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Estimating Spillover Benefits and Social Rate of Return of Fusion Research, Development, Demonstration and Deployment Program:

Conceptual Model and Implications for Practical Study

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Abstract

This report elucidates the main findings of EPFL-LASEN study on the socio-economic assessment of spillover effects of Fusion research, development, demonstration and deployment (RDDD) program. The main objective consists in elaboration of a novel methodological approach that would allow for estimating the total social payoffs of long-term large-scale RDDD programs in energy sector, such as Controlled Thermonuclear Fusion, taking into account its positive externalities represented by knowledge, technology, network and market spillovers.

Spillover effects are seen in the economic literature as one of the main drivers of technological change and economic growth. The idea behind this phenomenon is that the results of R&D efforts undertaken by a single organisation or within a particular program can not be appropriated in their integrity, and hence they “spill over” without due compensation to other market players and customers. Many theoretical and empirical studies exist pointing out to the general conclusion that due to spillover gap the social rates of return to R&D investments are significantly higher than the private (internal) returns.

This report starts with a review of economic literature analysing spillover effects and the social rates of return to innovation. Then a general taxonomy of spillovers in case of Fusion RDDD program is being elaborated. The appropriateness of different analytical methods for measuring spillover benefits is investigated basing on the documented studies of similar in size and complexity R&D activities, such as CERN high energy physics experiments, European space exploration program, etc.

The study argues that besides the promise of bringing sustainable energy supply in the future, Fusion technology RDDD are yielding additional societal benefits which should be taken into account in the allocation of public R&D funds. The report concludes with practical recommendations how to implement an integrated modelling & assessment framework that could allow for optimising future funding of Fusion demonstration and initial deployment activities subject to the perceived uncertainty and the expected net societal benefits.

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Disclaimer

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1. INTRODUCTION

Finding a solution to the global energy security problem depends greatly on the capability of energy industries to innovate. Meanwhile, the analysis of energy R&D spending shows alarming signs of underinvestment (Kammen & Nemet, 2005; Bernardini, 2004). The ongoing liberalization process in energy sector creates additional threats, because of the limited ability of free markets to account for the total social costs (Bureau & Glachant, 2006) and to channel private investments towards long-run strategic R&D programs (Dooley, 1998). Therefore, appropriate governmental policies have to be enacted in order to facilitate the development and deployment of advanced energy technologies, such as Controlled Thermonuclear Fusion.

The starting point in the formulation of long-term energy R&D policy consists in elaboration of energy demand & supply scenarios. The scenarios are usually developed with the help of sophisticated techno-economic models relying on a set of assumptions, input data and equations. IIASA / WEC "Global Energy Perspectives" (Nakicenovic *et al.*, 1998) and IPCC "Special Report on Emissions Scenarios" (Nakicenovic & Swart, 2000) are well known examples of such scenario studies. Descriptive scenarios provide several alternative images of what could be the plausible development paths of global / regional / national economies and energy systems. Normative scenarios allow further for estimating potential advantages and drawbacks of specific technology options and public policies.

Although being the product of joint efforts of many interdisciplinary researchers, the scenario studies may not represent a perfect guideline for the future decision making because of the extreme diversity in their results and conclusions. These disparities arise mainly from the differences in the underlying assumptions about exogenous factors, discrepancies among input parameters, as well as different model structures and computational techniques (Kann & Weyant, 2000). As a result, the policy decisions have to be taken in the presence of multiple uncertainties, which can be characterized according to (i) the *location*, i.e. where the uncertainty manifests within the model; (ii) the *level*, i.e. its position on the scale from deterministic knowledge towards complete ignorance; and (iii) the *nature*, i.e. whether the uncertainty is due to inherent variability of the observed phenomena[1] or stems from imperfect knowledge or incomplete information[2] (Walker *et al.*, 2003).

We take the example of Controlled Thermonuclear Fusion technology which has been recognized as one of the most prominent energy supply options expected to become available in the second half of the 21st century. Practically inexhaustible fuel resources, inherent safety, avoidance of long-lived radioactive wastes and significant potential for CO_2 emissions reduction are among the known merits of Fusion (IEA, 2003; Ongena & Van Oost, 2006). In the meantime, massive efforts of scientific and industrial communities as well as substantial amount of public funding are still required in order to demonstrate the practical feasibility of Fusion technology. Even if "fast track" approach to Fusion development is

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[1] In literature this type of uncertainty may be also referred to as aleatory, stochastic, irreducible, or objective uncertainty

[2] Also referred to as epistemic, parametric, reducible, or subjective uncertainty

followed (see Cook *et al.,* 2005), this process will take another 35 - 40 years from now. Furthermore, under the conditions of competitive electricity markets and in the presence of alternative energy supply options, the economic viability of Fusion power plants has to be additionally proved during the demonstration and initial deployment stages.

Several studies have been undertaken in recent years in order to elucidate the economical characteristics and the potential for market penetration of Fusion technology. So, Maisonnier *et al.* (2005) found that internal cost of electricity produced by different concepts of Fusion power plants could be in the range of estimates for the future costs of other electricity supply options (from 5-9 $€_{cents}$ / kWh for conservative reactor model to 3-5 $€_{cents}$ / kWh for most advanced model depending on the assumed level of technology maturity). Ward *et al.* (2004) using probabilistic theory demonstrated that under reasonable assumptions the net present value of Fusion R&D is substantially positive, and the expected benefits of accelerated introduction of Fusion into the market could be about € 20 billion for each year gained. Tokimatsu *et al.* (2002) analyzed the global potential for deployment of Fusion power using techno-economic energy & environment model and found that significant amount of Fusion power (20 to 30 % of total world electricity generation) could be introduced into the energy system based on economic criteria under 450 – 550 ppmv CO_2 concentration constraints. Eherer *et al.* (2004) and Lechon *et al.* (2005) using a global partial equilibrium bottom-up energy model demonstrated that Fusion could be an economically viable complement to intermittent renewable energy sources (solar, wind) in case of CO_2 emission caps and / or resource scarcity scenarios. Gnansounou & Bednyagin (2007) examined the potential role of Fusion technology on the basis of multi-regional long-term electricity supply scenarios and concluded that economic competitiveness of Fusion would depend on the amount of public funds invested in R&D, demonstration and initial deployment of Fusion power plants.

As recognized by the authors of above cited studies, their results are highly dependent on the assumptions regarding multiple parameters, such as future energy demand and its socio-economic drivers, generic technical and economical characteristics of energy technologies, pace and direction of technological change, economic and environmental policy regime, availability of resources, market structure, etc. Furthermore, the problem of choosing appropriate discount rate for economic analyses extending over one hundred years substantially increases the uncertainty about the potential outcome of Fusion RDDD program. So, the present value of €1000 benefit received in 100 years from now equals to €84.6 if discounted with 2.5% rate and only €7.6 with 5% discount rate. Newell & Pizer (2004) demonstrated that in long-term energy policy assessment the choice of constant discount rate leads to significant underestimation of prospective benefits compared to uncertain discount rate which can be modelled as mean-reverting or random walk stochastic process. Given the above mentioned uncertainties, it is not surprising that the decision makers may have a tendency to favour in their energy R&D policies and budget allotments the technologies that already exist on the market or could be technologically and economically proved within a short period of time, while additional funding required for accelerated development of Fusion technology may be opposed (see e.g. Zolti, 1999).

