UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Sede Amministrativa: Università degli Studi di Padova

Dipartimento di INGEGNERIA ELETTRICA

SCUOLA DI DOTTORATO DI RICERCA IN : INGEGNERIA INDUSTRIALE

INDIRIZZO: ENERGETICA

CICLO: XXIV

THE ROLE OF FUSION IN LONG TERM SCENARIOS

Direttore della Scuola: Ch.mo Prof. Paolo Bariani

Coordinatore d'indirizzo: Ch.mo Prof. Alberto Mirandola

Supervisore: Ch.mo Prof. Giuseppe Zollino

Dottorando : Chiara Bustreo

31 gennaio 2012

TABLE OF CONTENTS

Introduzione

A partire dagli anni Settanta sono stati realizzati i primi studi sulla possibile evoluzione del sistema energetico mondiale attraverso le analisi di scenario. La risposta è risultata essere univoca: la domanda energetica è destinata a crescere negli anni a venire. Se, tuttavia, l'energia richiesta, ed in particolare, l'energia elettrica, continuasse ad essere prodotta con le tecnologie fino ad ora utilizzate, l'impatto ambientale sarebbe insostenibile: la concentrazione di gas ad effetto serra nell'atmosfera, primo tra tutti l'anidride carbonica, determinerebbe un aumento di temperatura del pianeta tale da causare cambiamenti climatici che avrebbero un impatto negativo sull'ambiente e sulla società.

Da qui la necessità di studiare quali tecnologie saranno in grado di soddisfare la domanda energetica riducendo il consumo delle risorse energetiche e l'impatto ambientale. Fissione e fusione si presentato come le migliori candidate: la prima, tecnologia già sviluppata e in continuo miglioramento, la seconda, ancora in fase di studio.

In questo contesto, si è deciso di studiare mediante il generatore di modelli TIMES () scenari energetici a livello mondiale e di analizzare la competitività delle due tecnologie nucleari. TIMES è un codice di ottimizzazione, scritto in linguaggio GAMS, basato sulla programmazione lineare: se si considera il modello come un mercato energetico dove l'offerta è costituita da vettori energetici (commodity) e la domanda da tecnologie che utilizzano determinate risorse energetiche, l'obiettivo dell'analisi è quello di massimizzare il surplus totale, ovvero minimizzare i costi totali del sistema. Riferendosi solo al settore energetico, TIMES determina quale sia il mix di tecnologie, in base alla disponibilità delle risorse energetiche di cui necessitano, e alla domanda di energia elettrica, tale da minimizzare i costi totali del sistema. Considerando ancora solo il settore energetico, in TIMES ogni tecnologia deve essere completamente definita sia da un punto di vista tecnico, dichiarandone efficienza, consumo di combustibile, e disponibilità annuale, sia da un punto di vista economico.

Nel modello energetico globale EFDA TIMES (ETM), sviluppato in ambito europeo per lo studio del ruolo della fusione negli scenari di lungo periodo, i dati riguardati le centrali a fusione sono tratti dai risultati di uno studio condotto in ambito EFDA sui costi di un futuro reattore a fusione, ottenuti mediante l'utilizzo del codice PROCESS.

Nella presente tesi si propone la descrizione di un codice alternativo a PROCESS, scritto in linguaggio C++ e sviluppato grazie alla collaborazione con un gruppo di ricerca del Consorzio RFX. FRESCO ( ), analogamente a PROCESS, permette la realizzazione di un modello tecnico ed economico di una centrale a fusione commerciale. FRESCO, tuttavia, fornisce in più la possibilità di analizzare i due tipi di funzionamento ipotizzati per il reattore: stazionario o pulsato. Sebbene nato come codice di calcolo economico, FRESCO realizza anche il modello fisico della centrale, valutandone le dimensioni, la quota di energia ausiliaria richiesta per sostenere la reazione di fusione, l'energia prodotta ed il costo del reattore. Nella seconda parte della tesi verrà fornita una descrizione dettagliata del codice in cui saranno spiegate e giustificate tutte le ipotesi poste alla base della sua realizzazione.

Successivamente sarà presentato il lavoro condotto in collaborazione con l'istituto di fisica del plasma di Garching (IPP), nell'ambito della partecipazione al task SERF () di EFDA, per realizzare l'implementazione nel modello ETM del ciclo del combustibile nucleare. Saranno riportati i risultati di una vasta ricerca mirata alla raccolta di tutti i dati necessari alla completa definizione nel modello delle possibile future tecnologie nucleari a fissione, appartenenti alla generazione III+ e IV. L'implementazione del ciclo del combustibile permetterà in primo luogo di analizzare i costi ad esso associati e quindi di realizzare una analisi del tutto obiettiva della competitività delle tecnologie a fissione e fusione non trascurando i costi relativi alla produzione del combustibile e alla gestione del rifiuti radioattivi. Inoltre inserendo nel modello tutte le possibili future tecnologie nucleari e i relativi cicli di combustibile, sarà possibile studiare tramite analisi di scenario quali politiche energetiche comporterebbero minori costi a fronte della necessità di contenere la produzione di rifiuti altamente radioattivi. Infine, saranno presentati dei risultati preliminari che evidenzieranno la penetrazione delle centrali a fusione nel mercato energetico a seguito di alcune modifiche apportate al codice tramite lo studio condotto sino ad ora. Al momento l'implementazione del ciclo del combustibile nucleare non è stata ancora completata e quindi non è possibile fornire risultati definitivi. Nei prossimi mesi, quando l'aggiornamento del modello sarà completato da parte di tutti i membri del gruppo di ricerca, sarà possibile eseguire nuove analisi di scenario.

Nella presente tesi, dopo una parte introduttiva in cui si tratterà il problema energetico e si fornirà una panoramica dei modelli fino ad oggi utilizzati per lo studio di scenari energetici, completa di una presentazione del modello EFDA TIMES, verrà presentata una breve descrizione dei principi di funzionamento delle centrali a fissione fusione. Successivamente sarà descritto il codice di calcolo FRESCO, messo a punto durante il dottorato in collaborazione con il gruppo di ricerca di RFX, per la realizzazione di un modello tecnico-economico di una centrale a fusione i cui risultati potranno in futuro essere utilizzati per analisi di scenario con generatori di modelli analoghi a TIMES. Infine sarà presentato il lavoro condotto nell'ambito del task SERF di EFDA sulla realizzazione del modello del combustibile nucleare in EFDA TIMES, realizzato per render maggiormente obiettiva l'analisi della competitività delle tecnologie a fissione e fusione e per studiare gli effetti economici e ambientali connessi alla scelta delle future politiche in ambito nucleare.

Introduction

Since Seventies the first studies about the future evolution of the worldwide energy system has been carried out by scenario analysis. The answer is found to be unique: the energy demand will go on growing in the next decades. Nevertheless, if energy and, among final use, electricity, was produced by the same technologies as it is now, the environmental impact would be unsustainable: the green house gases concentration in the atmosphere, first of all the carbon dioxide concentration, would increase the Earth temperature leading to extreme atmospheric event as well as to the sea level rise, both having negative effect on agriculture, forestry, water resources, human health, industry and society.

This is the reason why the study of future technologies, able to satisfy the energy demand while reducing as much as possible the resource exploitation and the environmental impact is necessary. Fission and fusion are the best candidates: the first is a well known technology and still under improvment, the second is instead on a research phase.

In this contest, a scenario analysis of worldwide energy system has been carried out by using TIMES (). It is a optimisation code, written in GAMS language, founded on linear programming. Considering the model as a energy market, where the suppliers of a commodity are technologies that procure a given commodity and the consumer of a commodity are technologies or demands that consume a given commodity, the objective of the analysis is to reach the market equilibrium that is maximize the total surplus, (i.e. the sum of suppliers' and consumers' surplus) or, similarly, minimize the total system cost. Considering only the energy sector TIMES chooses which of the available power plants have to produce energy to satisfy the energy demand, depending on resource availability, at the least system cost over the entire horizon. All technologies in TIMES are fully described from a technical (efficiency, fuel consumptions, annual availability must be declared) and economical point of view

In the global energy system EFDA TIMES (ETM), developed in the European framework in order to study the role of fusion in long term scenarios, data about fusion power plants are the results of the economical code PROCESS, developed in the EFDA framework too.

In the second part of this thesis, a new economic code, developed during the Ph.D in collaboration with a research group of Consorzio RFX of Padua, FRESCO (Fusion Reactor Simplified Cost) code, is fully described. Aiming to model a future fusion power plant from an economic point of view, it calculates the reactor physical dimensions, the auxiliary energy need, the annual electricity production and the related capital cost. Moreover, unlike of PROCESS, two differ operative modes can be studies: stationary or pulsed. Results obtained by this kind of model could be used in future to derive new scenario analysis with model generators of the same kind of TIMES.

Then, the work carried out in cooperation with the Max Planck Institut für Plasmaphysik of Garching, in the framework of the SERF activity denominated "Further improving of advanced nuclear fission technologies in EFDA TIMES", will be presented. The results of a wide literature review on technical and economical aspects of future nuclear power plants (Gen III+ an IV) will be described. These data will be used to complete the nuclear fuel cycle implementation in ETM in order to evaluate the nuclear fuel cycle cost leading to a more objective analysis of fission and fusion competitiveness, since the cost of producing the nuclear fuel and the cost associated with the radioactive waste will be not neglected. Moreover thanks to the modeling of new nuclear technologies and related fuel cycles, scenario analysis about possible future energy policies aiming to reduce the radioactive waste production would be carried out. Then the preliminary results obtained by the ETM update according to the new data collected during this work, will be presented: they show the fusion power plants penetration in future energy markets. At present, the nuclear fuel cycle implementation has been not yet completed: as soon as all the EFDA members will have completed the model update, new scenario analysis could be carried out.

In this thesis, after an introductive section where the "energetic problem" will be described and the main results of energy model till now developed will be presented, including a presentation of the EFDA TIMES model, a short description of the operating principles of fission and fusion power plants will follow. Then the FRESCO code for the technical and economical modeling of a future power plant, developed with a research group of Consorzio RFX, will be described: its results could be used in future for scenario analysis with model generator of the same kind of TIMES. Finally, the work carried out in the framework of SERF activities will be presented: it is the nuclear fuel cycle implementation, aiming to allow a more objective analysis of fission and fusion competition and to evaluate the economical and environmental impact of future nuclear policies.

1 Worldwide energy demand

Energy, 'the ability to do work', is essential for meeting basic human needs, extending life expectancy, and providing an acceptable living standard.

We have progressed over many thousands of years from a primitive life and along the way, our primary energy consumption has increased more than a hundredfold because of the changed lifestyle and the population growth.

The strict relation among energy demand and population growth can be inferred from Figure 1.1 where the population increment over the years, from 1750 to 2050, is graphed. For a very long time the world population did not grow significantly, with periods of growth followed by periods of decline. According to the United Nation Population division study [UN,1999], it took more than 1600 years for the world population to double to 600 million, corresponding to an average increase of 2-3% per century. The world population was estimated at 791 million in 1750 and only in 1800, for the first time, the world inhabitants reached 1 billion. Because of the industrial revolution that leaded to improve the life style thanks to a higher final energy availability for people, the population grow rate increased with a maximum in 1980: after then the rapid growth of the world population, with a reductions in mortality in the less developed regions as well, slowed down reaching a population of 6.1 billion in the year 2000, nearly two-and-a-half times the population in 1950. Despite the slower growth, the world population go on increasing over the years (at the end of 2011 it was estimated at 6.9 billion) and it is likely to reach 9 billion in 2050.

year	*Population (in billions)*
0	0.30
1000	0.31
1250	0.40
1500	0.50
1750	0.79
1800	0.98
1850	1.26
1900	1.65
1950	2.52
1999	5.98
2011	*7*

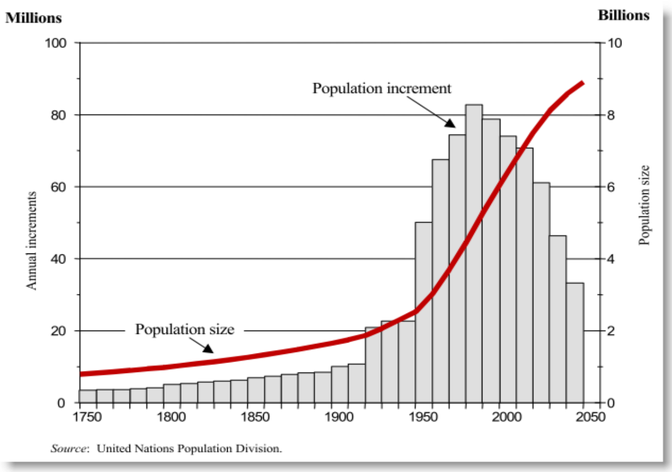


Figure 1.1: Population growth from year 0 to 2011 (table on the left). The graph on the right depicts both the population increment and its size (from [UN,1999] and United Nations Population Fund website.

The long term scenarios developed by United Nations show the population growth until 2100: depending of the fertility level, mortality and migratory fluxes assumed, a likely range is believed to be from 5 to 12.5 billion; similar results have been achieved by IIASA studies (from 6.2 to 11 billion). In the medium case scenario, both study agree in expecting a peak of 9 billion between 2050 and 2100.

Unfortunately scenarios are not perfect forecasting but only analysis of the possible future development of current situation. Nevertheless, a further population growth appears quite likely in the next future and then an energy demand increase too. This becomes even more probable when thinking that the population increase is mainly due to the economic development of the less developed countries: at present they are responsible of the most part of the world energy demand (77%) even if they account for only 28% of the world population [Ritch,2008]. According to World Energy Outlook 2008 [WEO,2008], in 2008 the primary energy demand by OECD countries equaled that of all other non-OECD countries (mainly China and India) and an increasing gap, reaching a 1:1.5 ratio before 2030, is believed to characterize the next future.

In Figure 1.2 the primary energy demand evolution from 1971 to 2008 is shown. The overall fossil fuel contribution over the years has decreased because of an increasing electrification: while the oil share was down by 13%, the coal one by 26%, the gas share raised by 8% and electricity by 83%: this reflects the increasing use by society of final devices supplied by electricity. In 2008 it was produced mainly by coal fired power plants, followed by gas and oil fuelled power plants. The overall contribute of fossil fuel, even decreasing, is still higher than 50% leading to energy system mainly made of carbon emitter and polluting technologies. However from years '70 , for the first time, nuclear power appeared in the worldwide energy mix. The installed fission power plant capacity has highly increased over only 30 years, raising its contribute in electricity production by a factor of four.

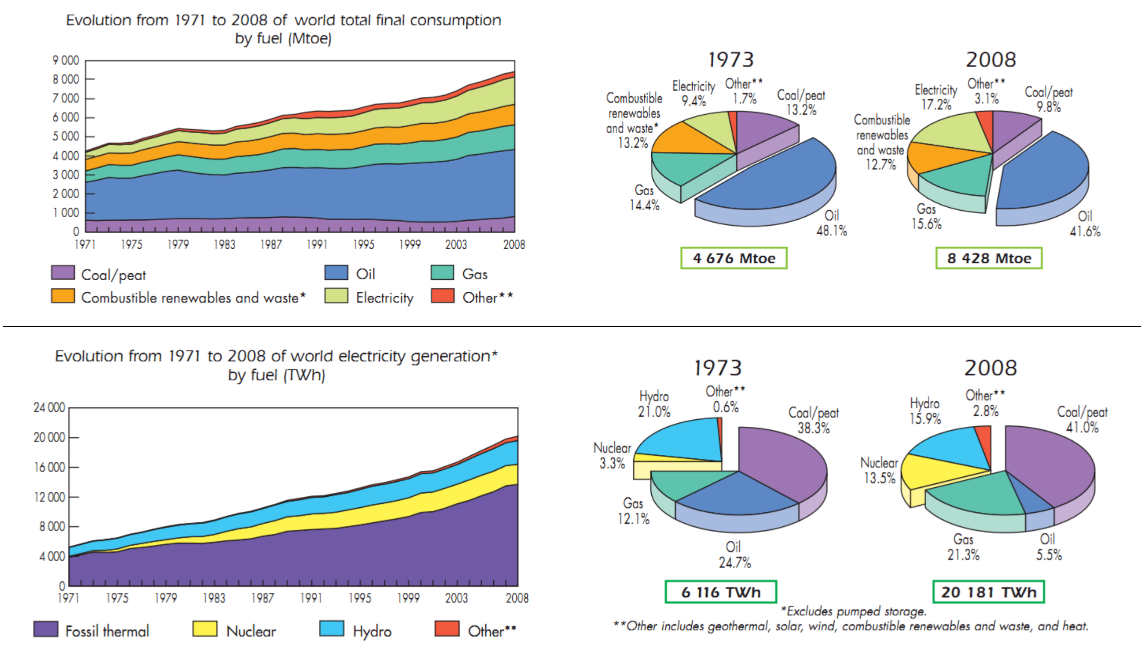


Figure 1.2: Primary energy and electricity worldwide demand from 1971 to 2008 [OECD/IEA,2010].

Such a big use of fossil fuels in the electricity sector leads to two main problems: firstly the progressive resources depletion due to a increasing exploitation leading to a higher resource cost in the short term, to the absence of fuel in the very long term. For example, the oil proven resource are expected to be exploited in 40 years keeping the consumption constant; the natural gas ones in 60 years, the coal in 150 years [Cumo,2008].

Besides of this, the fossil fuel combustion in the Energy sector is responsible of 26% of the total anthropogenic green house gases (GHG) emissions: carbon emissions account for 77%, followed by methane (14.3%) on the total GHG production (2004 data from [IPCC,2007])

It has been proven that human activities had contributed to climate change by causing changes in Earth's atmosphere in the amounts of greenhouse gases, aerosols (small particles, produced for example by coal combustion), and cloudiness (because of steam released by power plants). Greenhouse gases and aerosols affect climate by altering incoming solar radiation and out-going infrared (thermal) radiation that are part of Earth's energy balance. Changing the atmospheric abundance or properties of these gases and particles can lead to a warming or cooling of the climate system: while carbon has a positive radiative force, that is it leads to a warming of the Earth-atmosphere system, the aerosol, produced for example by explosive volcanic eruptions, contribute in cooling the system since it creates a short-lived (2 to 3 years) negative forcing through the temporary increases in sulphate aerosol in the stratosphere.

The differences in radiative forcing estimates between the present day and the start of the industrial era for solar irradiance changes and volcanoes are both very small compared to the differences in radiative forcing estimated to have resulted from human activities. As a result, in today's atmosphere, the radiative forcing from human activities is much more important for current and future climate change than the estimated radiative forcing from changes in natural processes.

As clearly show by the graph on the left of Figure 1.3, since the industrial era (i.e. from about 1750), the human activities contributed in a rapid increase of the GHG concentrations, causing an increasing warming of atmosphere that has lead to a increase of the Earth temperature of about 1°C in the last 140 years.

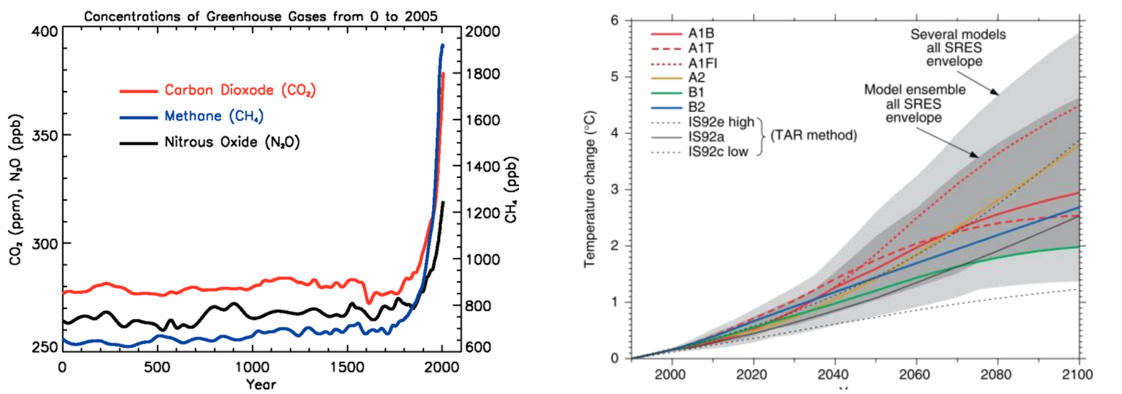


Figure 1.3: Concentration of the three main GHGs, carbon dioxide, methane and nitrous oxide, from year 0 to 2005 (on the left) possible temperature increase on long time horizon derived by IPPC scenarios (on the right) [IPCC,2007].

In 1996 the Intergovernmental Panel on Climate Change (IPPC) began the development of a new set of emissions scenarios, effectively to update and replace the old scenarios. Four different narrative storylines were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification. The resulting set of 40 scenarios (35 of which contain data on the full range of gases required to force climate models) cover a wide range of the main demographic, economic and technological driving forces of future greenhouse gas and sulphur emissions. By 2100, carbon cycle models project atmospheric CO_2 concentrations of 540 to 970 ppm that lead to a temperature increase (see graph on the right of Figure 1.3) from 2°C to 4.5°C (best estimated values) [IPCC,2007].

The temperature increase will likely lead to extreme atmospheric event as well as to the sea level rise, both having negative effect on agriculture, forestry, water resources, human health, industry and society.

In such a contest long term scenario analysis are carried out aiming to study the effects on future energy systems of the environmental and energy policies adopted by worldwide governments in these very days. Obviously the results of such a kind of studies can not be considered as perfect forecasts but a clue about the future possible evolution of current energy systems.

Recent studies, first among all the Energy Technologies Perspectives, carried out by International Energy Agency, state that the increasing energy demand could be satisfied, while reducing the CO2 emissions, by improving the energy efficiency as well as by changing the technologies mix electricity producing: a greater share of electricity should be produced by nuclear fission power plants, that are base load, zero-emission technologies, together with a big contribute by renewable.

Fusion power plants have been no mentioned so far: among energy studies through scenario analysis, only the EFDA (European Fusion Development Agreement) TIMES model, developed in the framework of SERF (Socio Economic Research on Fusion), takes into account fusion as a possible future technology for energy (thermal energy and electricity) production. Unlike fission power plants, the fusion ones can not be affected by extreme accidents because of their inherently safety due to the type of the physical reaction producing energy: while fission reaction needs to be turned off in case of accident in order to prevent an increasing energy production, on the contrary fusion reactions break downs in case of accident because it is not a self sustaining reactions. This characteristic, together with the absence of carbon and pollutants emissions as well as the low amount of radioactive material produced compared to fission power plants, make fusion power plants an attractive technology for electricity production.

In the following sections, an excursus on energy scenarios throughout the recent past will be described. Then, after a brief description of the physics basics of fission and fusion, the description of the FRESCO code for the physical, technological and economical modelling of a fusion power plant will follow: such a study is necessary in order to derive the main technical and economical parameters to be used in energy models for scenarios outline. Finally, the description of possible future nuclear fission fuel cycle, including a technical and economical analysis of all possible future fission power plants as well as of future nuclear facilities necessary for processing the nuclear fuel, will be carried out. These data will be used to implement the nuclear fuel cycle in the EFDA TIMES model in order to deeply study the competition between fission and fusion when the expenditure due to the fuel cycle and the radioactive waste production is considered.

2 Energy scenarios in literature

In this section the description of the most important energy models throughout history is presented. The most part of the information is taken from [Tosato,2007] where the results of literature review about the most important old energy studies and energy models are presented. This chapter aims to introduce the reader into the “world” of energy models and highlight both potentialities and deficiencies of such devices for long term analysis.

2.1 Models and scenarios

An energy system model is a simplified mathematical representation of real energy and economic fluxes [Botta,2005]. Model creation is the first step to build scenarios that are the description of possible future developments of an energy system. It must be underlined that the results of the analysis have to be consider as only hypothesis rather than detailed and precise future predictions: this is the reason why a model have not necessary to be highly exhaustive.

Each possible system model development, obtained by imposing constraints on its natural evolution, is called scenario: *“scenarios therefore describe hypothetical processes, sequence of events that could develop over a period of time”* [Tosato,2007], *“[they are] images of how the future can unfold […] derived from our understanding of the past and the present”* [IIASA/WEC,1995], *“[…] is a tool for helping us to take a long view in a world of great uncertainty (ignorance, for me).”* [Schwartz,1996].

Model generators such as TIMES let the analyst to study likely energy system developments through creating different models of future energy system: this could mean analyze the possible new technologies entry into the energy market or evaluate the impact of research and development policies or control ones on CO_2 emissions.

2.2 The history of energy models: from 1971 to nowadays

The first scenario study, entitled *“Limits to growth”* (1972) assessed that the human kind had been already gone beyond the limits of our planet sustainability because of both energy resource depletion and emissions growing. The results of this study attracted enormous attention on this topics and have been debated to this day. The importance of such kind of analysis became clear in October 1973 when the OAPEC embargo led to the first oil crisis.

Although the first *Shell scenarios* appeared only few months before the oil crisis, the related activity started inside the company in sixties. The long term energy scenario studies, whose aim was to make business decisions better, revealed their great potential during the oil crisis: in fact they let Shell to respond readily to the occurrence since that event was considered in previous years as a possible development of those times energy system.

In October 1974 an independent organization, *WAVES* (Workshop on Alternative Energy Strategies), outlined five scenarios using for the first time linear programming (LP) to study the probable future energy developments through the year 2000: the aim was to spread these information to public governments as they can be useful to support formulating strategies necessary to ensure a proper balance of energy supply and demand during the period 1985 to 2000 and beyond.

The results of the study were deeply worrying as it seemed that at the end of the century the increasing oil demand could not had been satisfied due to the depletion of oil reserves.

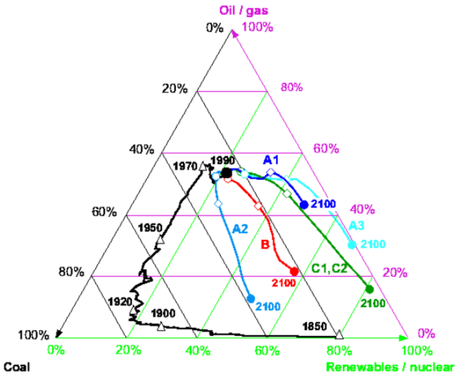
IIASA (International Institute of Applied System Analysis), whose studies on the global energy system lasted from 1973 to1981, reached the same conclusion: the energy problem, that is the difficult to satisfy the energy demand, they said, is primarily tied to the progressive depletion of oil reserve; the real energy problem, they continued, is really a liquid fluid problem. IIASA used a bottom-up technical economic optimization model, called MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental impact), working in UNIX environment.

The model was criticized as it seemed that the results could be hard wired to the inputs. Nevertheless the forecast on the global average energy consumption showed to be very close to reality. At last the IIASA model was labeled as nuclear both for strong arguments in favour of nuclear power plants (they said that their contribution on energy producing would be of 23%) and for the asserted need to build a grid for distributing the hydrogen produced by nuclear.

From the eighties the energy system started to be analyzed in order to show that an efficient and economic climate change mitigation was possible: the *ISEP* (International Project for Sustainable Energy Paths) assessed that the deployment of the most efficiency devices could reduce the future need of energy supply (1990). In 1995 the Global Scenario Group developed six scenarios in order to explore different future scenario trying to understand how can the contradiction between a continuous energy demand growth and a finite planet be resolved in a sustainable way, taking into account not only the technology development but also the human behavior and choice both in climate sphere and foreign politics (e.g. the possibility of wars is also considered) and the likelihood of extreme natural disasters.

From 1998 many instituted started to issue scenario studies regularly: the World Energy Council (WEC), the foremost multi-energy organization in the world today, established in 1923, whose aim is "to promote the sustainable supply and use of energy for the greatest benefit of all people" [WEC], and the International Institute of Applied System Analysis (IIASA), that studies also the possible development of the global energy system, in 1998 presented, after five years of common study, six alternative long term energy futures that represent the combination of WEC studies on the future availability of energy resource and IIASA analysis on how the future energy needs will be satisfied by fossil fuels, alternative fuels, efficiency increase and energy conservation. Three type of possible developments of energy system are considered and they are named "A", "B", "C": their main features are summarized in Figure 2.1.

The International Energy Outlook (IEO) is issued yearly by Energy Information Administration, which depends from the US Parliament: it assesses the outlook for international energy markets in the following 20-25 years; the study is carried out using SAGE (System of Analysis of Global Energy markets), a modelling tool derived from MARKAL that is the progenitor of TIMES: even though the way SAGE chooses the investment can be considered myopic as future benefit of using a more expensive but more efficient technology isn't taken into account, the reports can boast a rich historical database and a solid and well documented methodology that confer to them a high strength.



SCENARIO *A*: technology development and economic growth;

A1: high future availability of oil and gas;

A2: return to coal;

A3: nuclear and renewable energy technologies oust fossil fuels;

SCENARIO *B*: middle course;

SCENARIO *C*: assumes unprecedented progressive international cooperation on environmental protection and international equity.

C1: nuclear power proves a transient technology that is eventually phased out entirely by the end of 21st century;

C2: new generation of nuclear reactors, inherently safe and small scale, is developed;

Figure 2.1: Evolution of the primary energy structure for six scenarios for World, shares of oil and gas, coal, and non-fossil sources in percent. Each corner of the triangle represents a hypothetical case in which 100% of primary energy is supplied by a single source: oil and gas at top, coal left bottom, and non-fossil energy right bottom. The figure shows the historical evolution (in black) as well as the six scenarios for World to 2100. [IIASA/WEC,1995]

Since the early eighties, the Economic Analysis Division of the International Energy Agency (IEA) issues the World Energy Outlook (WEO) every two years: it describes the possible development of actual demand and supply of oil, coal, natural gas and electricity considering a

30 years time horizon, giving also details on particular region or country, different every time it is issued. Finally it hypothesizes and describes an alternative policy scenario that is an exploratory scenario, to be compared with the reference one that, instead, has to be considered as a baseline. The conclusion reached by the study in the most recent years is that the world energy system is not sustainable in the 30 years time horizon especially in terms of CO_2 emissions and investment. Giving such a pessimistic view of future, in 2006 the Office of Energy Technology and R&D of the IEA issued the first “Energy Technology Perspectives” (ETP) updated and published every two years as the WEO: it is a report that analyses all the present energy technologies, their possible development and their impact in a future energy market.

The ETP, at present the most reliable study about long term energy analysis, outlines several scenarios showing possible outcomes of more effective policies for the development and deployment of new energy technologies. Since the ETP time horizon ends with 2050, year when the first commercial fusion power plant should be available, among future nuclear technologies, only fission power plants belonging to Gen III+ are considered in the model.

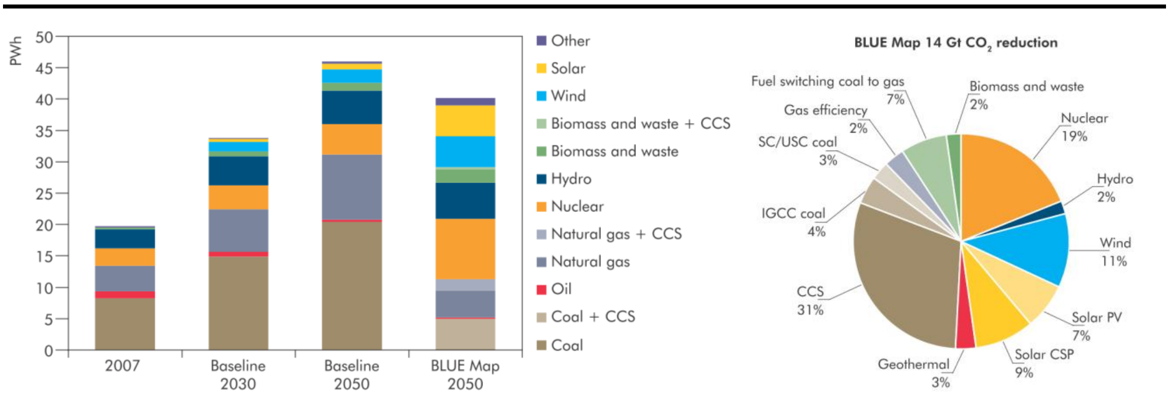


Figure 2.2: Global electricity production by source and scenarios according to ETP 2010. On the left, the contribution of different power sector technologies to reductions in CO_2 emissions in the BLUE Map scenario is shown.

In Figure 2.2 the results of the Business as Usual (BaU) ad BLUE Map scenarios are shown. The first is the natural evolution of the current worldwide energy system so emission constraints are set: in this case, in 2050, the fossil fuels share in electricity production is 66% quite close to their contribute in 2008 (see Figure 1.2) . On the other hand, the BLUE Map scenario assumes the halving of 2007 carbon dioxide concentration by 2050 that corresponds to a 2-3° temperature increase in the long term if the emission of all others GHGs is reduced too. This is obtained by increasing the end-use fuel and electricity efficiency (that reduces the electricity demand by 12.5%) as well as by enhancing carbon capture and storage technologies and nuclear fission power plants. In 2050 the installed nuclear capacity should be more than twofold than that of 2007: this would correspond to the grow rate occurred in the Eighties, the maximum ever registered so far.

Similar analysis are carried out with the EFDA TIMES model but extending the time horizon until 2100 and adding to the new technologies set fusion power plants too. The main characteristics of the TIMES model generator are described in section 3; the peculiarity of the EFDA TIMES model are instead presented in section 4.

3 The TIMES model generator

In 1976 the International Energy Agency (IEA) established the Energy Technology System Analysis Program (ETSAP), an implementing agreement between country researcher teams cooperating to maintain and implement a consistent multi-country energy, economy, environment, engineering (4E) analytical capability [ETSAP,2011].

