by setting "salvage value" / "expansion cost" / "savings" parameters equal to "zero" and "expansion" / "contraction" rates equal to unity (1.0). Not surprisingly, the model yielded exactly the same result (€ 226 billion) as in the case of simple compound real option (see Chapter 4.5).

In the second step, some non-zero values were assigned to salvage value parameters. So, for R&D stage the assumed salvage value was taken equal to €50 billion that roughly corresponds to the up-to-date amount of Fusion R&D funding (see Chapter 2.1.3); for Demo stage this salvage value was increased by the projected amount of funds to be invested during R&D stage that resulted in the total discounted salvage value of €73 billion; and for Deployment stage it was further increased by the projected investments in the construction and operation of Fusion Demo facilities with salvage value totalling €86 billion. In this case, the value of the compound real option increases by a relatively insignificant amount of €0.1 billion. This result can be interpreted as a proof of the fact that given the current expectations of future costs and revenues of Fusion power plants the value of the abandonment option is practically negligible, and hence it is worthwhile to pursue Fusion RDDD programme. A similar result was obtained with the introduction of specific contraction rate / savings parameters, meaning that under the same assumptions the possibility of voluntary reduction of the size of Fusion RDDD programme does not add any significant value.

At the next step, the expansion option parameters were also included in the computation of the compound real option value. The expansion costs were calculated by multiplying the expected costs in "Baseline" scenario by the expansion rate. Considering the different nature of the potential spillover benefits throughout different stages (mainly cross-industry spillovers during RD&D stage, and mainly intra-industry spillovers during deployment stage), it is reasonable to assume that the level of the expansion rate may also vary from one stage to another.

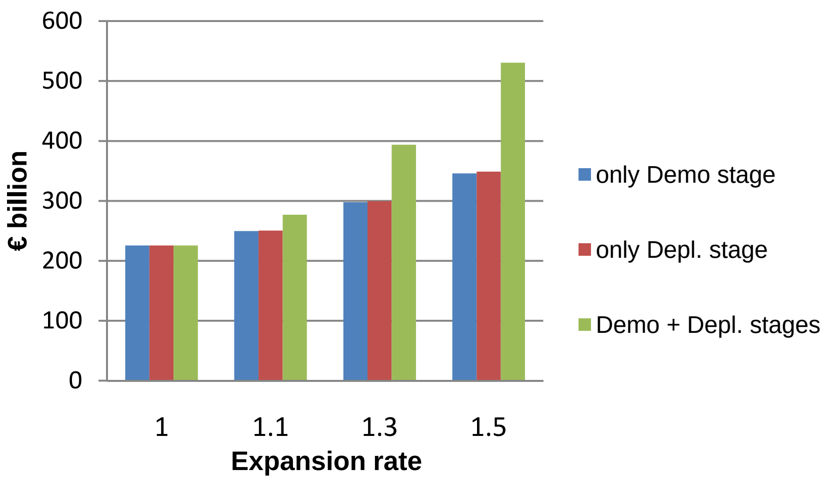

Figure 69. Influence of Different Expansion Rates on the Compound Option Value

The results of sensitivity analyses to the assumed values of the expansion rate are illustrated in ***Figure 69***. It appears that the model is highly sensitive to this parameter. So, in the case where expansion rate is equal to 1.5 in both demonstration and deployment stages, the value of the customised compound option increases to € 530 billion. If the same 1.5 expansion rate is applied during only one stage, the model yields the compound option value in the range of €346-349 billion. Somewhat more realistic case with the expansion rate equal to 1.1 during demonstration and 1.3 during deployment results in the total compound option value of €331 billion (a factor of 1.46 compared to the simple compound option).

This relatively high impact from the inclusion of expansion option in the analysis is not surprising considering the numerous empirical evidences of the magnitude of spillover effects and taking into account the multidisciplinary nature of Fusion R&D activities (see Chapter 2.2 for detailed discussion). Therefore, it can be concluded that the proposed integrated compound real option model is capable to provide a more accurate estimate of the total socio-economic pay-offs of Fusion RDDD programme including its spillover benefits and strategic options.

8. SUMMARY AND CONCLUSIONS

This final chapter provides a summary of the dissertation. First, an overview of the context, objectives and methodology is given. Then, the main findings, conclusions and contributions are presented. Finally, some limitations and the directions of future works are outlined.

8.1 Overview and Main Findings of the Research

This dissertation explores the issues of socio-economic evaluation of long-term energy RDDD programmes. The high relevance of this research is justified, on the one hand, by the global energy security problem and the need to find new sources of clean, safe and moderately priced energy supply and, on the other hand, by the decision makers' problem to allocate efficiently a limited budget among a variety of energy and non-energy R&D programmes. The study is focused on Thermonuclear Fusion technology, which may become in the second half of this century an important energy supply option with multiple environmental and economic benefits. However, the remaining RD&D works still require a substantial time (30 to 40 years) and a considerable amount of public funding (€1.5 to 2.5 billion per year). Therefore, given the opportunity cost of capital, it is important to optimise the future public investments in Fusion RDDD programme subject to the underlying risks and the expected net socio-economic benefits.