Without questioning the importance of long-term techno-economic modelling and scenario building for energy R&D policy making, this study proposes a slightly different approach to evaluation of Fusion energy RDDD program. Assuming that potential economic and environmental benefits from deployment of Fusion power plants are measurable, considerable in size, but highly uncertain, our study seeks to estimate the total social payoff of past and near-to-medium term investments in basic science, applied R&D and future demonstration activities (RD&D). A novel methodological approach is being elaborated with the aim to examine the dual nature of achieved and expected benefits of Fusion technology RD&D: (i) on the one hand, it generates a stream of positive externality effects, or in other terms “spillover” benefits, that offset the past and future public R&D expenditures; and (ii) on the other hand, it allows for reducing epistemic uncertainty in the estimation of technical and economical feasibility of Fusion power plants, whereby increasing the total expected socio-economic value of Fusion RDDD program. Accordingly, a proper evaluation of spillover benefits may provide additional arguments to the decision makers in case they need to justify the supplementary public funding for implementation of Fusion “fast track” development path.

The following chapter will provide an overview of the literature analysing different aspects of taxonomy and measurement of positive externality (spillover) effects and describing specific spillovers in the domains of high energy physics (CERN) and space exploration (ESA). The proposed classification of spillover effects of Fusion RDDD program is given Chapter 3. Then possible approaches to the design and implementation of integrated framework for evaluation of spillover benefits and social rate of return of investments in Fusion technology RDDD are being discussed. In chapter 5 we analyse the applicability of “Real Options” approach for estimating the expected net economic benefit from increased spending on Fusion R&D and demonstration. Chapter 6 concludes with main findings and recommendations.

2. LITERATURE REVIEW

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 rate of return to R&D became an issue of increasing concern in the context of national R&D 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 the advances in knowledge “spill over” to other firms and consumers. 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 (Romer, 1986; 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 programs.

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 (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.

Most existing studies make a distinction between "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 a 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). 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 (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 Spillover Benefits of Large-scale R&D Programs

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 program 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 embodied and disembodied “knowledge spillovers”. Cohendet (1997) in his study focusing on the 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 program gives rise to technological innovations, leading to the emergence of new products and sub-systems, which can be deployed by subsequent R&D programs. It also enables a technology developed through a given R&D program to be applied in other industrial sectors, resulting in the creation of new products, sometimes leading to a diversification of activity and improved characteristics (quality, performance) of existing products.

Commercial effects

Commercial effects basically take the form of increased sales of products or services that do not incorporate significant technological innovation. The contractors are able to take advantage of new markets that open following the implementation of R&D programs. Furthermore, many of these firms may have acquired a quality label associated with specific R&D activities, which is likely to give them considerable competitive leverage. On the commercial level, R&D programs also enable the participating companies to form closer business ties, which can be further extended to foster joint activities outside the specific R&D project's framework.

Effects on organisation and methods

Another important spin-off effect consists in the 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. These innovations result from the high standards imposed by the R&D program performance requirements and reliability specifications (e.g. principle of zero-fault in a hostile environment).

Work-factor effects

The economic effects induced by R&D programs are also related to a large extent to the formation of human capital. Participation in R&D projects is often regarded as training schools for personnel as well as for managers. The induced work-factor effects are related in particular to the heightened qualifications and skills acquired by the personnel employed in these programs, which enable them to feed expertise into company's departments not directly concerned with specific R&D program activities.

Besides the ***indirect industrial effects*** (spin-offs) Cohendet (1997) considered other forms of economic impacts of space-related R&D programs, which also can be treated as R&D spillovers. They 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).

The socio-economic benefits of high energy physics have been analysed in the studies of 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 programs had a four-fold multiplier impact upon the sales revenues of these 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 (i) education of scientists and providing of opportunities for training in experimental techniques; (ii) creation of social networks through which unpublished information can be rapidly diffused; (iii) elaboration of enhanced standards and novel techniques of scientific research allowing for reducing the costs and increasing the effectiveness of applied R&D; (iv) 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.

3. POTENTIAL SPILLOVER BENEFITS OF FUSION RDDD PROGRAM

A general classification of potential spillover benefits that may emerge from research, development, demonstration and deployment of Thermonuclear Fusion technology is given in Table 1. Herein, spillover effects are distinguished according to their form (*embodied* / *disembodied*) and the level at which they occur: within the energy sector (*intra-sectoral*), between different industrial sectors (*cross-industry*) and at economy-wide scale (*macroeconomic*).

Table 1. Potential spillover benefits of Fusion RDDD program

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*)	supply of competitively priced energy services (*consumer surplus = market spillovers*) ; 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*) ; international spillovers
Disembodied (knowledge spillovers)	accumulation of knowledge stock (*publications, patents*); formation of human capital (*PhDs, experienced researchers, research networks*); dissemination of knowledge (*due to human mobility and social networks*); success / failure signals to industry		

First of all, the past and ongoing activities in the areas of basic science and R&D related to plasma physics and Fusion technology have already resulted and will continue to generate a stream of 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 knowledge spillovers. This knowledge serves as the basis for advancement of future 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 power installations. The predominantly public nature of Fusion R&D funding, the technological complexity and significant number of researchers and institutions involved in Fusion R&D program explain the importance of knowledge spillover effect in case of Thermonuclear Fusion technology.

One of the most remarkable illustrations to the effect of knowledge spillover 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).

Meanwhile, the ongoing R&D on Fusion energy technology may have a significant potential to yield other ***cross-industry 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[3]. 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:

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[3] 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.

In longer-term perspective Fusion may offer a unique opportunity for high-efficiency propulsion of rocket engines (IFRC, 2005).

The scope 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 also could lead to the reduction of costs of other electricity generation technologies due to clustered endogenous learning mechanism.

The report of Sheffield et al. (2000) presents the results of the study which made an attempt to classify the most prominent products of Controlled Thermonuclear 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[4] 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 1. 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.

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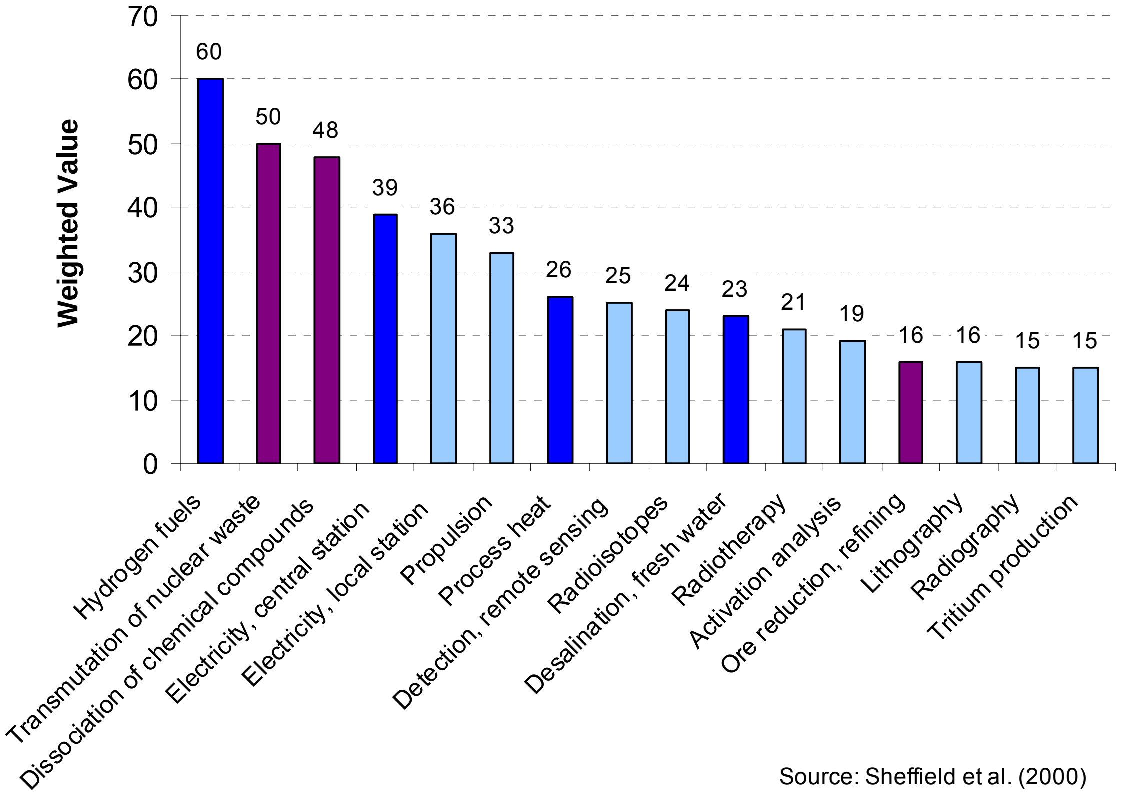
[4] Necessity / Uniqueness / Market Potential / Depletion of Resources / Environmental Impact / Economic Competitiveness / GNP Improvement / Return on Investment / Technology Maturity / Time to Market / National or Company Prestige / Public Support