Thanks to this project, the first energy and economic model generator, called MARKAL (MARKet Allocation), was developed; at the beginning of this century, changes and improvement on it leaded to shape a new and more powerful model generator, TIMES (The Integrated MARKAL-EFOM System).

The aim of both MARKAL and TIMES, as of all the other existing model generator, is to outline the possible scenarios on medium-long term time horizon developments of the actual energy system according to different assumptions on population, energy demand, supply, techno-economic development and on climate policies, e.g. restrictions on greenhouses gases emissions limit due to future, probably worse, climate conditions.

TIMES in written in a modular fashion employing GAMS (General Algebraic Modeling System) that consist of a language compiler and a stable of integrated high-performance solvers very suitable for mathematical programming and optimization [GAMS website], [Loulou vol. III,2005]. Moreover, the modeler can easily handle input and output data by using two application, developed by KanOrs, an organization expert in mathematical and economic modelling of energy and environment systems [KanOrs website]: VEDA_FE (VErsatile Data Analyst Front End) lets the user to simply access to all the excel files containing preformed tables that have to be filled with data to describe the energy scenario and the boundaries on its development; VEDA_BE (VErsatile Data Analyst Back End), is instead useful to view the results on cube data tables; Thanks to them, the user has only to care about the data collection and their correct entry: in fact it will be TIMES to translate the excel tables in GAMS language and formulate the mathematical optimization problem.

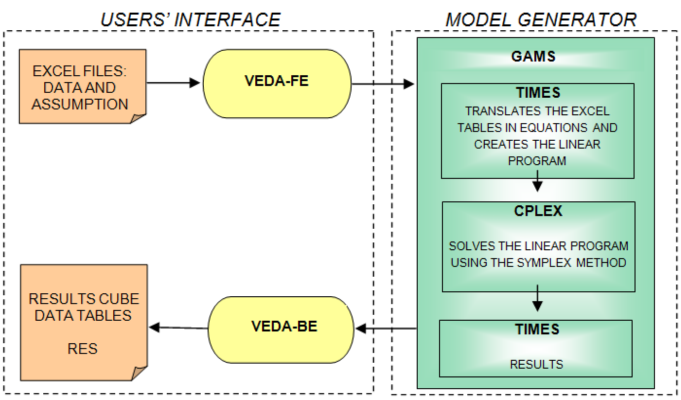
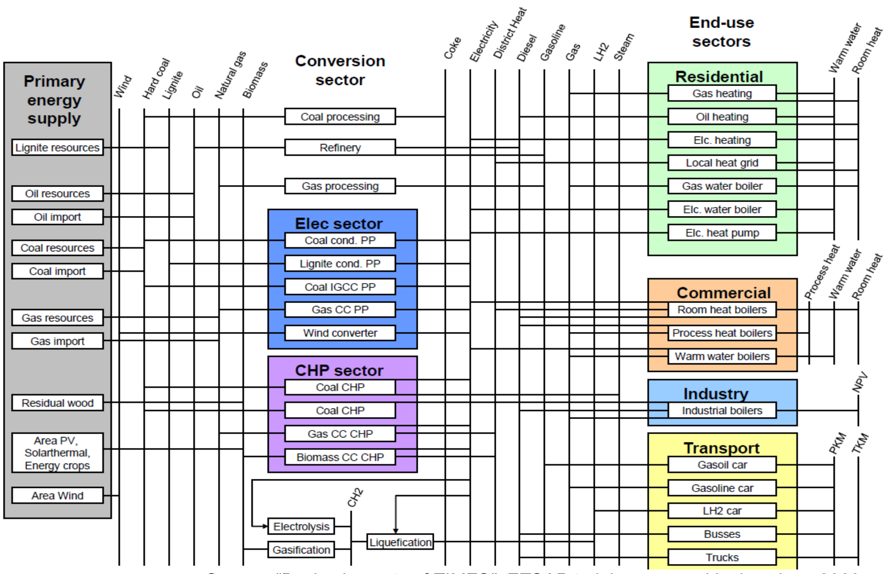


Figure 3.1: Scheme of connections through software for data processing.

The results of the optimization obtained applying the *simplex* method to the linear program, solved by an external GAMS code called CPLEX, will be translated from GAMS language in a way suitable to be displayed that is VEDA_BE cube data tables or through the RES (Figure 3.2), a graphical representation of the energy system where all the transformation processes of energy (represented by boxes) are connected by their input and output commodities[1] (vertical lines). The above description is schematized in Figure 3.1.



Source: "Basic elements of TIMES", ETSAP training course, Venice, June 2009.

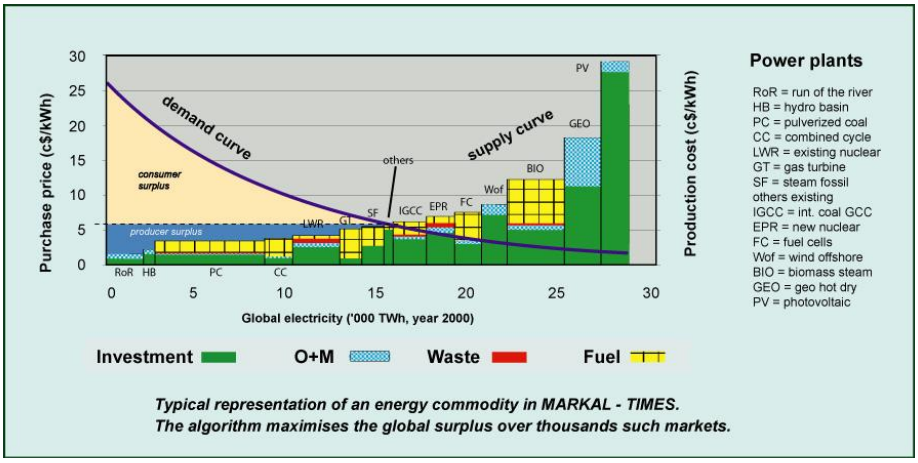
Figure 3.2: Example of RES (Representation of an Energy System): it consists of a sequential series of linked stages of energy transformation, from the primary one (energy embodied in resources as they exist in nature), to final one (energy transported and distributed to the point of final use), than to useful one, work or heat, that provides energy services such as warming up water or rooms, moving vehicles, lighting…).

Considering the model as a energy market, where the suppliers of a commodity are technologies that procure a given commodity and the consumer of a commodity are technologies or demands that consume a given commodity, the objective of the analysis is to reach the market equilibrium that is maximize the total surplus, (i.e. the sum of suppliers' and consumers' surplus) or, similarly, minimize the total system cost.

Considering only the energy sector, (Figure 3.3), TIMES chooses which of the available power plants have to produce energy to satisfy the energy demand at the least system cost over the entire horizon: the solution is found solving a linear program that consist of an objective function (the total system cost) to be minimize in respect to a system of constraint equations (power plant annual and seasonal availability, enter of new and powerful technologies, trend of the load curve, etc.). Such a kind of optimization is done on each sector included in a energy system at the same time: this means that, for example, also the best mix of primary energy fuels and, on the other hand, that of final uses devices has to be defined.

It must be underlined that the user has never to account the analysis resulting costs as the future real ones since like the study is derived from an approximation of the reality so the value of the results are rough amount. Therefore the right way to glean how the economic system evolution could be, consists in comparing the order of magnitude of different scenario result costs, obtained modifying boundaries, constrains and assumptions on the same model.

[1] Commodities are energy vectors such as materials, emissions and demand service.



Source: "Gargiulo M., "Getting started with TIMES-VEDA version 2.7", may 2009.

Figure 3.3: Example of step-wise (inverse) supply demand curve for electricity. Resolving the linear program means maximizing the total surplus that is the same of minimizing the total system cost.

TIMES is a bottom up model: this means that the input data concern information about the energy demand (some of which are results of macroeconomic analysis made using top down model like GEM-E3[2]), instead the result is the mix of technologies that satisfies the demand minimizing the total system cost. Ideally this kind of analysis let to go through the energy system in a way opposed to natural energy flow, from energy service to energy supply.

From an economic point of view, TIMES is a partial equilibrium model: this means that it is assumed that the quantities of goods offered and demanded inside the studied market are only influenced by the good price and all the other markets don't bias it.

It's also a technology explicit model as each device, both on demand and supply side, is fully described technologically and economically; the number of technologies studied can also reach a thousand: for example, the EFDA-TIMES model consider 1400 different types.

The geographic area studied using TIMES can deeply change due to the aim of the study: for example if the research project has to investigate on climate change, it should consider the entire world; instead if the objective of the analysis is an energy national plan, only the nation of interest will be studied. The model generator also let you divide the chose area, whatever its size, into region: EFDA-TIMES model shares out the world in 15 region, MATISSE model by ERSE S.p.A. split Italy in its 20 region, a potential model could divide an area of a nation in as region as the number of area's cities.

The user can also choose the length of the time horizon of the study, due to the aim of its analysis: a short term (10 years), a medium (50 years) or a long one (100 years). The energy dynamics usually are evaluated over a medium term to study the policy responses to climate change, or over a 100 years time horizon, more proper to analyze possible new energy markets where innovative technologies could take place, e.g. fusion power plants. The time horizon can also be split in time periods of variable lengths, yearly in the short term, every five years in the

---

[2] For more information see: *http://www.gem-e3.net/index.htm.*

medium, and every twenty or more years in the long period: such a partitioning offers the possibility to evaluate the system, and thus adjust decisions and strategies, more frequently [Gargiulo,2007]. Moreover every time period can be divided in time slices, usually eight, four for the seasons day and four for the seasons night, to describe the energy demand trend and the level of energy production, especially from renewable energy plants.

TIMES has also some extensions: one of this is the climate one that considers CH_4 and N_2O as well as CO_2 contribute to global temperature increasing using a commonly accepted approximation of Nordhaus-Boyer climate equation [Labriet, 2008]. Instead the stochastic model is employed to define a strategy of action, called hedging strategy, if the action recommended in each scenario are different also in the short term: this is necessary for example for a policy makers who can't wait until an uncertainties will be resolved but has to act immediately; this method offers to the user the possibility to impose a resolution time that is the time when uncertainty on a given parameter is resolved and so the time from which the number *n* of branches of the event tree, i.e. the possible system evolutions, to which is associated a probability percentage, decrease to only one. Therefore the alternative scenario started exactly in the year of resolution, before that the hedging strategy is applied [Tosato,2009], [Lenthila,2005].

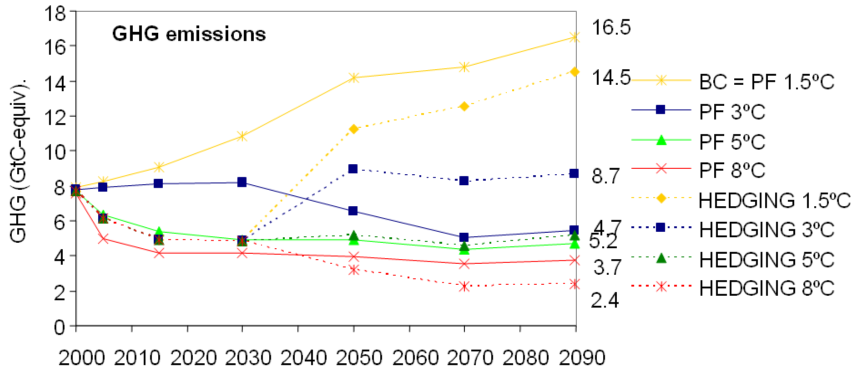


Figure 3.4: The graph represents a step of a study conducted using TIAM (TIMES Integrated Assessment Model) to evaluate the system cost to reach at 2100 a maximum global temperature increase of 2.5°C. Here the amount of GHG emission in respect to each scenario is highlighted. The continuous lines represent four alternative perfect forecast scenarios assuming different C_s (climate sensitivity) value (1.5°, 3°, 5°, 8°). Instead the dots lines represent the hedging strategy and the relative scenarios after the resolution time (2030) on the value of C_s, defined as "*the equilibrium response of global surface temperature to a doubling of equivalent CO2 concentration"* [Labriet, 2008]: a percentage of probability is associated to each branch, that is, in order, 0.25% , 0.45%, 0.15%, 0.15%.

3.1 The matematical formulation of the problem: LP.

Linear programming, sometimes known as linear optimization, is the problem of maximizing or minimizing a linear function, defined *objective function*, over a convex polyhedron specified by linear constraints [Mathworld,2010] that may be equalities or inequalities.[3] It is a special case of the general nonlinear programming problem in which there are no terms of second degree or higher in the objective function or constraints [Beightler,1979].

[3] Unlike Langrange multiplier method where *all* constraints are inequalities.

For example [Ferguson,2009] it has to be found the value of x_1 and x_2 that maximizes the sum $x_1 + x_2$ subject to the following constraints:

$$x_1 \geq 0,\ x_2 \geq 0, \text{ and}$$

$$x_1 + 2x_2 \leq 4$$

$$4x_1 + 2x_2 \leq 12$$

$$- x_1 + x_2 \leq 1$$

In this problem there are two unknowns, and five constraints that are linear in the sense that each involves an inequality in some linear function of the variables.

The first two constraints, $x_1 \geq 0$ and $x_2 \geq 0$, are called *non-negativity constraints* and are often found in linear programming problems. The other constraints are then called the *main constraints*.

Since there are only two variables, the problem can be solved by graphing the set of points in the plane that satisfies all the constraints (called the constraint set) and then finding which point of this set maximizes the value of the objective function. The linear inequalities in this formulation are called *half-lines* and serve to bound the region of the solution.

In this two-dimensional problem, the constraint set is the five sided figure shaded in Figure 3.5, that is the convex set bounded by the hyperplanes (degenerated to lines) $x_1 = 0$, $x_2 = 0$, $x_1 + 2x_2 = 4$, $4x_1 + 2x_2 = 12$ and $-x_1 + x_2 = 1$.

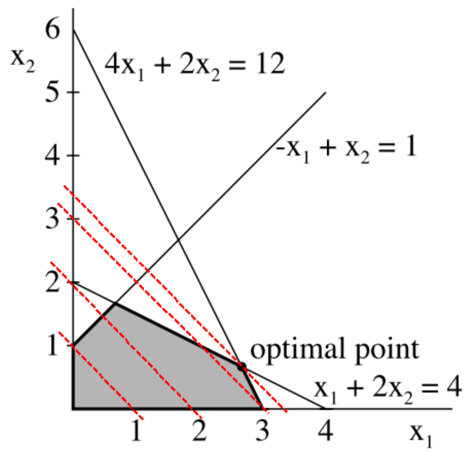


Figure 3.5: graphical representation of the problem.

In a N-dimensional problem, at points along these half-lines where the constraints functions hold as equalities, the constraints form hyperplanes. It has been proved that the optimal solution must lie on at least one of the extreme points that are defined through the intersections of hyperplanes but, as the optimal solution can be achieved at up to N points, alternative optima are the rule rather than the exception.

So, in a general case the extreme value (maximum or minimum) of the objective function can be reached by that member of the family of planes (or lines in a 3-dimensional problem) which touch the convex set on the boundary and this must include at least one extreme point.

Consequently in a two dimensional case the objective hyperplane (line) can touch the convex set at no more than two extreme points (this can occur when the slope of the line is the same of the slope of a constraint: then the optimal solution is achieved at all points on the line joining the two extreme points, producing alternative optimal solutions).

As the objective function is a family of parallel straight lines that move farther away from the origin, and the function $x_1 + x_2$ is constant on lines with slope −1, seeking the line of slope −1 that is farthest from the origin and still touches the constraint set the optimal solution point can be founded: it is the intersection of the lines $x_1 + 2x_2 = 4$ and 4x1 + 2x2 = 12, namely the point (x1,x2) = (8/3, 2/3). Then the optimal value is (8⁄3) + (2⁄3) = 10⁄3.

The earliest and most common algorithm in use to solve such an optimization problem is called the *simplex method*. The idea is to start at some “corner” of the feasible region and then we repeatedly do the following step: look at all neighboring corners of our current position and go to the best one (the one for which the objective function is greatest) if it is better than our current position. Stop when we get to a corner where no neighbor has a higher objective value than we currently have.

The key fact here is that since the objective is linear, the optimal solution will be at a corner (or maybe multiple corners). Furthermore, there are no local maxima: if you’re not optimal, then some neighbor of you must have a strictly larger objective value than you have. That’s because the feasible region is convex. So, the Simplex method is guaranteed to halt at the best solution.

4 The EFDA TIMES model

The EFDA/TIMES model [Han,2009] calculates the set of equipment investments (e.g., power plant, transport, lighting, etc.), and energy-supply operating and trade decisions which maximize total economic surplus (equivalent to minimizing cost) over a given time period. Any environmental constraints are simultaneously taken into account. The world is subdivided into 15 regions within each of which the following four categories of input data are required:

1. the demand scenario
2. the supply scenario
3. the technological scenario
4. the policy scenario

The demand scenario is represented in TIMES by a set of demand drivers and elasticities. The drivers are generated by the GEM-E3 general equilibrium model, and depend on data from exogenous sources deriving from the UN and IPCC. The context for the demand drivers is a situation with the following main characteristics: population growth is moderate over the present century, with a marked slowdown after 2050. This corresponds to the assumptions of the IPCC B2 storyline. GDP growth (as calculated by the GEM-E3 model) is strong, especially in less developed countries. There is a strong convergence in the developments of developed and less developed countries by the end of the century. This GDP growth structure is compatible with a continued globalization of the world economy, and with strong technical progress. Biomass availability is large, and nuclear capacity is allowed to grow significantly during this period. Given these drivers, the base case energy demands over the century are projected by TIMES on the basis of elasticities to those drivers. In addition to driver elasticities, the model also incorporates price elasticities which enable demand projections to take evolving energy prices into account, allowing exploration of scenarios which deviate from the above assumptions. The derivation of these elasticities has involved a degree of expert judgement. The supply and technology scenarios are represented by a database of costs and other technical parameters relating to energy resources and a rich set of technologies, also defined in the database. This database has been developed within the SERF programme. Policy scenarios can involve constraints on plant capacity, fuel taxes, emission constraints, emission taxes, emissions permit trading, etc. A wide range of options for the implementation of operational constraints, along with the detailed specifications with which the technologies in TIMES are represented, provides considerable flexibility for the simulation of such policies.

The results of the fusion power plant model development by the European Power Plant Conceptual Study (PPCS) has been used in the framework of Socio Economic Research in Fusion in order to carry out scenarios analyses about the future worldwide energetic system with the TIMES model generator.

Two kind of fusion power plants are taken into account: the *basic* and the *advanced*. The last becomes available later than the *basic* but with reduced costs and increased efficiency, which are - in the ETM - the only distinctive parameters.

The basic one is modelled around PPCS-C and is assumed to be available in 2050 (at a cost characteristic of 10^{th} of a kind plant), with a cost reduction resulting from technological maturity (characteristic of 100th of a kind plant) occurring in 2060. The advanced plant, broadly equivalent to PPCS-D or ARIES-AT, is instead assumed to be available in 2070 (at 10th of a kind cost), with a cost reduction due to technological maturity (or 100th of a kind) in 2080 [Han,2009].

The results of the scenarios dated 2010 [Mühlich,2010] show that energy production by fusion power plant appears only when environmental constraints are fixed: retaining *advanced* fusion power plant and a 650 ppmv boundary on GHG emissions (see Figure 4.1), the coal contribution completely disappears in 2060; on the other hand the amount of electricity by fission increases leading to a high uranium resource consumption that accordingly favours fusion penetration: it in fact becomes one of the cheapest solutions to produce energy.

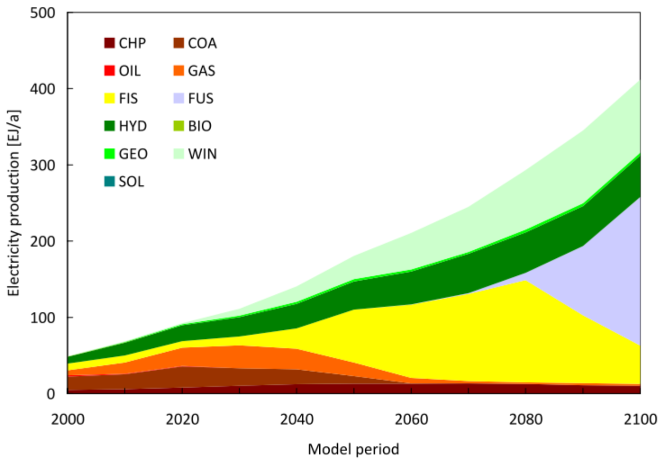


Figure 4.1: Global electricity generation mix in the CO2 650PPM scenario; run including advanced fusion [Mühlich,2010].

On the other hand, when only the *basic* fusion power plant option is included the results change slightly in share and technology kind: in 2100 electricity production by fusion is lower, higher by fission and, in order to achieve the carbon emissions reduction, CCS grows significantly near the end of the century. Making the GHG constraints tighten (550 ppmv) the electricity production trend of each technology does not deeply change compared to previous analyses.

It is therefore clear that coal fired production will be going to disappeared due to environmental constraints; consequently, it is likely that electricity production by fission will firstly rise in a short time and then will decline because of the fast consumption of uranium resources and the present neglect of breeder reactor. As a consequence, fusion production grows and takes over the role of fission in order to satisfy the electricity demand: its penetration decreases when constraints are relaxed or advanced fusion option is removed from the available fusion technologies.

It becomes apparent the importance of both representing the nuclear power sector in a more detailed manner and the inclusion of a nuclear fuel cycle in the EFDA TIMES model. The results of this work, carried out in cooperation with IPP research centre and included in the activity “Further improving of advanced nuclear fission technologies in EFDA TIMES” of the 2011 SERF (Socio Economic Research on Fusion) work program, are described in section 5.8.

Previous scenario results highlight that nuclear technologies (both fission and fusion) have the most important role in producing electricity in future energy scenarios either with emission boundaries or not. They are both base load power plants as coal ones but, compared to fossil fuelled, they produce higher amount of energy by using smaller quantity of "fuel". Then, the new fission power plant generation (Gen. III +) is characterized by an inherent safety, for limiting the consequences of a severe accident; fusion power plants are even more safety compared to fission ones since in case of accident no radioactive release would occur. Moreover, they are both zero-emission technologies since no carbon dioxide is produced during operation. Finally, no radioactive waste material is produced in a fusion power plants but only some reactor component activated during the power plant operation have to be handled; on the other hand, with regard to fission power plants, the production of highly radioactive spent fuel, together with the safety in case of accident, is the main debated aspects when talking about the sustainability of fission. At present the spent fuel as well as the radioactive waste coming from fuel reprocessing or from fission power plants (activated material) is placed in temporary storages: this is a forward-looking solution that takes into account a possible use of current radioactive waste in future when new technologies will have been developed. Another solution is the definitively underground storage: the first storage of this kind is currently being built in Finland.

In the next two paragraphs a brief description of fission and fusion power plants will be presented.

4.1 Fission power plants

In this section, two kind of fission power plants will be presented: the pressurized water reactor (PWR) and fast reactors (FR) that rely on two different strategies for achieving fission reaction ([WNA,2010d], [Areva,2009],[WNA,2011a], [WNA,2011c]) .The first is currently the most used technology: 265 of the 439 nuclear power plants in commercial operation are in fact PWRs. On the other hand, at present no fast reactors are currently part of the fission power plant fleet (even about 20 have already been operating, some since the 1950s, and some supplying electricity commercially). However several countries have research and development programs for improved Fast Neutron Reactors, and the IAEA's INPRO program involving 22 countries has fast neutron reactors as a major emphasis, in connection with closed fuel cycle. For instance one scenario in France is for half of the present nuclear capacity to be replaced by fast neutron reactors by 2050 (the first half being replaced by 3rd-generation EPR units). This is because of technology that is a step beyond conventional power reactors; moreover they allows to burn actinides which are otherwise the long-lived component of high-level nuclear wastes and offer of vastly more efficient use of uranium resources.

Figure 4.2 to which the following description refers, depicts the simplified scheme of an EPR (European Pressurized reactor): while the operating principle is the same of a standard PWR, it differs from it because of the higher level of safety (see section 6.2.1).

Uranium is the basic fuel of a fission power plant. After being mined, it is crushed and ground to a fine slurry which is leached in sulfuric acid to allow the separation of uranium from the waste rock. It is then recovered from solution and precipitated as uranium oxide (U_3O_8) concentrate, sometimes known as "jellowcake", that is the uranium product which is sold. At his phase, has the same elemental composition as when it was mined (0.7% ^{235}U and over 99.2% ^{238}U) but, in order to be used in a PWR, the proportion of the fissile isotope (^{235}U) has to be increased to commonly 3.5 - 5.0% (by enrichment process): this elements share is necessary to make the fission reaction chain self-sustainable: Because uranium needs to be in the form of a gas before it can be enriched, the U_3O_8 is converted into the gas uranium hexafluoride (UF_6) at conversion plant. Enriched UF_6 is then transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2) powder and pressed into small pellets. These pellets are inserted into thin tubes, usually of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies for use in the core of the nuclear reactor. These steps, necessary to make uranium usable in a fission power plant, is known as the "front end" of the nuclear fuel cycle.

The reactor core, containing the fuel material, is the place where the fission reaction takes place, releasing energy.

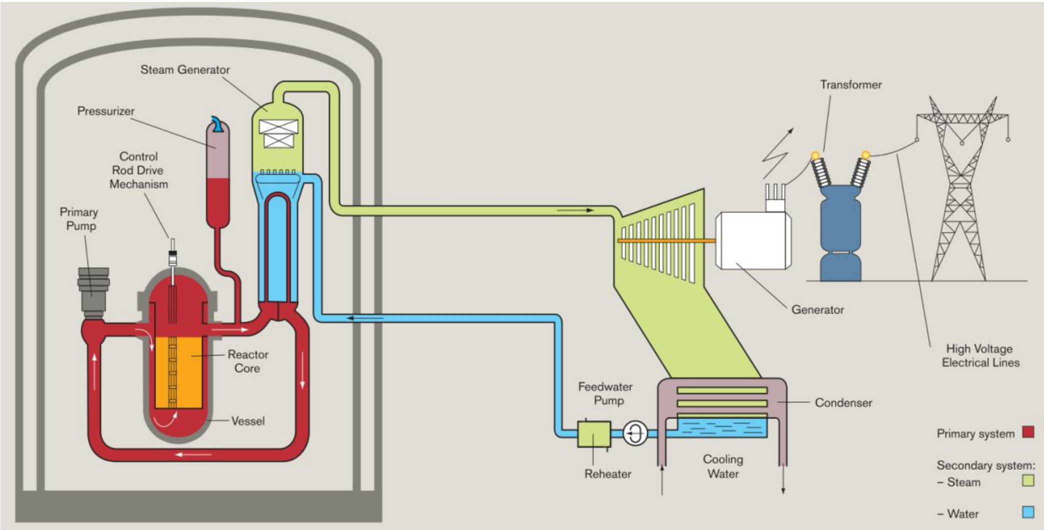


Figure 4.2: Simplified scheme of a PWR: the use of two separated system for heating exchange is highlighted. [Areva,2009]

The fission reaction takes place when a neutron, passing near to a heavy nucleus, for example ^{235}U is captured: since the new nucleus, ^{236}U, is relative unstable, it is likely to break into two fragments of around half the mass: ^{235}U is therefore called *fissile*. While the number of nucleons (protons + neutrons) is conserved during fission reaction, a small loss in atomic mass occurs: it is equivalent to the energy released, according to the Einstein law. Fission produces a great amount of energy compared to fossil fuel burning: $8.21*10^{10}$ J/g, $2.8*10^{6}$ times more than burning 1g of coal.

Creation of the fission fragments is followed almost instantaneously by emission of a number of neutrons (typically 2 or 3, average 2.5), which enable the chain reaction to be sustained. Since the probability of ^{235}U fission increase the more low-energy are neutrons, and therefore the more slowly they move, a device slowing but not absorbing them is necessary to sustain the reaction chain. Ordinary water is a good compromise: besides slowing down neutrons, it is used to remove the heat formed inside the reactor core by the nuclear fission process.

The reactor internal structures support the fuel assemblies, channel the coolant and guide the control rods that control the fission reaction: these are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it if needed.

The heat produced inside the reactor core is transferred to the turbine through the steam generators. From the reactor core coolant circuit (primary circuit) to the steam circuit used to feed the turbine (secondary circuit). Only heat is transferred and there is no water exchange preventing from radioactive release.

The primary water is pumped through the reactor core and the primary side of the steam generators by electric-powered coolant pumps. The reactor operating pressure and temperature are such that the cooling water does not evaporate and remains in the liquid state, which intensifies its cooling efficiency. A pressurizer controls the pressure of primary system; the feedwater entering the secondary side of the steam generators absorbs the heat transferred from the primary side and boils to produce saturated steam. The steam is dried in the steam generators then routed to the turbine to drive it. The steam is then condensed and returns as feedwater to the steam generators. The turbine drives the electrical generator to produce electricity for delivery to the grid.

The structure around the reactor core is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any malfunction inside. It is typically a metre-thick concrete and steel structure.

Used fuel assemblies taken from the reactor core are highly radioactive and give off a lot of heat. They are therefore stored in special ponds which are usually located at the reactor site, to allow both their heat and radioactivity to decrease. The water in the ponds serves the dual purpose of acting as a barrier against radiation and dispersing the heat from the spent fuel.

Used fuel can be stored safely in these ponds for long periods. It can also be dry stored in engineered facilities, cooled by air. However, both kinds of storage are intended only as an interim step before the used fuel is either reprocessed or sent to final disposal. The longer it is stored, the easier it is to handle, due to decay of radioactivity. There are two alternatives for used fuel (the fuel cycle back end):

- *reprocessing to recover the usable portion of it* : reprocessing separates uranium (used fuel still contains approximately 96% of its original uranium, of which the fissionable U-235 content has been reduced to less than 1%) and plutonium (produced by ^{238}U that decays after absorbing one neutron – for this reason is called *fertile*) from waste products by chopping up the fuel rods and dissolving them in acid to separate the various materials. Recovered uranium can be returned to the conversion plant for conversion to uranium hexafluoride and subsequent re-enrichment. The reactor-grade plutonium can be blended with enriched uranium to produce a mixed oxide (MOX) fuel, in a fuel fabrication plant. The remaining high-level radioactive wastes can be stored in liquid form and subsequently solidified through vetrification and then stored in the same way of not reprocessed fuel.

- *long-term storage and final disposal without reprocessing*: used fuel rods are encapsulated in corrosion-resistant metals such as copper or stainless steel. All national policies intend either kind of canisters to be buried in stable rock structures deep underground. Many geological formations such as granite, volcanic tuff, salt or shale are suitable.

Fast reactor relies on the process of turning ^{238}U in ^{239}Pu and ^{241}Pu that then undergo fission in the same way as ^{235}U to produce heat. In a fast reactor this process is optimised so that they can utilise uranium about 60 times more efficiently than a normal reactor.

Two kind of fast reactors can be identified according to the value of the “burn ratio” or “breeding ratio” i.e. the ratio of final to initial fissile content. They are called “breeders” if it is more than 1; on the other hand, if they consume more fissile material (^{235}U, Pu and minor actinides) than they produce (fissile Pu) the ratio is less than 1, hence they are named “burners”.

The fast reactor has no moderator and relies on fast neutrons alone to cause fission, which for uranium is less efficient than using slow neutrons. Hence a fast reactor usually uses plutonium as its basic fuel, since it fissions sufficiently with fast neutrons to keep going. At the same time the number of neutrons produced per plutonium-239 fission is 25% more than from uranium, and this means that there are enough (after losses) not only to maintain the chain reaction but also continually to convert ^{238}U into more ^{239}Pu. Furthermore, the fast neutrons are more efficient than slow ones in doing this breeding, due to more neutrons being released per fission. These are the main reasons for avoiding the use of a moderator: the coolant is therefore a liquid metal (normally sodium) to avoid any neutron moderation and provide a very efficient heat transfer medium.

The conventional fast reactors built so far are generally fast breeder reactors (FBRs) implying a net increase in ^{239}Pu from breeding, due to a conversion ratio above 1.0. These have a “fertile blanket” of depleted uranium (^{238}U) around the core, and this is where much of the ^{239}Pu is produced. Neutron activity is very low in the blanket, so the plutonium produced there remains almost pure ^{239}Pu - largely not burned or changed to ^{240}Pu.

However, apart from India, there are apparently no plans to build any more fast reactors with this design; fast reactor concepts being developed for the Generation IV program will simply have a core so that the plutonium production and consumption both occur there. Russia’s BREST is the most advanced design. Conceptually, refuelling means simply adding a little natural or depleted uranium – about one or two percent of the total required for a comparable light water reactor. Due to the high radiation levels in the core, using simply a core and noblanket gives rise to some new challenges in how the fuel is fabricated and managed.

Reprocessing used fuel, and especially the blanket assemblies, is fundamental to the FBR fuel cycle: typically the recovered plutonium from aqueous reprocessing is incorporated into the core as MOX fuel and any surplus deployed for further FNRs. With the transition from core and blanket designs to integrated core designs, it is likely that used fuel will be reprocessed using electrometallurgical processes (so-called pyroprocessing) and plutonium will not be separated but will remain with some highly radioactive isotopes. Pyroprocessing is also said to have several advantages for fast reactors which greatly simplify waste management.

At present they are expensive to build and operate, including the reprocessing; they are only justified economically if uranium prices will go over 1990s low levels. Moreover the economics of FNRs still depends on the value of the plutonium fuel which is bred and used, relative to the cost of fresh uranium: however the international concern over the disposal of ex-military plutonium has lead to proposals to use fast reactors (as “burners”) for this purpose.