At the present stage, the optimisation problem is confined to the decision either to pursue Fusion RDDD programme at its current relatively "moderate" pace, or to adopt a more ambitious programme, which assumes construction of several DEMO installations of alternative concept and general speeding-up of all RD&D activities. Compared to the former option, the latter accelerated "New Paradigm" approach requires higher RD&D expenditures, but potentially it may offer superior return due to earlier technology availability on the market and greater volume of various fringe benefits. For sound decision making, in both cases, a comprehensive socio-economic evaluation of the whole Fusion RDDD programme is needed. Meanwhile, such evaluation represents an extremely difficult task, because the projection has to be made over very long period of time (≈100 years) and multiple types of uncertainty should be taken in to account. The problem is exacerbated by the fact that analytical methodologies and practical tools for estimating several important components of the programme's revenues stream, such as the value of strategic real options due to managerial flexibility and the spillover benefits due to positive externality effects, are still missing or substantially incomplete.

Accordingly, the ultimate goal of this thesis consisted in performing a more comprehensive socio-economic evaluation of Fusion RDDD programme through elaboration of integrated modelling framework that would provide a holistic view of the total socio-economic costs and benefits of Fusion RDDD programme. The main components of the proposed integrated modelling framework and its application in the analysis of specific research questions are outlined below.

Long-term Electricity Supply Scenarios with Fusion

This part of the thesis aimed to explore the potential role of Fusion power in future electricity supply mixes and to quantify its advantages and possible drawbacks. A general assessment of the electricity generation systems in different world regions was carried out at its current and anticipated state through estimating the future electricity demand, availability and prices of main power generation fuels, generic technical and economical parameters of the existing and prospective electricity generating technologies and building on this basis a set of multi-regional electricity markets scenarios for the time horizon 2100. The methodological tool applied in the study consists of probabilistic simulation dynamic programming model PLANELEC-Pro, which allows to determine the expansion plans of the power generation system that adequately meet the electricity demand at minimum cost, while respecting the constraints related to the quality of electricity supply and CO_2 emissions. The competitiveness of Fusion was estimated through assessing the impact of various market shares of Fusion power plants on the discounted total cost of the power generation system, levelised electricity cost and cumulative CO_2 emissions.

It was found that Fusion power potentially may become an important energy supply option attaining the maximum market share of approx. 20% in most developed world regions, such as North America, Western Europe and Japan. During initial stages, the deployment of Fusion power plants is projected to increase the levelized system electricity cost. However, this effect may be attenuated thorough accelerated technology learning process, imposition of stricter environmental policy regime (e.g. real price of carbon dioxide emissions nearing € 50 per ton), limited access to nuclear fission technologies, and general upward fluctuation of hydrocarbon fuel prices. The two main Fusion deployment scenarios envisage the total world-wide Fusion power generation capacity of 330 GWe by 2100 in "Moderate Introduction" case and 950 GWe in "Massive Deployment" case.

Real Options Model

The strategic value of Fusion technology was estimated with the help of real options model based on the expected discounted cash flows from construction and operation of Fusion power plants, exogenous assumptions regarding the costs of Fusion RD&D activities and the probabilities of success at each programme stage. Net present value of Fusion RDDD programme estimated in a probabilistic setting was taken as benchmark for calculating the real options value attributable to different managerial decisions that may affect the prospective cash-flows. Two different strategies were compared: "Baseline" corresponding to the current relatively moderate pace of Fusion RDDD programme vs. "Accelerated" strategy assuming more rapid development and massive deployment of Fusion technology.

The results of real options valuation indicate that potential revenues from deployment of Fusion technology could substantially exceed the RD&D and deployment costs, and confirm that it is worthwhile to pursue Fusion RDDD programme given the current state of knowledge and the level of uncertainty. The analysis also shows that substantial strategic value of Fusion RDDD programme is being ignored by traditional NPV method: e.g. the value of compound real option is €222 billion (if calculated with traditional crisp numbers) and €184 billion (if calculated as possibilistic mean of fuzzy number), compared to €85 billion which is the expected static NPV calculated in a stochastic probabilistic setting. The results of real options analysis also suggest that a more ambitious "Accelerated" Fusion RDDD programme may yield a significant incremental return that could surpass the corresponding increase of the programme costs.

Spillovers Model

A conceptual model was developed for estimating spillover benefits at the level of individual companies participating in Fusion RDDD programme. Herein, spillover effects are understood as different types of technological, commercial and organisational learning, which may be acquired by the companies through their participation in publicly funded Fusion R&D projects. The model assumes that Fusion R&D spillovers could have a positive impact on the key driving factors of the company value in multiple ways, e.g. increase in sales revenues, acquisition of new technological competences; building of knowledge stock embodied in company's personnel, patents, manufacturing know-how; development of prototype or ready-to-market innovative products; strengthening of marketing capabilities, etc. Accordingly, the pecuniary value of spillover benefits is calculated based on the estimated increment of the company value due to its participation in Fusion R&D, demonstration and deployment activities. Practical viability of the proposed method is demonstrated through a generic numerical example. Additional empirical data were gathered through a case-study of Wendelstein 7-X Fusion stellarator project which confirmed that Fusion R&D experiments had yielded important technological and commercial spillover benefits for the involved industry.