Source: Sheffield et al. (2000)

Figure 1. Market Attractiveness of Fusion Products

As discussed in Bogusch *et al*. (2002) Fusion R&D opens also a significant potential for ***network spillovers*** due to industry accession to Fusion - related public procurement contracts. In fact, the progress of Fusion RDDD program will rely heavily on the development of a set of subjacent 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 the related industries. Moreover, if Fusion proves to be economically competitive, accordingly its commercialisation will spur further advancements in underlying technologies leading to the expansion of their markets and allowing for decreasing overall technology costs.

Finally, successful demonstration and deployment of Fusion technology may create substantial opportunities for ***market spillovers*** and other types of macroeconomic benefits, including international spillovers. It can be expected that deployment of Fusion power plants will lead to gradual reduction of its production cost bellow 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 if the opportunity for substitution of fossil fuels import as well as technology export is envisaged.

4. CONCEPTUAL EVALUATION FRAMEWORK

The evaluation of strategic energy R&D programs is an extremely challenging task considering the complexity of the energy system as well as the uncertainties about its driving factors and the pace of technological progress which have to be assessed over very long period of time. Nevertheless, in order to justify the allocation of public R&D funds the decision makers ought to rely on some reasonable estimates of expected net benefits of the proposed R&D programs. During the past decades several normative documents have been elaborated with the objective to provide a robust methodological framework for evaluation of publicly funded research. The examples of such guidelines can be found in Holdsworth (1999) and Tassey (2003). The recommendations regarding specific approaches to evaluation of energy R&D programs are given in Carter (1997), NRC (2005), EC (2005). Practically all these studies recognise that the "social rate of return" should be considered as one of the decisive measures that have to be taken into account while assessing the potential economic impact of public R&D investments.

According to Jaffe (1996) the general criterion for selection of projects requesting public support can be formulated as follows: the managers of public R&D funds should seek to maximize the social rate of return of their investment through selecting the projects with highest "spillover gap" while trying to avoid the displacement of private R&D funding. This rule emphasises the importance of reliable estimation of the expected spillover benefits as well as total social costs and benefits of publicly funded R&D programs. In practical terms, the indicator of *social rate of return* (SRR) is analogous to the *internal rate of return* (IRR), or private rate of return, which can be calculated as discount rate that reduces to zero the net present value (NPV) of a project under consideration. A distinctive feature of the social rate of return, compared to private rate of return, is that the former is calculated on the basis of total social costs and benefits including positive and negative externality effects, while the latter accounts only for internal[5] costs and benefits inherent to a specific project or R&D program. The existence of "spillover gap", i.e. additional net benefits that can not be appropriated by the organisation undertaking R&D project and accruing to other market players, explains the practical difference in the estimated values of private and social rates of return to R&D.

The question arises how to estimate in practice the realised and prospective spillover benefits and the overall social rate of return of Fusion RDDD program. To answer this question we have to analyse, first and foremost, the nature and inter-temporal structure of the costs and benefits incurred through the Fusion RDDD process. As it is shown in Figure 2, the start of Fusion RDDD program is dated back in 1950's, or even earlier, when the first understanding of fusion reaction was acquired. The consecutive steps involved significant amount of basic research efforts followed by applied R&D stage. The upcoming construction of ITER / IFMIF experimental facilities can be considered as the final step before proceeding

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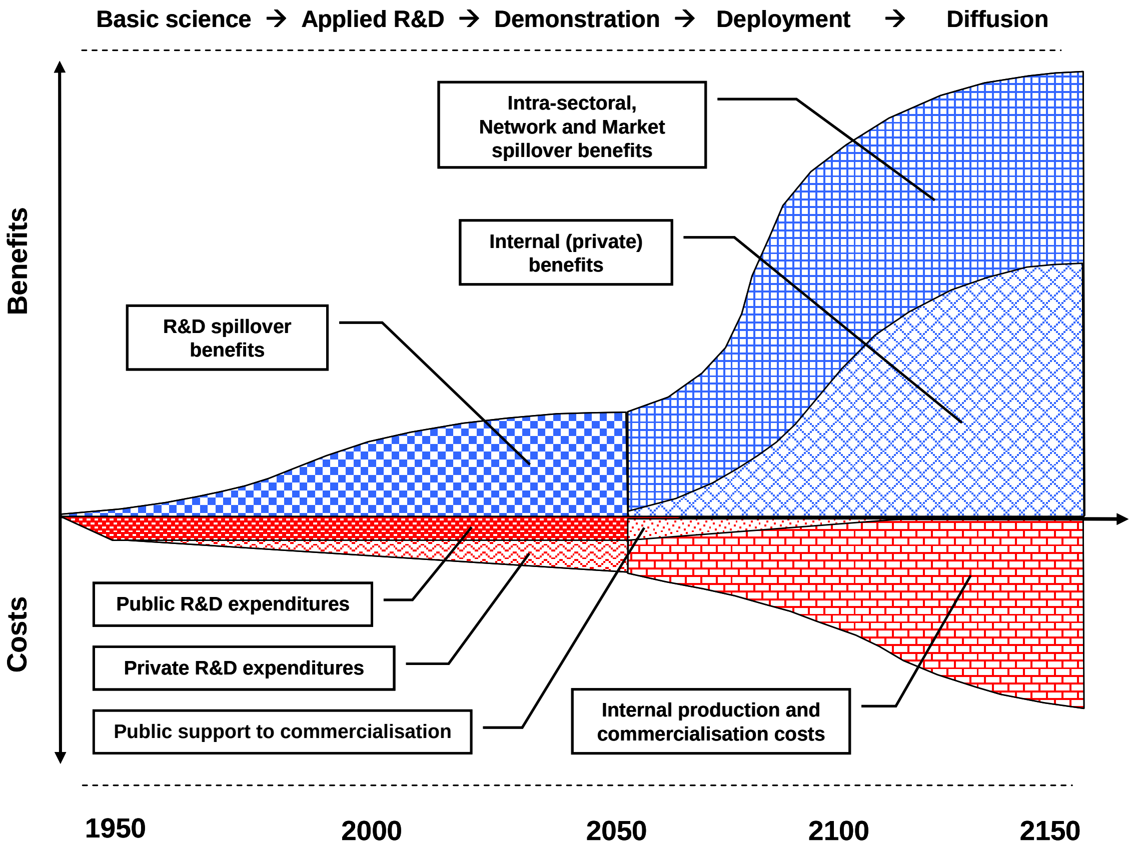
[5] Hereinafter, the term "internal" costs and benefits is used as opposite to "external" costs and benefits. Further classification leads to distinction between direct and indirect both internal/external costs and benefits

to the demonstration activities. The costs of all these initial stages were covered predominantly by the public funds, while an increasing amount of private funding can be expected towards the end of main RD&D period (≈ by 2050).