4.2 *Fusion power plants*

In a fusion reaction two light atomic nuclei fuse together to form heavier ones releasing a great amount of energy: this kind of energy powers the Sun and stars. Although many different fusion reactions are possible, the fusion reaction that is easiest to accomplish on earth is that between deuterium and tritium, two isotopes of hydrogen: its fusion produces $3.36 \cdot 10^{11}$ J/g, 10^{7} times more than that produced by burning 1 g of coal.

A fusion reaction does not happen easily because the nuclei of atoms (D and T) have both a positive electric charge, and equal charges repel. But if two nuclei manage to get close enough together in spite of the repelling force, another force manifests itself: the nuclear force that is extremely powerful, but only acts on very small distances. To bring the two nuclei close enough together, they need to collide with a very high speed, which means that the temperature of the gas must be really high: the gas has to be in a plasma state i.e. its temperature has to be so high so that electrons are separated from the atoms which they belong to, forming a gas of charged particles, in which the electrons and nuclei move independently.

To produce enough fusion reactions, the deuterium-tritium mixture has to be brought to a temperature ten times higher than the temperature in the centre of the Sun. In order to maintain the plasma hot, it must be kept away from walls of the plasma vessel. To accomplish this isolation from the walls, a strong magnetic field is applied to the plasma: in a magnetic field the charged plasma particles are forced to spiral along the magnetic field lines, thus enabling the plasma to be heated to temperatures in excess of 100 million Kelvin. The most promising magnetic confinement systems are toroidal (from torus: ring-shaped) and, of these, the most advanced is the Tokamak.

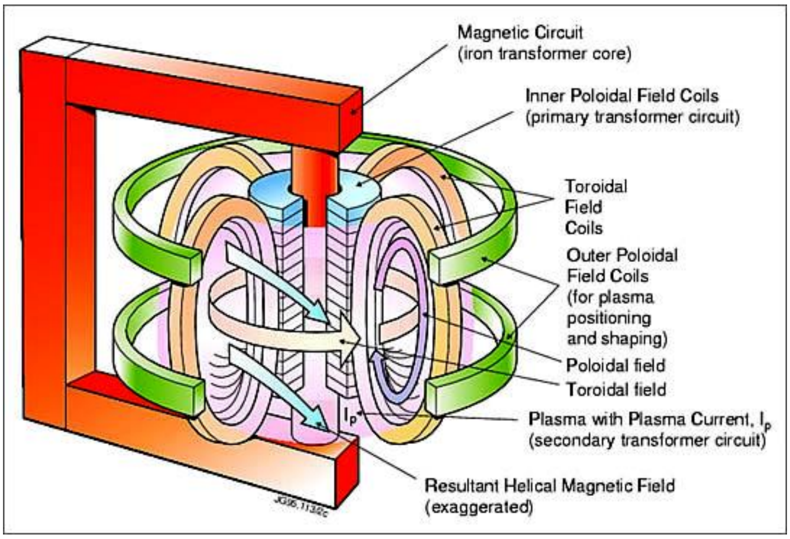


Figure 4.3: The principle magnetic circuits of JET's Tokamak

In a Tokamak the basic components of the magnetic confinement system (see Figure 4.3) are the toroidal field, which produces a field around the torus providing the primary mechanism of confinement of the plasma particles and poloidal field which produces a field around the plasma cross section pinching the plasma away from the walls and maintaining the plasma's shape and stability. The first is produced by the toroidal field coil system, the second by the coils positioned around the perimeter of the vessel (poloidal field coils) and by the current driven in the plasma, one of the plasma heating mechanisms. 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.

Since the heat transferred through high-intensity current, known as ohmic heating, is limited to a defined level, in order to obtain still higher temperatures and reach the threshold where fusion can occur, heating methods must be applied from outside of the tokamak. Two families of external heating methods: neutral beam injection and high-frequency electromagnetic waves. They will complement ohmic heating to bring the ITER plasma to temperature.

Neutral beam injection consists in shooting high energy particles into the plasma. Outside of the tokamak, charged Deuterium particles are accelerated to the required energy level. These accelerated ions then pass through an "ion beam neutralizer" where their electrical charge is removed. The high velocity neutral particles can then be injected into the heart of the plasma where, by way of rapid collision, they transfer their energy to the plasma particles. On the other hand, in the same way that microwaves transfer heat to food in a microwave oven, the energy carried by high-frequency waves introduced into the plasma is transferred to the charged particles, increasing the velocity of their chaotic motion, and at the same time their temperature.

Three main parameters need to be simultaneously achieved for sustained fusion to occur in a plasma: plasma temperature, density and confinement time. The product of these is called the fusion (or triple) product and, for D-T fusion to occur, this product has to exceed a certain quantity derived from the so-called Lawson Criterion:

- *temperature*: fusion reactions occur at a sufficient rate only at very high temperatures when the positively charged plasma ions can overcome their natural repulsive forces. Typically over 100 million Kelvin is needed for the Deuterium-Tritium reaction to occur.

- *density*: The number of fusion reactions per unit volume is roughly proportional to the square of the density. Therefore the density of fuel ions must be sufficiently large for fusion reactions to take place at the required rate. The fusion power generated is therefore reduced in case the fuel is diluted by impurity atoms or by the accumulation of Helium ions from the fusion reaction itself. As fuel ions are burnt in the fusion process they must be replaced by new fuel and the Helium products (the “ash”) must be removed. The device used for ash removing is called divertor and it is placed on the vacuum vessel basis. A plasma density of $1 \div 2 * 10^{20}$ particles m^{-3} (approx. 1/1000 gram m^{-3}, i.e. one millionth of the density of air) is necessary to sustain fusion reactions.

- *energy confinement time*: it is a measure of how long the energy in the plasma is retained before being lost. It is officially defined as the ratio of the thermal energy contained in the plasma and the power input required to maintain these conditions. In order to sustain fusion reaction it needs to be 4-6 second at least.

In the fifty years that research on nuclear fusion has been carried out, enormous scientific and technological progress has been made: the triple product has seen an increase of a factor of 10.000 in the last thirty years but another factor of 6 is needed to arrive at the level required for a power plant.

In a fusion power plant neutrons generated from the D-T fusion reaction will be absorbed in a blanket containing lithium which surrounds the core. The lithium is then transformed into tritium which is used to fuel the reactor. The blanket must be thick enough to slow down the neutrons. The kinetic energy of the neutrons is absorbed by the blanket, causing it to heat up. The heat energy is collected by the coolant flowing through the blanket: in a fusion power plant this energy will be used to generate electricity by conventional methods, as it is in fission power plants.

Fusion is a particularly attractive energy source as it uses fuels that are abundant and available around the globe: deuterium is a hydrogen isotope, which can be readily extracted from water (there is around 33g of deuterium in every cubic metre of water), and lithium is an abundant light metal. Moreover, even the plasma in a fusion power plant will have a volume of 1000 cubic meters or more, the total amount of fusion fuel in the vessel is very small and, if the fuel supply is closed, the reaction stops without problems within seconds. This because fusion, unlike fission, is not a chain reaction and can therefore not run out of hand.

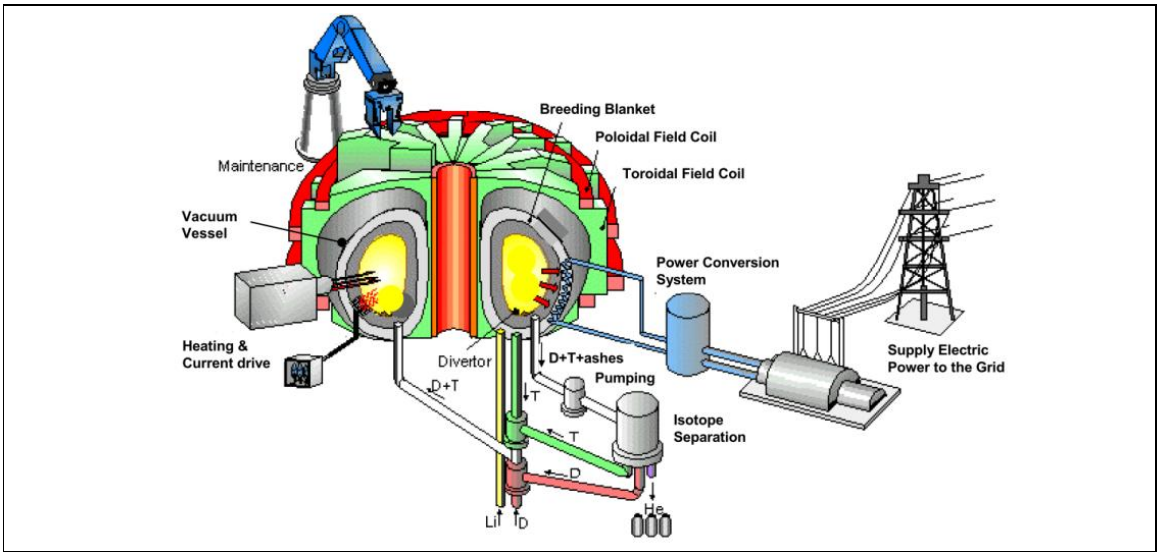


Figure 4.4: Schematic diagram of a tokamak fusion power station.

Then, even tritium is a radioactive substance, it is produced inside the plant in a closed circuit and the total amount of tritium present can be limited to about 1 kg. Moreover outside the plant, no transport of tritium is needed, except for a new fusion power plant, which needs to be ‘primed’ with tritium the first time it is used; after that it can produce its own supply. Only the structural material of the vessel are activated by neutrons and therefore radioactive: if a proper materials are used, the half life of such waste can be limited to about 10 years, meaning that after a period of 100 years the radioactivity drops to a value of a 10.000th of its initial value and can be largely recycled.

At present the Joint European Torus JET, based in Culham, Great Britain, is the central research facility of the European Fusion Programme. JET has produced significant fusion power in deterium/tritium plasmas (up to 16 MW) in the short pulses characteristic of existing experimental devices. ‘Break-even’ conditions, where the fusion output power equals the external input power required to heat the plasma, were almost reached.

Moreover, JET has demonstrated that fusion devices can be operated safely with tritium fuel and that activated structures can be maintained and modified using remote handling techniques.

Thanks to the success of JET and other experiments, the world fusion community is now ready to take the “Next Step” of constructing a larger device, ITER, which will produce plasmas under reactor conditions of high power gain and provide a reliable basis for proceeding to a demonstration reactor, capable of producing electricity.

ITER has twice the size of JET in its linear dimensions which means it has a plasma volume that is almost ten times larger. ITER is a global project: the current partners in the ITER project are Europe, Japan, the Russian Federation, China, India, Korea and the USA. It will allow the study of plasmas in conditions similar to those expected in a electricity generating fusion power plant. It is designed to generate 500 MW of fusion power for extended periods of time, ten times more then the energy input needed to keep the plasma at the right temperature and therefore will be the first fusion experiment to produce net power. ITER will also test a number of key technologies for fusion including the heating, control, diagnostic and remote maintenance that are expected to be needed for a real fusion power station. (The main source are: [Westra,2010] and [ITER website])

5 FRESCO code

The FRESCO (Fusion Reactor Simplified Cost) code, written in C++ language, allows the user to study a D-T fusion power plant of Tokamak type from a technical and economical point of view: it calculates the physical dimensions of the power plants, the auxiliary energy need, the annual electricity production, the related capital cost and, finally, the cost of electricity.

Compared to nowadays available economic codes which model only the steady-state operational mode, FRESCO allows to analyse the pulsed mode too: thanks to such a peculiarity, the modeler can compare performances and costs of a future power plant assuming different operative modes.

Whatever possible, the data about geometric parameters, construction materials and their related cost evaluation is extrapolated starting from the ITER experiment corresponding values.

Data about items not included in ITER, such as the tritium production inside the breeding blanket and the thermal to electricity conversion plant, are inferred from the technical description of the two power plant models of the European Fusion Power Plant Conceptual Study (PPCS), namely, Model B and Model AB, that are the two European breeding blanket proposals for testing in ITER.

The code is made of five main parts: the first is the power plant input data collection; then, an evaluation of the main geometrical dimension both of the vessel and the plasma is carried out. In order to evaluate the main electromagnetic parameters of plasma, a physical analysis follows. Then the two operational modes present in the model (pulsed and steady state) are presented and the amount f auxiliary heating, when needed, is evaluated. In the costing section the capital cost, the operational and maintenance costs, deriving from neither a cost evaluation of each part of the power plant or from the power balance, are calculated. Finally the levelised cost of electricity (LCOE) can be derived: it is one of the most important information about a power plant since it allows for comparing different technologies over their economical life. Moreover, in this contest a sensitivity analysis of the cost of electricity to the operational mode can be performed and the reactor's main technical parameters influencing the cost of electricity can be identified and more deeply studied and further improved.

In the next paragraphs a detailed description of each code section, equipped with equations and costs data assumptions, will be carried out. All physical and technical assumptions used to built the simplified fusion power plant model will be made precised as well.

5.1 Tokamak geometrical parameters

Fusion power (P_F) can be expressed as a function of the square of ion density, *n*®, of reactivity, $<\sigma v>$, and of the energy released by a single fusion, ξ (eq. 5.1.1); starting from this relation, the code derives the plasma radius (*a*) then used to evaluate the plasma volume and the vessel size.

$$P_F = \int_V \frac{n(r)^2}{4} \langle\sigma v\rangle \, \xi \, dV \qquad 5.1.1$$

In order to solve the equation, the following assumptions are set:

1) flat ion density profile, according to eq. 5.1.2:

$$n(r) = \begin{cases} N \; if \; 0 < r < 0.8a \\ 0 \; if \; 0.8a < r < a \end{cases} \qquad 5.1.2$$

2) reactivity <σv> is assumed to be a function of the plasma temperature according to eq.5.1.3:

$$\langle \sigma v \rangle \propto \alpha \, T^2(r) \qquad 5.1.3$$

where α is equal to 1.53*10^{-24} keV in the ignition temperatures range and plasma temperature has a triangular profile (eq. 5.1.4):

$$T(r) = -\frac{T_{max}}{a} r + T_{max} \qquad 5.1.4$$

with T_{max} calculated by the average temperature and peaking factor (input data) product.

3) a plasma configuration partially elongated (*k* is defined as the elongation factor).

A fair approximation of plasma volume (*V*), derived with respect to *r*, is given by equation 5.1.5:

$$dV = (2\pi R)\,(2\pi rk)\,dr \qquad 5.1.5$$

where *R* is the plasma major radius.

By replacing the equations described above in 5.1.1, the fusion power can be rewritten as (eq. 5.1.6):

$$P_f = (k\pi^2 Aa)\alpha\xi \int_0^{0.8a} N^2\, T^2(r)\, rdr \qquad 5.1.6$$

where the interval of integration is reduced because of the null value of ion density in the range from *0.8a* and *a*.

The plasma minor radius can be now easily derived from the previous equation (eq. 5.1.7):

$$a = \sqrt[3]{\frac{P_F}{0.08\, N^2 \xi\alpha\, (k\pi^2 A)\, \left(T_{av} p_f\right)^2}} \qquad 5.1.7$$

The major radius *R* (*R* = *Aa*) as well as the lateral plasma surface can be now calculated from the plasma volume and used to evaluate the average wall loading (*W*), defined as the ratio between fusion power and plasma lateral surface.

The definition of the machine radial profile of its main technical parameters is the second step of the FRESCO code. Starting from the plasma surface, the elements surrounding the plasma are: first wall (FW), blanket (BLK) (made of a breeder layer and manifolds), high temperature (HTS) and low temperature (LTS) shields, vacuum vessel and toroidal field coils (TFC); each of them are characterized by different thickness depending on which part is considered (inboard or outboard).

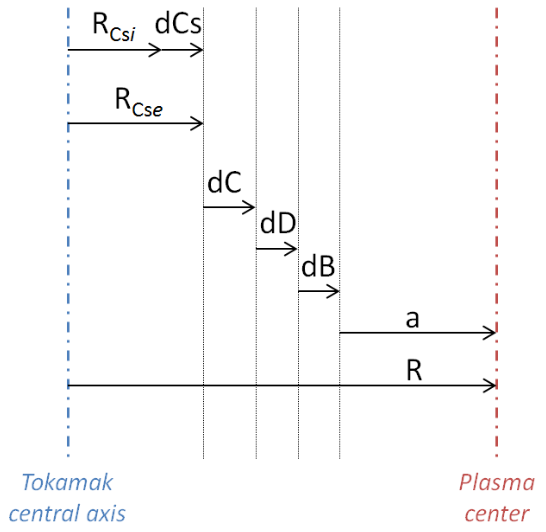
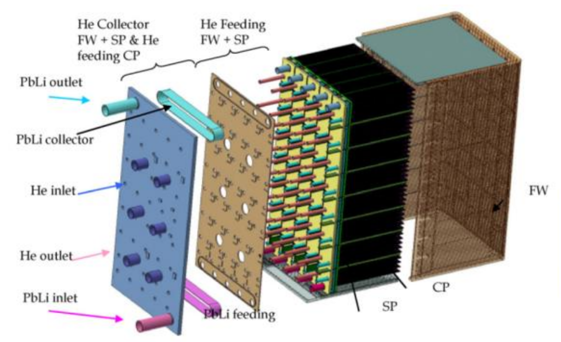


Figure 5.1: Radial inboard *unscaled* extension of a tokamak as modelled in FRESCO. It must be underlined that dB is obtained by the sum of shields, manifolds and first wall thickness).

In Figure 5.1, where an *unscaled* scheme of the radial inboard extension of a tokamak is pointed out, the symbols of the radial components are given, namely: blanket including first wall, shields and manifold (dB), vacuum vessel (dD), toroidal field coils (dC) and central solenoid (dCs, difference between the central solenoid external radius, R_{Cse}, and the internal one, R_{Csi}).

In FRESCO, two types of breeding blanket models are considered, according to the PPCS study (Figure 5.2). The first (model AB in PPCS [Puma,2005]) is made of the eutectic PbLi as breeder and neutron multiplier and low activation ferritic/martensitic steel (EUROFER) as structural material; the second is made of solid ceramic lithium ($LiSiO_4$) as breeder, beryllium as multiplier, and zirconium hydride as shielding material (model B of PPCS [Hermsmeyer,2003]). The blanket thickness (dB) is assumed to be a linear function of the blanket energy multiplication factor (*M*): it is calculated starting from model AB and B blanket layers thickness (see Table 5.1 and Table 5.2) and respective multiplication factor (1.18 for model AB and 1.3 for model B).

HCPB BLANKET – model B	*HCLL BLANKET – models A, AB, C,*



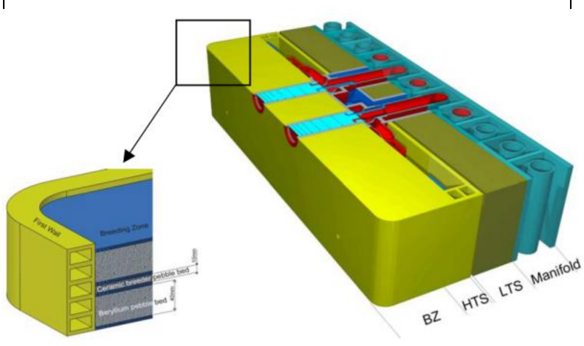


Figure 5.2: Blanket options [PPCS,2005].

The vacuum vessel thickness, dD, is instead assumed to be the same as model AB and B respectively; the central solenoid thickness dC_s is set 0.8 m in all cases, according to ITER design.

Table 5.1: Radial building of model AB of PPCS study [Puma,2005].

Layer	Component	Outboard thikness [m]	Inboard thikness [m]	Material composition
1	FW layer	0.002	0.002	W
2	FW	0.025	0.025	EUROFER(70%) + He (30% vol)
3	Blanket breeder	0.775	0.425	LiPb (80%) + EUROFER (10%) + He (10%)
4	BLK manifold	0.254	0.254	EUROFER + He (50/50% vol)
5	HT shield	0.4	0.3	EUROFER + He (50/50% vol)
6	LT shield	0.3	0.2	WC + EUROFER +H2O (65/10/25 % vol)
7	Vacuum Vessel (VV)	1.02	0.47	316SS + H2O + boron (61.4/37.0/1.6 % vol)
8	TF coils	2.7	1.5	ITER coil mixture

Table 5.2: Radial building of model B of PPCS study [Hermsmeyer,2003].

Layer	Component	Outboard thikness [m]	Inboard thikness [m]	Material composition
1	FW layer	0.004	0.004	EUROFER
2	FW	0.014	0.014	EUROFER (73%) + He (27% vol)
3	Blanket breeder	0.465	0.365	$LiSiO_4$ (15.4%) + Be (69.2%) + EUROFER (9.8%) + He (5.5%)
4	BLK back wall	0.02	0.02	EUROFER
5	HT shield	0.27	0.17	EUROFER (60%) + He (40% vol)
6	*Gap*	*0.02*	*0.02*	*Void*
7	LT shield	0.25	0.22	90%(60% EUROFER + 40% ZrH) + He(10%)
8	Manifolds	0.25	0.15	EUROFER (15%)

Finally, the inboard toroidal field coils thickness is evaluated thanks to considerations about the maximum allowable current density (j_{cond}) in the TFC inner leg. It is driven by the maximum magnetic field on the conductor and by considerations about the safety discharge of the magnet in case of quench: past studies have shown that for larger tokamak TF inner leg requires thicker mechanical structure (TF coil case in Figure 5.3) in order to resist high Lorentz forces [Puma,2009].

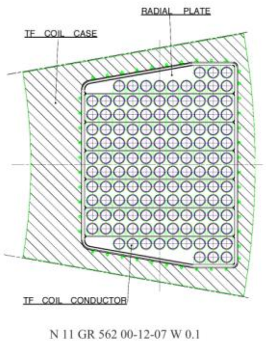
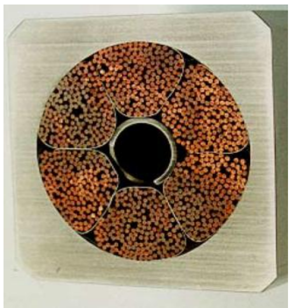
<table>
<tr><th>Cross Section of TF Coil at Inboard Leg [EDA,2002]</th><th>ITER type conductor [Duchateau,2007]</th></tr>
<tr><td>
</td><td></td></tr>
</table>

Figure 5.3: The TF coils consist of a winding pack contained in a thick steelcase (image on the left) The winding pack is a bonded structure of radial plates (which contain the conductor) with an outer ground insulation. The winding pack design is based on the use of Nb3Sn-type superconductor [Mitchell,2009] (image on the right) supported by radial plates. This design has advantages in terms of the conductor insulation, long-term quality, and reliability. *[EDA,2002]*

In order to evaluate the coils thickness, the Ampère-turns have to be firstly calculated; they are obtained by the relation derived from the Ampère's circuital law (eq. 5.1.8):

$$I_{TOR} = \frac{2\pi R\, B_{t\,0}}{\mu_0} \qquad 5.1.8$$

where the on-axis toroidal magnetic field value (Bt_0) is derived from the maximum allowable magnetic field value (Bt_m), taken as an input datum, is calculated as (eq. 5.1.9):

$$Bt_0 = Bt_m \cdot \frac{R - a - dB - dD}{R} \qquad 5.1.9$$

If a upper value of current density over the all coil system (j_{cond}) is fixed, the area of the TFC poloidal section (S_{TC}) can easily calculated according to eq. 5.1.10, where j_{cond} is the TF overall current density and S_{TC} is the inner leg section along the equatorial plane ($S_{TC} = \pi(r_e^2 - r_i^2)$, [Duchateau,2007] with r_i the mean of the inboard coil case and winding pack radii). In FRESCO the assumed value of j_{cond} is 10 A/mm^2, arise from the analysis carried out for DEMO [Duchateau,2008] and close to the ITER value (12.2 A/mm^2 [Puma,2009]).

$$S_{TC} = \frac{I_{TOR}}{j_{cond}} \qquad 5.1.10$$

Once S_{TC} is known, the TFC thickness can be easily derived from geometrical considerations[4].

---

[4] The magnetic toroidal field on axis in Model AB is 5.3 T and the major radius R is 6.2 m. It descends that I_{tor} is 320.26 MA. If a 9 A/mm^2 conductor current density is assumed (that is close to FRESCO assumption), the inner leg poloidal section S_{TC} is 35.58 m^2. Since the external radius ($r_e = R\text{-}a\text{-}dB\text{-}dD$) is 4.71 m (see Table 5.1), the internal radius (r_i) has to be 3.29 m:

$$r_i = \sqrt{r_e^2 - \frac{S_{TC}}{\pi}}$$

This means that the inboard TFC thickness is 1.4 m, quite close to PPCS data (see Table 5.1).

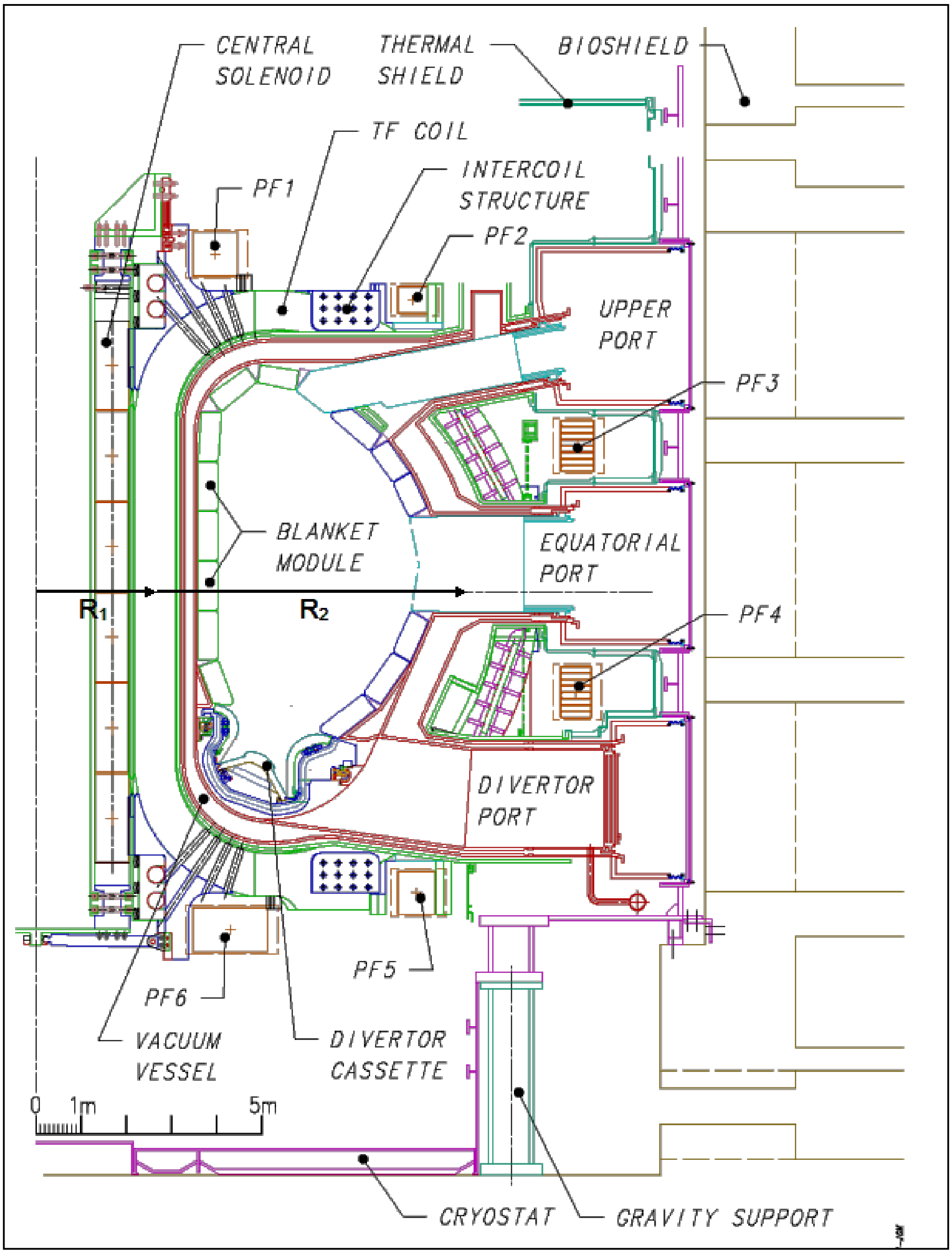


Figure 5.4: ITER tokamak cross section: the image is taken from [FDR,2001] and modified in order to highlight R_1 and R_2.

5.1.1 Toroidal field coil stress analysis

The current density value of TFC is also used to evaluate the mechanical stress to which the coil case is subjected: with reference to eq. 5.1.11 [Raeder,1986], the data needed to calculate it are the maximum value of the toroidal field on conductor, B_{tmax} - that is an input datum - and the distance of the inner leg (R_1) and outer leg (R_2) from the tokamak axis.

$$\langle \sigma_{TC} \rangle = \frac{1}{4} \langle j_{cond} \rangle B_{t_{max}} R_1 \; ln \frac{R_2}{R_1} \qquad 5.1.11$$

where R_1 and R_2 is calculated - see Figure 5.1 and Figure 5.4 - as the sum of (eq. 5.1.12):

$$R_1 = R_{Cse} + \frac{dC}{2} = (R - a - dB - dD) - \frac{dC}{2}$$
$$R_2 = R + a + dB + dD + \frac{dC}{2} \qquad 5.1.12$$

Finally R_{Csi} is calculated (R_{Cse} – *dCs)*: if its value was negative, i.e. the sizing is not feasible, the code makes appear an error message.

5.2 Plasma electromagnetic parameters

In this section the plasma ring is totally defined from a electromagnetic point of view. Such information, i.e. plasma inductance, resistivity and plasma current as well, are mainly needed to determine the auxiliary heating system size (MWe) (§ 0). Besides this, the physical features of the plasma are analysed and, in order to assure a suitable plasma tolerance to instabilities, the plasma beta parameter is checked to be lower than Troyon limit .

The inductance of the plasma ring, L_P, is derived from the sum of the internal (L_i) and external (L_e) inductance. Because of the strict relation with either the current density profile within the plasma and aspect ratio, only a rough estimate of the L_i value can be derived. According to [Bobbio,1980], in case of a plasma whose cross-section is not strongly elongated, the internal inductance can be calculated with a good degree of accuracy through equation 5.2.1:

$$L_i = 2\pi R\ l_i \qquad 5.2.1$$

where l_i is the specific inductance for unit of length; when a plasma is characterized by a large aspect ratio and a uniform current density profiles, l_i is independent on the plasma minor radius and its value is 0.05 *H/m*; on the other hand, for low aspect ratio and more “peaked” current profiles, its value can be much higher: e.g. for A = 3 ÷ 5 and current profile not very peaked, $l_i \approx$ 0.1 μ*H/m* [Bobbio,1980].

The external inductance depends on plasma ring geometric parameters only and is calculated as follow [Bobbio,1980] (eq. 5.2.2):

$$L_e = \mu_0 R\left[\left(1 + \frac{a^2}{8R^2}\right) ln\frac{8R}{a} + \frac{a^2}{24R^2} - 2\right] \qquad 5.2.2$$

An estimate of plasma resistance (R_p) can be given, on the basis of the expected current profile within the plasma, assuming for the plasma resistivity (ρ_p) [Ωm] the Spitzer value (eq. 5.2.3):

$$\rho_P = 6 \cdot 10^{-5} \cdot T^{-\frac{3}{2}} \cdot ln\,\Lambda \qquad 5.2.3$$

where L is the plasma parameter and $ln\Lambda$ is set equal to 15.

Assuming that plasma behaves as an ohmic conductor, the plasma ring resistance is defines as (eq. 5.2.4):

$$R_P = \rho_P \frac{2\pi R}{\pi a^2 \delta} \qquad 5.2.4$$

where the parameter δ, whose value is usually in the range from 0.6 to 0.7, takes into account both the plasma elongation and the ion density profile.

The total plasma current I_{tot} is calculated through equation 5.2.5, derived from Ampère's law; the D-shaped plasma radial section is taken into account through the triangularity factor (Δ).

$$I_{tot} = \frac{2\pi}{\mu_0} \frac{a}{A} \frac{Bt_0}{q(a)} \frac{k^2(1+2\Delta^2)}{2} \qquad 5.2.5$$

where q(a) is the boundary safety factor, defined as "[…] the average number of toroidal revolutions required to complete one poloidal revolution." From "[…] the Kruskal–Shafranov stability criterion [descends that] the ratio of toroidal to poloidal magnetic field must exceed the aspect ratio […]" [Boyd,2003], that is q(a) has to be higher the unity. In FRESCO the boundary safety factor is an input datum.

Finally the beta of the plasma, β, that is the ratio of the plasma pressure to the magnetic pressure, is calculated in order to check the "Troyon limit" fulfilment, related to the plasma high-n instabilities tolerance (eq. 5.2.6):

$$\beta_t = \frac{n k_B T}{\left(Bt_0{}^2/2\,\mu_0\right)} < \beta_N \, \frac{I_P}{a\,Bt_0} \qquad 5.2.6$$

where k_B is the Boltzmann's constant and β_n is the Troyon limit, set equal to 3.5% in the stationary mode [Najmabadi,1996], to 2.8% if the pulsed mode is selected [Najmabadi,1994].

5.3 Central solenoid sizing and electromechanical characterization

The main plasma current is induced by the changing current in the central solenoid which is essentially a large air-core superconducting transformer. It contributes to the inductive flux that drives the plasma, i.e. the CS coils must initiate, ramp-up, and sustain the plasma, during the entire burn, then ramp it down in a controlled manner [Schultz,2005].

The central solenoid sizing is necessary in order to evaluate the amount of inductive current available during the start up phase and, in case, during the burning: if the central solenoid size is enough to avoid the auxiliary heating systems use during the burn up, the power plant operational mode is defined "inductive".