Integrated Analysis

Overall socio-economic evaluation of Fusion RDDD programme was carried out using integrated modelling framework comprising all three model components outlined above. The scenarios elaborated with the first model were taken as inputs for real options analysis of different Fusion demonstration and deployment strategies and estimation of the economic value of spillover benefits at the level of individual companies. Bibliographic analysis and exemplary calculations with spillovers model allowed to specify a generic Fusion RDDD spillover rate, which was used as additional input ("expansion rate") in integrated compound real options model for estimating the strategic value of Fusion RDDD programme taking into account it's both internal and external cost and benefits.

The study confirmed the idea that inclusion of hidden real options value, due to managerial flexibility, and the value of positive externalities, due to spillover effects, provides a more comprehensive picture of the total social returns of Fusion RDDD programme. So, the expanded strategic net social present value of Fusion RDDD programme, estimated in this study, is equal to €416 billion: €85 billion probabilistic ENPV + €331 billion value of integrated compound real option taking into account spillover benefits and strategic value due to managerial flexibility. 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 the failure probability.

8.2 Conclusions and Recommendations

The theoretical work and practical calculations presented in this thesis confirm the importance of Fusion R&D activities for assurance of sustainable energy future of the humankind. This type of socio-economic analysis of the ongoing R&D programmes is certainly helpful for comparison of different alternatives and sound decision making. In relation to different choices existing within current Fusion R&D programme, this research provides clear arguments in favour of maintaining several design options and increasing the overall scientific and industrial efforts. Accordingly, the analytical framework developed in this thesis can be considered as a decision-aid tool for monitoring the ongoing Fusion R&D activities and optimising its future funding subject to the expected net socio-economic return and the underlying uncertainty. It can be also used as a component of the knowledge management system by the private companies interested to secure their strategic position on Fusion technology market.

As pointed out by Foray (2009) structuring a policy response to a "Grand Challenge" (e.g. global climate change, energy security, etc.) requires a fine policy mix, involving non-neutrality at the very general level of the identification of the challenge (to build a broad political consensus) and neutrality at the more specific level of the selection of R&D priorities and technologies within the large scope of operation (to leave the market free to experiment and select). The Fusion RDDD programme embracing two different plasma confinement concepts (Magnetic vs. Inertial) and multiple design configurations represents a perfect example of such a "Grand Challenge" which requires strong political decisions regarding the allocation of sufficient financial resources required to maintain the desired pace of programme implementation, while leaving the scientists and industrial community the liberty to decide on the optimal ways to achieve the targets and to explore the alternative pathways. The author hopes that this dissertation may help to advance the political decision-making process in the right direction.

8.3 Main Contributions of the Thesis

The main contributions of thesis can be summarized as follows:

- A novel methodology for socio-economic evaluation of global long-term energy R&D programmes, such as thermonuclear Fusion, based on integrated technological and socio-economic modelling framework.
- A novel financial model for evaluation of spillover benefits of publicly funded R&D programmes focused on private companies participating in thermonuclear Fusion R&D.
- A novel methodology based on real options approach allowing for calculation of the expected net social present value of long term R&D programmes in energy sector subject to different types of uncertainty.
- Integration of scenario building, market simulation, real options analysis, company evaluation, strategy optimisation and decision-support.
- Practical estimation of the strategic net social present value of Fusion RDDD programme.

8.4 Limitations and Further Research Needs

The main limitations of the proposed analytical approach concern the methodology of global energy scenarios building and gathering of empirical data for company evaluation with spillovers model. In this dissertation the scenario development relied on the soft linkage of PLANELEC model with a more complicated global energy systems model EFDA-TIMES, which is still undergoing development, fine-tuning and external review process. Finalisation of work on EFDA-TIMES and its hard-linkage with PLANELEC model would help to elaborate more transparent and more universally accepted Fusion deployment scenarios.

The application of spillovers financial evaluation model is limited in this thesis to the hypothetical company dataset, while for more convincing analysis it is desirable to use real data. The problem is that private not-listed companies most times are not willing to disclose their financial accounting data. Therefore, special provisions should be made while preparation of industry procurement contracts of future Fusion RD&D experiments that would allow for more comprehensive evaluation of their spillover benefits, including the possible disclosure of financial data or at least an obligation to participate in a formalised industry survey.