Source: adapted from Lee (2002)

Figure 2. Structure of costs and benefits of Fusion RDDD program

The public and private R&D expenditures are yielding societal benefits due to R&D spillovers. Herein, we introduce the term “R&D spillovers” which is meant to include the disembodied knowledge spillovers as well as embodied cross-industry spillovers due to technological spin-offs and learning through collaborative public-private R&D activities. The macroeconomic effects from construction of large scale experimental facilities may also constitute tangible benefits for regional / local economies (see e.g. EFDA, 2001, pp. 114-115).

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 due to construction and commercialisation of Fusion will be borne by the private sector, a certain amount of public funding or other forms of support will be required during the initial stage to allow technology maturing and decreasing of its upfront investment costs to economically competitive level. At this time, building and operation of Fusion power plants will start to generate a stream of financial revenues (internal benefits) through the sale of energy services. Additional societal benefits are also expected to rapidly increase at this stage due to growing importance of embodied market, network and intra-sectoral spillovers as well as macroeconomic effects from technology export and substitution of costly hydrocarbon fuels import.

Next, we have to choose the numerical indicators that should allow for estimating the magnitude of spillover effects and determining their impact on the total socio-economic value of Fusion RDDD program. In this study we propose to perform this analysis using an integrated evaluation framework based on the amended NRC “benefits matrix” (see NRC, 2001; Lee *et al*., 2003). Table 2 presents the main components of this framework.

Table 2. Costs / benefits matrix for evaluation of Fusion RDDD program

	Past	**Future**	
Benefits and Costs	Realised	Projected	Options
Knowledge	+	+	+
Economic	+ / -	+ / -	+ / -
Environmental		+	+
Security		+	+

Source: Adapted from Lee *et al*. (2003)

The columns of the above matrix contain the pecuniary estimates of the past and future total social costs and benefits of Fusion RDDD program. The column “Projected” includes the costs and benefits corresponding to the baseline case, while “Options” represents additional costs and benefits that can be expected in case of alternative scenarios. The sign “+” highlights the presence of benefits, while “+ / -“ indicates the presence of both costs and benefits. The realised knowledge benefits correspond to the accumulated knowledge stock which can be approximated by different metrics: e.g. literature based indicators, such as scientific publications, patents, citations thereof, the number of the trained research staff, etc. Given the practical impossibility to assign a pecuniary value to each particular publication, patent or trained person it is possible to estimate the value of realised knowledge benefits with a proxi indicator such as historical R&D expenditures adjusted in time with depreciation factor. The future knowledge benefits can be assessed in the same manner or using “real options” approach as discussed in the next chapter.

The estimates of realised economic costs can be derived from available public energy R&D statistics, while future costs should be assessed on the basis global long-term energy supply scenarios developed with the help of techno-economic models, such as MARKAL-TIMES (Loulou *et al.,* 2004) and / or its advanced version EFDA-TIMES emphasised on Fusion technology (Haurie *et al.*, 2004). The evaluation of realised and future benefits should include both (i) internal benefits due to sale of energy services and (ii) value of external benefits due to spillover effects. Similar to the future internal cost, the expected internal benefits can be assessed on the basis of long-term energy scenarios taking into account the future energy prices as well as the costs and potential market shares of alternative energy technologies, including Fusion. This approach is also suitable for evaluation of potential energy consumers' surplus (market spillovers).

External economic benefits can be measured in several different ways depending on the specific type of considered spillover effect. So, economic effects from creation of new markets and opening of new businesses (spin-offs) due to non-electrical applications of technologies, materials and techniques developed in the process of Fusion energy R&D can be assessed basing on expert judgements and ranking of weighted values as presented in Sheffield *et al.* (2000). Induced economic activity due to industry accession to Fusion procurement contracts (network spillovers) can be estimated on the basis of projected expenditures and economic multipliers derived from regional I/O matrices. Economic effects due to improved performance and/or lowered cost of related energy technologies which contain the same clustered technological components as Fusion (intra-sectoral spillovers) can be assessed using techno-economic models with clustered endogenous learning.

A general scheme relating different types of Fusion RDDD program expenditures, their spillover effects and the resulting economic benefits is shown in Figure 3. Although the environmental and security aspects are also important drivers of Fusion RDDD program, the respective external benefits are not shown in this graph, because their evaluation goes beyond the scope of this study. Nevertheless, an approximate estimation can be made using available data. So, according to Hamacher *et al.* (2001), Fusion technology benefits of rather low external cost comparable with that of wind and photovoltaic. In principle, the negative environmental impacts (external costs) of other energy supply technologies (mainly based on fossil fuels) can be internalised via political decisions to impose taxes on CO_2 emissions and other atmospheric pollutants or introduction of emission constraints. This will improve the economic performance of Fusion and will increase its prospective socio-economic benefits. Meanwhile, the evaluation of security benefits of Fusion technology deserves a further in-depth study.

5. IMPLICATIONS FOR PRACTICAL STUDY

5.1 Fusion RD&D Funding

We start our evaluation of Fusion energy RDDD program from the assessment of past expenditures on basic science and applied R&D, including the construction of currently existing experimental facilities, which have enabled further R&D of Fusion technology.

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 (2003) 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 / year.