In FRESCO it is assumed that the ratio of the height versus the major radius remains the same as that of ITER[5]; then, in order to evaluate the number of turns, the Ampère turns density (number of turns per meters) is set in all cases as that of ITER[6].

Once the central solenoid height (*h*) , number of turns (N) and internal S_{Csi} and annulus section S_{dCs} (*dCs* is an input data, see section 5.1, page 31), are calculated, the CS inductance and the

---

[5] The ITER central solenoid is made of 6 pancakes each 2.075 m tall leading to a total solenoid height of 12.45 m [Schultz,2005]. ITER major radius is 6.2 m [EDA,2002].

[6] The ITER central solenoid is made of 3288 turns [Schultz,2005], so that the Ampère turns density is 264.1 turns/m.

amount of energy stored can be calculated by the well known electrical relations (eq. 5.3.1 and 5.3.2):

$$L_{CS} = \frac{\mu_0 N^2 (S_{Csi} + 0.5 S_{dCs})}{h} \qquad 5.3.1$$

and

$$E_{CS} = \frac{1}{2} L_{Cs} {I_{Cs}}^2 \qquad 5.3.2$$

where I_{CS} is the current in the central solenoid turns so that the maximum magnetic field it produces is 13 T [Schultz,2005].

5.4 Operation phases

The length of one machine cycle (τ_C) is given by the sum of the burn time (τ_{burn}) and the dwell time (τ_{dwell}). The first, in case of pulsed mode, is an input datum.

With reference to Figure 5.5, the dwell time is calculated as the sum of (eq. 5.4.1):

$$\tau_{DWELL} = \tau_{RC} + \tau_{RU} + \tau_H + \tau_{RD} \qquad 5.4.1$$

where:

- τ_{RC} is the time needed for central solenoid winding recharging;
- τ_{RU} is the ramp-up time of the plasma current. The current ramp-up speed is assumed to be as larger as in the ITER inductive operation scenario (0.15 MA/s) and quite close to the steady-state operation scenario (0.25 MA/s) where a fast current increase, together with an additional heating power, are needed in order to prevent current peaking [Shimada,2004]. In FRESCO such a parameter is actually used to evaluate the dwell time in case of pulsed operation mode (it therefore affects the number of cycle and thermal storage power evaluation only): if this is so, the chosen current speed ramp up is more conservative to that assumed in PULSAR (0.45 MA/s) [Najmabadi,1994].
- τ_H is the time needed for plasma heating, that is the time from the beginning of the flat top to the start of burn. In FRESCO the ratio of the plasma heating time versus the average plasma temperature is assumed to be the same as that of PULSAR (τ_H = 54s [Najmabadi,1994], quite close to that in ITER, 56s [EDA,2002], versus a plasma temperature of 14 keV [Najmabadi,1994]).
- τ_{RD}, whose length is assumed to be equal to τ_{RU}, is the current ramp-down period necessary to avoid disruption onset.

The time needed for central solenoid winding recharging is a function of CS electrical parameter, i.e. current and inductance (§ 0) and the voltage of the electrical feeders, that in FRESCO is assumed to be 1550 V in DC. The length of this phase is calculated as follows (eq. 5.4.2):

$$\tau_{RC} = \frac{L_{Cs} I_{Cs}}{V_{Cs}} \qquad 5.4.2$$

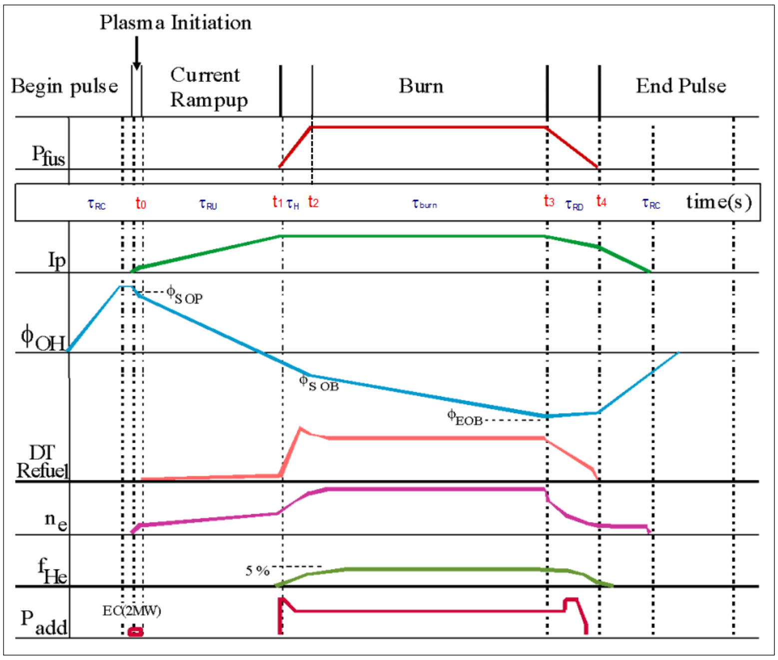


Figure 5.5: Operation phases of ITER inductive mode (figure from [EDA,2002] and modified in order to highlight the operation phases modelled in FRESCO).

5.5 *Auxiliary energy need*

The amount of auxiliary energy need is deduced from a flux balance between the volt-seconds produced by the CS driving a current inside the plasma and the actual magnetic flux necessary to reach and sustain the burning phase.

The flux produced by the central solenoid, φ_{Cs}, can be defined as a part of the "available flux": by inducing a current in the plasma ring, it contributes to heat plasma during the ramp-up phase, then during the heating and, possibly, during the burning one[7].

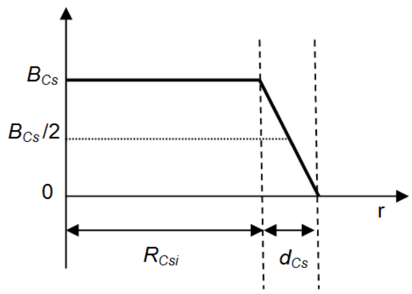


Figure 5.6: Magnetic flux pattern in the central solenoid inner space and in the edge.

Given the CS geometrical parameters (R_{Csi} and R_{Cse}), the maximum allowable magnetic flux inside the solenoid (B_{Cs} = 13 T, § 0) and magnetic field pattern inside the solenoid[8] (Figure 5.6), the volts-second produced by CS, calculated in the middle of its edge thickness, are calculated

[7] In the steady state operation scenario the total plasma current at the current flat top phase is generated non-inductively by additional current drive (NB and RF) and bootstrap current [Shimada,2004].

[8] For the sake of simplicity, BCs is thought to be constant in the inner space while linear decreasing to zero through the solenoid thickness.

as follows (eq. 5.5.1):

$$\varphi_{Cs} = 2\left(B_{Cs}\pi {R_{Cs_i}}^2 + \frac{1}{2}B_{Cs}\pi\left({R_{Cs_e}}^2 - {R_{Cs_i}}^2\right)\right) \quad 5.5.1$$

where the hypothesis of using the complete magnetic field reversal (from $+B_{Cs}$ to $-B_{Cs}$) is used.

Moreover a contribute during the start up[9] phase by a current drive heating system is assumed to be always available: according to ITER scenarios analysis, if it was done during the ramp up phase, an increased burning time would follow thanks to some flux saving [Shimada,2004]. However, in this contest, a more simplified analysis is carried out: no distinction is made between the ramp up phase and heating one for what concerns the auxiliary heating.

In FRESCO code the external heating device contribute is handled as a magnetic flux: during the start up phase, the flux needed by plasma in order to make the plasma current I_{tot} appear ($\varphi_{start\text{-}up}$) can be produced by the simultaneous action of central solenoid (producing φ_{Cs}) and auxiliary heating system (producing φ_{AH}).

The balance between the "available flux" ($\varphi_{available} = \varphi_{Cs}+\varphi_{AH}$) and the $\varphi_{start\text{-}up}$ flux, that can be called "consumed flux", is made clear in equation 5.5.2, integrated between t_0 and t_2 , i.e. the "start up phase":

$$\int_{t_0}^{t_2} M_{Cs,P}\frac{di_{CS}(t)}{dt}dt + \int_{t_0}^{t_2} V_{AH}\,dt = \int_{t_0}^{t_2} L_P\frac{di_{tot}(t)}{dt}dt + \int_{t_0}^{t_2} R_P\, i_{tot}(t)dt \quad 5.5.2$$

where $M_{Cs,p}$ is the mutual inductance between the CS windings and the plasma ring, V_{AH} is the is the loop voltage generated by the auxiliary current drive and heating device (assumed to be a 25 MW RF system) and L_p (plasma inductance) is known (§ 5.2). A linear trend of current in CS and inside the plasma is also assumed.

The plasma resistivity during the ramp-up is quite variable due to the continuous temperature increase: for this reason the value of the last integral is quite difficult to be evaluated. However it has been proven that it is in the range from 20 Vs to 30 Vs: therefore in FRESCO the plasma resistance during the start up phase is handled as an input datum (30 Vs).

A fixed auxiliary power during the start up is considered in case of pulsed operation modes as well. Three different situation can therefore occur:

1. $\varphi_{available} > \varphi_{start\text{-}up}$: in this case the "surplus flux" can be used during the burning phase by inducing a current I_i in the plasma. In this operative mode, called *inductive*, it is assumed that any further auxiliary heating is not needed during the τ_{burn} period.
2. $\varphi_{available} = \varphi_{start\text{-}up}$: in such a case, φ_{Cs} is enough to be used only during start up phase. Since an auxiliary heating is necessary during the τ_{burn} period, such an operation mode can be called *hybrid*.

---

[9] The start up phase is defined as the sum of the current ramp up (τ_{RU}) and current heating (τ_H) periods before the burning phase (τ_{burn}).

3. $\varphi_{available} < \varphi_{start\text{-}up}$: in this case the contributes of CS and AH system are *not* enough to produce the plasma current I_{tot}: in this case a stop message in the FRESCO calculation appears.

If the selected operation mode is pulsed and $\varphi_{available} > \varphi_{start\text{-}up}$ (case 1) the flux balance during the burning time becomes (eq. 5.5.3):

$$\int_{t_2}^{t_3} M_{CS,P} \frac{di_{CS}(t)}{dt} dt = \int_{t_2}^{t_3} L_P \frac{di_{tot}(t)}{dt} dt + \int_{t_2}^{t_3} R_P \, i_{tot}(t) dt \tag{5.5.3}$$

Since the plasma current is constant during the burning phase, the equation can be rewritten as (eq. 5.5.4):

$$\varphi_{CS|_{\tau_{burn}}} = R_P \, I_i \, \tau_{burn} \tag{5.5.4}$$

where φ_{Cs} during the burning phase is the "surplus flux" and R_p value is constant (see eq. 5.2.4).

On the other hand, in case of a steady state operation mode, the power of auxiliary heating devices is calculated in such a way so that at the end of the start-up phase the conditions necessary to sustain fusion reactions appear and they can last during the burning phase too (from t_2 to t_3) when the CS contribute is over (eq. 5.5.5).

$$\int_{t_2}^{t_3} V_{AH} \, dt = \int_{t_2}^{t_3} L_P \frac{di_{tot}(t)}{dt} dt + \int_{t_2}^{t_3} R_P \, i_{tot}(t) dt \tag{5.5.5}$$

In FRESCO the basic auxiliary power plant equipment is supposed to be made of a 60 MW NBI system and a 50 MW RF system, according to the ITER start up scenario described in [EDA,2002]: if such a heating power is not enough in order to sustain fusion reactions, the auxiliary power of further NBI systems is calculated while keeping constant the RF system size (MWe).

All this given, the current to be produced by auxiliary systems (RF or/and NBI) during the burning phase can be now calculated. It must be underlined that the equation has to be changed if a steady state or pulsed mode is analysed because of the heating contribute by the inductive current (pulsed mode) or not (steady state mode) during the τ_{burn} period.

The not-inductive current produced by auxiliary heating devices, in case of steady state operative mode is therefore (eq. 5.5.6):

$$I_{AH} = I_{tot} - I_{bs} \tag{5.5.6}$$

where I_{bs} is the bootstrap current, that is an input datum. In case of pulsed mode (eq. 5.5.7):

$$I_{AH} = I_{tot} - I_{bs} - I_i \tag{5.5.7}$$

It is of fundamental importance evaluating therefore the inductive current and the related power heating transfer efficiency of the neutral beams (NBI) and radiofrequency (RF) systems into the plasma, in order to calculate the size of the heating devices and their cost.

The following considerations refer to the heating transfer during the burning phase and therefore to only steady-state or hybrid fusion power plants since only in these cases an auxiliary heating is needed while burning.

According to [Pamela,2009], with reference to Figure 5.7, two efficiency can be defined:

1. η_{conv} that is the *conversion efficiency* defined as the ratio between the power of external heating devices measured after transmissions devices and the combined power of the sources (of radiofrequency or neutral beam) (eq. 5.5.8):

$$\eta_{conv} = \frac{P_{launched}}{P_{source+aux}} \tag{5.5.8}$$

2. η_{coupl} that is the *coupled efficiency* defined as the ratio of the power actually injected in the plasma, the “coupled power” versus the power of external heating devices measured after transmissions devices (eq. 5.5.9)

$$\eta_{coupl} = \frac{P_{coupl}}{P_{launched}} \tag{5.5.9}$$

The values of both efficiencies are handled as input data: it very likely that their variations lead to different costs of electricity.

The coupled power can be expressed as a function of the auxiliary heating current according to the Mikkelsen-Singer relation (eq. 5.5.10):

$$P_{coupl} = \frac{I_{AH}\,\gamma}{n\,R} \tag{5.5.10}$$

The figure of merit, γ, is thought to be a plasma temperature function [PPCS,2005] and is calculated through equation 5.5.11:

$$\gamma = \alpha \cdot \frac{T}{10} \tag{5.5.11}$$

where T is the average plasma temperature measure in keV and α is a constant, assumed to be 0.35 for NBI and 0.2 for RF systems (Annex 1 of [PPCS,2005] and [Toschi,2000]).

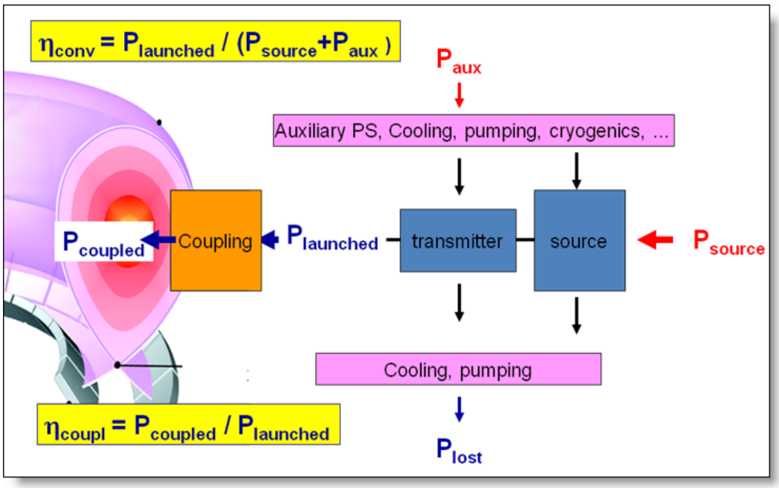


Figure 5.7: Auxiliary heating conversion and coupled efficiency definition, from [Pamela,2009].

The coupling efficiency, which depends on plasma physics only, cannot be subject to sensible variations and it has been estimated to be equal to 0.75 [Pamela,2009]: it is used to calculate the amount of not-inductive re-circulating power (that is the sum of source and auxiliary power, $P_{source+aux}$).

5.6 Power balance

With reference to Figure 5.8, the thermal fusion power produced in the plasma (P_f) can be written as (eq. 5.6.1):

$$P_f = P_\alpha + P_n \tag{5.6.1}$$

where P_α, is the thermal power produced by the α-particles (about 20% of fusion power) and P_n the thermal power produced by the neutrons (about 80% of P_f).

The thermal power produced by neutrons in the breeding blanket is $M \cdot P_n$ (M is the energy neutron multiplication factor) whereas the α-thermal power is recovered in first wall, divertor and high temperature shields (HTS). The energy deposited on LTS and on VV is lost (1.1% of P_{th}). A portion of the pumping power used for blanket and divertor cooling, is furthermore reinserted in the cycle as thermal power.

Then the overall thermal power can be written as (eq. 5.6.2):

$$P_{th} = P_\alpha + MP_n + P_{AH} \tag{5.6.2}$$

P_{AH} being the auxiliary heating power supplied from outside.

While in the steady-state regime, P_{th} is fully converted into gross electric power, P_{gross}, in the pulsed regimes (hybrid or inductive) a fraction of the thermal power must be used to feed a thermal energy storage system (TES) necessary to ensures a continuous electric production during the dwell phase when the fusion power is null. Such a power, denoted with P_{TES} is calculated according equation 5.6.3:

$$P_{TES} = \frac{P_{th}}{\eta_{TES}} \frac{\tau_{DWELL}}{\tau_{BURN}} \tag{5.6.3}$$

where τ_{dwell} and τ_{burn} have been defined in section 5.4 and η_{TES} is the global heating transfer process efficiency (from the reactor to the thermal storage system), assumed to be 80% according to the molten salt thermal energy storage in the “Archimede” project [Gaggioli,2007].

The gross electric power, P_{gross}, is derived from the thermodynamic efficiency evaluated on the basis of a Rainkine cycle, common to both the AB and B PPCS models. The related efficiency, set equal to 43.7% [Puma,2005], is an input datum in FRESCO and it can therefore be freely changed by the user.

The net electric power, P_e, that is the power enter delivered to electricity transmission grid is derived from the following power balance (eq. 5.6.4):

$$P_e = P_{gross} - (P_{AH} + P_{pump} + P_{cryo} + P_{aux}) \tag{5.6.4}$$

where P_{pump} is the pumping system electric power, P_{cryo} and P_{aux} are the power needed by auxiliary and cryogenic systems; the sum between parentheses is denoted as re-circulating power ($P_{re\text{-}circ}$) and is usually indicated as fraction (f_R) of the gross electric power, P_{gross} (eq. 5.6.5):

$$f_R = \frac{P_{re-circ}}{P_{gross}} \tag{5.6.5}$$

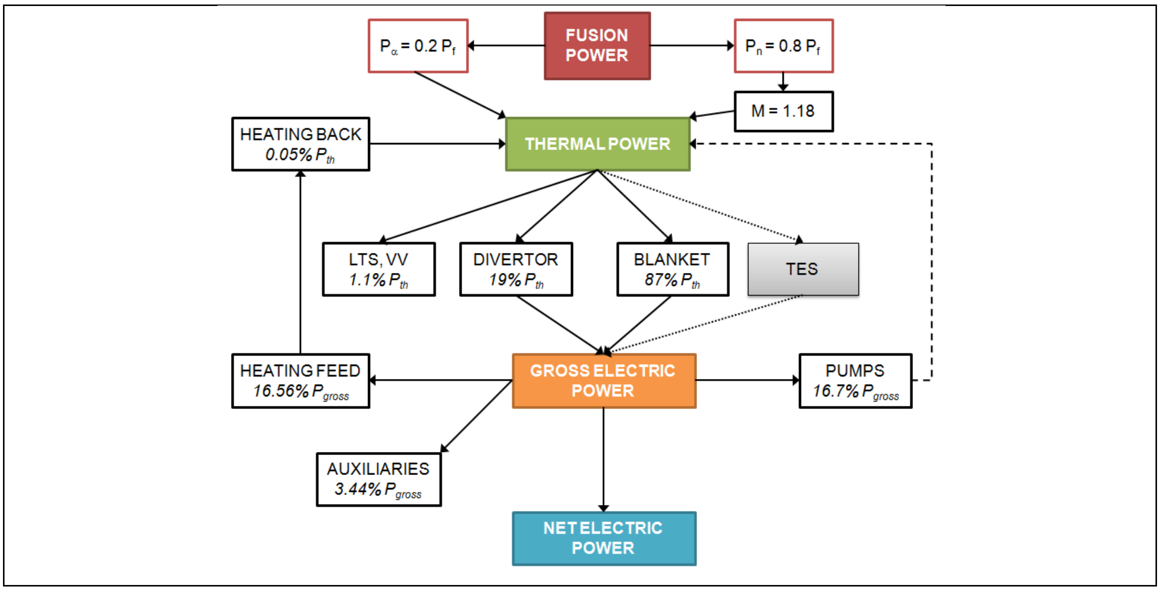


Figure 5.8: Power balance according to [Puma,2005].

5.7 *Cost evaluation*

The aim of the FRESCO code is the fusion power plant cost of electricity evaluation in case of stationary and pulsed operation mode: such a comparison should help in defining which is the most economically sustainable choice and the subsequent technical aspects of the power plant to be improved or deeply studied.

The cost of electricity will be calculated thanks to the LCOE (Levelised Cost of Electricity) method (§ 5.7.4). The data needed for the cost of electricity calculation are :

1. *investment cost* : it descends from the cost of capital and then from the overnight cost of the power plant. The cost of capital, C_C, is defined as the total expenditure incurred in order to complete the construction of the power plant and to face the periodic substitutions of the replaceable items (i.e. divertor and blanket structural materials). By adding to it the owner's and the contingency costs, the overnight cost is derived: this is the amount of money that should be paid if the power plant was built in a night. Because of the unavoidable construction lead time - that should not exceed 5 years [Maisonnier, 2007] - the cost of the power plant construction increases because of the interest during construction (IDC): the final cost, discounted to the first year of power plant operation (or, that is the same, at the end of the construction period), is the investment cost: it is the amount of money that, together with the costs incurred during power plant operation, should be recovered thanks to electricity sell.

2. variable operation and maintenance costs i.e. standard operation and staff costs;
3. fuel cost.

A detailed description of all these costs components, taken into account in the code, is carried out in the next paragraphs.

5.7.1 The investment cost

In FRESCO the capital cost of a generic power plant is derived from the sum of the cost of its main components costs. Whatever possible, the capital cost of a single component is obtained by extrapolating through ad hoc “scaling factors” the cost of corresponding ITER component. The most used scaling factor in FRESCO is a geometric one, denoted GEOM and defined as the ratio among the plasma major radius of the power plant under study and the major radius of ITER (6,2 m [PPCS,2005]).

The ITER costs data source is the “*Resource*” chapter of the “*Plant Description Document”* in *“ITER Technical Basis”* published in 2002 [EDA,2002] where the evaluated cost estimates for ITER are presented. In the same document, one can read: *“[...] Globally for ITER construction they represent the most credible cost estimates, given the present uncertainties on ITER Construction Management, Siting and Cost sharing: a global value inside which one can be confident to be able to build ITER.”*

The costs of main ITER components are listed in Table 5.3; in the first column costs in kIUA, the currency used in ITER EDA document[10], are shown; the conversion rate from IUA_{2000} to $€_{2000}$ (1 kIUA = 1.279 M€) pointed out in the same document has been used to calculate the values in the second column. It must be underlined that FRESCO discounts each of these costs to the first year of construction period.

Table 5.3: ITER components costs [EDA,2002] expressed both in IUA and Euros currencies.

All costs refer to year 2000.	***kIUA***	***M€***	***Learning factor***
MAGNET SYSTEM	**762.1**	**974.7**	
Toroidal field coils windings	*117*	*149.6*	*yes*
Magnet structure	*168.3*	*215.3*	*yes*
Poloidal field coil & correction coils	*49.7*	*63.6*	*yes*
Central solenoid coil	*31.1*	*39.8*	*yes*
Conductor	*355*	*454.0*	*yes*
VACUUM VESSEL	**230**	**294.2**	*yes*
Main vessel	*155*	*198.2*	
Port Assembler	*75*	*95.9*	

[10] IUA is the acronyms of International Unit of Accounting. 1 IUA corresponds to 1000$ in 1989, year when it was first used in the fusion community.

DIVERTOR	**76**	**97.2**	*yes*
MACHINE ASSEMBLY	**92.7**	**118.6**	*no*
Assembly operations	*50.3*	*64.3*	
Assembly tooling	*42.4*	*54.2*	
CRYOSTAT AND CRYODISTRIBUTION	**164.7**	**210.7**	*yes*
Cryostat	*75.8*	*96.9*	
Cryodistribution	*88.9*	*113.7*	
VACUUM PUMPING & FUELLING SYSTEM	**34.2**	**43.7**	*yes*
Vacuum pumping	*27.4*	*32.4*	
Fuelling system	*6.8*	*11.4*	
REMOTE HANDLING	**61.1**	**78.1**	*yes*
TRITIUM PLANT	**36.6**	**46.8**	*yes*
HEATING AND CURRENT DRIVE	**173.5**	**221.9**	*yes*
NBI	*96*	*122.8*	
RF	*77.5*	*99.1*	
DIAGNOSTICS	**118**	**150.9**	*no*
BUILDINGS	**380.3**	**486.4**	*no*

5.7.1.1 Magnetic system

The magnetic system modelled in FRESCO reflects that of ITER (Figure 5.9): the toroidal field (TF) and central solenoid (CS) coils are made of Nb_3Sn, while the poloidal system (PF) building material is NbTi. It is also assumed that temperature, current density and magnetic field values measured in nominal operating conditions are always under critical values.

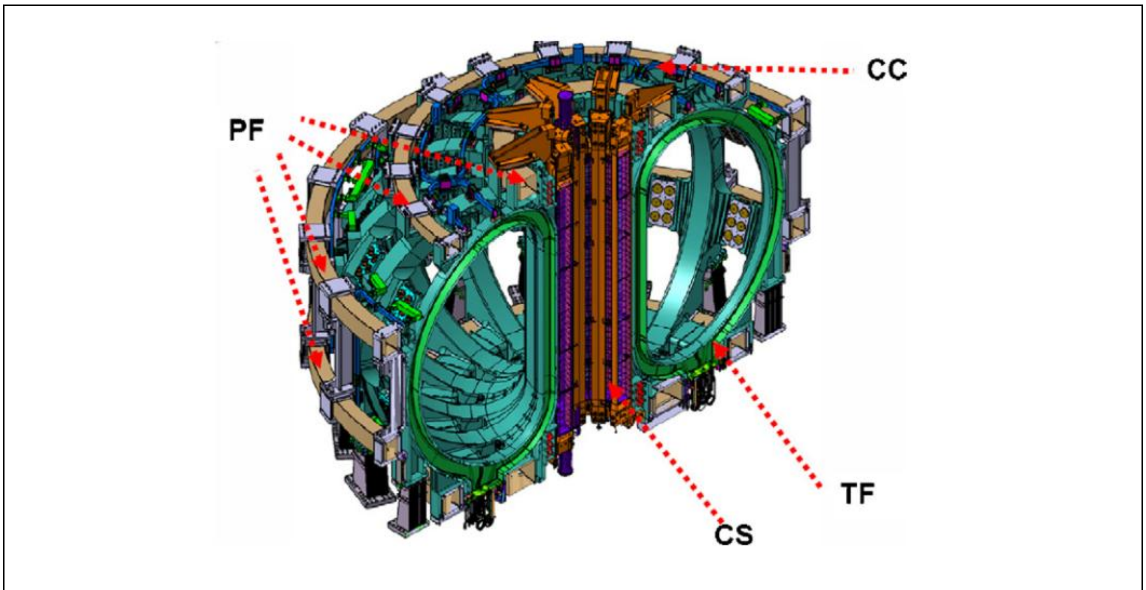


Figure 5.9: Main components of ITER magnet systems [Mitchell,2009]

The cost of *toroidal field coils* is thought to be proportional to its volume and, therefore, to the amount of Nb_3Sn needed to build them. Since the plasma major radius increase with the power plant capacity (P_f), it is assumed that the toroidal field coils outer radius and then the volume increase proportionally to fusion power.

By multiplying the ITER cost (C_{TFITER}) by the geometrical scaling factor raised to the power of three, the cost of TF system of the power plant under study (C_{TF}) is derived (eq. 5.7.1):

$$C_{TF} = C_{TF_{ITER}} \cdot GM^3 \tag{5.7.1}$$

The toroidal coil windings are placed inside a coil case that is the coil steel *magnetic structure*: it is used to both props up the central solenoid and the poloidal field coils and sustain the vacuum vessel to which it is fixed. Because of its retaining role and since "*[…] for larger tokamak TF inner leg requires thicker mechanical structure in order to resist high Lorentz forces […]"* (§ 5.1, page 33), the magnetic structure cost is assumed to be a function of the reactor physical dimensions.

Beside this, in case of pulsed operation mode, the cost of magnetic structure is function of the mechanical stress to which it undergoes. In [Hamada,2005] a fatigue characteristic of case material due to the cyclic electromagnetic load ($3*10^4$ cycles assumed for ITER), is performed. With reference to the S-N (stress amplitude vs number of cycles to failure) of Figure 5.10, the stress amplitude value corresponding to the number of cycles to which the machine is subjected – depending on the length of the cycle and the operational life - is derived.

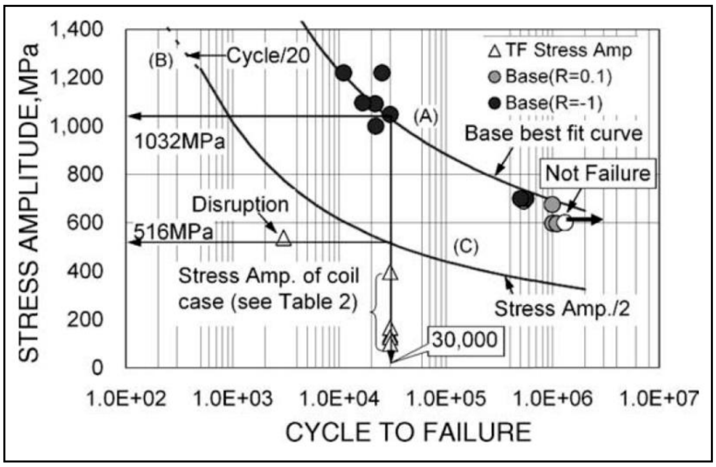


Figure 5.10: *"S–N curve of JJ1 base metal at 4.2 K. The TF coil case stress amplitude includes the residual stress of 50 MPa. Curve (A) is the best-fit S–N curve using Eq. (1). Design S–N curve consist of curves (B and C)."* [Hamada,2005]

The coil case cost is derived from ITER cost as shown in equation 5.7.2:

$$C_{MS} = C_{MS_{ITER}} \, GM^3 \, \frac{\sigma_{ITER}}{\sigma_{max}} \tag{5.7.2}$$

where σ_{max} is the maximum allowable stress amplitude derived from graph of Figure 5.10 at the number of cycles *N* to which the reactor is subjected, and σ_{ITER} is set equal to 516 MPa.

Similarly to the toroidal field coils system, the cost of the *poloidal field coils system* (correction coils included) is a function of its volume that is assumed to increase with reactor enlarging (eq. 5.7.3):

$$C_{PF} = C_{PF_{ITER}}\, GM^3 \qquad 5.7.3$$

In FRESCO, the cost of the central solenoid is considered a function of both its volume (the larger it is, the more superconductive material is used) and of maximum magnetic field it can produce (eq. 5.7.4). Two scaling factors are used in this case: the cost of ITER CS is scaled accordingly to the volume and magnetic field value (V_{Cs} and B_{Cs}) of the power plant under study compared to ITER ones (V_{CsITER} and B_{CsITER}).

$$C_{Cs} = C_{Cs_{ITER}} \cdot \frac{V_{Cs}}{V_{Cs_{ITER}}} \cdot \frac{B_{Cs}}{B_{Cs_{ITER}}} \qquad 5.7.4$$

For the sake of simplicity, the item "*conductors"* of Table 5.3 is handled as if it referred to the toroidal winding pack conductors only. The cost of conductors is estimated by equation 5.7.5:

$$C_{cond} = C_{cond_{ITER}}\, \frac{S_{TC}}{S_{TC_{ITER}}} \qquad 5.7.5$$

where the cost of conductors is defined as a function the inner leg toroidal coil section along the equatorial plane S_{TC}.

5.7.1.2 Vacuum Vessel

The overall cost of the vacuum vessel is derived from the sum of two terms (eq. 5.7.6) : the main vessel cost (C_{mainVV}) and that of the airtight doors (C_{VV}) necessary to allow items substitution by the remote handling system. The first has been considered proportional to the depressurized volume so that the geometric scale factor has been raised to the power of three. On the other hand, since further improvements of the airtight doors are not expected, their cost is set the same as ITER.

$$C_{VV} = C_{mainVV_{ITER}}\, GM^3 + C_{VVport_{ITER}} \qquad 5.7.6$$

5.7.1.3 Divertor

Because of the neutron flux that wear the divertor, this item is one of the most stressed one among items facing plasma and, for this reason, it must be periodically replaced.

In FRESCO the divertor is supposed to be projected to sustain a 10 MW/m^2 thermal flux , quite close to that foreseen in ITER: if the ITER divertor cost ($C_{divITER}$) was adjusted proportionally to the plasma facing surface, a good approximation of new divertor cost should be derived. However, the different type of coolant that is planned to be used in a fusion power plant (helium instead of steam) has to be taken into account: in fact a larger than ITER thermal exchange surface will be needed due to the lower thermal exchange coefficient of helium than that of steam. In order to take into account the divertor geometrical size increase, the geometric factor raised to the power of three is used in the cost equation (eq. 5.7.7).

$$C_{DIV} = C_{DIV_{ITER}} GM^3 \qquad 5.7.7$$

5.7.1.4 Assembly

The overall ITER assembly cost (C_{ass}) of the basic machine (reactor) is derived from the manual operation and remote handling (C_{oper}) cost as well as from the cost of structures, instrumentations and tooling necessary to complete the assembly ($C_{instrum}$).