Future research should be geared towards further consolidation and practical implementation of the proposed integrated modelling & assessment framework. More comprehensive input data and information can be gathered throughout the continuation of field survey, and the credibility of assumptions may be endorsed by external review. Special attention shall be also given to adequate treatment of the epistemic uncertainty. Such an enhanced and validated evaluation framework may be used as a decision-aid tool for optimising future funding of Fusion programme. Another important axis in future research work may consist in a more thorough investigation of the energy security benefits of Fusion technology.

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ANNEX I. NUMERICAL RESULTS OF REAL OPTIONS VALUATION

Table I-A. ROV Sensitivity to the Expected Revenues (Price of the Underlying Asset)

	-100%	-75%	-50%	-25%	0%	25%	50%	75%	100%
Expected revenues	0	81	162	243	324	405	486	567	648
Expected costs	-//-	-//-	-//-	-//-	203	-//-	-//-	-//-	-//-
Time to expiration	-//-	-//-	-//-	-//-	42	-//-	-//-	-//-	-//-
Risk-free rate	-//-	-//-	-//-	-//-	2.25%	-//-	-//-	-//-	-//-
Annualised volatility	-//-	-//-	-//-	-//-	6.6%	-//-	-//-	-//-	-//-
e	-//-	-//-	-//-	-//-	2.72	-//-	-//-	-//-	-//-
d1	-12.63	0.28	1.90	2.84	3.52	4.04	4.46	4.82	5.14
d2	-13.06	-0.15	1.47	2.42	3.09	3.61	4.04	4.40	4.71
N(d1)	0.00	0.61	0.97	1.00	1.00	1.00	1.00	1.00	1.00
N(d2)	0.00	0.44	0.93	0.99	1.00	1.00	1.00	1.00	1.00
Call option value	**0**	**15**	**84**	**164**	**245**	**326**	**407**	**488**	**569**

Table I-B. ROV Sensitivity to the Expected Costs (Exercise Price)

	-100%	-75%	-50%	-25%	0%	25%	50%	75%	100%
Expected revenues	-//-	-//-	-//-	-//-	324	-//-	-//-	-//-	-//-
Expected costs	0	51	102	152	203	254	305	355	406
Time to expiration	-//-	-//-	-//-	-//-	42	-//-	-//-	-//-	-//-
Risk-free rate	-//-	-//-	-//-	-//-	2.25%	-//-	-//-	-//-	-//-
Annualised volatility	-//-	-//-	-//-	-//-	6.6%	-//-	-//-	-//-	-//-
e	-//-	-//-	-//-	-//-	2.72	-//-	-//-	-//-	-//-
d1	19.67	6.76	5.14	4.19	3.52	2.99	2.57	2.21	1.90
d2	19.24	6.33	4.71	3.76	3.09	2.57	2.14	1.78	1.47
N(d1)	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.97
N(d2)	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.93
Call option value	**324**	**304**	**285**	**265**	**245**	**225**	**206**	**187**	**168**

Table I-C. ROV Sensitivity to the Time to Expiration

	-100%	-75%	-50%	-25%	0%	25%	50%	75%	100%
Expected revenues	-//-	-//-	-//-	-//-	324	-//-	-//-	-//-	-//-
Expected costs	-//-	-//-	-//-	-//-	203	-//-	-//-	-//-	-//-
Time to expiration	0	11	21	32	42	53	63	74	84
Risk-free rate	-//-	-//-	-//-	-//-	2.25%	-//-	-//-	-//-	-//-
Annualised volatility	-//-	-//-	-//-	-//-	6.6%	-//-	-//-	-//-	-//-
e	-//-	-//-	-//-	-//-	2.72	-//-	-//-	-//-	-//-
d1	34.64	3.40	3.26	3.36	3.52	3.69	3.86	4.03	4.20
d2	34.63	3.18	2.96	2.99	3.09	3.21	3.34	3.47	3.59
N(d1)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
N(d2)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Call option value	**121**	**164**	**197**	**224**	**245**	**262**	**275**	**285**	**293**

Table I-D. ROV Sensitivity to the Risk-free Rate

	-100%	-75%	-50%	-25%	0%	25%	50%	75%	100%
Expected revenues	-//-	-//-	-//-	-//-	324	-//-	-//-	-//-	-//-
Expected costs	-//-	-//-	-//-	-//-	203	-//-	-//-	-//-	-//-
Time to expiration	-//-	-//-	-//-	-//-	42	-//-	-//-	-//-	-//-
Risk-free rate	0.00%	0.56%	1.13%	1.69%	2.25%	2.81%	3.38%	3.94%	4.50%
Annualised volatility	-//-	-//-	-//-	-//-	6.6%	-//-	-//-	-//-	-//-
e	-//-	-//-	-//-	-//-	2.72	-//-	-//-	-//-	-//-
d1	1.31	1.86	2.41	2.96	3.52	4.07	4.62	5.17	5.72
d2	0.88	1.43	1.98	2.54	3.09	3.64	4.19	4.75	5.30
N(d1)	0.90	0.97	0.99	1.00	1.00	1.00	1.00	1.00	1.00
N(d2)	0.81	0.92	0.98	0.99	1.00	1.00	1.00	1.00	1.00
Call option value	**129**	**166**	**198**	**224**	**245**	**262**	**275**	**285**	**293**