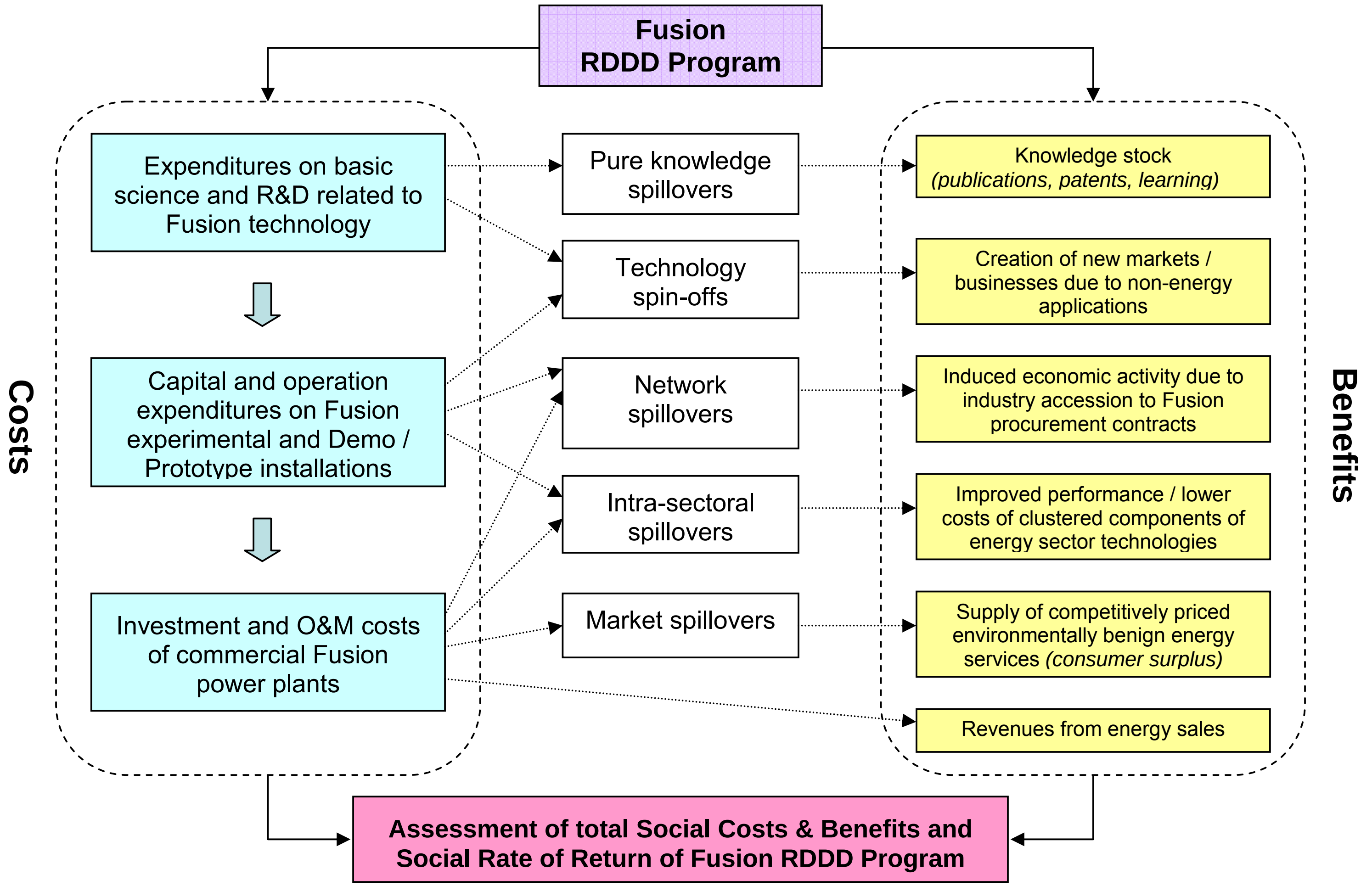


Figure 3. Fusion RDDD funding and its spillover benefits

Unfortunately, it was not possible to get reliable data regarding total Fusion R&D funding during the earlier stages dating back to the fifties, except for publication of 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}$). Basing on these estimates, it is reasonable to assume that up to now the total OECD public funding of civilian Fusion R&D did not exceed €$_{2007}$ 50 billion.

As regards the future cost of Fusion RD&D it can be extrapolated basing on the current estimates of investment and operation costs of ITER / IFMIF facilities and assuming some prudent hypotheses about scale up of these costs for DEMO / Prototype 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 and alternative design installations, such as Wendelstein 7-X stellarator, and pursuing other Fusion-related R&D activities.

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 (Grunwald *et al.*, 2003). In a recent paper of Goldston *et al.* (2006) the total global cost of rather ambitious Fusion development plan presuming construction of several competitive DEMO power plants by 2035 amounts to US$$_{2005}$ 107 billion.

5.2 Realised and Projected Near-term Benefits of Fusion RD&D

As it is shown in Figure 3 above the expenditures on Fusion RD&D are yielding multiple benefits through “spill over” mechanism. Considering that at the present stage, besides the advancement of Fusion science, spillovers represent the main socio-economic outcome of the ongoing Fusion RDDD program, it is important for decision makers to have a credible estimate of their magnitude in monetary values as well as to assess their near-to-medium term accrual potential. Basing on the proposed Fusion RDDD evaluation matrix (see Table 2) two different types of benefits have to be distinguished, namely: “pure knowledge” and “economic” benefits.

In order to estimate “realised” and “future” knowledge benefits we propose to use the “knowledge stock” indicator which can be defined as a function of R&D expenditures and depreciation factor. The build-up of knowledge stock will affect probabilities of successful transition from ITER / IFMIF experimental R&D stage to demonstration stage and later on to commercial deployment stage. The accumulated knowledge stock can be also assigned a specific “Option” value which will depend on the expected net economic benefits from deployment of Fusion power plants and the uncertainty (variance) underlying its estimate (see Chapter 5.4 for more detailed discussion of this issue).

The pecuniary estimate of the knowledge stock produced in the process of Fusion energy R&D can be complemented with an assessment of “literature-based” indicators, such as publications, patents and citations thereof. It should be borne in mind that bibliometric studies could provide biased results because of its inherent limitations due to uneven quality of publications / patents, time lag, different propensity to publish, different registration rules of patents etc. However, it will be useful to trace a statistical relationship between Fusion R&D expenditures and the counts of publications / patents, and to compare these data with R&D productivity indicators in other domains. Finally, basing on a comprehensive dataset of Fusion-related patents and citations thereof, the methodological framework developed by Jaffe (1986) can be applied in order to define technological proximity of the firms involved in Fusion R&D and to estimate the magnitude of knowledge spillovers among them.

As regards the evaluation of “realised” and “projected” economic benefits of Fusion R&D stage, our investigation have shown that the most suitable and probably the only “realistic” approach consists in carrying out a survey of the public research institutions and private companies involved in Fusion R&D program activities. If the response rate to the questionnaire of such a microeconomic study will be sufficient enough to assure its statistical significance, then its results could be extrapolated to allow evaluation of the whole program (or at least its European component). Basing on the experience from evaluation of CERN and ESA procurement activities described in Autio *et al.* (2003) and Bach *et al.* (2002) it is recommendable to elucidate throughout this survey the following possible outcomes of past and ongoing Fusion research and development:

- Technological effects
    - ✓ Introduction of new products / services in company’s business portfolio
    - ✓ Improvement of manufacturing, R&D processes and quality systems
    - ✓ Patenting / licensing
- Commercial effects
    - ✓ Growth in sales
    - ✓ Opening of new markets / increase of international exposure
- Managerial effects
    - ✓ Strengthening of marketing and managerial capabilities
    - ✓ Set up of new R&D teams / business units / networks
    - ✓ Increase of the number of employees
- Expectations about future Fusion-related activities and its potential benefits, etc.

A preliminary version of the questionnaire inspired by the structure of CERN 2002 Industrial Procurement Survey (Autio *et al.,* 2003) is given in Annex I. Before sending out the questionnaire, it is important to validate it through the series of structured interviews with EFDA officials and the representatives of other international scientific organisations involved in Fusion R&D. An internationally recognised methodological approach developed by B.E.T.A. group at the University of Strasbourg (Cohendet, 1997; Bach *et al.,* 2002) and applied in several evaluation studies of European Space Agency and other programs can be used for structuring these interviews.

5.3 Projected Costs and Benefits of Fusion Technology

The future costs and benefits of Fusion technology will depend on successful completion of its RD&D and the state of global and regional energy systems. More specifically the following factors will affect the expected net economic benefits from the deployment of Fusion power plants: projected energy / electricity demand and the market share of Fusion; levelised energy / electricity cost of Fusion and competing technologies; future wholesale prices of electricity and other energy services that can be supplied by Fusion; environmental policy regime and availability of public support to initial deployment of Fusion reactors. Furthermore, the choice of the level of magnitude and the type of discount rate (*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*) will also have a substantial impact on the estimations of expected present value of Fusion technology.

In order to make sound assumptions on all these parameters one has to rely on a recognised energy – economy – environment modelling framework, such as EFDA–TIMES which is being currently under development within EFDA SERF programme. As demonstrated by Eherer & Baumann (2005) and Han *et al.* (2006) the EFDA-TIMES modelling framework may be particularly useful for evaluation of intra-sectoral spillover benefits due to its clustered endogenous learning feature. It can also allow for estimating market spillover benefits in case of specific policy scenarios, such as introduction of CO_2 taxes or emission caps, which may result in reduction of the total energy system cost due to deployment of Fusion technology.