In the code, the first cost component is set proportional to the geometric factor raised to the power of three, the second is instead kept constant.

$$C_{ass} = C_{oper_{ITER}} GM^3 + C_{instrum_{ITER}} \qquad 5.7.8$$

5.7.1.5 Cryostat e cryodistribution

The cost of cryostat (eq. 5.7.9) is considered a linear function of the volume to be kept at cryogenic temperature: geometric scale factor raised to the power of three is therefore used to adjust ITER cost ($C_{cryostatITER}$). On the other hand, since the cryodistribution system size are strictly connected to heat exchanging surface extent, the scaling factor is raised to the power of two in the cost equation.

$$C_{cryo} = C_{cryostat_{ITER}} GM^3 + C_{cryodistr_{ITER}} GM^2 \qquad 5.7.9$$

5.7.1.6 Vacuum pumps

The cost of the vacuum pumps (C_{vp}) , eq. 5.1.9, is derived from ITER cost (C_{vpITER}) by using the third power of the geometric factor since it is expected to be function of the volume to be depressurized.

$$\mathrm{C_{vp}} = \mathrm{C_{vp_{ITER}}} \cdot \mathrm{GM}^3 \qquad 5.7.10$$

5.7.1.7 Fuel injection

The fuelling system that injects a D – T mixture in the plasma chamber is considered a function of the fusion power since the more thermal power is produced, the more “fuel” is needed.

Then the cost of fuel injection system in ITER ($C_{fuelinjITER}$) is increased by a factor that accounts the fusion power ($C_{fuelinj}$), eq. 5.1.10:

$$C_{fuelinj} = C_{fuelinj_{ITER}} \cdot \frac{P_f}{P_{f_{ITER}}} \qquad 5.7.11$$

5.7.1.8 Remote handling

The cost of remote handling operation in power plants is expected ti be much larger as compared to that of ITER. This as a consequence of the increased weight of the blanket and divertor modules and larger frequency of module replacements. Because of this, in FRESCO the cost of the remote handling of ITER (C_{RHITER}) is inferred by using the geometric factor raised to the power of three (eq. 5.7.12).

$$C_{RH} = C_{RH_{ITER}} GM^3 \tag{5.7.12}$$

5.7.1.9 Tritium plant

The tritium plant includes the exhaust fuel extraction, the manifolds of tritium from breeding blanket and the isotopic separation and storage systems. It is seems reasonable to consider the cost of such a system a function of plasma volume: the ITER cost ($C_{tritiumITER}$) is therefore increased by the third power of the geometric factor (eq. 5.7.13).

$$C_{tritium} = C_{tritium_{ITER}} GM^3 \tag{5.7.13}$$

5.7.1.10 Blanket

As mentioned in the introduction of this chapter (5.7), since no breeder material is used in ITER[11], the cost of blanket items in FRESCO is made by taking as reference the PPCS studies ([Puma,2005] and [Hermsmeyer,2003]) as follows.

The code can allows to chose among two types of blankets (§ 5.1, page 31), with the geometrical configuration shown in Table 5.2 and Table 5.3. Starting from the radial building of model AB and B of PPCS study and by using the shown thickness values as calculated in section 5.1, the evaluation of the volume of the blanket layer is derived. Then the cost of the blanket, net of the manufacturing cost, is (eq. 5.7.14):

$$C_{blanket} = \sum_{m=1}^{n} (C_m \, V_m \, W_m) \tag{5.7.14}$$

where *m* is the *n*-th material composing the in-vessel layers, C_m is its unitary cost, V_m is its overall volume and W_m its overall weight per unit of volume.

The materials composition and weight are those of Figure 5.2 whereas the unitary costs are given as input. At present in the FRESCO code the final cost of the blanket, manufacturing included, is assumed to be 50% more of that calculated through equation 5.7.14.

---

[11] In the ITER machine the blanket covers the interior surfaces of the vacuum vessel, providing shielding to the vessel and the superconducting magnets from the heat and neutron fluxes of the fusion reaction. The neutrons are slowed down in the blanket where their kinetic energy is transformed into heat energy and collected by the coolants. No lithium is deposited on it so the tritium breeding can not take place. At a later stage of the ITER project, test breeding modules will be used to test materials for tritium breeding concepts [ITER website].

5.7.1.11 Heating and current drive systems

As indicated un section 0 the basic H&CD equipment is assumed to be made of 60MW NBI and 50MW RF units. The corresponding cost of auxiliary power in FRESCO will depend on the selected operation mode, namely:

- in case of inductive mode, the auxiliary power heating will be that of ½ of a RF unit.
- in case of steady state and hybrid mode the operative cost is calculated on the hypothesis that the auxiliary power is supplied by one full RF unit and one or more NBI system as needed.

The cost of H&CD systems are derived from PPCS data and conservatively doubled.

5.7.1.12 Diagnostic

Being an experimental machine, ITER necessarily needs a large number of diagnostic systems (magnetic windings diagnostic systems, optical and spectroscopic systems, common diagnostics etc.; in a future nuclear fusion power reactor the need of a high number of diagnostic systems won't be so pressing: in fact, if a great development of fusion technologies during the next 30-40 years occurs, all physical aspects of the nuclear fusion phenomena will be at that time completely known. Because of that, the cost of the whole diagnostic systems has been set equal to half as that of ITER.

5.7.1.13 Electric power generation systems

The cost of electric power generation systems including turbines, alternators and BT/AT transformers, is assumed in line with cost estimation of the turbine building of an advanced fission power plants according to the PPCS model A whose "[...] power conversion system [...] is based on the fully qualified PWR technology" [PPCS,2005]. From the cost estimation of an ABWR to be built in USA, the turbine building is thought to cost 360$\$_{2004}$/kW. This is a first rough estimation of the electric power generation system cost of a fusion power plant, where helium instead of steam is used as thermal fluid: such a cost has been set equal to the cost of an advanced fission power plant per unit of gross electric power produced but a deeper study about this should be carried out.

5.7.1.14 Electric power supplies and distribution systems

The power supply systems include:

- AT/MT and MT/BT substation;
- AC distribution systems;
- AT/MT and MT/BT substations;
- AC/DC converters;
- Reactive power compensators;
- Harmonic filters;
- DC distribution systems;
- Control instrumentation.

In FRESCO the total cost of all those systems, thought to be function of the power plant size, is taken equal to that of ITER increased of the geometrical scaling factor *GM*.

The toroidal and poloidal field coils power supply system's cost have been deduced from *Scan II* report [Spears,1986] (all cost[12] are discounted to year 2000).

Concerning the toroidal field coils power supply the cost is the same in the pulsed or steady state mode and is calculated as follows (eq. 5.7.15)

$$C_{TCPS} = c_{TCPS} \cdot P_{TCPS}^{0.67} \tag{5.7.15}$$

where c_{TCPS} is the unitary cost of this power supply (15.15 €/W$^{0.67}$) and P_{TCPS} is the peak TFC grid power supply (10 MW).

On the other hand, concerning the poloidal field coils:

- in case of a steady state operational regime, the equation used to evaluate the poloidal field coil power supply cost is the same as before, but c_{PCPS} is set equal to 28.34 €/W$^{0.67}$ and P_{PCPS}, that is the power required to support ohmic and lead losses in PFCs, is 5 MW.
- in case of pulsed mode the cost increases the shorter is the ramp-up time (eq. 5.7.16):

$$C_{PCPS} = c_{PFPS} \cdot \left(\frac{8.4 \cdot 10^{-5} \cdot I_p^2}{\tau_{ramp-up}}\right)^{0.67} \tag{5.7.16}$$

Moreover in case of pulsed modes, in order to recover the magnetic energy produced by the central solenoid and stored by plasma inductance during the burning phase, the cost of the inductive store system has to be included in cost estimation too. According to [Spears,1986], such a cost (C_{IS}) is (eq. 5.7.17):

$$C_{IS} = c_{IS} \cdot \left(\frac{2 \cdot E_s}{\eta_{TR}}\right)^{0.47} \tag{5.7.17}$$

where c_{IS} is the unitary cost of the inductive store per unit of energy (872 €/J$^{0.47}$), η_{TR} is the energy transfer efficiency (0.9 assumed) and E_s is the energy stored in the storage device, assumed to be equal to E_{Cs} (§ 0).

5.7.1.15 Thermal storage

In a pulsed (hybrid or inductive) regime a thermal energy storage device is required in order to ensure a continuous electricity production even during the dwell phase, when no fusion power is produced. The thermal energy storage can be made either inside, by exploiting the shields thermal inertia or outside the reactor. In FRESCO the second alternative is considered. A cost

---

[12] In the *Scan II report* the currency used is ECU_{1984} (European Currency Unit) that corresponds to 1.09 €$_{2000}$:
1 ECU_{1984} = 0.822 \$$_{1984}$ [Spears,1986]=1.36 \$$_{2000}$ [inflation website]=1.09 €$_{2000}$ [x-rates.com]

of 35 €/kWh$_{th}$ is assumed taken from the case of a molten salt storage devices (“Progetto Archimede” by ENEA, [Gaggioli,2007]).

5.7.1.16 Civil works.

Similarly to ITER, in a fusion power plant the reactor will be placed inside the main building (tokamak building of Figure 5.11) that acts as radioactive confinement in event of failure. The devices concerning the fuel cycle and the tritium isotopic separation and recovery systems will be gathered inside the “tritium building”.

Since the nuclear power plant will produce electricity, buildings where the heat extraction, electricity generation systems are placed and finally offices for personnel and administration are also needed. Because of these difference among the ITER and a fusion power plant layout, the cost of civil works needed to build a future plant is conservatively estimated to be twice as large as in ITER.

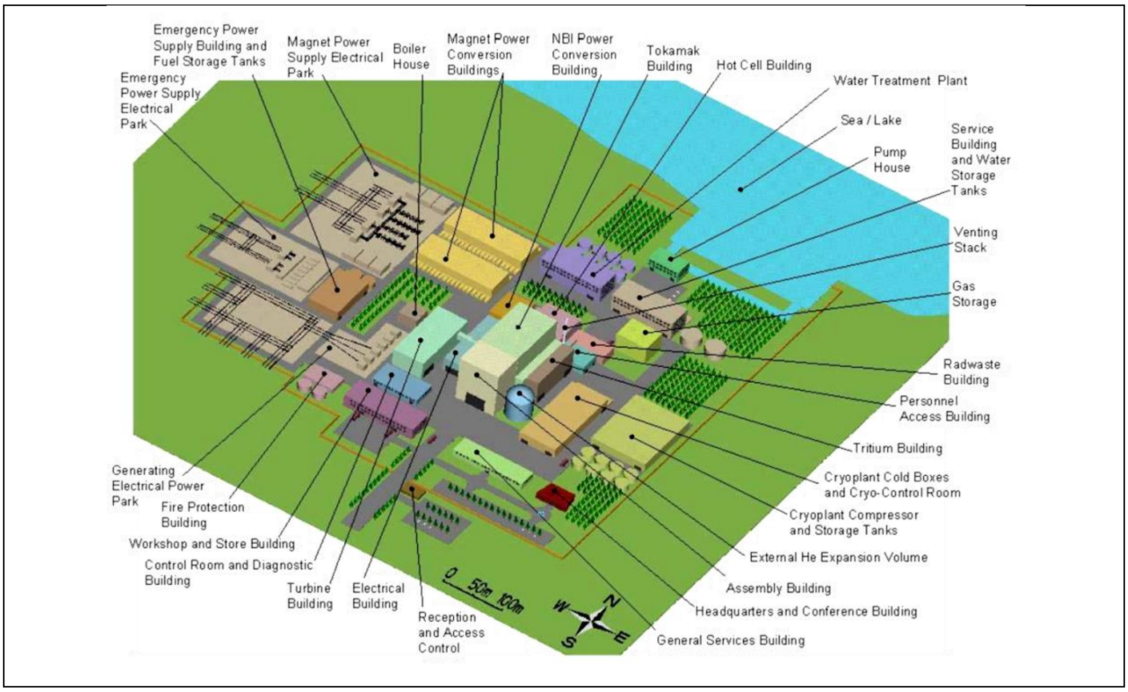


Figure 5.11: Fusion power plant layout [PPCS,2005].

5.7.2 Operation and maintenance costs

The operation cost are divided in two categories:

- standard operation and staff cost that, according to [Spears,1986], account for 1% of total capital cost;
- fuel cost that includes the deuterium consumption and the breeder depletion

Information about expenditures for ordinary maintenance, personnel and fuel costs, has been taken from [Spears,1986]; similarly to section 5.7.1.14, all costs have been discounted to year 2000.

With reference to the fuel cost, the yearly deuterium cost is set (eq. 5.7.18):

$$C_D = c_D \frac{P_f}{3.6} \frac{AV}{0.75} \qquad 5.7.18$$

where c_D is the unitary deuterium cost (set equal to 2180 €/kg [Spears,1986]) and AV the availability factor.

The breeding material depletion cost is instead accounted in the blanket modules replacements. This means that the breeder is renewed each time the other structures of the blanket damaged by neutronic flux are replaced.

5.7.3 The technological learning

When industry matures, usually the cost of its products decreases due to technological learning: it shows how much the cost decrease every items production doubling. Accordingly to the Annex 11, “Assessment of the direct costs of the PPSC plant model” of [PPCS,2005], the cost at year *y* of an item subjected to technological learning is defined as:

$$C_y = C_{y-1}(1 - LF)^{log_2 n} = C_{y-1} PR^N \qquad 5.7.19$$

where *LF* is the learning factor, *n* is the number items and *N* the number of doublings; the term *(1-LF)* is also called progress ratio, that is the overall cost reduction factor.

The items composing a fusion power plant can be already mature or, if not, can be characterized by different learning factor [Ward,2009]. For the sake of simplicity, in FRESCO the same learning factor is considered for all technologies whose cost will potentially decrease since a sensible technologic development is expected (see Table 5.3), namely: magnets, H&CD systems, blanket, diagnostics; on the other hand, no cost reduction is provided for assembly, civil works, electric generation systems etc., elements whose design or manufacturing can be considered already consolidated.

When a fusion power plant prototype, e.g. DEMO, is modelled, a unitary cost reduction factor, i.e. PG^n, has to be assumed since, being the plant a 1st of a kind no reduction in the costs is expected. On the other hand, if a 10th of a kind power plant is modelled, a 65% cost reduction is recommended to be used (Annex 11 of [PPCS,2005]).

5.7.4 LCOE calculation

The cost of electricity has been calculated by using the levelised cost of electricity (LCOE) method [IEA/NEA,2005], a handy tool for comparing the unit cost of different technologies over their economical life. The LCOE method neglects the presence of specific market or technology risks so the electricity cost correspond to the cost of an investor assuming the certainty of production costs and the stability of electricity price. Due to these assumptions a gap between the LCOE and true financial cost of an investor operating in real electricity market with their specific uncertainties is usually verified.

The LCOE can be considered as the price for output (electricity in our case) that would equalise two discounted cash-flow (costs and revenues). The equivalence between electricity price and LCOE is based on two assumptions: both the interest rate use for discounting costs and benefits and the electricity price don’t change during the lifetime of the project. Moreover all variable are real and thus net of inflation.

On the left hand side of equation 5.7.20 one finds the discounted sum of all benefits, on the right hand side the discounted sum of all costs:

$$\sum_t E_t c_{el}(1+r)^{-t} = \sum_t (I_t + O\&M_t + F_t + C_t + D_t)(1+r)^{-t} \tag{5.7.20}$$

where:

E_t	amount of electricity produced in year *t*
P_{elc}	constant price of electricity
$(1+r)^{-t}$	discount factor for year *t*
I_t	investment cost in year *t*
$O\&M_t$	operation and maintenance cost in year *t*
F_t	fuel cost in year *t*
C_t	carbon costs in year t
D_t	decommissioning in year

The previous equation can be rewritten (eq. 5.7.21) highlighting the electricity price and leaving out the carbon cost (since no CO_2 is produced by a fusion power plant) and decommissioning cost , that is not currently included: even such an omission leads to an incorrect electricity cost from a formal point of view, the approximation can be considered quite good since it accounts for only some percents in cost of electricity (as it is in case of fission power plants).

$$LCOE = \frac{\sum_t (I_t + O\&M_t + F_t)(1+r)^{-t}}{\sum_t E_t(1+r)^{-t}} \tag{5.7.21}$$

The overall electricity production , E_t, is calculated as (eq. 5.7.22):

$$E_t = (\,8760\, P_e\, AV) - \frac{8760\, AV}{\tau_C} E_{RC} \tag{5.7.22}$$

where E_{RC} is the electricity needed for CS recharging.

5.8 Conclusive considerations

The FRESCO code has been developed with the aim of creating a handy tool for deriving an economic model of a fusion power plant. The main aim is to study the connection between the technological aspects of a power plant and the cost of electricity. The last has to be handled only as a benchmark, useful to identify the power plant configuration that could likely be economically competitive in future energy systems. In fact, while the first target of fusion research is ability of producing electricity, the second is lowering costs as much as possible. Fusion power plants will likely be commercial when an increased energy demand will occur and more strict environmental policies should be respected.

As it will be made clear in the next chapter, where preliminary scenario results about the future energy mix will be presented, the current fusion power plant cost estimations by PPCS entail an increasing contribution by electricity from fusion with the raising of carbon tax costs and the more stringent constrains on CO_2 emission. Two inherent aspects of fusion power plants should work in its favour: it is a clean technology, since no carbon emissions are produced during operation and only a small amount of radioactive items has to be managed and, the last but not least, it is inherently safe since, unlike fission reactions that need for moderation, fusion reactions completely disappear if even one of the physical conditions necessary to produce it changes. This aspect increases the social acceptability towards this kind of electricity producer, is essential for its development in worldwide energy systems.

In order to estimate the capital cost of a fusion power plant, a technical and physical analysis is necessary too: depending on the assumed fusion power, the operative mode, the physical plasma parameters, the geometrical size and the technology devices needed to assure and then sustain the fusion power reaction, the cost of the power plant is expected to change. For this reason the FRESCO code creates a simplified technical and physical model of the power plant too: all assumptions necessary to develop this part of the code reflect the results of the technical and physical studied carried out so far thanks to the ITER experiment. The “Power plant conceptual study” has been instead the main reference with regard to the blanket modelling, the only reactor item currently not available in ITER. The economical aspects of the power plant has been instead extrapolated from the ITER cost, taking into account the increased capacity of a commercial power plant.

At present the code is ready to be used: a benchmarking test with PPCS models will be done for checking its level of accuracy with regard to both technical, physical and economical aspects. Then, the economics of a pulsed power plant will be compared to a stationary one to stress the derived different technological aspects of the power plant and their impact on the cost of electricity.

6 The nuclear fuel cycle model in EFDA TIMES

The EFDA TIMES model (ETM) scenario results described in chapter 4 make clear that the future uranium resources exploitation is a key point in defining the energy production share over the years: it is in fact because of uranium depletion that fusion became a more economically competitive solution compared to fission.

The aim of the work carried out in cooperation with the Max Planck Institut für Plasmaphysik of Garching, in the framework of the SERF activity denominated “Further improving of advanced nuclear fission technologies in EFDA TIMES”, was to model the complete nuclear fuel cycle (NFC) - reprocessing phase included - and nuclear technologies for electricity production available from 2010 (MOX fuelled nuclear power plants, fast reactors[13] and accelerated driven system) in order to produce a better economic description of fission power plants and make the comparison between fission and fusion technologies more realistic.

The study of reference for the fuel cycle implementation was edited by NEA in 2002 ([NEA,2002]). Here, together with a detailed study of future nuclear technologies, the analysis of their possible combination, leading to different nuclear strategies, is carried out.

The nuclear fuel cycle model has been therefore built in order to include all future nuclear pathways described in this study. This allows two different kind of scenario analysis: if no preferences are set about the nuclear policy to be followed in the future, the model results will make clear which is the most cheaper nuclear pathway according to the environmental (e.g. the amount and typology of nuclear waste) constraints, if any. On the other hand, if the model is forced to follow one of the possible pathways, neither the environmental and economic effects of such a choice can be studied.

From a modeling point of view, each nuclear strategy is obtained by a proper combination of two or more “modules” of NFC model, each having the same structure: the fresh fuel is produced, than “burned” to produce electricity and finally stored or reprocessed. This structure, made clear in Figure 6.1, where the technologies (black box) are liked to each other through input and output commodities (green box), is used for modeling the fuel cycle of each type of power plant; only the values of each parameter are changed from time to time accordingly to the technologies characteristics.

The main peculiarity of this NFC model is the way the fission power plants are handled. So far they have been modelled similarly to all others technologies devoted to electricity production: a nuclear fission power plant could have been schematically represented by a black box with an input commodity (uranium) and an output one (electricity). In the new NFC the nuclear power plants are split in two technologies: the first, denoted as “reactor core” is used in order to calculate the amount and the composition of the waste bred and the heat produced by fission

[13] It must be remembered that fast reactor has been already included among available future technologies but are not yet properly described from an economic point of view; therefore the model run does not consider in the solution so far.

reactions inside the core as well; on the other hand, the second, the technology whose “fuel” is the heat produced by the previous one, is that really producing electricity.

All this given, the data necessary to complete the implementation of such a cycle consequently regard physics, technical and economical aspects of each technology involved: therefore, since the spent fuel composition is of great importance to evaluate the environmental impact and economic sustainability of each strategy, the share of the main groups of elements composing the fuel has to be known starting from the fuel fabrication phase. Then, in order to make the model choose the best technology mix, each one has to be described from a technical and economical point of view so that the electricity consumption or production, the carbon emissions and the overall costs can be derived.

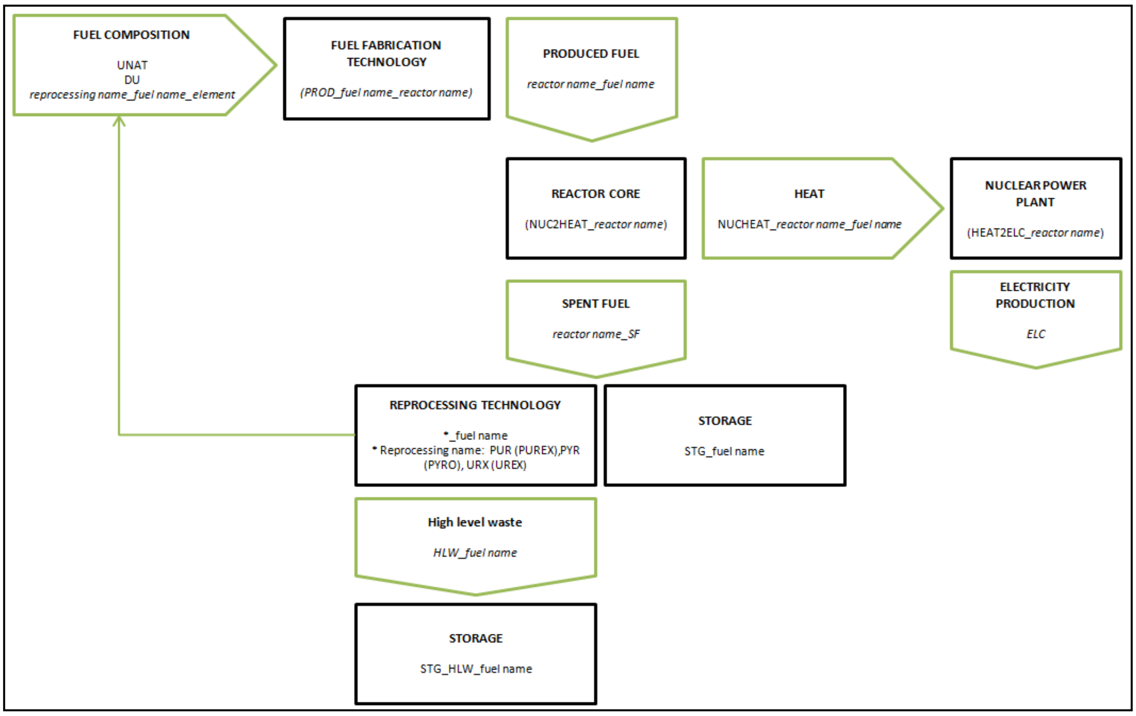


Figure 6.1: Fuel cycle structure.

The commodity balance in each phase of the fuel cycle is described in the first part of this section together with a technical description of each technology: the main data source is the NEA study again, where the fuel composition before and after the irradiation, in each of the future possible nuclear pathways is described. This data allow for the INPUT and OUTPUT declaration in VEDA for each nuclear technology.

The second part is instead devoted to an economic assessment of all nuclear technologies. A special attention to Gen III+ cost evaluation (from which Gen IV costs descend too) is given: because of the large numbers of data about fission power plants investment costs but the lack of information about the items taken into account (discounting year, inclusion of interest during construction or not, etc.) and because of the increasing investment costs trend in the last few years, only one of the more recent literature source has been chosen as reference. Therefore all data about Generation III+ reactors, that means nuclear power plant to be built by 2015, differentiated by country, are taken from “Projected cost of Generating electricity 2010” of NEA/IEA. Moreover the homogeneity of the selected costs to that of other base load power plants in ETM is checked by the CoE (Cost of Electricity) comparison of base loads technologies, fusion included, belonging to the same country.

Similarly, the homogeneity of data about nuclear technologies and nuclear power plants is verified by comparing the weight of front end, back end, investment and uranium price on the cost of electricity derived from a OTC modelling with results described in “The future of the nuclear fuel cycle” by MIT and “Projected cost of generating electricity” analysis.

Finally, to allow the model the nuclear fuel cycle CO_2 emissions calculation, the fuel consumption throughout the fuel cycle is described.

6.1 Nuclear fission fuel cycle scheme

The first nuclear pathway described by NEA is called “once-through strategy” (OTC): at present the most used by worldwide countries, it is characterized by the absence of reprocessing facilities: the spent fuel produced by the light water reactors (LWRs), handled as “waste”, is directly sent to the repository.

However the spent fuel from LWR fuelled by LEU (Low Enriched Uranium), instead of being straight taken to repository could be reprocessed: MOX (Mixed Oxide), obtain by reprocessing the spent fuel of LWR (light water reactors) would be therefore used as fuel in traditional fission power plants.

This policy, here labelled as “MOX production”, nowadays followed by only few countries, allows the plutonium depletion and reduce the volume of waste to be stored, but unfortunately has two main perceived problems: the amount of minor actinides[14] (MA) in the final waste increase comparing to the OTC (2.43% vs 1.75%, [EFDA,2011]) leading to handling materials with higher radioactivity level; moreover plutonium separation and therefore the availability of big amounts of this material might increase the proliferation risk.

In the next years the “MOX production” could lead to the NEA “plutonium burning strategy” that would allow for a multiple recycling of plutonium, thanks to the use of fast reactors (FR) where the plutonium separated from spent MOX is reused to produce a new kind of fuel. It must be underlined that MOX reprocessing is not consider an economic viable solution at the moment: the high amount of heat produced by HLW leads to the use of more expensive technologies for its reprocessing and higher costs for the storage of wastes produced.

In Figure 6.2 a simplified picture of the schemes described above is given using the NEA symbology but the acronyms used in this document (like in all the other fuel cycle schemes displayed from here onwards).

---

[14] Americium, curium and neptunium are defined minor actinides; they constitute a subset of transuranic elements (TRU) that are all that ones with the atomic number higher than 92.

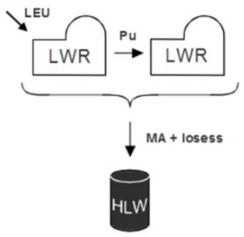
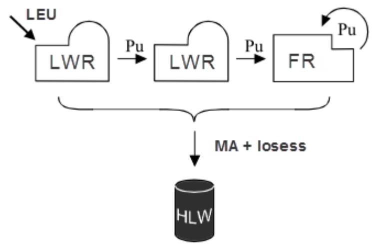
Once through cycle *(nowadays)*	**MOX production** *(nowadays)*	**Plutonium burning** *(available from 2025*)* **[NEA,2002]*
		

Figure 6.2: Possible evolution of the nowadays “Once through cycle strategy” to the “Plutonium burning one” through the “MOX production” strategy.

In order to achieve a sustainable development of nuclear energy systems, it is necessary to use systems closed for plutonium as well as for minor actinides to ensure the minimum natural uranium resource usage and the less as possible long-lived radioactive waste amounts production.

This can be achieve by using the “partitioning and transmutation strategy” (P&T) that aims at reducing the amount of actinides, and thus the radiotoxicity of the high-level waste (HLW) going to disposal: the geological disposal of the spent fuel would be therefore facilitated. Nevertheless such a complex chain would became worthwhile only if a reduction of the long-term radiotoxicity of HLW by a factor of at least one hundred was gained.

The “MOX production” and the “plutonium burning” strategies, even though useful for the management of plutonium, cannot be qualified as transmutation strategy because of the to the absence of minor actinide transmutation [NEA,2002] that leads to a long term radiotoxicity reduction by only a factor of about five compared to the OTC strategy.

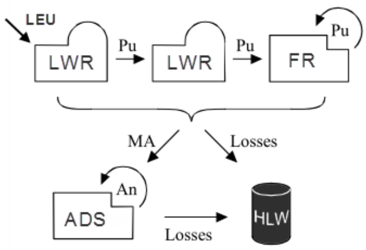
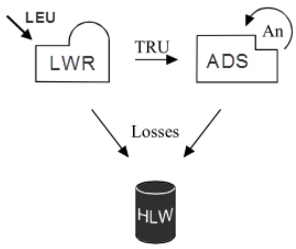
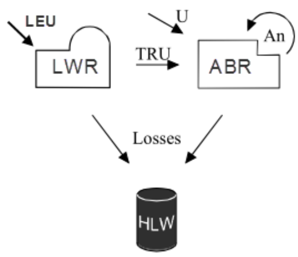
Double strata *(available from 2025*)* **[NS,2010], [WNA,2011a]*	**TRU burning in ADS** *(available from 2025*)* **[NS,2010], [WNA,2011a]*	**TRU burning in FR** *(available from 2030*)* **[ANL,2006]*
		

Figure 6.3: Simplified representation of partitioning and transmutation strategies studied in the NEA study.

On the contrary fast reactors and accelerator driven systems (ADS) that are minor actinides or transuranics (TRU) burners, can give a big contribute in reducing the radiotoxicity level of waste. Both technologies are potentially able to achieve the same reduction, consequently the choice among them is mainly based on economic and safety considerations. In the NEA study the role of ADS and FR in P&T strategy is studied through comparing three fuel cycle (Figure 6.3).

A fourth strategy is finally proposed: since it addresses to both improve the uranium utilization and recycle plutonium and minor actinides through the pyro-reprocessing by the use of only one kind of nuclear power plant (an advanced fast reactor), it represents the long-term goal for the nuclear development (Figure 6.4).

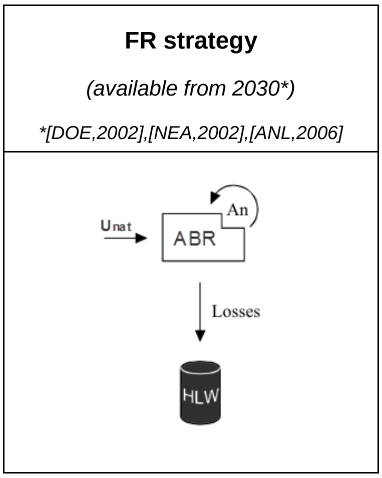


Figure 6.4: Simplified representation of fast reactor strategy.

6.2 Future nuclear power plants technical description

In this section all reactors involved in the strategies discussed above are described from a technical point of view, focusing on the data necessary for the fuel cycle implementation. It must be underlined that, even the ETM base year is 2000, it is assumed that the nuclear strategies described in the previous section can take place since 2010: therefore the technologies involved, labeled as “New technologies” in ETM, belong to the Gen III or IV power plants (see Figure 6.5).

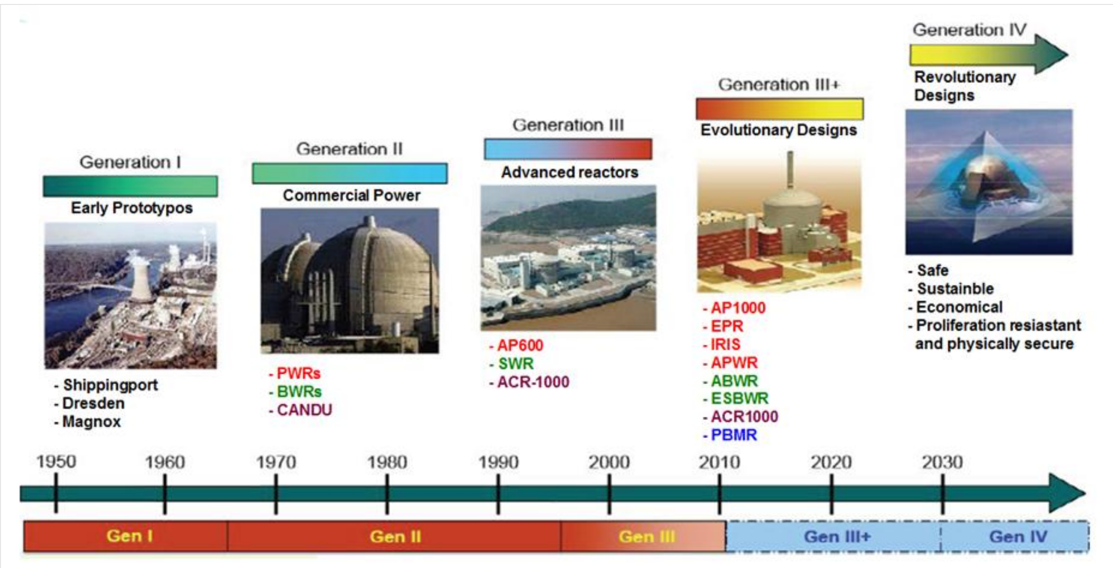


Figure 6.5: Scheme of the temporal evolution of nuclear power plants
(from: http://www.gen-4.org/Technology/evolution.htm and modified by the author)

Reactors are in fact commonly distinguished in 5 groups: the Generation I reactors were developed in 1950-60s, and outside the UK none are still running today. Generation II are typified by the present USA and French fleet and most in operation elsewhere. Generation III (and III+) are Advanced Reactors: the first is in operation in Japan and others are under construction or ready to be ordered. Generation IV designs are still on the drawing board and will not be operational before 2020 at the earliest [WNA,2011a].