Table I-E. ROV Sensitivity to the Annualised Volatility

	-100%	-75%	-50%	-25%	0%	25%	50%	75%	100%
Expected revenues	-//-	-//-	-//-	-//-	324	-//-	-//-	-//-	-//-
Expected costs	-//-	-//-	-//-	-//-	203	-//-	-//-	-//-	-//-
Time to expiration	-//-	-//-	-//-	-//-	42	-//-	-//-	-//-	-//-
Risk-free rate	-//-	-//-	-//-	-//-	2.25%	-//-	-//-	-//-	-//-
Annualised volatility	0.0%	1.7%	3.3%	5.0%	6.6%	8.3%	9.9%	11.6%	13.2%
e	-//-	-//-	-//-	-//-	2.72	-//-	-//-	-//-	-//-
d1	3302.4	13.26	6.71	4.56	3.52	2.91	2.52	2.26	2.08
d2	3302.4	13.16	6.50	4.24	3.09	2.37	1.88	1.51	1.22
N(d1)	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.98
N(d2)	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.93	0.89
Call option value	245	245	245	245	245	245	246	246	248

ANNEX II. QUESTIONNAIRE FOR INDUSTRY SURVEY

1. COMPANY INFORMATION

1.1 Company name ____________________________

1.2 Year company started | | | | |

1.3 Country ____________________________

1.4 Company size

❍ Large (headcount > 250; turnover > € 50 million)
❍ Medium (headcount ≤ 250; turnover ≤ € 50 million)
❍ Small (headcount ≤ 50; turnover ≤ € 10 million)
❍ Micro (headcount ≤ 10; turnover ≤ € 2 million)

2. INVOLVEMENT IN FUSION R&D

2.1 Please, describe the current level of your company's involvement in Fusion R&D activities

❍	Tight relationships with Fusion research centres and joint R&D projects
❍	Regular supplies to Fusion research labs / experimental installations
❍	Occasional supplies to Fusion R&D projects
❍	No experience as Fusion R&D supplier

2.2 For how long your company has been doing business with Fusion research centres?

never	< 5 years	6 – 10 yrs	11 – 15 yrs	16 – 20 yrs	21 – 25 yrs	25 years and more
❍	❍	❍	❍	❍	❍	❍

2.3 What motivates your company's decision to participate in Fusion R&D projects?

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Our company wants to have "First mover" advantage	❍	❍	❍	❍	❍
Fusion R&D projects may lead to creation of important new markets	❍	❍	❍	❍	❍
Fusion R&D projects open opportunities for technological learning and improvement of the existing products / services in our business portfolio	❍	❍	❍	❍	❍
Participation in Fusion R&D projects leads to development of innovative products / services	❍	❍	❍	❍	❍
Fusion R&D contracts represent a profit opportunity	❍	❍	❍	❍	❍

Other motivation (please, explain) . . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .

2.4 Please, describe the degree of technological novelty of your company's product(s) / service(s) supplied to past and ongoing Fusion R&D project(s)

❍	Standard delivery of off-the-shelf products or services
❍	Standard delivery with minor modifications
❍	Non-standard delivery with major modifications
❍	R&D project which involved the development of a new product or technology
❍	Cutting-edge R&D with very demanding specifications and high uncertainty

2.5 Please indicate the technical category(s) of work corresponding to the past and potential future supplies of your company to Fusion R&D projects ?

- ❑ Electromechanical (heavy)
- ❑ Mechanical (heavy)
- ❑ Metallurgical
- ❑ Mechanical (precision)
- ❑ Assembly Contractors
- ❑ Electrical (heavy)
- ❑ Robotics and remote handling
- ❑ Software
- ❑ Power electronics
- ❑ Fluid process and distribution
- ❑ Main building contractor
- ❑ Computer hardware
- ❑ Instrumentation and Control

2.6 Please indicate to which of the following ITER procurement packages your company may supply products / services

- ❑ 1.1 Magnet
- ❑ 1.5 Vacuum Vessel
- ❑ 1.6 Blanket System
- ❑ 1.7 Divertor
- ❑ 2.2 Machine Assembly
- ❑ 2.3 Remote Handling Equipment
- ❑ 2.4 Cryostat
- ❑ 2.6 Cooling Water System
- ❑ 2.7 Thermal Shield
- ❑ 3.1 Vacuum Pumping & Fuelling
- ❑ 3.2 Tritium Plant
- ❑ 3.4 Cryoplant Cryodistribution
- ❑ 4.1 Pulsed Power Supply
- ❑ 4.1 Steady State Power Supply
- ❑ 4.5 Command Control and Data Acquisition and Communication
- ❑ 5.1 Ion Cyclotron Heating & Current Drive
- ❑ 5.2 Electron Cyclotron Heating & Current Drive
- ❑ 5.3 Neutral Beam Heating & Current Drive
- ❑ 5.5 Diagnostics
- ❑ 6.2 Building
- ❑ 6.3 Waste
- ❑ 6.4 Radiological Protection
- ❑ 4.1 Pulsed Power Supply
- ❑ 4.1 Steady State Power Supply

3. OUTCOMES OF FUSION R&D PROJECTS

3.1 a) Has your company developed new product(s) / service(s) as a direct result of participation in Wendelstein 7 - X project ?