An apparent limitation of EFDA-TIMES, at least in its current version, is that it can not explicitly represent the uncertainties underlying Fusion RD&D process. Indeed, by defining exogenously the starting year for deployment of Fusion power plants and their initial cost, the user ignores the fact that availability of Fusion technology is subject to the probabilities of successful passing through all R&D and demonstration stages. In its turn the probability of success and duration of each RD&D stage is subject to the endowed funding. To cope with this issue we propose to elaborate a simplified RDDD model which will allow for capturing the effect of increased public funding during the Fusion demonstration stage on the total program payoff (see Figure 4). The main inputs of the model are the following:

p_i – *probability of success of ITER/IFMIF, DEMO-1 and DEMO-2 (if needed) stages*
T_i – *time to completion of each stage*
C_i – *costs of construction and operation of experimental installations, DEMO facilities and commercial Fusion power plants (FPPs)*
S_i – *spillover benefits at each stage*
R_i – *revenues from energy sales.*

The basic idea behind this model is that building several DEMO reactors of alternative concepts, as it is advocated in Cook *et al.,* 2005 (page 12), may increase by several percentage points the probability of success in meeting the objectives of the demonstration stage and reducing its expected time to completion, thereby opening opportunity for earlier deployment of commercial Fusion power plants. If the market conditions turn out to be favourable, then earlier availability of Fusion technology will result in a higher expected net present value of the whole Fusion RDDD program.

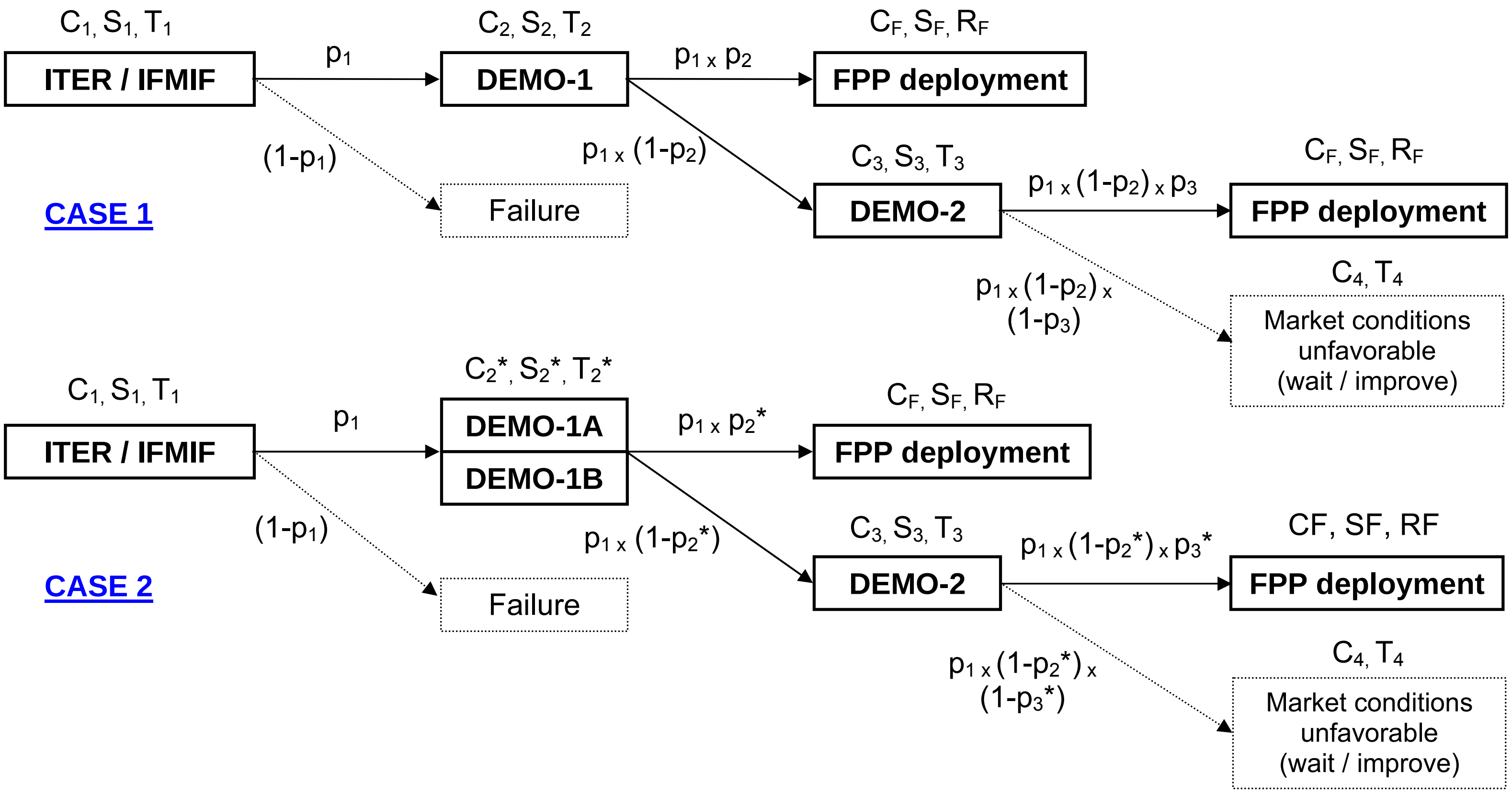


Figure 4. Fusion RDDD Model: alternative realisations of the demonstration stage of Fusion RDDD program

Two hypothetical cases depicted in Figure 4 can be considered. In “Case-1” only one demonstration Fusion reactor (DEMO-1) is built after successful completion of ITER / IFMIF experimental program, whereas in “Case-2” two DEMO (1A / 1B) reactors of alternative concept are built simultaneously. The second case is characterised by a higher demand for public funding [$C_2^* > C_2$], but in the same time it enhances probability of success of the demonstration stage of Fusion RDDD program [$p_1 \times p_2^* > p_1 \times p_2$; $p_1 \times (1-p_2^*) \times p_3^* > p_1 \times (1-p_2) \times p_3$] and reduces the time to completion [$T_2^* < T_2$].

Surely, the results to be obtained with such a model will largely depend on the input assumptions, especially the assumed future wholesale prices of energy services and the costs of Fusion power plants. The choice of discount rate may also have a substantial impact, because of the different time structure of expected costs and benefits in both scenarios. Nevertheless, the model can provide useful information regarding economic nexus between Fusion RD&D funding and the expected total program payoffs, and it can be particularly helpful to perform sensitivity analyses to all of the abovementioned input parameters. To increase credibility of model assumptions, it is proposed to consort them with the input data (*cost and learning factors of Fusion*) and output results (*Fusion build-up rate and levelised system energy / electricity costs*) of EFDA-TIMES model. Structured interviews with Fusion R&D professionals will provide additional insights regarding the transitional probabilities of success as well as the costs and spillover benefits of each RD&D stage.

Meanwhile, a preliminary analysis of both cases with the illustrative numerical assumptions listed in Annex II demonstrates that simultaneous construction of two Fusion DEMO facilities could increase economic value of the whole Fusion RDDD program by approx. € 62 billion: in Case-1 the expected present value of the program is € 74 billion, while in Case-2 it increases to € 136 billion. Such a significant difference may be explained by the fact that the second case increases probability of creating substantial net positive value earlier in time compared to the first case of single DEMO reactor. Theses results confirm the idea that major socio-economic effect of Fusion R&D and demonstration resides in the possibility to reduce the uncertainty about the final outcome of the whole Fusion RDDD program. Basing on one of these cases and independent review of their input assumptions it will be possible to provide numerical estimates of the total expected costs and benefits of Fusion technology which will be taken as input for calculation of the social rate of return of Fusion RDDD program.

5.4 Options Benefits

In recent years the so-called “*Real Options*” approach has gained particular attention in the economic and industrial literature dealing with evaluation of long-term investment projects. The specifics of this approach is that it allows for capturing the intangible value due to flexibility in the investment decisions which is normally ignored by traditional discounted cash flow (DCF) analysis. The body of literature on this subject has emerged following a seminal work of Dixit & Pindyck (1994).