The acronyms used to label both commodities and technologies are built according to the rules defined inside each box of Figure 6.1.

6.2.1 Gen III+ (EPR and AP1000)

The EPR (European Pressurized Water Reactor) and AP1000 both belong to Gen III+ reactors so they are both characterized by:

- a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life - typically 60 years,
- further reduced possibility of core melt accidents,
- resistance to serious damage that would allow radiological release from an aircraft impact,
- higher burn-up to reduce fuel use and the amount of waste,
- burnable absorbers (“poisons”) to extend fuel life.
- passive or inherent safety features which require no active controls or operational intervention to avoid accidents in the event of malfunction, and may rely on gravity, natural convection or resistance to high temperatures.

The EPR [AREVA,2011] is a large (4590 MWt, typically 1750 MWe gross and 1630 MWe net) PWR with an evolutionary nuclear reactor design derived from the German Konvoi series and the French N4 series that is expected to provide power about 10% cheaper than the N4.

It has a fuel burn-up[15] of 65 GW_d/t, the highest thermal efficiency of any light water reactor (37%) and a net efficiency of 36%. It is also capable of using a full core load of MOX. Finally the availability is expected to be 92% over a 60-year service life.

The first EPR unit is being built at Olkiluoto in Finland, the second at Flamanville in France, the third European one will be at Penly in France, and two further units are under construction at Taishan in China. A US version, the US-EPR (known as the Evolutionary PWR) quoted as 1710

[15] The burn up is a measure of how much energy is extracted from a primary nuclear fuel source. It is measured as the actual energy released per mass of initial fuel in gigawatt-days/metric ton of heavy metal (GW_d/t_{HM}).

MWe gross and about 1580 MWe net, was submitted for US design certification in December 2007, and this is expected to be granted early 2012.

The AP1000 is an advanced 1200 MWe gross and 1117 MWe net (3415 MWt) PWR developed by Westinghouse. Simplification was a major design objective of the AP1000, in overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems that provides cost savings with improved safety margins. It has a passive core cooling system including passive residual heat removal, improved containment isolation, passive containment cooling system and in-vessel retention of core damage.

It has a 60-year operating life, a fuel burn-up of 60 GW_d/t and a net efficiency of 33%. The capacity factor is estimated to be 93%. Even MOX fuel is not part of the AP1000 GDA (Generic Design Assessment) [HSE,2009], it can be fuelled by up 50% of MOX as demonstrated in [Fetterman,2009].

The generation III+ reactors can be therefore considered an evolution of the existing LWRs with a higher security level that leads to higher investment costs (§ 6.4.1).

In VEDA the EPR is modelled as an advanced LWR with a higher efficiency and burn up rate compared to previous LWRs; it is also allowed to be fully fuelled by MOX. On the other hand, AP1000 is defined as another possible development of the actual nuclear power plant fleet: the main difference between EPR and AP1000 are the investment cost and the amount of MOX that can fuel the core.

The technology attribute used in VEDA to describe the nuclear power plant are made clear in Table 6.1; here the bound on the minimum capacity potentially usable in order to respect the size of real power plants is highlighted too.

Table 6.1: Gen III+ technology attributes in VEDA.

NPP	**TechName**	**START**	**EFF**	**AFA**	**Life**	**Share~UP**		**-**
	Technology name	*Starting year*	*Efficiency*	*Annual availability factor*	*Technolog y Life*	*Upper share between UOX and MOX*		*Size [MWe]*
LWR	HEAT2ELC_LWR	2000	34.2%	85%	50	1	0.5	1450
EPR	HEAT2ELC_EPR	2010	36%	92%	60	1	1	1600
AP1000	HEAT2ELC_AP1000	2010	33%	93%	60	1	0.5	1117

In Table 6.2 the heat produced by the reactor core, related to the burn up level, and the spent fuel production per units of fuel input are exibited: since no mass loss is assumed, the unit of spent fuel is equal to 1 in each reactor analysed.

The spent fuel amount is inferred by the LWR core mass balance pointed out in [EPLF,2003]: it is assumed that the spent fuel composition is the same for the three reactors since the small different element share caused by the different burn up values can be neglected in this framework. Information about the amount of each elements in the spent fuel is fundamental neither if spent fuel is considered as waste and therefore directly sent to the repository or if reprocessing take place. In the first case it allows to estimate the MA amounts, that is the amount of the long-lasting radioactivity elements, strictly related to the dangerous level of the waste; in the second it lets to calculate the amount of plutonium that can be recovered by reprocessing. Moreover the composition of the fresh fuel is also needed in order to model the fuel fabrication technology.

Table 6.2: Gen III+ core attributes in VEDA.

TechName	**Comm-OUT**	**CommDesc**	**Output~FX**
Technology name	*Output commodity name*	*Commodity description*	*Units of comm. output per unit of input comm.**
NUC2HEAT_UOX	NUCHEAT_LWR_UOX		4.32
	NUCHEAT_EPR_UOX	Heat produced by fission reactions inside the core	5.616
	NUCHEAT_AP1000_UOX		5.184
	UOX_SF	Spent fuel	1
NUC2HEAT_MOX	NUCHEAT_LWR_MOX		4.32
	NUCHEAT_EPR_MOX	Heat produced by fission reactions inside the core	5.616
	NUCHEAT_AP1000_MOX		5.184
	MOX_SF	Spent fuel	1

**These values measured in [GJ//t HM] corresponds to a burn up of 50,65,60 GWd/t HM respectively. It is assumed that the burn up rate does not change depending on the use of UOX or MOX.*

In [EPLF,2003] the amount of each fuel components[16] is made clear in each of the four cycle phases: when it is produced (T_0), filled in the vessel (T_1), extracted (T_4) and after cooling (T_5) (see Figure 6.6). These values are calculated through the use of the neutron code APOLLO I – Cesar (*Simplified Evolution Code Applied to Reprocessing*) of CEA (*Commissariat à l'Energie Atomique*): the code can distinguish more than 100 heavy nuclides, 200 fission products and 100 activation products; it can also make depletion calculations from 3 mounts to 1 million years of cooling time.

The starting fuel composition – that is the equilibrium mix – is calculated through the use of another code, called ERANOS: it is assumed that the whole core is changed after a cycle[17], without considering a possible fractionated discharge; after the cooling phase, the fuel is separated and the most part of HM is mixed with fresh uranium to obtain new fuel. For simplicity reasons it is also supposed that the reprocessing and producing phase take place immediately. The iterative calculus stops when the difference in fuel composition – considering only the most important isotopes - is minor than 0.05% after two successive iterations.

---

[16] The elements considered are: uranium, plutonium, niobium, americium and curium isotopes. They can be classified in: Heavy Metals (HM) (uranium and plutonium isotopes), Transuranic Elements (TRU) that are elements with atomic number higher than 92, and Minor Actinides (MA) a subset of TRU, made of americium, curium and neptunium.

[17] Actually the core has a modular structure: the outwards bars usually substitute the inner ones when they are exhausted as the fuel discharge decreases from the core centre to the external.

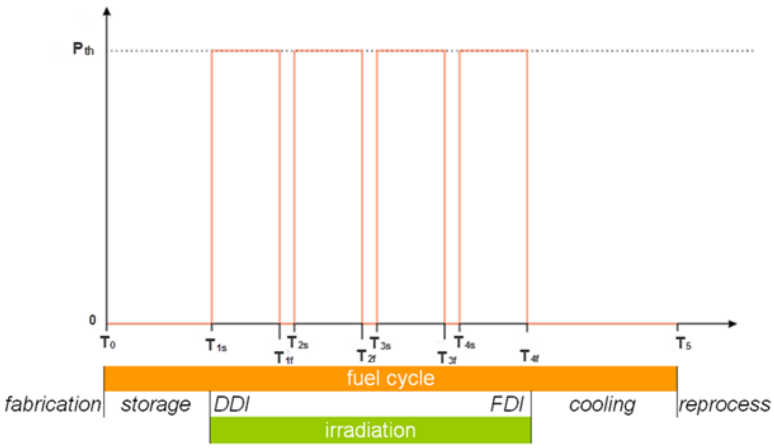


Figure 6.6: Schematic phases description of a single nuclear cycle.

In Table 6.3 the share of U, Pu, MA and fission products (FP) in the fresh and spent fuel (phase T_1 and T_5 respectively) are shown. The data refers to the core of a French PWR-N4 type, characterized by a thermal power of 4240 MW, equipped with a 1450 MWe turbine generator. The fuel is enriched to 4.2% ^{235}U and then irradiated till an average burn-up of 50.05 GW_d/t_{HM} is reached[18]. For the sake of simplicity, in the fuel cycle implementation the same enrichment value is assumed for each kind of light water reactors: actually the EPR needs a 4.5% enriched fuel and on the other hand the AP1000 can works with a 2.35-4.8% enriched UOX.

Table 6.3: Fresh and spent fuel composition of a French PWR-N4 fuelled by UOX, assumed valid for both EPR and AP1000 in the model. This LWR takes part in all the fuel cycles except for the integral fast reactor strategy.

ELEMENT	**Input commodity of fuel technology**	**Commodity description**	**Fresh Fuel composition**	**Commodity name**	**Spent fuel composition**
Uranium	235U	^{235}U	4.25%	DRIV_U	93.5%
	238U	^{238}U	95.75%		
	Total		*100%*		
TRU	-			DRIV_Pu	1.2%
				DRIV_MA	0.15%
	Total		*0%*		*1.35%*
FP	-			DRIV_FP	5.14%

Table 6.4 points out the MOX fuel composition before and after the irradiation in the same kind of LWRs: the plutonium amount comes from the reprocessing technology assumed to be PUREX.

[18] This means that one fifth of the core is replaced with new fuel about each mounts.

Table 6.4: Fresh and spent fuel composition of a French PWR-N4 fuelled by MOX, assumed valid for both EPR and AP1000 in the model; it takes part to both the plutonium burning strategy and to the double strata strategy.

ELEMENT	**Input commodity of fuel technology**	**Commodity description**	**Fresh Fuel composition**	**Commodity name**	**Spent fuel composition**
Uranium	DU	Depleted uranium	91.9%	DRIV_U	88.68%
TRU	PUR_LEU_Pu	Pu from LWR spent fuel reprocessing (PUREX)	12.21%	DRIV_Pu	5.15%
				DRIV_MA	0.74%
	Total				*5.89%*
FP	-			DRIV_FP	5.07%

6.2.2 Fast reactors plutonium burners

In [EPLF,2003] the fast reactor under study is CAPRA (Consommation améliorée de Plutonium dans les rapides) HBU (High Burn Up) kind: it is cooled by sodium, as usual in fast reactors in order to avoid any neutron moderator and provide a very efficient heat transfer medium [WNA,2011a], and fuelled by a mixture of uranium and plutonium (a MOX kind fuel). The core is built in a way so that the burn-up value raises to 185 GW_d/t HM and the losses are reduced. The CAPRA core contains 25.7 tons of HM: it is subdivided in two concentric regions with different enrichment degree in order to make the power production smooth: the inner is enriched with a 38.1% of plutonium, the outer with a 41%; since its breeding ratio is null, it means that it is a burner reactor, that is it consumes more fissile material (235U, Pu and MA) than they consume [WNA,2011a]: for this reason it can be used in a plutonium depletion policy. Finally it is featured by a thermal power of 3600 MWth and an electric one of than 1450 MWe.

The technical data used in the model, according to the assumptions in [EPLF,2003], are made clear in Table 6.5; the only not available data is the forecasted lifetime: it was therefore decided to assume it equal to that of advanced LWR (EPR and AP1000).

Table 6.5: Fast reactors plutonium burners technology attributes in VEDA.

NPP	**TechName** *Technology name*	**START** *Starting year*	**EFF** *Efficiency*	**AFA** *Annual availability factor*	**Life** *Technolog y Life*	**Share~UP** *Upper share between UOX and MOX*		**-** *Size [MWe]*
CAPRA	HEAT2ELC_FR	2025	40.28%	85%	60	0	1	1450

The assumed burn up is 185 GW_d/t HM that means 15.984 GJ/t_{HM}; again the spent fuel mass is equal to the initial loading one since no mass loss is assumed. These data are collected in

Table 6.6.

With reference to Figure 6.2, the fresh fast reactor fuel is made of elements coming from a LWR and from its spent fuel: both are separated from the spent fuel through the PUREX technology. Table 6.7 makes clear the contribute of each spent fuel in the fast reactor fuel fabrication phase.

Table 6.6: FR core attributes in VEDA.

TechName	Comm-OUT	CommDesc	Output~FX
Technology name	*Output commodity name*	*Commodity description*	*Units of comm. output per unit of input comm.**
NUC2HEAT_FRF	NUCHEAT_FR_FRF	Heat produced by fission reactions inside the core	15.984
	FRF_SF	Spent fuel	1

Table 6.7: Fresh and spent fuel composition of a CAPRA HBU fast reactor MOX fuelled; it takes part to both the plutonium burning strategy and to the double strata strategy.

ELEMENT	INPUT COMM. OF FUEL TECH.	COMMODITY DESCRIPTION	FRESH FUEL COMPOSITION	COMMODITY NAME	SPENT FUEL COMPOSITION
U	DU	Depleted uranium	8.98%	DRIV_U	46.59%
	PUR_FRF_U	Uranium from spent fuel reprocessing (PYRO)	46.59%		
	Total		*55.57%*		
TRU	PUR_MOX_Pu	Pu from MOX reprocessing (PUREX)	12.21%	DRIV_Pu	32.25%
	PUR_FRF_Pu	Pu from FRF reprocessing (PUREX)	32.23%	DRIV_MA	2.73%
	Total		*44.43%*		*34.98%*
FP	-			DRIV_FP	18.43%

6.2.3 Advanced burner reactor

The fast reactor model of both strategies “TRU burning in FR” and “FR strategy” is an advanced liquid metal reactor (ALMR), the same as that used in the 600 MWe, metal-fuelled, multiple recycle burner core benchmark exercise of the NEANSC Working Party on Plutonium Recycling [OECD,1995], [OECD,1996]. They belong to the Integral fast Reactor (IFR) concept that aims to demonstrating improved management of high level nuclear wastes by recycling all the actinides, so that only fission products remain as HLW [WNA,2011a], improving the uranium utilisation and, to this end, substitutes LWRs by fast reactors at a large scale.

In the first strategy the reactor is an actinide burner with a conversion ratio of 0.5 (advance burner reactor – ABR). Its feed consists of depleted uranium and TRU from the LWR discharged UOX fuel reprocessed by a pyrometallurgical technology; it is assumed that the LWR spent fuel is cooled for about three years prior to reprocessing and that the fast reactor fuel contains all TRU admixed together (Pu plus MA). The TRU content of the fuel for the equilibrium core is 33% at beginning-of-life.

The technical data about the ABR are taken from [NEA,2002] and the starting year from [ANL,2006]; both are made clear in Table 6.8. As for fast reactors MOX fuelled, a 60 years lifetime is assumed.

The burn up capability of different types of MA- and TRU-dominated fuels has not yet been verified experimentally and is therefore uncertain. Since the MA waste production depends on the burn up value, the use of project-specific burn up rate necessary for the core mass balance calculation, could lead to a not realistic comparison between the six strategy if the MA production is compared. If this is the case, the minor actinides production should be scaled in order to compare reactors with the same burn up value. The nominal burn up of the ABR is 139 GWd/t_{HM} (see Table 6.9); the minor actinides waste production should be multiplied by 0.99[19] if scaled to a reactor with a 140 GWd/tHM burn up.

Table 6.8: ABR technology attributes in VEDA.

NPP	TechName *Technology name*	START *Starting year*	EFF *Efficiency*	AFA *Annual availability factor*	Life *Technology Life*	Share~UP *Upper share between UOX and MOX*		- *Size [MWe]*
ABR	HEAT2ELC_ABR	2025	38.1%	85%	60	-	-	600

According to the "FR TRU burning", the fresh fuel is made of depleted uranium (DU), TRU from LEU spent fuel reprocessed by UREX technology and uranium and of TRU extracted by spent ABR fuel through pyroprocessing (Table 6.10).

Table 6.9: ABR core attributes in VEDA.

TechName *Technology name*	Comm-OUT *Output commodity name*	CommDesc *Commodity description*	Output~FX *Units of comm. output per unit of input comm.**
NUC2HEAT_ABR	NUCHEAT_FR_ABR	Heat produced by fission reactions inside the core	12.01
	ABR_SF	Spent fuel	1

Table 6.10: Fresh and spent fuel composition of a ABR; it takes part to the fast reactor TRU strategy.

ELEMENT	INPUT COMM. OF FUEL TECH.	COMMODITY DESCRIPTION	FRESH FUEL COMPOSITION	COMMODITY NAME	SPENT FUEL COMPOSITION
U	DU	Depleted uranium	6.96%	DRIV_U	59.91%
	PYR_ABRF_U	Uranium from spent fuel reprocessing (PYRO)	60.04%		
	Total				*59.91%*
TRU	URX_TRU	TRU from LWR spent fuel reprocessing (UREX)	7.07%	DRIV_Pu	22.84%
	PYR_ABRF_TRU	TRU from ABR spent fuel reprocessing (PYRO)	26.04%	DRIV_MA	3.11%
	Total		*%*		*25.96%*
FP	-			DRIV_FP	14.13%

[19] The formula used for the multiplier calculation is [EPLF,2003] : $\frac{1\text{-}B_n}{B_n}\frac{B_{ref}}{1\text{-}B_{ref}}$ where B_n is the new burn up value and B_{ref} the burn up of reference.

6.2.4 Integral fast reactor

This reactor is of the same kind of that in the previous strategy, that is ALMR, but has a different core geometry (the lower steel reflector and the outermost fuel element ring are replaced by uranium blankets, see Figure 6.7) that makes it a self-sustained reactor (its breeding ratio (BR) is equal to 1). The fuel and the blankets are reprocessed together, the new blankets are fabricated from reprocessed uranium, and the new fuel is fabricated from reprocessed TRU, reprocessed uranium and a natural uranium top-up [NEA,2002].

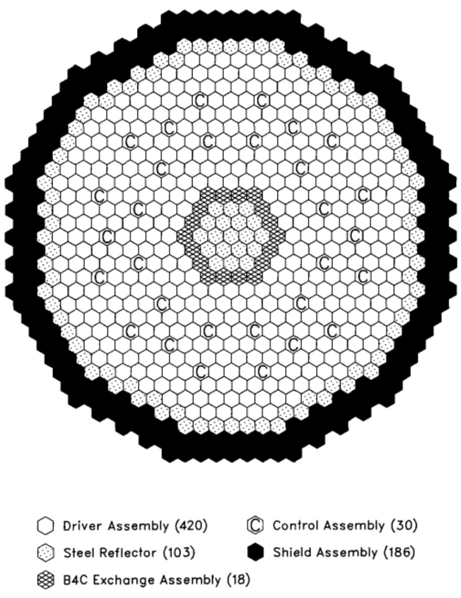
From a modeling point of view, no distinction is made between blanket and driver: their sum is considered to be the fuel of the fast reactor. For this reason an equivalent burn up, referred to the entire core, is used: instead of using the nominal driver burn up value (139 GWd/t_{HM}), a lower one (50 GWd/t_{HM}) is therefore declared in VEDA table (see Table 6.12).

The reactor technical data used in VEDA are the same of the reactor described in 6.2.3 (see Table 6.11). The only difference is the breeding ratio whose influence clearly appears in the mass balance (Table 6.13).

Moreover it is supposed that an integral fast reactor strategy, that means the shut-down of the most of the current light water reactors will take place from 2030 as declared in [NEA,2002], [DOE,2002], [ANL,2006]. The same hypothesis of the ABR about the technology life is used.

ABR

ALMR, CR = 0.5



IFR

ALMR, CR = 1

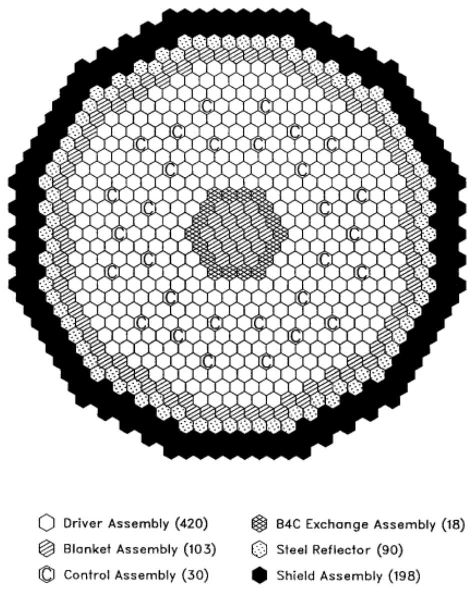


Figure 6.7: Geometry of a breeding ratio 0.5 and 1 core of an advanced liquid metal reactor.

Table 6.11: IFR technology attributes in VEDA.

NPP	TechName	START	EFF	AFA	Life	Share~UP	-
	Technology name	*Starting year*	*Efficiency*	*Annual availability factor*	*Technology Life*	*Upper share between UOX and MOX*	*Size [MWe]*
IFR	HEAT2ELC_IFR	2030	38.1%	85%	60	- -	600

Table 6.12: IFR core attributes in VEDA.

TechName	Comm-IN	Input~FX	Comm-OUT	CommDesc	Output~FX
Technology name	*Fuel name*	*Units of input*	*Output commodity name*	*Commodity description*	*Units of comm. output per unit of input comm.**
NUC2HEAT_IFR	DRIV_IFR	35.60%	NUCHEAT_FR_IFR	Heat produced by fission reactions inside the core	4.32
	BLK_IFR	64.40%			
			IFR_SF	Spent fuel	1

Table 6.13: Fresh and spent fuel composition of the IFR core(driver and blanket); it takes part to the fast reactor strategy.

ELEMENT	INPUT COMM. OF FUEL TECH.	COMMODITY DESCRIPTION	FRESH FUEL COMPOSITION	COMMODITY NAME	SPENT FUEL COMPOSITION
U	UNAT	Natural uranium	14.38%	DRIV_U	68.40%
	PYR_DRIV_U	Uranium from driver reprocessing (PYRO)	61.75%		
	Total		*76.13%*		*68.40%*
TRU	PYR_DRIV_TRU	TRU from driver reprocessing (PYRO)	23.56%	DRIV_Pu	18.01%
				DRIV_MA	0.67%
	Total		*23.56%*		*18.68%*
FP	-			DRIV_FP	12.92%
U	PYR_BLK_U	Uranium from blanket reprocessing (PYRO)	100%	BLK_U	92.72%
	Total		*100%*		*92.72%*
TRU	-		-	BLK_Pu	2.70%
				BLK_MA	0.01%
	Total		*0%*		*2.71%*
FP	-			BLK_FP	0.56%

6.2.5 Accelerator driven system

The transmutation of long-lived radioactive waste [WNA,2010b] can be carried out in an accelerator-driven system (ADS), where neutrons produced by an accelerator are directed at a blanket assembly containing the waste along with fissionable fuel. Following neutron capture, the heavy isotopes in the blanket assembly subsequently fission, producing energy in doing so.

The ADS principle of functioning can be described as follow: a beam of high-energy protons (usually >500 MeV) is directed at a high-atomic number target (*e.g.* tungsten, tantalum, depleted uranium, thorium, zirconium, lead, lead-bismuth, mercury) and up to one neutron can be produced per 25 MeV of the incident proton beam. These, called spallation neutrons, have only a very small probability of causing additional fission events in the target. However, the target still needs to be cooled due to heating caused by the accelerator beam. If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or thorium-232 which can breed to U-233), there is a possibility of sustaining a fission reaction.

In such a system, the neutrons produced by spallation would cause fission in the fuel, assisted by further neutrons arising from that fission. Up to 10% of the neutrons could come from the spallation, though it would normally be less, with the rest of the neutrons arising from fission events in the blanket assembly. An ADS can only run when neutrons are supplied to it because it burns material which does not have a high enough fission-to-capture ratio for neutrons to maintain a fission chain reaction. One then has a nuclear reactor which could be turned off simply by stopping the proton beam, rather than needing to insert control rods to absorb neutrons and make the fuel assembly subcritical. Because they stop when the input current is switched off, accelerator-driven systems are seen as safer than normal fission reactors.

An ADS can be used to destroy heavy isotopes contained in the used fuel from a conventional nuclear reactor – particularly actinides. Here the blanket assembly is actinide fuel and/or used nuclear fuel. One approach is to start with fresh used fuel from conventional reactors in the outer blanket region and progressively move it inwards. It is then removed and reprocessed, with the uranium recycled and most fission products separated as waste. The actinides are then placed back in the system for further ‘incineration’.

Another area of current interest in the use of ADSs is in their potential to dispose of weapons-grade plutonium, as an alternative to burning it as mixed oxide fuel in conventional reactors. Two alternative strategies are envisaged: the plutonium and minor actinides being managed separately, with the latter burned in ADSs while plutonium is burned in fast reactors, and the plutonium and minor actinides being burned together in ADSs, providing better proliferation resistance but posing some technical challenges. Both can achieve major reduction in waste radiotoxicity, and the first would add only 10-20% to electricity costs (compared with the once-through fuel cycle).

Two kind of ADS are analysed in the NEA study: in the double strata strategy it is used to burn the MA from the spent fuel of the plutonium burning strategy reactors chain; in the transuranic burning strategy it is instead assumed that the accelerator driven systems are driven in order to burn the spent fuel from light water reactors. In both cases the aim is reducing the long live radioactivity content in the fuel to be definitely stored.

A prototype of an ADS is planning to be built in Belgium. The reactor name will be MYRRHA (Multipurpose Hybrid Research Reactor for High tech Applications) and it will be initially a 57 MWt accelerator driven system, consisting of an accelerator delivering a 6000 MWe proton beam to a liquid lead-bismuth spallation target; later it is intended to be run a s a critical fat reactor facility, decoupling the accelerator and removing the spallation loop from the reactor core.

Since the main reason why the ADS system is used in the double strata strategy is that of lowering the dangerous level of spent fuel and not to produce electricity, the related capacity is smaller than that of the ADS in the transmutation strategy that has to concur in electricity production.

The technical data of both reactors are given in Table 6.14 and Table 6.15; the starting year are in line with the technology deployment forecast presented in [NS,2010] and [WNA,2011a]. The assumed burn up is 250 GWd/t HM if TRU are burned, 140GWd/t HM if MA (Table 6.16 and Table 6.17).

Table 6.14: MYR technology attributes in VEDA.

NPP	**TechName**	**START**	**EFF**	**AFA**	**Life**	**Share~UP**		**-**
	Technology name	*Starting year*	*Efficiency*	*Annual availability factor*	*Technology Life*	*Upper share between UOX and MOX*		*Size [MWe]*
ADS	HEAT2ELC_MYR	2025	35.31%	85%	60	-	-	119

Table 6.15: ADS technology attributes in VEDA.

NPP	**TechName**	**START**	**EFF**	**AFA**	**Life**	**Share~UP**		**-**
	Technology name	*Starting year*	*Efficiency*	*Annual availability factor*	*Technology Life*	*Upper share between UOX and MOX*		*Size [MWe]*
ADS	HEAT2ELC_ADS	2025	32.74%	80%	60	-	-	275

Table 6.16: MYR core attributes in VEDA.

TechName	**Comm-OUT**	**CommDesc**	**Output~FX**
Technology name	*Output commodity name*	*Commodity description*	*Units of comm. output per unit of input comm.**
NUC2HEAT_MYR	NUCHEAT_MYR_TRU	Heat produced by fission reactions inside the core	21.6
	MYR_SF	Spent fuel	1

Table 6.17: ASD core attributes in VEDA.

TechName	**Comm-OUT**	**CommDesc**	**Output~FX**
Technology name	*Output commodity name*	*Commodity description*	*Units of comm. output per unit of input comm.**
NUC2HEAT_ADS	NUCHEAT_ADS_MA	Heat produced by fission reactions inside the core	12.096
	ADS_SF	Spent fuel	1

In the transuranic burning strategy the spent fuel of light water reactors is reprocessed by UREX process that leads to the separation of the all TRU from the irradiated fuel. This, together with the uranium and other transuranic elements coming from the pyroporcessing of the core of ADS, are used to produce fresh fuel for the ADS reactor. The related mass balance is made clear in Table 6.18.

Table 6.18: Fresh and spent fuel composition of the MYR core; it takes part to the transuranic burning reactor strategy.

ELEMENT	INPUT COMM. OF FUEL TECH.	COMMODITY DESCRIPTION	FRESH FUEL COMPOSITION	COMMODITY NAME	SPENT FUEL COMPOSITION
U	PYR_MYR_U	U from MYR spent fuel reprocessing (PYRO)	1.16%	DRIV_U	1.21%
TRU	URX_TRU	TRU from LWR spent fuel reprocessing (UREX)	24.93%	DRIV_Pu	60.20%
	PYR_MYR_TRU	TRU from MYR spent fuel reprocessing (PYRO)	73.91%	DRIV_MA	13.69%
	Total		*98.84%*		*73.89%*
FP	-			DRIV_FP	24.90%

In the double strata strategy, ADS are used as "incineration device" that burn the spent fuel of a plutonium burning strategy. The fresh fuel of the ADS is therefore made of the MA extract through the use of an advance PUREX technology that allows the separation of MA from the rest of the spent fuel, and the uranium and transuranic elements from the ADS fuel reprocessing (Table 6.19).

Table 6.19: Fresh and spent fuel composition of the ADS core; it takes part to the double strata strategy.

ELEMENT	INPUT COMM. OF FUEL TECH.	COMMODITY DESCRIPTION	FRESH FUEL COMPOSITION	COMMODITY NAME	SPENT FUEL COMPOSITION
U	PYR_ADS_U	U from ADS spent fuel reprocessing (PYRO)	4.63%	DRIV_U	4.62%
TRU	REP_MA	MA from LWR and FR spent fuel reprocessing (advanced PUREX)	15.06%	DRIV_Pu	40.46%
	PYR_ADS_TRU	TRU from ADS spent fuel reprocessing (PYRO)	80.30%	DRIV_MA	39.94%
	Total		*95.36%*		*80.40 %*
FP	-			DRIV_FP	14.98%

6.3 Reprocessing facilities

In this section a short description of reprocessing technologies used in the strategies discussed above is carried out. Moreover, a mass balance is inferred from the analysis of the mass flows in each of the schemes in [EPLF,2003] depicting in a schematic way the six strategies.

6.3.1 PUREX

The name is the acronymic for plutonium uranium extraction: it is a well-proven and the most currently used hydrometallurgical process used to separate plutonium and uranium from other fuel components.

After a phase called "de-cladding" used to open or dissolve the cladding in order to expose the contents of the irradiated uranium fuel, a dissolution phase takes place where the fuel elements are dissolved in concentrated nitric acid; it must be underlined that both processes release radioactive gases.

After that, the chemical separation of uranium and plutonium is made by the exposition to a solvent called "*tributyl phosphate*" (TBP) mixed with kerosene: it selectively separates out the plutonium and uranium from the fission products, generating a solution of plutonium nitrate and uranium nitrate. The plutonium and uranium recovered can be returned to the input side of the fuel cycle - the uranium to the conversion plant prior to re-enrichment and the plutonium straight to MOX fuel fabrication.

The remaining liquid after plutonium and uranium removing is a high-level waste, containing about 3% of the used fuel in the form of fission products and minor actinides (Np, Am, Cm). It is highly radioactive and continues to generate a lot of heat. It is conditioned by calcining and incorporation of the dry material into borosilicate glass, then stored pending disposal. In principle any compact, stable, insoluble solid is satisfactory for disposal [WNA,2010c].

This process is used in the plutonium burning strategy and in the double strata strategy in order to reprocess the spent fuel of light water reactors fuelled by LEU or MOX and that of fast reactors fuelled by MOX.

An efficiency of 99.9% in uranium and plutonium recovery is assumed: therefore the technology plutonium and uranium output is a fixed share of the input (the uranium and plutonium share in the spent fuels are made clear in the tables above). On the other hand, the HLW composition depends on the kind of fuel reprocessed: the reprocessing waste composition is therefore made clear for each three cases.

It is important to note that PUREX technology can reprocess fuel with a plutonium content up to 30% since an higher amount inhibits the plutonium dissolution.

Table 6.20: Elements share of the output of a PUREX facility, subdivided in recovered elements and wastes.

		Fuel reprocessed		
		LEU	**MOX**	**FRF**
Elements recovered	**Plutonium**	1.2%	5.51%	32.22%
(99.9% efficiency is assumed)	**Uranium**	93.39%	88.66%	46.54%
HLW composition	**HLW_U**	0.09%	0.09%	0.05%
	HLW_Pu	0%	0.01%	0.03%
	HLW_MA	0.15%	0.74%	2.73%
	HLW_FP	5.17%	5.00%	18.43%

6.3.2 UREX

A variation of the PUREX process [WSRC,2003] was conceived to provide the ability to treat large quantities of spent nuclear fuel and to provide the selectivity required for the process.

The PUREX process was therefore modified so that only uranium and technetium (Tc) are extracted and the TRU isotopes are rejected to the aqueous raffinate with the fission products. This uranium extraction process is called UREX.

The goals for the UREX process are to recover more than 99.9 % of the U and more than 95 % of the Tc in separate product streams while rejecting >99.9 % of the TRU isotopes to the raffinate. The process must also minimize the waste volume by converting all chemicals to gases during subsequent processing.