- ❍ Yes
- ❍ No

b) If Yes, how many new products or services?. . . . .

Please, describe the products or services below:

. . . .
. . . .

. . . .
. . . .
. . . .
. . . .
. . . .

3.2 a) Has your company applied for or obtained new patents, copyrights, or other IPR as a direct result of participation in W7-X project ?

❍ Yes

❍ No

b) If Yes, how many new patents or other IPR?. . . . .

Please describe the patents, copyrights, or other IPR below:
. . . .
. . . .
. . . .
. . . .
. . . .

3.3 Please, assess the potential applications of new product(s) / service(s) developed as a result of your company's participation in W7-X project

Potential applications …

❑ … were strictly limited to particular Fusion R&D project

❑ … can be extended to other Fusion R&D experiments

❑ … can be extended to the experiments in other R&D domains

❑ … can be extended to a limited number of commercial and industrial applications

❑ … can be extended to a large number of commercial and industrial applications

If the applications of your company's Fusion specific product(s) / service(s) can be extended to other commercial or industrial applications, please describe these:
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .
. . . .

3.4 How useful was your company's participation in W7-X project in terms of the following benefits?

Fusion R&D project helped us…	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
... to strengthen our competitive advantage through improvement of core technological competences	❍	❍	❍	❍	❍
… to advance our R&D activities (new theories, prototypes, demos, models, etc.; decisions on further R&D)	❍	❍	❍	❍	❍
…to improve our R&D process (adoption of new R&D tools / methods / techniques, integration of technologies)	❍	❍	❍	❍	❍
…to improve our manufacturing process through adoption of new production techniques	❍	❍	❍	❍	❍
… to improve our quality system	❍	❍	❍	❍	❍
… to improve our project management capability	❍	❍	❍	❍	❍
… to strengthen our marketing capability	❍	❍	❍	❍	❍

3.5 Please, analyze the following potential outcomes of Wendelstein 7-X project

Due to participation in W7-X project our company….	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
… acquired new production equipment and other infrastructure	❍	❍	❍	❍	❍
… acquired new licences	❍	❍	❍	❍	❍
… increased the number of scientific & engineering staff	❍	❍	❍	❍	❍
… established new R&D team(s)	❍	❍	❍	❍	❍
… started a new business unit	❍	❍	❍	❍	❍
… created a joint venture	❍	❍	❍	❍	❍
… established new technological partnership(s)	❍	❍	❍	❍	❍
… established new commercial links	❍	❍	❍	❍	❍

3.6 Please, analyze the following commercial and work-factor related effects of Wendelstein 7-X project

Due to participation in W7-X project our company….	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
... realized additional sales of innovative products / services to other Fusion R&D projects	❍	❍	❍	❍	❍
... realized additional sales of innovative products / services in other non-Fusion markets	❍	❍	❍	❍	❍
... realized additional revenues due to sale of licenses	❍	❍	❍	❍	❍
… achieved reduction in manufacturing costs	❍	❍	❍	❍	❍
... improved capabilities of the personnel through training and experience	❍	❍	❍	❍	❍
… improved the personnel's capacity to absorb & exploit knowledge	❍	❍	❍	❍	❍

3.7 Please analyze the direct financial return of Wendelstein 7-X project to your company

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
W7-X project was financially profitable	❍	❍	❍	❍	❍
The realized cost of the project was higher than agreed in the project contract	❍	❍	❍	❍	❍

3.7 Considering the results of your company over the past decade, what do you imagine they would have been if you had not participated in Fusion R&D project(s)?

	Much better	Slightly better	No change	Slightly lower	Much lower
Growth in sales	❍	❍	❍	❍	❍
Growth in assets	❍	❍	❍	❍	❍
Growth in number of employees	❍	❍	❍	❍	❍
Technological excellence	❍	❍	❍	❍	❍

4. OVERALL IMPACT AND OUTLOOK

4.1 Please, estimate the impact of Wendelstein 7-X project on the following financial parameters

A. How much lower (higher) would be your company's sales revenues without W7-X project?

lower by > 50%	40 - 50 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	lower by < 5 %	same and higher
❍	❍	❍	❍	❍	❍	❍	❍

B. How much lower (higher) would be the book value of your company's Property , Plant & Equipment without W7-X project?

lower by > 50%	40 - 50 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	lower by < 5 %	same and higher
❍	❍	❍	❍	❍	❍	❍	❍