Many publications deal specifically with the case of public R&D investments. So, Vonortas & Lackey (2000) identified the following analogies between undertaking a R&D project and buying a stock option: (i) the cost of 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. The uncertainty about these returns gives value to the option. Accordingly the *Real Options* valuation allows for completely different treatment of uncertainty in the appraisal of strategic long term R&D projects. In fact, in traditional DCF analysis longer time horizons lead to substantial decrease of the present value of an investment. Contrary to this, the option value increases with time and the higher degree of uncertainty (volatility). These specifics of *Real Options* approach appear to be particularly useful for evaluation of long-term energy R&D programs.

Kumbaroglu *et al.* (2006), Siddiqui *et al.* (2005) applied *Real Options* approach to evaluation of renewable energy RDDD program. Rothwell (2004) analysed the deployment of new nuclear fission power plants using *Real Options* approach as well. One of the first attempts to perform *Real Options* valuation of Fusion energy R&D is documented in Goldenberg & Linton (2006). They applied Black-Scholes option pricing model and demonstrated that Fusion R&D is economically justified. Although the underlying assumptions in the paper of Goldenberg & Linton are not very clear or even questionable (e.g. cost of nuclear fusion power in the range 1.6-3.6 cents / kWh), the proposed *Real Option* approach deserves to be further investigated.

If we apply options reasoning to the sequential Fusion RDDD model presented in section 5.3 we will realise that all traditional types of “real options” (*option to defer, option to expand, option to abandon, option to switch, option to grow, compound option*) may be revealed and evaluated in this model. To make these calculations, one will have to make the assumptions on several input parameters, such as (i) volatility of the expected returns, (ii) time to completion of RD&D stages, or in other terms option expiration date, (iii) risk-free rate, (iv) RD&D expenditures, or option exercise price, (v) NPV of future cash flows or value of the underlying asset. Although definition of all these parameters may incur some arbitrary choices, there is still possibility to make them credible by using stochastic simulation (Monte-Carlo) techniques to represent uncertainty and by consorting data inputs with that of EFDA-TIMES modelling framework (in respect of future cash-flows and discount rates).

6. CONCLUSIONS AND RECOMMENDATIONS

In this study we have elaborated a conceptual framework for estimating spillover benefits and social rate of return of global long-term public R&D programs aimed at development and deployment of advanced energy supply technologies, such as Controlled Thermonuclear Fusion. The advantage of our approach consists in the fact that it is capable to reveal important societal benefits of the past, ongoing and future Fusion RD&D activities which have been overlooked by the traditional techno-economic modelling analysis. According to our findings these benefits largely offset the incurred costs, especially if industrial applications of low temperature plasmas are taken in to account. These external benefits may be much higher due to “network and market spillover” effects when industrial scale deployment of Fusion power plants will be started. This argument can be used by the proponents of Fusion “fast track” development path in their debates on the public funding with the critics of Fusion R&D program (e.g. Parkins, 2006).

A more precise estimation in monetary terms of the spillover benefits and the expected total social payoffs of Fusion RDDD program does not appear to be plausible at this stage, because of the extreme diversity of spillover effects, the lack of appropriate panel data, as well as overall high level of uncertainty about the pace of Fusion RD&D and the future state of the global energy system. Additional empirical studies investigating each specific type of spillover and harmonisation of the underlying techno-economic assumptions with the input data and basic results of EFDA-TIMES modelling framework are needed.

As a follow up of this study we propose to carry out a survey of the European companies which have already supplied equipment and services to the existing Fusion experimental facilities or have expressed their interest to participate in publicly funded procurement of ITER project. The objective of this survey is to elucidate the potential of Fusion R&D to yield technological spin-offs and other types of cross-industry spillovers. In parallel, series of structured interviews with the scientists involved in Fusion R&D will be organised with the aim to calibrate the parameters of the proposed Fusion RDDD model. It is recommendable to perform these tasks in cooperation with B.E.T.A. group of the University of Strasbourg who possess a recognised methodology well proved throughout the studies of socio-economic effects of European Space Agency and other European programs.

Future research will be geared towards further development and implementation of Fusion RDDD model which should allow for adequate representation of the different types of uncertainties in Fusion RDDD process. Provided with credible assumptions and input data, gathered throughout field survey, this model will be used for estimating *real options* value of Fusion energy RD&D and will serve for analysis of the possible ways to optimise public funding of Fusion RDDD program. Another important axis in the future work will consist in the investigation of security benefits of Fusion technology.

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ANNEX I. QUESTIONNAIRE FOR INDUSTRY SURVEY [6]

INDUSTRY BENEFITS FROM PARTICIPATION IN FUSION R&D PROCUREMENT

The decision to build International Thermonuclear Experimental Reactor (ITER) in Cadarache (France) opens vast opportunities for technological innovation and economical advancement of European industry. This survey is carried out within the framework of EFDA Socio-Economic Research on Fusion (SERF) program. It aims to elucidate the realised benefits for European companies from participation in the construction and operation of the existing Fusion experimental facilities and the ITER project. Your views and expert opinion will be highly appreciated. All answers will remain strictly confidential. Results will be presented in aggregate format only. If you have any questions regarding this survey, please contact Edgard Gnansounou (Head of the Laboratory of Energy Systems, Swiss Federal Institute of Technology – Lausanne, LASEN-ICARE-ENAC, Station 18, EPFL, CH-1015, Lausanne, Switzerland, Tel. 41 21 / 693 24 95, Fax: + 41 21 / 693 28 63, E-mail edgard.gnansounou@epfl.ch).

SECTION A. COMPANY INFORMATION

A1 Name of the company . . . .,. . . . .

A2 Year company started . . . . A3 Country . . . .

A4 Your name . . . . .A5 Your position . . . .

A6 Company size

☐ Large ☐ Medium ☐ Small ☐ Micro

Please tell us the approximate number of employees (full-time or equivalent part-time) and sales turnover in your company in the end of last year.

Total Number of Employees……………..

Sales Turnover (Euro) ……………

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[6] This questionnaire largely draws upon the work of Autio et al. (2003). It should be considered as preliminary draft only.

A7 Please assess your company's (business unit's) previous experience as supplier of Fusion R&D projects

When we started our last Fusion R&D project	Disagree ←				Agree →
…we had lots of experience as supplier of other Fusion R&D projects	1	2	3	4	5
…we had lots of experience from collaborations with other big-science R&D experiments	1	2	3	4	5
…we had lots of experience from collaboration with universities and research institutes in other areas not related to Fusion	1	2	3	4	5

SECTION B. INFORMATION OF THE PAST FUSION R&D SUPPLIER PROJECT(S)

B1. Please describe the technology sector of the project(s) .
If a specific application was developed, please name it below.
. . . .
. . . .
. . . .

B2. Overall, would you consider this Fusion R&D supplier project(s) as…

Description of the Fusion R&D supplier project	Disagree ←				Agree →
Standard delivery of off-the-shelf products or services	1	2	3	4	5
Standard delivery with minor modifications	1	2	3	4	5
Non-standard delivery with major modifications	1	2	3	4	5
R&D project which involved the development of a new product or	1	2	3	4	5
Cutting-edge R&D with very demanding specifications and high uncertainty	1	2	3	4	5

B3. Please assess the potential applications of the technology concerned

The potential applications of the project…	Disagree ←				Agree →
…were strictly limited to this particular use	1	2	3	4	5
…extended to other Fusion R&D experiments	1	2	3	4	5
…extended to other experiments in other R&D domains	1	2	3	4	5
…extended to a limited number of commercial and industrial applications	1	2	3	4	5
…extended to a large number of commercial and industrial applications	1	2	3	4	5

If the applications extended to commercial or industrial applications, please describe these:
. . . .
. . . .
. . . .