The central feature of this system is to increase proliferation resistance by keeping the plutonium with other transuranics - all of which are then destroyed by recycling in fast reactors.

Several variations of such a technology are under study with the differences being in how the plutonium is combined with various minor actinides. The US Department of Energy is developing the UREX+ where only uranium is recovered initially for recycle and the residual is treated to recover plutonium with other transuranics. The fission products then comprise most of the high-level waste. UREX+1a combines plutonium with three minor actinides, but this gives rise to problems in fuel fabrication due to americium being volatile and curium a neutron emitter. Remote fuel fabrication facilities would therefore be required, leading to high fuel fabrication costs and requiring significant technological development. UREX+3 leaves instead only neptunium with the plutonium and the result is closer to a conventional MOX fuel; however, it is less proliferation-resistant than UREX+1a.

In the fuel cycle schemes a generic Reprocessing technology that divide uranium from transuranic is considered. The UREX technology is used in the transuranic burning strategies (burning in fast reactors and in ADSs): in both cases the input fuel is the irradiated LEU from a LWR. The uranium recovered is the 99.9% of the uranium in the LWR UOX fuelled spent fuel (that is 93.5% of the entire amount of HM – see Table 6.3): its share in the output is therefore 93.4%. The elements share in the HLW is made clear in Table 6.21.

Table 6.21: Elements share of the output of a UREX facility, subdivided in recovered elements and wastes.

		Fuel reprocessed
		LEU
Elements recovered *(99.9% efficiency is assumed)*	**Uranium**	93.4%
	Plutonium	1.19%
	Minor Actinides	0.15%
HLW composition	**HLW_U**	0.09%
	HLW_Pu	0.001%
	HLW_MA	0.0001%
	HLW_FP	5.17%

6.3.3 Pyroprocessing

Pyroprocessing is an electrolytic/electrometallurgical processing techniques used to separate the actinides from a radioactive waste stream; it has been under development in the US Department of Energy laboratories, notably Argonne, as well as by the Korea Atomic Energy

Research Institute (KAERI).

Such processes are at an early stage of development compared with hydrometallurgical processes already operational; unlike PUREX that handles spent fuel cooled 7 years at least[20], this technique can readily be applied to high burn-up fuel and fuel which has had little cooling time (2 years), since the operating temperatures are high already.

The actinides contained are separated by the use of electrodeposition on a cathode in a fused salt bath: therefore it involves all the positive ions without the possibility of chemical separation of heavy elements such as in PUREX and its derivatives. This cathode product can then be used in a fast reactor: nevertheless only one electrometallurgical technique has been licensed for use on a significant scale so far.

The pyroprocessing technology is used for FR spent fuel reprocessing; in order to use it to reprocess ADS spent fuel, it has to be further developed to tolerate from ten to more than twenty times higher decay heat levels than those encountered in the pyrochemical reprocessing of fast reactor fuels.

Moreover due to the high radioactivity of FR-MOX fuel, its handling will require measures to be taken to reduce the radiation doses in the fabrication plant and during the transportation of the fuel assemblies: the increased requirements for shielding, and the preference for short transportation paths, of multiple recycled fuels also favour the pyrochemical reprocessing method at the reactor site instead of using PUREX process.

A striking feature is that the pyroprocessing requirement of the all-FR scheme is much higher than that of the transmutation schemes. This is a consequence of accommodating the driver and the blanket fuel in the same fuel rod and blending the two components before processing. The blending has the advantage of reducing the decay heat of the fuel to be reprocessed and increasing the proliferation resistance of the system, but imposes high fuel throughput, and hence also economic, penalties on the scheme. These penalties could be reduced if the blanket were separated from the driver fuel and reprocessed using PUREX or UREX technology.

This technology is used in four nuclear strategies: the double strata, the TRU burning in FR and ADS and finally in FR strategy. It is assumed that the reprocessing facility is placed in the same site of the NPP. The HLW composition and the output share of recovered uranium and transuranics are made clear in Table 6.22; again, a 99.9% efficiency is assumed.

It must be highlighted that the output shares are strictly related to the fresh fuel composition; moreover it should be remembered that a comparison of the amount of waste production between different fuel cycles has to be carried out normalizing the mass flow inferred from shares to the electricity production.

---

[20] Reprocessing of this fuel within short cooling times and with the required high recovery yields, however, will require the plutonium dissolution yield to be improved and the PUREX process to be modified [NEA,2002].

Table 6.22: Elements share of the output of a PYRO facility, subdivided in recovered elements and wastes.

		Fuel reprocessed			
		ABRF	FRF	MYR	ADSF
Elements recovered	**Uranium**	59.98%	86.12%*	1.16%	4.36%
(99.9% efficiency is assumed)	**TRU**	26.01%	8.38%	73.9%	80.31%
HLW composition	**HLW_U**	0.06%	0.09%	0.001%	0.0043%
	HLW_Pu	0.02%	0.01%	0.06%	0.04%
	HLW_MA	0.003%	0.0003%	0.01%	0.04%
	HLW_FP	13.93%	5.4%	24.85%	14.98%

* Recovered uranium from blanket and driver.

6.3.4 Advanced PUREX

The advanced PUREX process refers to a generic future technology that will be able to achieve the complete MA separation from the irradiated fuel. To gain this, a modification of the standard PUREX process is needed. Neptunium can be easily taken out from the spent fuel jointly to uranium or plutonium: the chemical reduction or oxidation make its chemical valence changing from V to IV or VI, that are respectively the same valence of plutonium and uranium. Subsequently NP is reduced (or oxidized) to a V valence in order to be separated from plutonium or uranium.

Since americium and curium have a different chemical valence (III) a different chemical process has to be used to separate them from the other FP: some variations of this exist (DIAMEX; TRUEX; TRPO or DIDPA) that firstly takes out Am and Cm together with lanthanides, then isolate actinides by using proper reagents [EPLF,2003].

Table 6.23: Elements share of the output of a advanced PUREX facility, subdivided in recovered elements and wastes.

		Fuel reprocessed		
		LEU	MOX	FRF
Elements recovered	**Plutonium**	1.2%	5.51%	32.23%
	Uranium	93.39%	88.66%	46.54%
	MA	0.15%	0.74%	2.72%
HLW composition	**HLW_U**	0.09%	0.09%	0.05%
	HLW_Pu	0.002%	0.01%	0.03%
	HLW_MA	0.0001%	0.0028%	0.0028%
	HLW_FP	5.17%	5.00%	18.43%

However, at the moment, the most part of the methods described are only laboratory tests and the separation rate is at experimental level.

Such a reprocessing technology is used only in the double strata scheme, where the spent fuels from LWR fuelled by LEU or MOX and from FR are reprocessed in order to withdraw the MA from FP, U and Pu. The inferred mass balance is shown in Table 6.23: if compared to Table 6.20 referring to PUREX technology, it can be easily noted that the shares of MA is the only difference between the two processes: the minor actinides content in the HLW is nearly zero in the last since it is assumed that the most part of them can be recovered.

6.4 NPPs and nuclear facilities economic assessment

In addition to a technical description of nuclear facilities involved in the NEA strategies, an economic assessment is necessary too, in order to define the investment and O&M costs of each technology. Moreover decommissioning and interests during construction costs will be considered as well because of their influence on the cost of electricity. In order to make the nuclear technology comparable with others, the leading time of all others new technologies, necessary to the model to calculate the amount of IDC has been declared.

6.4.1 LWR, EPR and AP1000 costs.

An extensive research has been carried out to collect data about the costs of current and next nuclear power plants: although the large literature on this items, the investment cost declared by companies are not always comparable. The main reason is the lack of information about the cost components taken into account.

Generally, the amount of money necessary to build a nuclear power plant is used to be expressed as *overnight cost*, that is amount of money that would be necessary if the nuclear plant was built in a night, or as *investment cost*, higher than the former since it comes from adding interests during construction up the overnight cost.

According to [MIT,2009] four different kind of cost are usually declared in economical studies:

1. *The vendor EPC overnight cost, discounted to the current year*:

   It is the amount of money necessary to remunerate the engineering, procurement and construction contract (EPC) costs.

2. *Overnight cost.*

   It is the sum of the vendor EPC overnight cost and owner's cost, discounted to the current year, inflation included. This is instead the overnight cost to which both the MIT studies (from 2003 to 2009) and the [IEA/NEA,2010] ones refer when calculating the LCOE.

3. *Total cost, capital recovery charge excluded, in nominal currency as expended*.

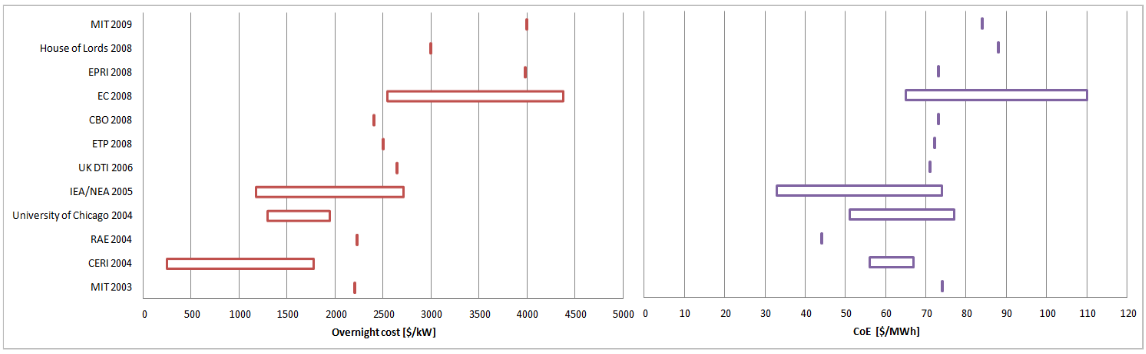
   It is the sum of the vendor EPC overnight costs, the owner's costs and the transmission system upgrade costs at a specific inflation rate but without discounting to the current year. Moreover, the interests during construction are not included.

4. *Total cost, capital recovery charge included.*

   It differs from the latter because the charge of the interest along the lead time is also taken into account.

The lack of uniformity in declaring costs, together with an incomplete description of the cost components, has lead to a nuclear power plants cost inventory quite inhomogeneous [Osouf,2007]. Moreover, since 2003 construction costs for all types of large-scale engineered projects have escalated dramatically: “*[...] The estimated cost of constructing a nuclear power plant has increased at a rate of 15% per year heading into the current economic downturn. This is based both on the cost of actual builds in Japan and Korea and on the projected cost of new plants planned for in the United States [...]* ” [MIT,2009]. Because of both reasons a comparison among overnight costs and LCOE resulting from the main studies from 2003 to 2009 highlights a quite wide range of possible values whose upper limit increases over years (Figure 6.8).

Figure 6.8: Overnight cost and related cost of electricity in twelve studies from 2003 to 2009 (data from [IEA/NEA,2010]).



For such reason, in this framework, it was decided to refers to only the more recent IEA/OECD study ([IEA/NEA,2010]): it focus on the costs of fossil, nuclear and renewable technologies that are expected to be commissioned by 2015 and compares the related cost of electricity.

With regards to nuclear technologies, the *Projected Cost of Generating Electricity*, that is the main source of the Energy Technologies Perspectives ([IEA,2010]) as well, presents costs of Gen III+ nuclear power plants. The cost data of 18 planned nuclear power plants (PWR, ABWR and a generic LWR Gen III+) of 11 countries (8 OECD member countries and 3 non-OECD countries) and 2 companies are listed; the costs refers to 2008 USD and two different possible discount rates (5% and 10%) are assumed. Since the ETM hurdle rate assumed for nuclear power plants is 10%, only data referring to this value have been taken into account. This hurdle rate, that corresponds the weighted average cost of capital (WACC) and declared to be a quite realistic value in [Keppler,2010], reflects a 50/50 equity to debt ratio, according to the equation 6.4.1:

$$WACC = debt\ fraction * debt\ rate + (1 - debt\ fraction) * equity\ rate \qquad 6.4.1$$

In *Projected Cost of Generating Electricity* a median overnight value of 4102 $\$_{2008}$/kW has been chosen to represent a generic worldwide Gen III+ reactor of OECD countries.

In Table 6.24 the overnight and O&M costs of the next future reactors are listed according to [IEA/NEA,2010] study (columns 1 and 2, costs in 2008 USD); the same costs discounted to ETM base year (2000) using a 0.3% inflation rate according to [MIT,2009], are also made precise (columns 3 and 4).

Whenever possible, the reactor cost in each region of the model, with reference to the regional aggregation in ETM is made precise. Otherwise, in case of lack of data an average value is declared: 2800 $\$_{2008}$/kW for non-OECD countries and 4180 $\$_{2008}$/kW for OECD[21].

Table 6.24: PWR and Gen III+ costs from Projected cost of generating electricity. All cost are declared in 2000$.

	2008 USD		*2000 USD*	
Regions	**Overnight cost** *[$/kW]*	**O&M** *[$/MWh]*	**Overnight cost** *[$/kW]*	**O&M** *[$/MWh]*
WEU	4700	14	3710	11
SKO	1700	9	1342	7
JPN	3000	17	2368	13
USA	3380	13	2668	10
Others OECD	4000	13	3158	11
CHI	1900	8	1500	6
RUS	2900	17	2289	13
BRA	3800	16	3000	12
*Others non-OECD**	2400	11	1895	9

**Hungary excluded since it belongs to WEU.*

The ETP study consider a range cost for new nuclear power plants to be installed in US in 2010 of 3000-3700 $/kW that is a ±10% with respect to the value proposed in *Projected Cost of Generating Electricity* that refers to a generic light water reactor Gen III+. Moreover it is assumed that the cost in 2050 is 2700 $/kW: accordingly to such an assumption, the same cost reduction rate (-0.26%/yr) is applied in ETM.

The fuel cycle cost is not used as input data of ETM since it is inherently calculated by the model; however it has been used as benchmark in the preliminary results analysis. Moreover it was assumed a 90% availability factor and the life 60 years for all the nuclear power plants, in line with the AF declared for coal and gas power plants and their technical life: in the reference IEA study the assumed value are 85% and 60 years.

In the next paragraphs a brief discussion on the cost data necessary to implement the fuel cycle in VEDA is carried out.

6.4.1.1 Overnight cost, IDC and investment costs

In the TIMES manual [ETSAP,2005] the INVCOST attribute is said to be the investment cost of a technology (including interests during construction - IDC) if no lead time is specified; on the other hand, whenever the lead time is explicitly modeled, the attribute switch to overnight cost,

[21] The last is in line with [MIT,2009] assumption where a 4000 $2007/kW (4026 $2008/kW [inflation website]) is used to calculate the cost of electricity of a generic nuclear power plant

that means that any interest during construction is excluded.

Since the lead time of a nuclear power plants is higher than that of all the others technologies for electricity production, the resulting total investment cost is quite different from the overnight. Together with the overnight cost made clear in Table 6.24, where EPC, contingency and owner's costs are included, the time needed to build a nuclear plant has been therefore declared in VEDA tables, and, for the sake of homogeneity, the lead time of all other new technologies involved in electricity production has been specified too.

Nevertheless, the lead time is not the only element influencing the IDC amount since it depends on the construction schedule too: therefore different interests during construction can be derived from the same lead time but different construction schedule (constant, S-shape or bell-shaped pattern). The surplus of money to be paid during the construction is calculated according to equation 6.4.2:

$$IDC = \sum_{k=1}^{CT} [(1 + WACC)^{CT-k+1} - 1] \qquad 6.4.2$$

where:

CT length of the construction period

k k-th year of the construction period (1, 2, ... ,k)

W_k share of overnight cost in year k, according to the construction schedule

WACC weighted average cost of capital (see equation 6.4.1)

The length of construction period depends on country experience but also on the requirement of a long list of licenses and approvals, all varying with the project and location: except for Asia, the construction of new nuclear units has been inactive for practically around two decades in OECD countries. Therefore, due to limited recent experience with building nuclear power plants, the emerging nuclear renaissance will face a number of first-of-a-kind risks. Nevertheless concerted efforts to reduce construction delays have already allowed reporting average construction times of 62 months for recent and anticipated nuclear builds in Asia, notably in China and Korea [IEA/NEA,2010].

According to data presented in the previous version of *Projected cost of generating electricity 2005* the total expense period ranges from 5 years in three countries to 10 years in one country. In nearly all countries, however, 90% or more of the expenses are incurred within 5 years or less [IEA/NEA,2005].

Five years is assumed in [MIT,2009] too, so this lead time has been considered as the reference one in modeling nuclear power plants.

Data in [IEA/NEA,2005] demonstrate that the construction schedule can differ a lot among countries: in [MIT,2009] a bell-shaped pattern over 5 years is assumed and the maximum spread is fixed in the middle of the period (10%, 25%, 30%, 25%,10%): this assumption, together with a 10% WACC, leads to a 25.5% IDC.

On the other hand in [IEA/NEA,2010] a lead time for nuclear technology of 7 years is assumed if not explicitly declared; however the construction schedule is not made clear so the IDC can be

only inferred from values in [PPCS,2005]: it is on average 22% of investment cost (with the exception of EPR whose IDC results to be 26%).

Since in TIMES the interests during construction are uniformly spread throughout the lead-time, that is the construction schedule is made of equal shares during the construction period, there would be no possibility to model a IDC of 22%: therefore, the time needed for construction is assumed to be 5 years (20% construction share each year) that lead to a 25.5% IDC. This cost would be higher of the real electricity cost of 3% so the overnight cost is accordingly decrease by 4% in order to indirectly model a 22% IDC.

Then an assumption about the IDC of coal and gas fired power plants has to be made: the reference studies were both [MIT,2009] and [IEA/NEA,2010]: in the first a lead time of 4 and 2 years and a construction schedule with a bell-shaped pattern (15%, 35%, 35%, 15% and 50%, 50%) were respectively assumed. Since the nuclear IDC in this study is higher than that deduced by *Projected cost of generating electricity* (22%), these data were used to only infer the ratio between the IDC of nuclear and the two others technologies and compared to ratios calculated from [IEA/NEA,2010] data. The lead time of coal and gas power plants has been then chosen in order to respect as more as possible the IDC ratios proposed by MIT and IEA, according to the fixed TIMES interest spread over the lead time. This reasoning and data used in the ETM is summarized in Table 6.25.

Finally, [IEA/NEA,2010] assumes that all renewable technologies, hydropower excluded, are characterized by the same lead time (1 year): the same lead time is considered in ETM too.

The data used in VEDA are listed in Table 6.26, where also the names of technologies to which the value in the column labeled “NCAP_ILED” is assigned, are listed. Since oil fired power plant is not taken into account in both the reference studies, the length of construction period has been set equal to that of the gas fired power plants

Table 6.25: Lead time of nuclear, coal and gas power plants and related IDC share over investment cost calculated with the discount rate made clear in each study.

Technology	[MIT,2009] *WACC* : 11.5%			[IEA/NEA,2010] *Discount rate* : 10%			ETM *Hurdle rate* : 10%		
	Lead time	*IDC*	*Nuclear IDC to coal and gas IDC ratio*	*Lead time*[1]	*IDC*	*Nuclear IDC to coal and gas IDC ratio*	*Lead time*	*IDC*	*Nuclear IDC to coal and gas IDC ratio*
Nuclear	5	28.2%	-	-	22%	-	5	25.5%[2]	-
Coal	4	24.2%	0.86	-	18%	0.81	3	17.6%	0.80
Gas	2	15.2%	0.54	-	15%	0.68	2	13.4%	0.61

[1]The lead time declared in this study is used to calculate the LCOE of power plants whose construction period length was not declared by owners. Because of this and the leakage of information about the construction schedule, it was not used to calculate IDC. It is instead inferred from the overnight (O) and investment (I) cost declared in the study: IDC= (I-O)/I.

[2]Since a 22% IDC can't be modelled by TIMES, a lead time of 5 years has been used but the overnight cost has been decreased by 4% in order to obtain an investment cost coherent to that proposed in Projected cost of generating electricity. The IDC ratios have been calculated referring to the real IDC share, that is 22%.

Table 6.26: Assumed lead time for new technologies; the attribute is declared in the “SubRes_B_NewTech” template.

Technology kind	TECH_NAME *Technologies name*	NCAP_ILED *Length of construction period*
Non Hydro Renewables	EBIO* EGEO* EWIN* ESOL* EMAR*	1
Gas fired power plants	EGOI* EGAS* EOIL*	2
Coal fired power plants	ECOA*	3
Nuclear power plants	ENUC*	5

6.4.1.2 Decommissioning costs

The decommissioning cost represents the amount of money necessary to cope with the power plant dismantling at the end of its life. It can be put aside at the beginning of the plant life or during operation.

In [IEA/NEA,2010] an average value, coming from experiences with decommissioning costs and practices in OECD countries, is used where no data on decommissioning costs was submitted. It assumed that the payment for decommissioning, equal to 15% of the overnight cost, starts at the end of the plant life and is spread over a period of 10 years: this leads to a decommissioning cost between 250 and 800 $/kW that weigh on the cost of electricity only by 0.2%[22].

The same assumption is made in ETM and the values related to VEDA attribute are made clear in Table 6.27.

The absence of a period of delay between the shut-down of a power plant and its decommissioning reflects one of the three possible options defined by the International Atomic Energy Agency (IAEA) [WNA,2011b]:

1. *Immediate Dismantling.*

   This option allows for the facility to be removed from regulatory control relatively soon after shutdown or termination of regulated activities. Usually, the final dismantling or decontamination activities begin within a few months or years, depending on the facility.

[22] The decommissioning cost has to be discounted at the beginning of the plant life since it represents a future output cash flow: in order to do so, discount rates of 3% (i.e. 5% - 2%) and 8% (i.e. 10% - 2%) have to be used in order to take into account the “provisioning rate” (usually equal to 2-3%), that is lower that the discount rate because of the low risk accepted. If the Belgium power plant is considered (5% discount rate), the discounted decommissioning is therefore: $(5383*15\%)/(1+3\%)^{70}$=101.98 $/kW. Considering plant size (1600 MWe) and energy produced on the entire power plant life, it derives that the decommissioning contribute on the cost of electricity is 0.23 $/MWh that is 0.4% of the total cost (61.06 $/MWh, [IEA/NEA,2010]).

Following removal from regulatory control, the site is then available for re-use.

2. *Safe Enclosure.*

   This option postpones the final removal of controls for a longer period, usually in the order of 40 to 60 years. The facility is placed into a safe storage configuration until the eventual dismantling and decontamination activities occur.

3. *Entombment.*

   This option entails placing the facility into a condition that will allow the remaining on-site radioactive material to remain on-site without the requirement of ever removing it totally. This option usually involves reducing the size of the area where the radioactive material is located and then encasing the facility in a long-lived structure such as concrete, that will last for a period of time to ensure the remaining radioactivity is no longer of concern.

Even if no right or wrong approach exists - each having its benefits and disadvantages - and it is up to national policy determining which approach to adopt, the immediate dismantling (or early site release) has been modeled in ETM for two reasons: the first is its inherent aspect of not transferring any responsibility for the decommissioning to future generations; the second is a modeling issue since if a 40 years delay after shut down together with a 60 years life was considered, the most power plants dismantling would occur after the end of the time horizon and therefore accounted in salvage costs.

Table 6.27: VEDA attributes for nuclear power plants decommissioning modelling. The overnight costs have been lowered by 4% with reference to Table 6.24 because of the higher than reality IDC resulting from a 5 years lead time in TIMES (§ 6.4.1.1).

2000 USD	INVCOST *Investment cost* *[$/kW]*	NCAP_DCOST *Decommissioning cost* *[$/kW]*	NCAP_DLAG *Number of years delay before decommissioning* *[years]*	NCAP_DELIF *Economic life of the decommissioning activity* *[years]*
WEU	3562	534	0	10
SKO	1288	193	0	10
JPN	2273	341	0	10
USA	2561	384	0	10
Others OECD	3031	455	0	10
CHI	1440	216	0	10
RUS	2198	330	0	10
BRA	2880	432	0	10
*Others non-OECD**	1819	273	0	10

6.4.1.3 CoE assessment

The technical and economical data listed in the previous paragraphs and data about base load new technologies assumed in ETM, have been used to calculate the corresponding cost of electricity. This assessment aims to check the homogeneity of new nuclear fission power plans economical data to that of other new technologies studied in the model.

The analysis has been limited to the WEU region in only two years: 2010, in order to compare the results to this very days situation as it is depicted in [IEA/NEA,2010], and 2050, in order to roughly depict the competitiveness between fusion and fission power plants in long term scenarios.

The cost of electricity has been calculated by using the levelised cost of electricity (LCOE) method, the same used in FRESCO (for more details see section 5.7.4). If both decommissioning cost and carbon cost are considered, equation can be rewritten as follow (eq. 6.4.3):

$$LCOE = \frac{\sum_t (I_t + O\&M_t + F_t + C_t + D_t) \cdot (1+r)^{-t}}{\sum_t E_t \cdot (1+r)^{-t}} \quad 6.4.3$$

This is the formula used in [IEA/NEA,2010] study to calculate levelised average lifetime costs on the basis of the costs for investment, operations and maintenance, fuel, carbon emissions and decommissioning provided by OECD member countries and selected non-member countries, and industry organisations.

Then, the cost of electricity from nuclear, has been compared to the cost of electricity produced in Europe (WEU region) by fossil fuelled and fusion power plants, belonging to the new technologies set (see SubRes_B_NewTech.xls file) derived by the LCOE method as well:

ECOACCO105 Integrated Gasification Combined Cycle (IGCC)

ECOAPFB105 Pressurized Fluidised Bed

ECOAPUL105 Pulverized coal

EGASCCY105 Natural Gas Combined Cycle (NGCC)

ENUCFUB150 10^{th} of kind fusion power plant

ENUCFUA170 Advanced Fusion power plant

The gas and coal costs have been inferred by the price projections for the Baseline scenarios described in [IEA,2010]; costs have been discounted to year 2000 (an inflation rate of 3% has been assumed accordingly to [MIT,2009]) and converted in $/GJ.

Table 6.28: Natural gas and coal cost used to calculate the LCOE from coal and gas new power plants.

Fuel		**2008**		**2050**	
		2008 USD	2000 USD	2008 USD	2000 USD
Natural Gas	$/MBtu	10.32		14.7	
	$/GJ	10.89	**8.59**	15.51	**12.24**
Coal	$/t	120.59		115	
	$/GJ	3.01	**2.38**	2.88	**2.27**

[1] 1 Btu = 1.055 kJ; LHV of 1 m^3 of natural gas: 36 MJ=10 KWht [IEA,2010]

[2] LHV of 1 Kg of coal: 6000 Kcal=25 MJ=~7 KWht [IEA,2010]

The uranium cost is assumed to be 50$/lb (110$/kg) that is the average value (peak excluded) of uranium cost from 2005 to 2007 [UCx,2011], discounted to year 2000. The lithium cost is instead taken from the results of PROCESS model. Both costs are assumed not to change over next years: this hypothesis does not affect the resulting CoE since its contribute on the cost of electricity is quite small (the uranium cost account for less than 1% of the cost of electricity in the worse case, i.e. if its costs reaches the 2007 peak of 110 $$_{2000}$/lb) (Table 6.29).

Table 6.29: Uranium and lithium cost estimation.

		2000 USD
Uranium	$/lb	50
	$/GJ	0.025
Lithium	$/GJ	0.0045

If a 10% discount rate and a 10$/t CO_2 carbon tax are assumed, according to ETM hypothesis, it descends that in 2010 the cost of electricity from nuclear power plant is more expensive than electricity from coal and gas. Obviously, if no carbon tax was considered, the cost difference would be higher; on the other hand, if a 30 $/t CO_2 carbon tax was assumed, according to the hypothesis in [IEA/NEA,2010], the competitiveness of nuclear would really increases (

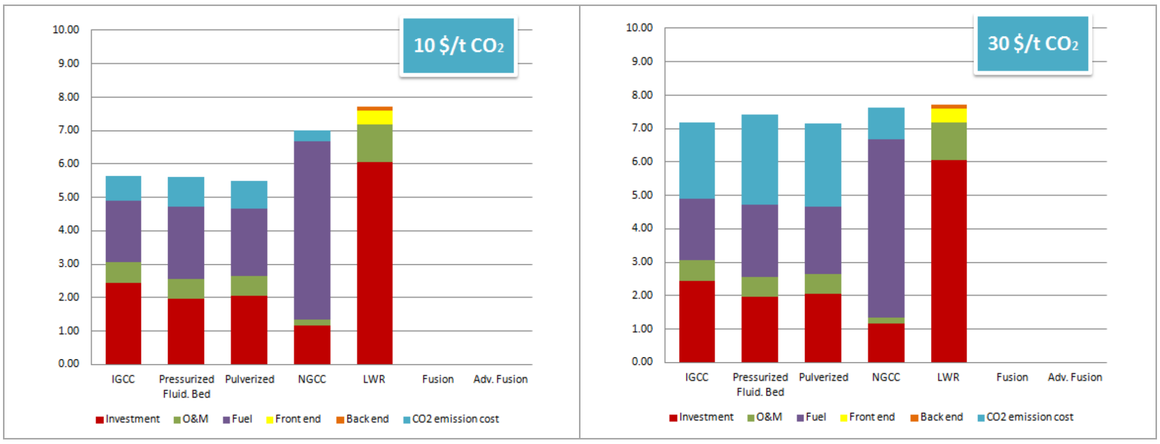


Figure 6.9 and resulting competiveness would be comparable with that exposed in "Projected cost of Generating Electricity".

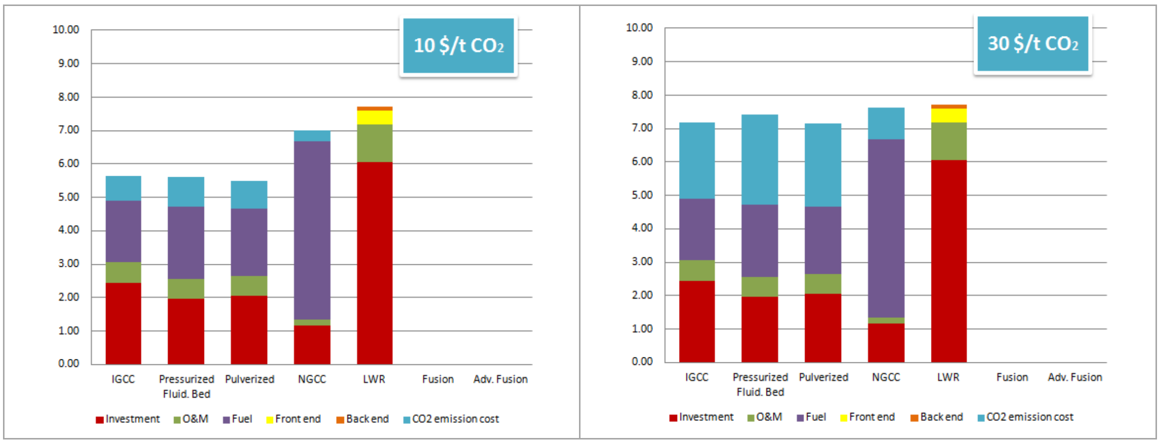


Figure 6.9: CoE from coal, gas and nuclear European power plant in 2010, assuming a 10$/t CO_2 (ETM hypothesis) and 30$/t CO_2 (IEA hypothesis)

In 2050, when fusion power plants[23] will be quite likely available and carbon tax will have reached 30 $/t CO_2 (ETM assumption), the electricity from LWRs in Europe would be the cheapest solution compared to both gas fuelled power plants and fusion technologies.

Only if the carbon emission had a higher cost (40 $/t CO_2) nuclear technologies would be economically competitive (Figure 6.10).

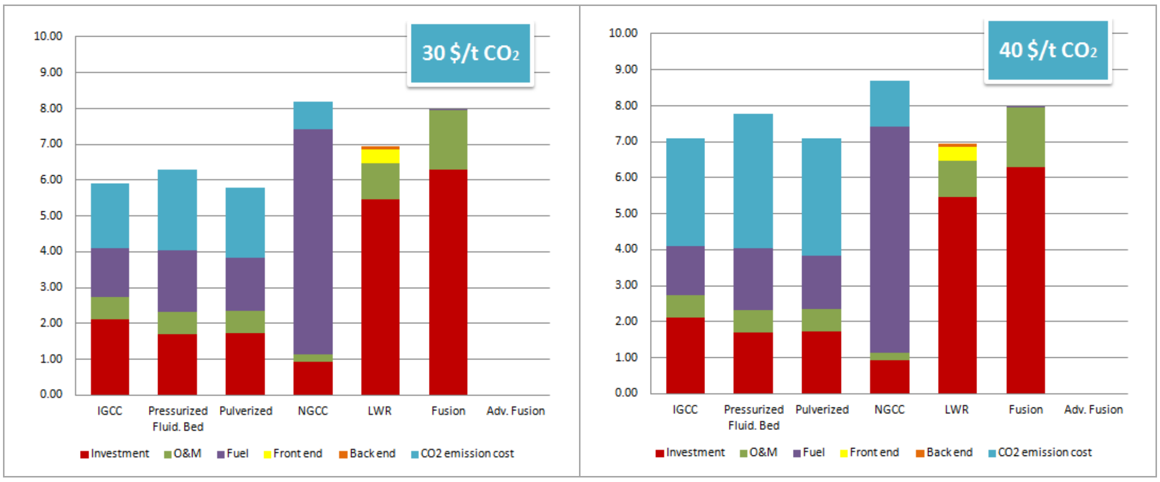


Figure 6.10: CoE from coal, gas and nuclear power plant in 2050 in Europe, assuming a 30$/t CO_2 (ETM hypothesis) and a 40 $/t CO_2.