C. How much lower (higher) would be the book value of your company's Goodwill & Intangibles without W7-X project?

lower by > 50%	40 - 50 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	lower by < 5 %	same and higher
❍	❍	❍	❍	❍	❍	❍	❍

D. How much lower (higher) would be the book value of your company's other assets (e.g. participation in Joint Ventures) without W7-X project?

lower by > 50%	40 - 50 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	lower by < 5 %	same and higher
❍	❍	❍	❍	❍	❍	❍	❍

4.2 What would be the chances for your company to become a supplier of ITER without prior participation in W7-X project ?

lower by > 50%	40 - 50 %	30 - 40 %	20 - 30 %	10 - 20 %	5 - 10 %	lower by < 5 %	same and higher
❍	❍	❍	❍	❍	❍	❍	❍

4.3 Please, analyse the relative importance of the following categories of effects in respect of your company's future operating profits during ITER construction (2008-2016)

Technological effects vs. **Commercial effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Technological effects vs. **Organisation & Methods effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Technological effects vs. **Work factor effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Commercial effects vs. **Organisation & Methods effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Commercial effects vs. **Work factor effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

Organisation & Methods effects vs. **Work factor effects**

Extreme		Very strong		Strong		Moderate		Equal		Moderate		Strong		Very strong		Extreme
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

4.4 – 4.6. Please, analyse the relative importance of the following categories of effects in respect of your company's invested capital during ITER construction (2008-2016) / Growth rate in net operating profits after ITER construction / rate of return on new invested capital after ITER construction (the same scale as question 4.3 applies)

THANK YOU VERY MUCH FOR YOUR VALUABLE HELP!

ANNEX III. APPLICATION OF ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process (AHP) is a powerful and well-recognized decision making instrument which involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives[37]. The AHP uses pair-wise comparison which allows for deriving weights or priorities for each criterion from a set of judgements. The comparison can be performed using words, numbers, or graphical bars, and it typically incorporates redundancy, which results in a reduction of measurement error. To cope with vagueness type of uncertainty introduced by human subjectivity in judgement, the AHP approach can be further amended by using fuzzy arithmetic techniques.

In the proposed "Fusion R&D spillovers model" the AHP approach can be used in order to determine spillovers influence rates for NOPLAT (during explicit forecast period), Invested capital (during explicit forecast period), RONIC (after explicit forecast period) and growth rate in NOPLAT (after explicit forecast period). ***Figure AIII-1*** demonstrates an example of application of AHP software (ExpertChoice) to the calculation of influence rate for NOPLAT. The numerical values next to each category of spillovers effects correspond to their "intensity of contribution" coefficients, and values next to specific spillover effect indicate the relative weight of its assessment indicator.

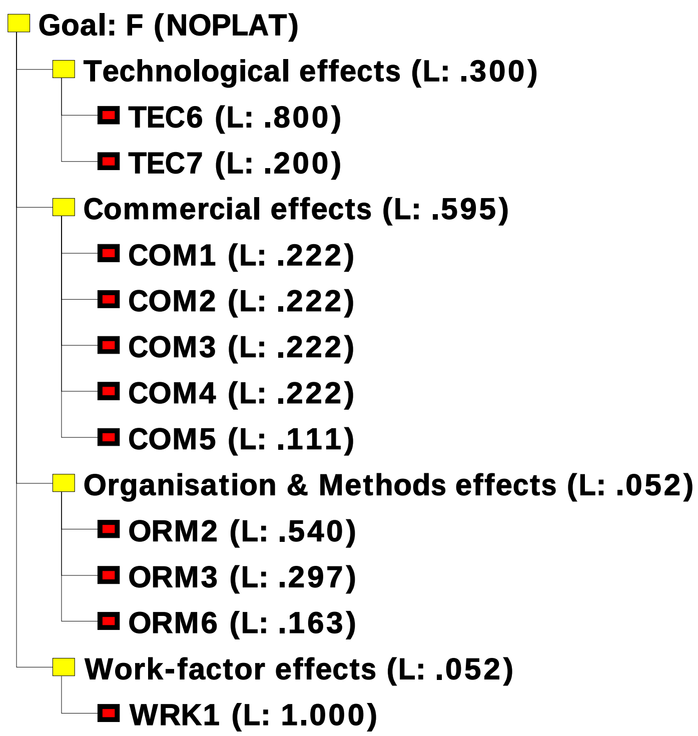
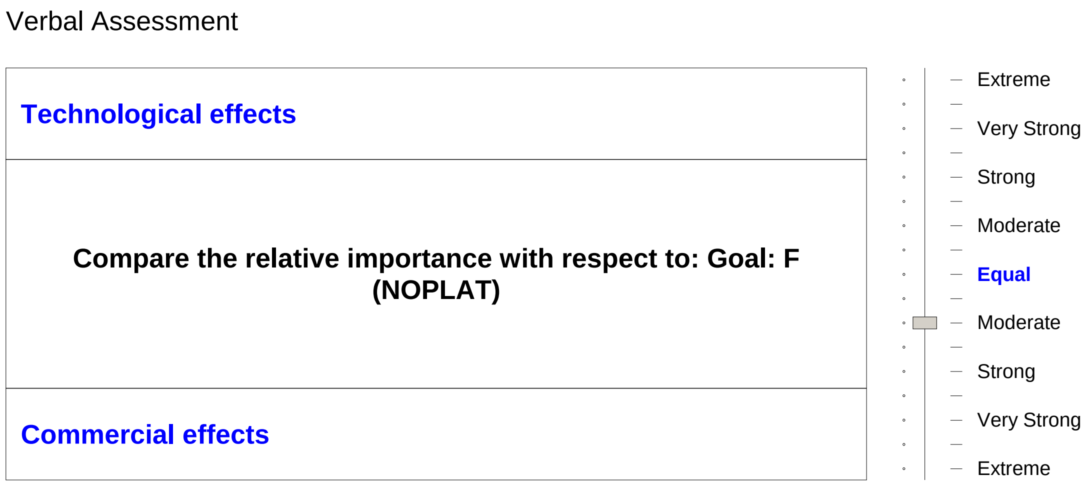