B4. How widely used or known was this technology at the time when the project started? And now?

	Completely new; never before applied in industry	Very new; still unproven; few existing applications	Still developing; many applications introduced	Established; applications numerous	Widely used
At the start	☐	☐	☐	☐	☐
Now (2007)	☐	☐	☐	☐	☐

B5. And how about the market for this technology. How new was it then and now?

	Non-existent; we created it	Emerging market	Rapidly growing new market	Stable or slow growth	Mature; may be decreasing
At the start	☐	☐	☐	☐	☐
Now (2007)	☐	☐	☐	☐	☐

B6. We would like to learn more about the technological uncertainties faced by you at the time of your last Fusion R&D project. Please evaluate the following statements.

At the time when the project started…	Disagree ←				Agree →
…it was difficult to predict how the technology was going to develop	1	2	3	4	5
…the technology in this particular sector was developing very rapidly	1	2	3	4	5
…there were many alternative, competing technologies in this sector	1	2	3	4	5
…no standard, widely accepted solution existed to the problem	1	2	3	4	5

SECTION C. OUTCOMES OF YOUR RELATIONSHIP WITH FUSION R&D ORGANISATIONS

C1. For how long has your company been doing business with Fusion R&D organisations?

……………. years.

C2. Has your company developed new products or services as a direct result of your relationship with Fusion R&D organisations?

☐ YES ☐ NO If Yes, how many new products or services?. . . . .

Please describe the products or services below:

. . . .

. . . .

C3. Has your company applied for or obtained new patents, copyrights, or other IPR as a direct result of your involvement in Fusion R&D ?

☐ YES ☐ NO If Yes, how many new patents or other IPR?. . . . .

Please describe the patents, copyrights, or other IPR below:

. . . .

. . . .

C4. With you Fusion R&D customer organisation in mind, please indicate the extent to which you agree with the statements below.

Importance of Fusion R&D contracts for the company	Disagree ←				Agree →
If we no longer sold to our Fusion R&D customer organisation, we could easily compensate for the loss in revenue by switching our efforts to another customer	1	2	3	4	5
It would be virtually impossible to find another customer in the short run to whom we could make a similar amount of sales	1	2	3	4	5
Because we have devoted specific assets and people to Fusion R&D, it would be costly to find another customer	1	2	3	4	5
The people, machines, and instruments devoted to supplying Fusion R&D could easily be switched to another customer	1	2	3	4	5
The technological know-how required to supply Fusion R&D can easily be used for other customers	1	2	3	4	5

C5. With your Fusion R&D project in mind, please indicate the extent to which you agree with the statements below.

Learning benefits	Disagree ←				Agree →
Because we supplied to Fusion R&D project we were able to obtain a tremendous amount of market knowledge	1	2	3	4	5
At the time of the project, we got most of our valuable information on market needs and trends from our Fusion R&D customer	1	2	3	4	5
It would be costly to get this market knowledge from elsewhere	1	2	3	4	5
The Fusion R&D project really strengthened our market competitiveness	1	2	3	4	5
Because we supplied to Fusion R&D project we were able to build up a tremendous amount of technical know-how	1	2	3	4	5
Because we supplied to Fusion R&D project, we were able to develop valuable intellectual property rights The Fusion R&D project really strengthened our technology-based competitive advantage	1	2	3	4	5

C6. With your Fusion R&D project in mind, please indicate the extent to which you agree with the statements below.

Fusion R&D Related Customer Benefits	Disagree ←				Agree →
We received new customer contacts through our Fusion R&D project	1	2	3	4	5
Fusion R&D project helped 'open the doors' to other customers for us	1	2	3	4	5
We had to turn down other sales opportunities to satisfy our Fusion R&D project needs	1	2	3	4	5
Participation in Fusion R&D is an important marketing reference for us	1	2	3	4	5
Participation in Fusion R&D project improved our credibility as a supplier	1	2	3	4	5
Participation in Fusion R&D project enhanced our reputation as a technology company	1	2	3	4	5

C7. Considering the results of your company over the past decade, what do you imagine they would have been if you had not participated in your Fusion R&D project?

	Much lower	Slightly lower	No change	Slightly better	Much better
Growth in sales	☐	☐	☐	☐	☐
Growth in number of employees	☐	☐	☐	☐	☐
Technological excellence	☐	☐	☐	☐	☐
Net value of the company	☐	☐	☐	☐	☐

C8. Thinking about other learning benefits, how useful was your Fusion R&D procurement project in terms of the following benefits?

Other Learning Benefits from Participation in Fusion R&D procurement	Disagree ←				Agree →
Fusion R&D project helped us improve our manufacturing process	1	2	3	4	5
Fusion R&D project helped us improve our quality systems	1	2	3	4	5
Fusion R&D project helped us improve our R&D processes	1	2	3	4	5
Fusion R&D project helped us strengthen our marketing capability	1	2	3	4	5
Fusion R&D project helped us strengthen our project management capability	1	2	3	4	5
	1	2	3	4	5

C9. Thinking about medium to long-term benefits, please consider the following organizational impacts.

Because of the Fusion R&D procurement project	Disagree ←				Agree →
…we established new R&D team(s	1	2	3	4	5
…we introduced new products or services	1	2	3	4	5
…we started a new business unit	1	2	3	4	5
…we opened a new market	1	2	3	4	5
…we increased our international exposure	1	2	3	4	5

C10. Thinking of the financial outcome, how would you rate the overall financial return of the Fusion R&D procurement project?

Financial Outcome of the Fusion R&D Project	Disagree ←				Agree →
Fusion R&D project was financially profitable for us	1	2	3	4	5
The realized cost of the project was higher than initially estimated by us	1	2	3	4	5
The realized cost of the project was higher than agreed in the project contract	1	2	3	4	5

THANK YOU VERY MUCH FOR YOUR VALUABLE HELP!

Please use the remainder of this page for any comments or questions you may have

ANNEX II. ILLUSTRATIVE NUMERICAL ASSUMPTIONS FOR RDDD MODEL

The numerical data regarding the costs of Fusion power plants (FPPs) and their deployment sequence are based on the assumptions adopted in the study of Gnansounou & Bednyagin (2007). Estimations of transitional probabilities of success are derived from Ward et al. (2004). Assumptions on the costs of ITER / DEMO stages are based on average expenditure of € 1 billion per year for a single experimental / Demo facility. The assumed market electricity price is 0.08 € / kWh for all the periods, discount rate 4.5 %.

STAGE	DURATION	PROBABILITY OF SUCCESS	COST
	YEARS	%	€ BILLION
ITER / IFMIF	20	95	20
DEMO-1	20	65	20
DEMO-1A/B	18	80	36
DEMO-2	10	85	10

CASE 1

PERIOD	AVERAGE LEVELISED ELECTRICITY COST OF FPPS	AVERAGE AVAILABILITY FACTORS OF FPPS	AVERAGE FPPS CAPACITY DURING THE PERIOD
	€ / KWH	%	GW
2040 - 2060	0.074	78	90
2061 - 2080	0.055	80	300
2081 - 2100	0.043	81	600

CASE 2

PERIOD	AVERAGE LEVELISED ELECTRICITY COST OF FPPS	AVERAGE AVAILABILITY FACTORS OF FPPS	AVERAGE FPPS CAPACITY DURING THE PERIOD
	€ / KWH	%	GW
2040 - 2060	0.078	77	30
2061 - 2080	0.065	79	180
2081 - 2100	0.049	80	450