6.4.2 Future NPPs costs

Data about fast reactors (FR), advanced burner reactors (ABR), integral fast reactors (IFR) and accelerator driven system (ADS) are extracted - again for the sake of homogeneity - by the same study, edited by the Nuclear Energy Agency in 2002 ([NEA,2002], where a cost analysis of technologies involved in the more advanced nuclear fuel cycle option described in section 6.1 is carried out.

The construction cost of a first of a kind fast reactors are thought to be 20% higher than that of a standard LWR [NEA,2002] [MIT,2011] [INL,2008]: this evaluation is derived from an evaluation of the EFR reactor as designed by Framatone and the S-PRISM design by GE; on the other hand, the n^{th} of a kind would only be marginally more costly then LWRs. Accordingly, the O&M costs are set 20% higher than that of Gen III+ reactors.

The overnight cost of an accelerator driven system is instead thought to be higher because of the accelerator and the target: generally the target accounts for only few percent of the total accelerator cost whose cost is estimated on the basis of of proton beam power, using unit cost in the range 5-20$/$W_{beam}$ [NEA,2002]. In this framework, a 10% cost increase with respect to

[23] Data about fusion power plants come from the PPCS-C power plant analysis through the PROCESS code [Ward,2009] and, in this case, refer to the 10th of a kind basic plant (overnight cost 3940 $2000/kWe, fix O&M 65.8 M$/GWa, variable O&M 2.16 M$/PJ, efficiency 42%).

fast reactor technology, due to the presence of accelerator, is assumed. A more detailed analysis on this item should be carried out. The O&M cost are assumed to be 3.5%/yr of the overnight cost [NEA,2002] as estimated in the S-PRISM cost assessment.

In Table 6.30, all such costs, derived from the costs of Gen III+ power plants to be built in WEU, are made clear; costs of the same power plants located in other countries have to be calculated by the cost multiplier derived from Table 6.27.

Technology names are the same of that used in section 6.2. Moreover the same assumption of Gen III+ power plants about lead time, IDC and decommissioning, are set.

Table 6.30:New nuclear technologies investment and variable cost. All cost are expressed in 2000USD and refer to a power plant built in WEU: the overnight cost is therefore 20% higher than that declared in Table 6.27.

NPP	***Technology name***	Overnight cost	O&M
		[$/kW]	*[$/MWh]*
CAPRA	HEAT2ELC_FR	4274	14
ABR	HEAT2ELC_ABR	4274	24
IFR	HEAT2ELC_IFR	4274	24
ADS	HEAT2ELC_MYR	4700	24

6.4.3 Nuclear facilities costs

In this paragraph, the activity cost, that is the technology cost per unit of consumed commodity, are listed. Since the data sources are different, they are made clear in the last column of

This data have been used to check the cost of electricity of a generic Gen III+ nuclear power plant and highlight the contribute of each phase of the fuel cycle on the LCOE in a once through fuel cycle.

Table 6.31, for each technology involved in the nuclear fuel cycle.

All costs are expressed in 2000USD since they are average value, they can be considered valid all over the world and no country specific multipliers have to be used.

Conversion cost is distinguished in case the triuranium octoxide (U_3O_8) or the depleted uranium is converted in UF_6. The first is derived by the assumption in the MIT study where a 10 $\$_{2007}$/kg is set for LCOE calculation. In the same study it is declared that conversion cost from depleted uranium is 200% higher than the previous; on the other hand, in NEA study a range of 24±5 $\$_{2000}$/kg is considered. The cost assumed in this study (19 $/kg) is therefore coherent with both studies.

The enrichment cost of UF_6 from U_3O_8 is derived from historical data collected in UCx website: 102 $/SWU is the average value on years from 2005 to 2007: it is higher than NEA forecast (80 $\$_{2000}$/SWU) and lower than that of MIT (130 $\$_{2000}$/SWU). The cost of enrichment of UF_6 from depleted uranium is set 10% higher than the previous according to MIT hypothesis.

The UOX fabrication cost, 200 $\$_{2000}$/kg HM, is equal to MIT assumption (250 $\$_{2007}$/ kg HM) and to the lower bound proposed by NEA (250±50 $\$_{2000}$/kg HM). The MOX fabrication cost, 1300 $\$_{2000}$/kg HM is the higher bound assumed in NEA: it appears optimistic compared to the MIT value (2400 $\$_{2007}$/ kg HM). Only NEA makes precise the cost of MOX fabrication from reprocessed MOX: it is declared to be 7% higher than the cost of "fresh" MOX fabrication.

Cost of reprocess both UOX and MOX are set equal to 900 $/kg HM: this value, the higher value of the range proposed by NEA, is lower than MIT assumption (1300 $\$_{2000}$/kg HM).

Finally, the cost of the interim waste storage, from both UOX and MOX, is set equal to 200 $/kg HM according to MIT assumption; the UOX and MOX disposal, the HLW from PUREX and FR are taken from the same source.

This data have been used to check the cost of electricity of a generic Gen III+ nuclear power plant and highlight the contribute of each phase of the fuel cycle on the LCOE in a once through fuel cycle.

Table 6.31: Activity cost of nuclear technologies involved in the nuclear fuel cycle.

	Technology name	ACT_COST			*source*
FRONT END	*Mining and milling*		30	$/kg U	*[NEA,2002]*
	Conversion	U to UF_6	8	$/kg U	*[MIT,2011] [NEA,2002]*
		UO_2 to UF_6	19	$/kg U	*[NEA,2002]*
	Enrichment	of U	102	$/kg SWU	*[UCx,2011]*
		of UO_2	112	$/kg SWU	*[MIT,2011]*
	Fabrication	of UOX	200	$/kg HM	*[NEA,2002][MIT,2011]*
		of MOX	1300	$/kg HM	*[NEA,2002]*
		of reprocessed MOX	267.5	$/kg HM	*[MIT,2011]*
BACK END	*Reprocessing*	of UOX	900	$/kg HM	*[NEA,2002]*
		of MOX	900	$/kg HM	
	Waste disposal	interim	160	$/kg HM	*[MIT,2011]*
		Spent UOX	380	$/kg iHM	
		Spent MOX	2500	$/kg iHM	
		HLW from PUREX	190	$/kg iHM	

The median case proposed in *Projected cost of generating electricity* has been used to define the nuclear power plant from both an economical and technical point of view. The resulting cost of electricity is 10 c$\$_{2007}$/kWh (~7 c$€_{2007}$/kWh) that is in line with IEA/NEA estimation for the media case. It results that capital cost account for 79.8% on LCOE, the uranium cost only for 2.9%: this makes clear that the cost of uranium has a very little impact on the cost of electricity. On the other hand, the most part of the cost is due to the capital cost. Front end and back end are instead less than 5% of the total levelised cost Figure 6.11.

The cost share appears in line with that reported by MIT [MIT,2011].

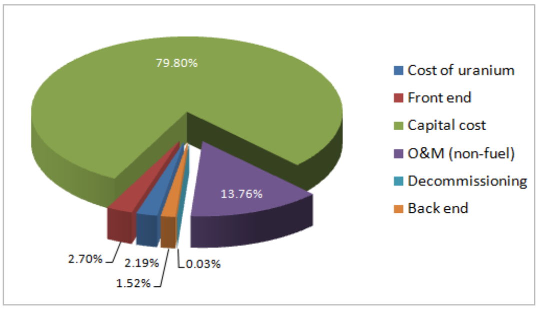


Figure 6.11: Contributes on LCOE by main parts of the nuclear fuel cycle.

6.5 Energy consumptions of the nuclear fuel cycle facilities

A literature review about the kind and the amount of commodity consumed by technologies involved in the nuclear fuel cycle have been carried out in order to allow the model to calculate the associated CO_2 emissions.

The main sources of data listed in Table 6.32 are [Kunakemakorn,2011] and [Lenzen,2008]: the first is a review of all available data in literature about energy and greenhouses gas emissions of the nuclear fuel cycle; the second makes clear the EPR fuel cycle emissions.

It must be highlighted that only dry conversion process is considered since it is the most energy consuming. Then the thermal energy in reprocessing is assumed to be produced by natural gas, according to [Lenzen,2008] where a centrifuge separation method is analysed.

Finally, in the worldwide capacity estimation of the same technologies in 2010 is reported: these data could be used to define the technologies capacity in ETM: the data source is made clear in the last column of the same table.

Table 6.32: Nuclear technologies fuel consumption.

	Technology name	FUEL	CONSUMPTION		CAPACITY		*source*
FRONT END	Mining	DIESEL	0.22	GJ/t U			
		ELC	0.99	GJ/t U			
	Milling	DIESEL	1.46	GJ/t U			
		ELC	0.20	GJ/t U			
	Conversion	FOSSIL FUEL	558.00	GJ/t U	74562	k tons U	[IAEA,2009]
		ELC	75.60	GJ/t U			
	Enrichment	ELC *(diffusion)*	8.64	GJ/SWU	60	M SWU	[IAEA,2011]
		NAT GAS *(diffusion)*	0.08	GJ/SWU			
		ELC *(centrifuge)*	0.36	GJ/SWU			
		NAT GAS *(centrifuge)*	0.07	GJ/SWU			

BACK END	Fabrication	NAT GAS	1403.00	GJ/t Uenrich	10400	t U/year	[IAEA,2011]
		ELC	522.00	GJ/t Uenrich	312	t HM MOX/y	[IAEA,2011] [WISE Uranium]
	Reprocessing	thermal	20000.00	GJ/t iHM	5000	t HM/year	[IAEA,2011] [WNA,2011c]
		ELC	4000.00	GJ/t iHM			
	Waste disposal				17	M m^3	[IAEA,2011]
					24.6	M m^3	

6.6 Conclusive considerations

A physical, technical and economic review of the nuclear fuel cycle has been carried out: the data gathered so far will be used to model the fuel cycle in ETM. During the next months a report describing the implementation of the nuclear fuel cycle in ETM will be published. It must be underlined that some difference can occur between the theoretical description carried out in this thesis and the real cycle implementation, mainly due to a need for simplification in creating a model: however every modification will be described and properly justified.

It has to be also stressed that the model is still under development and that besides the nuclear fuel cycle implementation, other changes and improvements are still in progress. In this section, *preliminary* results will be shown in order to carry out a sensitivity analysis to nuclear investment cost: however we must view them as indicative only.

In Figure 6.12 scenarios resulting from the following assumptions are shown:

- fission power plant costs are the average worldwide values (derived from Table 6.24);
- the lead time of each new technology is that declared in Table 6.26; moreover, the lead time of fusion and fission power plants is set equal (5 years)
- only base-fusion power plant will be available since 2050.

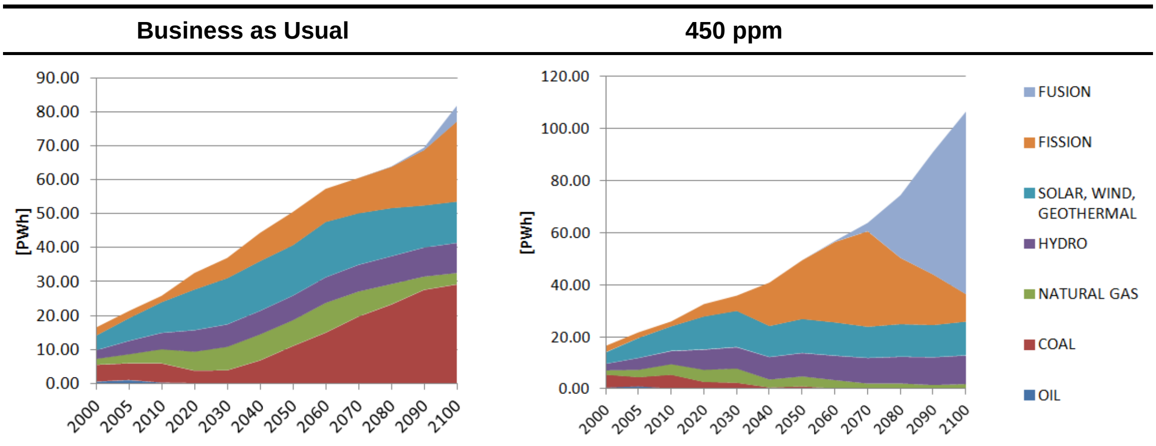


Figure 6.12: *Preliminary* scenario results.

In the BaU scenario, where no boundaries on carbon emission are set, a great part of electricity is produced by fossil fuels over the entire horizon. The contribute by fission power plants increases over the years. In this scenario electricity from fusion power plants is produced at the end of the time horizon. On the other hand, if a emissions boundary is considered (the CO_2 concentration in the long term has not to exceed 450 ppm), in the resulting scenario the share of electricity from fusion considerably increases while disappearing the coal and gas contribute.

The amount of electricity from renewable, even about constant over the years, is higher in the 450 ppm scenario. In these graphs the single contribution of solar, wind and geothermal has not been specified because more precise data about the availability of renewable depending on region, due to climate conditions, and the maximum allowable capacity to be installed, according to the land availability, are not yet implemented in ETM.

More detailed results will be available as soon as the updating phase of the model will be completed. Moreover , thanks to the nuclear fuel cycle implementation in ETM fission and fusion competitiveness will be more impartially evaluated since also costs due to fuel production and waste management are taken into account.

Then the model of the nuclear fuel chain, from mining to production, will allow for evaluating the primary energy consumption and fuel cycle carbon emission, as it is for all other kind of fuel. Finally an assessment of the amount of spent fuel production according to either the nuclear share in the energy mix and to the nuclear strategy adopted could be carried out in order to evaluate the external costs of each possible future nuclear policy.

7 Conclusion

In this study the role of fission and fusion power plants in possible future energy systems has been studied through scenario analysis carried out with the TIMES (The Integrated MARKAL-EFOM System) model generator, developed by Energy Technology System Analysis Program (ETSAP), an implementing agreement between country researcher teams cooperating to maintain and implement a consistent multi-country energy, economy, environment, engineering (4E) analytical capability.

Fission and fusion have in fact could have a great role in future energy systems: they should contribute to satisfy an increasing energy demand with small environmental impact since both are zero-emissions technologies. While fission is currently used to produce electricity, fusion is still at research phase. Nevertheless, a study of the possible competition between the two nuclear technologies on the long term is of fundamental importance in order to plan the energy policies of the next future.

The device used in this study in order to derive global energy scenarios, has been the EFDA TIMES model, developed in the framework of the SERF (Socio Economic Research on Fusion) activities promoted by the European Fusion Development Agreement (EFDA). It is a global energy model created in order to evaluate the fusion competitiveness among technologies for electricity production. Here, each technology is fully described from both a technical and economical point of view. The data about fusion power plants are that derived from the PROCESS code, developed in EFDA framework too, which estimates the cost of a future power plant.

In the thesis, a new economic code, developed during the Ph.D in collaboration with a research group of Consorzio RFX of Padua, FRESCO (Fusion Reactor Simplified Cost) code, is fully described. Aiming to model a future fusion power plant, it calculates the reactor physical dimensions, the auxiliary energy need, the annual electricity production and the related capital cost. Moreover, unlike of PROCESS, two differ operative modes can be studies: stationary or pulsed. At present the code is ready to be used: a benchmarking test with PPCS models will be done for checking its level of accuracy with regard to both technical, physical and economical aspects. Then, the economics of a pulsed power plant will be compared to a stationary one to stress the derived different technological aspects of the power plant and their impact on the cost of electricity. The data obtained by this kind of model could be used in future to derive new scenario analysis with model generators of the same kind of TIMES.

Then, the work carried out in the framework of a SERF task of EFDA, has been presented: future fission power plants have been described from both a technical and economical point of view in order to be implemented in the EFDA TIMES model. Moreover, also the related fuel cycles have been studied and all data necessary to include them in ETM have been collected in a way suitable for the model. The implementation of the nuclear fuel cycle will allow for a more objective analysis of the competitiveness of fission and fusion power plant in the future since the cost of producing the nuclear fuel and the cost associated with the radioactive waste will be not neglected. Then, the effects of different nuclear pathways, defined by different nuclear policies, could be investigated: for example, the most economically competitive solution could be defined when upper bounds on the amounts of waste productions are set. This kind of analysis would in fact reflect the effects of social acceptability of fission, one of the main aspects of this technology to be studied. At present the nuclear fuel cycle implementation is not yet completed. More detailed scenario results will be available as soon as the updating phase of the model will be completed by all members of the EFDA group.

This study has demonstrated the preeminent role of nuclear technologies in future energy scenarios: still a high number of uncertainties affects both fission and fusion power plants. To the first, the problem of a social acceptability due to the fear of severe nuclear accidents, especially after Fukushima, is connected. On the other hand, fusion technology is not yet ready to enter the energy market since still some physical and technical issues have to be overcome. Nevertheless, because of the great inertia of energy systems, scenario analysis becomes a useful device to outline possible future pathways of the worldwide energy systems, allowing for studying the possible effects of nowadays energy policies and for adjust them in order to be able to satisfy the increasing energy demand without damaging the worldwide ecosystem.

Since the large time horizon to be studied, also the contribute by new technologies have to be taken into account even they are not available or not accepted by the society now: this means trusting in the potentialities of research.

Acronyms

ABR	Advanced burner reactor
ADS	Accelerator driven system
ALMR	Advanced liquid metal reactor
Am	Americium
BaU	Business As Usual scenario
BLK	Blanket (made of a breeder layer and manifolds) of a fusion power plant
BR	Breeding ratio
BU	Burn up rate
CC	Control Coils
Cm	Curium
CS	Central Solenoid
D	Deuterium
ECU	European Currency Unit
EPR	European pressurized water reactor
ETM	EFDA TIMES model
FBR	Fast breeder reactors
FP	Fission products
FR	Fast reactor
FRESCO	Fusion REactor Simplified COst
FW	First wall of a fusion power plant
GHG	Green house gases
HCLL	Helium Cooled Lithium Lead blanket
HCPB	Helium Cooled Pebble Bed blanket
HM	Heavy metal
HTS	High temperature shield of a fusion power plant
IAEA	International Atomic Energy Agency
IDC	Interest during construction
LTS	Low temperature shield of a fusion power plant
LWR	Light water reactor
MA	Minor actinides (americium, neptunium, curium)
MOX	Mixed oxide fuel
MOX	Mixed OXide fuel
NEA	Nuclear Energy Agency
NEA	Nuclear Energy Agency

NFC	Nuclear fuel cycle
Np	Neptunium
OTC	Once through strategy
P&T	Partitioning and transmutation strategy
PF	Poloidal field
PPCS	Power Plant Conceptual Study
PWR	Pressurized Water Reactor
T	Tritium
TF	Toroidal field
TFC	Toroidal field coils of a fusion power plant
TRU	Transuranic elements (minor actinides plus plutonium)
UOX	Uranium OXide fue
VV	Vacuum vessel of a fusion power plant
WEU	Western Europe

References

[ANL,2006] Argonne National Laboratory, Preliminary core design studies for the advanced burner reactor over a wide range of conversion ratios, Nuclear Engineering Division, ANL-AFCI-177, September 29, 2006

[Areva,2009] Areva, U.S. EPR^{TM} Nuclear plant, The Path of greatest certainty, Areva, 2009

[AREVA,2011] AREVA, The EPR™'s key assets to support a strategic choice, Evolutionary & innovative design, visited on October 2011

(http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/show.asp?P=85&L=EN)

[Beightler,1979] Beightler C., Phillips Don T., Douglass J.W., Foundation of optimization, second edition, Prentice-Hall international series in industrial and systems engineering

[Bobbio,1980] Bobbio S., Engineering aspects of thermonuclear fusion reactor Electromagnetic system,1980.

[Botta,2005] Botta, Grattieri et al., "Modello Matisse. Documentazione del modello", CESI and Politecnico di Torino, Dicembre 2005

[Boyd,2003] Boyd T.J.M., Sanderson J.J., The physics of plasmas, Cambridge University Press, ISBN-13 978-0-511-07733-3 eBook (NetLibrary), 2003

[Cumo,2008] Cumo M. , Impianti Nucleari, Università La Sapienza, Dicembre 2008

[DOE,2002] U.S. DOE Nuclear energy research Advisory Committee and the Generation IV international forum, *A technology roadmap for Generation IV Nuclear Energy System*, GIF-002-00, December 2002

[Duchateau,2007] Duchateau J.L., Hertout P., Johner J., Discussion about the size of future fusion demonstration reactor: the impact of the toroidal magnetic field, IEEE Transactions on applied superconductivity, Vol. 17, No. 2, June 2007

[Duchateau,2008] Duchateau J.L., Hertout P., Which superconducting material for the toroidal field system of the fusione DEMO resctor? – 80 th European conference on applied superconductivity (EUCAS 2007) – Journal of physiscs: conference series 97 (2008) 012038

[EDA,2002] IAEA, ITER technical basis, ITER EDA (Engineering Design Activities) DOCUMENTATION SERIES No. 24, Vienna, 2002

[EFDA,2011] Eder T., Bustreo C., EFDA-TIMES Model: Nuclear Fuel Cycle, technical report, EFDA Technology Workprogramme 2010, May 2011

[EPLF,2003] Cometto M., Standardisation des outils de calcul pour les ADS et leur application à différents scénarios de transmutation des déchets. Ph.D thesis, EPFL, Lousanna, 2003

[ETSAP,2005] Loulou R., Remne U., Kanudia A., Lehtila A., Goldstain G., Documentation for the TIMES model, Part II, Energy Technology System Analysis Programme, April 2005

[ETSAP,2011] ETSAP website: *http://www.etsap.org/contactus.asp*

[FDR,2001] Summary of the ITER Final Design Report, ITER Report G A0 FDR 4 01-06-28 R 0.2, July 2001

[Ferguson,2009] Ferguson T.S., Linear Programming - A Concise Introduction, University of California at Los Angeles, 2009

[Fetterman,2009] Fetterman R.J., AP1000 core design with 50% MOX loading, Ann Nucl Energ

36(3):324-330 (2009)

[Gaggioli,2007] Gaggioli W., Tecnologia del solare termodinamico ad alta temperatura con accumulo a sali fusi, tesi di dottorato, ENEA, Roma, 2007

[GAMS website] GAMS website: http://www.gams.com/ visited on January 2011

[Gargiulo,2007] Gargiulo M., “Getting started with TIMES-VEDA version 2.7”, May 2009

[Hamada,2005] Hamada K., Nakajima H., Takano K., Y. Kudo Y., Tsutsumi F., Okuno K., Jong C., Fatigue assessment of the ITER TF coil case based on JJ1 fatigue tests, Fusion Engineering and Design 75–79 (2005) 87–91

[Han,2009] Han W.E., Ward D.J., Revised assessments of the economics of fusion power, Fusion Engineering and Design 84 (2009) 895–898

[Han,2010] Han W.E., Ward D.J., Validation of the EFDA-TIMES Model trough Sensitivity Analysis of the key fusion variables, SERF09 Final Report (Activity 2.4), May 2010

[Hermsmeyer,2003] Hermsmeyer S., Conceptual Design of the Helium Cooled Pebble Bed Blanket Plant Model in the Frame of the EU Power Plant Conceptual Study, plant model, PPCS/FZK/PPCS2D10, May 2003

[HSE,2009] Health and safety Executive, Nuclear directorate, Generic design assessment - new civil reactor build, Division 6 Assessment Report No. AR 09/035

[IAEA,2009] IAEA, Nuclear Fuel Cycle Informatin System, A Directory of Nuclear Fule Cycle Facilities, 2009 Edition, IAEA-TECDOC-1613

[IAEA,2011] IAEA, Nuclear technology review, Vienna, 2011

[IEA,2010] IEA, Energy Technologies Perspectives, 2010

[IEA/NEA,2005] IEA, NEA, Projected cost of generating electricity, 2005

[IEA/NEA,2010] IEA, NEA, Projected cost of generating electricity, 2010

[IIASA/WEC,1995] IIASA/WEC, Global Energy perspectives, 1995 *(http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py)*

[inflation website] link to website: *http://www.westegg.com/inflation/*, last visit 12/2011

[INL,2008] D. E. Shropshire, K. A. Williamset, W. B. Boore et al., *Advanced Fuel Cycle Cost Basis*, Idaho National Laboratory, INL/EXT-07-12107, March 2008

[IPCC,2007] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: Synthesis Report, 2007

[ITER website] ITER website, ITER the way to energy, Blanket, visited on October 2011 *(http://www.iter.org/mach/blanket)*

[ITER website] ITER website (*http://www.iter.org/)*

[KanOrs website] KanOrs website: *http://www.kanors.com/* visited on January 2011

[Keppler,2010] Kepller J. H., How competitive is nuclear energy?, NEA News 2010, No. 28.1

[Kunakemakorn,2011] J. Kunakemakorn, P. Wongsuchoto, P. Pavasant, N. Laosiripojana, Greenhouse Gas Emission of European Pressurized Reactor (EPR); Nuclear Power Plant Technology: A Life Cycle Approach , Journal of Sustainable Energy & Environment 2 (2011) 45-50

[Labriet, 2008] Labriet M., Loulou R., Kanudia A., “Is a 2 degrees Celsius warming achievable under high uncertainty?Analysis with the TIMES integrated assessment model.”

Cahier du GERAD, G–2008–30, 29 p.

[Lenthila,2005] Lehtila A., Loulou R., “Stochastic TIMES”, TIMES Version 2.0 User Note, november 2005

[Lenzen,2008] Lenzen M., Life cycle energy and greenhouse gas emissions of nuclear energy: A review, Energy Conversion and Management 49 (2008) 2178–2199

[Loulou vol. III,2005] Loulou R., Remne U., Kanudia A., Lehtila A., Goldstain G., “Documentation of the TIMES model part III”, april 2005

[Maisonnier, 2007] Maisonnier D., Campbell D., Cook I., et al., Power plant conceptual studies in Europe, Nuclear Fusion 47 (2007) 1524–1532

[Mathworld,2010] Noyes, James and Weisstein, Eric W. “Linear Programming.” From MathWorld—A Wolfram Web Resource*. (http://mathworld.wolfram.com/LinearProgramming.html)*

[MIT,2009] Du Y., Parsons J.E., Update on the cost of nuclear power, MIT, May 2009

[MIT,2009b] Deutch J.M., Forsberg C.W., Kadak A.C. at al., Update of the MIT 2003 Future of nuclear power, an interdisciplinary MIT study, Massachusetts Institute of Technology, 2009

[MIT,2011] MIT, The future of the nuclear fuel cycle, Massachusetts Institute of Technology, 2011

[Mitchell,2009] N. Mitchell, P. Bauer, D. Bessette, A. Devred, R. Gallix, C. Jong, J. Knaster, P. Libeyre, B. Lim, A. Sahu, F. Simon, Status of the ITER magnets, Fusion Engineering and Design 84 (2009) 113–121

[Mitchell,2009] Mitchell N., Bauer P., Bessette D., Devred A., Gallix R., Jong C., Knaster , Libeyre P., Lim B., Sahu A., Simon F., Status of the ITER magnets, Fusion Engineering and Design 84 (2009) 113–121

[Mühlich,2010] Mühlich, P.; Hamacher, T.; Ward, D.; Han, W.; Eherer, C.; Silva, C. A. S.; Gracceva, F.; Ciorba, U.; Biberacher, M.; Gronheit, P. E.; Lechon, Y.; Pina, A.; Cabal Cuesta, H.; Hartmann, T.; Tosato, G. C., The Potential Role for Fusion Power in Future Energy Markets, 23^{rd} IAEA Fusion Energy Conference - 23, 2010, Daejeon (KR), 11-16 Oct.

[Najmabadi,1994] Najmabadi F., Overview of the PULSAR study: a pulsed tokamak fusion power plant, US-Japan Workshop on Power reactor studies (Q185), University of California, San Diego, USA, March 14-17, 1994

[Najmabadi,1996] Najmabadi F. and the ARIES team, Assessment of options for attractive commercial and demonstration tokamak fusion power plants, Fusion Technology, Fusion Technology 30, 3 (1996) 1286.

[NEA,2002] Nuclear Energy Agency, *Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in advanced nuclear fuel cycle*, A comparative study, Nuclear Development, OECD 2002

[NS,2010] Technology and Components of Accelerator-driven Systems: Workshop proceedings, Karlsruhe, Germany, 15-17 March 2010, Nuclear Science 2010

[OECD,1995] OECD documents, Physics of Plutonium Recycling; Vol. IV, Fast Plutonium-burner Reactors: Beginning of Life (1995), OECD/NEA, Paris (France)

[OECD,1996] OECD documents, Physics of Plutonium Recycling; Vol. V, Plutonium Recycling in Fast Reactors (1996), OECD/NEA, Paris (France)

[OECD/IEA,2010] International Energy Agency, Key world energy statistics 2010, OECD/IEA 2010

[Osouf,2007] Osouf N, The potential for nuclear renaissance: the development of nuclear power under climate change mitigation policies, Master thesis, MIT, June 2007

[Pamela,2009] J.Pamela, EFDA with contributions from A.Bécoulet, CEA, D.Borba, EFDA, J-L.Boutard, EFDA, L.Horton, IPP, D.Maisonnier, EC, Key R&D Issues for DEMO an analysis based on functional requirements, JET, 2 February 2009

[PPCS,2005] European Fusion Development Agreement, A conceptual study of commercial fusion power plants (PPCS) Final report of the European Fusion Power Plant Conceptual Study, EFDA(05)-27/4.10 revision 1 (revision 0: STAC 10/4.1). April 13th, 2005

[Puma,2005] A.Li Puma, L. Giancarli, Helium-Cooled Lithium-Lead Fusion Power Ptlant (PPCS model AB) Design and integration of in-vessel components and associated systems Task EFDA TW4-TRP-002-D04, CEA Report, SSERMA/LCA/RT/04-3543/A, February 2005

[Puma,2009] Li-Puma A., Bonnemasonb J., Cachonc L., Duchateaud J.L., Gabriela F., Consistent integration in preparing the helium cooled lithium lead DEMO-2007 reactor, Fusion Engineering and Design 84 (2009) 1197–1205

[Raeder,1986] Raeder J., Borrass K., Bünde R., Dänner, Klingelhöfer R., Lengyel L., Leuterer F., Söll M., Controlled nuclear fusion Fundamentals of its utilization for energy supply, John Wiley & Sons Ltd, ISBN 0 471 10312 8, 1986

[Ritch,2008] Ritch J., The necessity of nuclear power: a global and environmental imperative, World Nuclear Association, Keynote Address Bulatom International Nuclear Forum, 28 May 2008, Varna, Bulgaria

[Schultz,2005] Schultz J.H., Joel H., Antaya T., Feng J., Gung C., Martovetsky N., Minervini J.V., Michael P., Radovinsky A., Titus P., ITER central solenoid, Twenty-First IEEE/NPS Symposium on Fusion Engineering 2005, Sept. 2005 Page(s):1 - 4

[Schwartz,1996] Schwartz P., The art of long view: Planning for the future in an Uncertain World, New York, Doubleday, 1996, 256 pp.

[Shimada,2004] Shimada M., Plasma Performance Assessment, ITER report 27SZNW v1.0, August. 2004

[Spears,1986] Spears W. R., The SCAN-2 cost model, EUR-FU/XII-80/86/62, July 1986

[Tosato,2007] Tosato G.C., Global long term energy scenarios: lessons learnt, II Report No:16/13, March 2007

[Tosato,2009] Tosato GC., “Energy scenarios hedging strategy”, ETSAP training course, Venice, June 2009.

[Toschi,2000] Toschi, R. et al, Proc 21st Symposium on Fusion Technology, Madrid, 2000

[UCx,2011] The Ux consulting company website *(http://www.uxc.com/review/uxc_PriceTable.aspx)*

[UN,1999] Population division, Departement of Economic and Social Affairs, United nation Secretariat, The worls at six Billion, United Nations, ESA/P/WP.154, 12 October 1999

[Ward,2009] Han W.E., Ward D.J., Revised assessments of the economics of fusion power, Fusion Engineering and Design 84 (2009) 895–898

[WEO,2008] International Energy Agency, World energy outlook 2008, OECD/IEA, 2008

[Westra,2010] Westra T.M., Fusion Energy: an introduction, EFDA website *(http://www.efda.org/)*

[WISE Uranium] WISE Uranium Project website *(http://www.wise-uranium.org/index.html)*

[WNA,2010a] World Nuclear Association (WNA), Advanced Nuclear Power Reactors, last update October 2010 *(http://www.world-nuclear.org/info/inf08.html)*

[WNA,2010b] World Nuclear Association (WNA), Accelerator-driven Nuclear Energy, last update October 2010 *(http://www.world-nuclear.org/info/default.aspx?id=478&terms=ads)*

[WNA,2010c] World Nuclear Association (WNA), Processing of Used Nuclear Fuel, last update: October 2010 *(http://www.world-nuclear.org/info/inf69.html)*

[WNA,2010d] World Nuclear Association (WNA), Physics of Uranium and Nuclear Energy, last update: September 2010

[WNA,2011a] World Nuclear Association (WNA), Fast neutron reactors, updated August 2011 *(http://www.world-nuclear.org/info/inf98.html)*

[WNA,2011b] World Nuclear Association (WNA), Decommissioning nuclear facilities, July 2011 *(http://www.world-nuclear.org/info/inf19.html)*

[WNA,2011c] World Nuclear Association (WNA), Processing of Used Nuclear Fuel, January 2011 *(http://www.world-nuclear.org/info/inf69.html)*

[WSRC,2003] T. S. Rudisill, M. C. Thompson, M. A. Norato, G. F. Kessinger, R. A. Pierce, and J. D. Johnson, Demonstration of the UREX Solvent Extraction Process with Dresden Reactor Fuel, Westinghouse Savannah River Company, Aiken, 2003

[x-rates.com] x-rates.com, Hystoric Lookup, last access October 2011 *(http://www.x-rates.com/)*