Figure AIII-1. Tree view in AHP "Expert Choice" software

[37] http://www.dssresources.com/glossary/53.php

Figure AIII-2 and ***Figure AIII-3*** demonstrate the procedure and final result of pair-wise comparison process which underlies the calculation of values shown in ***Figure AIII-1***.



	Technologi	Commercia	Organisatio	Work-factor
Technological effects		(3.0)	7.0	7.0
Commercial effects			9.0	9.0
Organisation & Methods effects				1.0
Work-factor effects	Incon: 0.03			

Figure AIII-2. Verbal pair-wise comparison process in AHP "Expert Choice" software

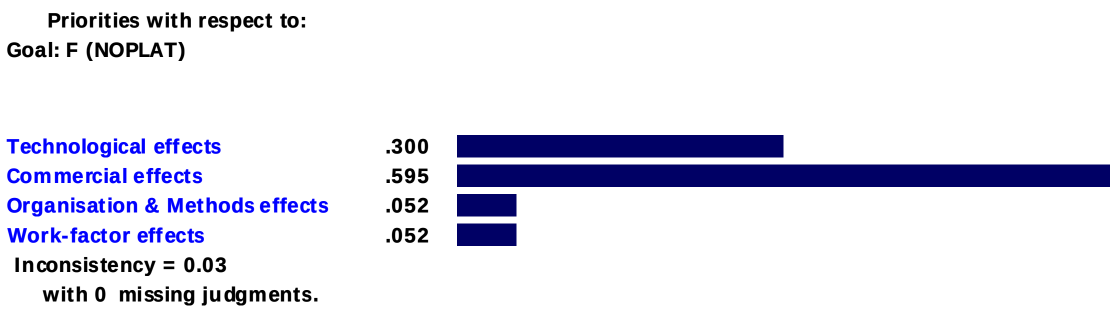


Figure AIII-3. Results of pair-wise comparison in AHP "Expert Choice" software

CURRICULUM VITAE

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EDUCATION

2002 / 2010	**Swiss Federal Institute of Technology - Lausanne (EPFL), Switzerland** PhD (*Economics of Innovation in Energy Sector*) Postgraduate Master's Degree in Energy
1991 / 1996	**Moscow State Institute of International Relations (MGIMO), Russia** Diploma of Economist Specialising in International Economic Relations
1995	**Ecole des Hautes Etudes Commerciales (HEC), Jouy-en-Josas, France** Students Exchange Programme in International Management

PROFESSIONAL EXPERIENCE

2009 / 2010	**EIC Partners AG, Switzerland** /Director, Client Advisory/ Asset management and advisory services focused on energy sector
2002 / 2010	**Laboratory of Energy Systems, EPFL, Switzerland** /Research Assistant/ Performed research on the economics of energy systems and climate change mitigation
2000 / 2002	**LMZ - Power Machines Group, Russia** /Project Manager/ Representative at the construction site of "Alholmens Kraft" 256 MW TPP, Finland
1999 / 2000	**Renaissance Insurance Group, Russia** /Marketing Manager/ Elaborated marketing strategy; conducted market studies; structured deals with key clients
1998 / 1999	**S.I.Lesaffre /France/, Representative office in Russia** /Marketing Manager/ Responsible for market research and public communication
1996 / 1998	**LMZ Energy, Ireland - Russia – India** /Project Manager/ Supervised execution of contracts for construction of power plants on turn-key basis

LANGUAGES & COMPUTER SKILLS & OTHER

Russian (mother tongue) / **English** (fluent) / **French** (fluent) / **Hindi** (advanced) / **German** (beginner)

PC experienced user (MS Office, Adobe, HTML-Jahia, Risk Simulator, Planelec, MARKAL)

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PUBLICATIONS IN PEER-REVIEWED JOURNALS

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