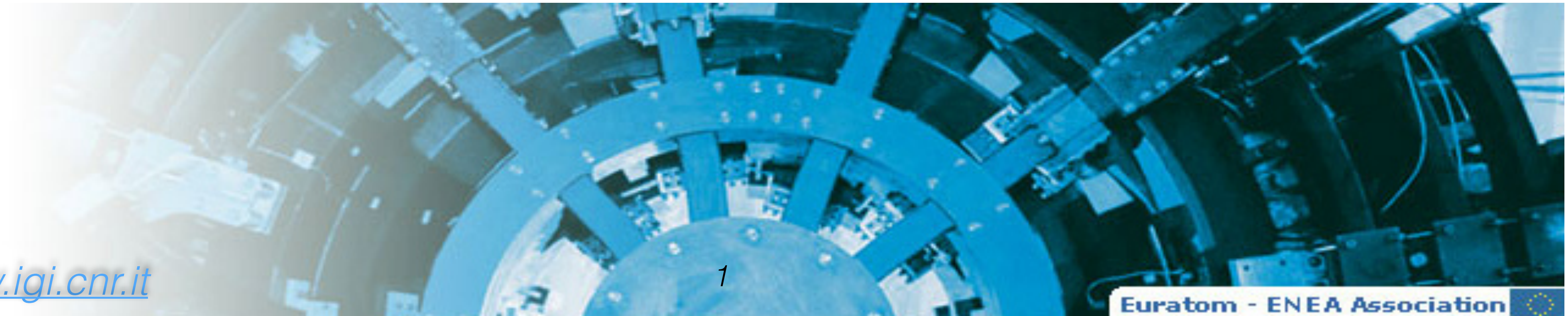
CONSORZIO RFX
Ricerca Formazione Innovazione

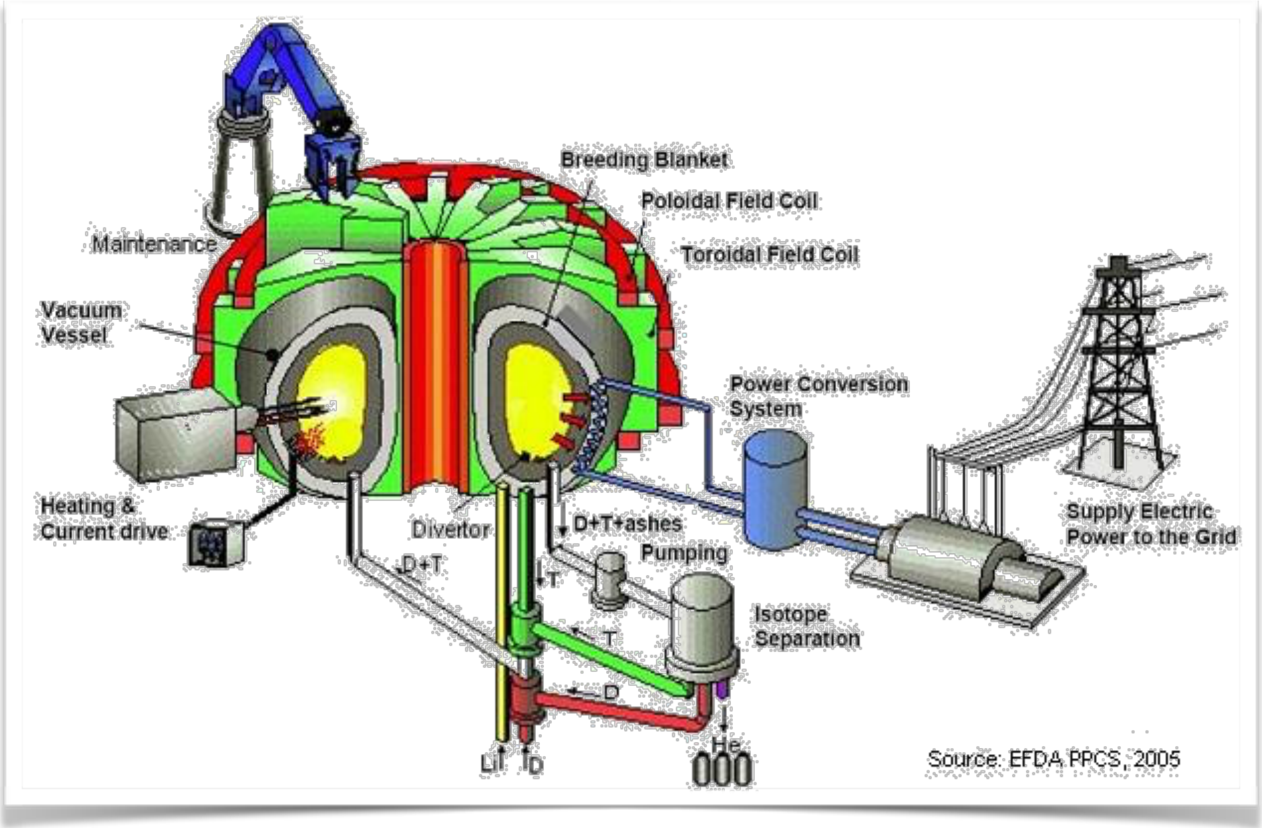
The role of fusion in long term energy scenarios

Eng. Chiara Bustreo
17 May 2017



A fusion power plant.

A fusion power plant is a ***complex*** system whose backbone is a structure of superconducting magnets devoted to confine, shape and make current flow in a D-T plasma.



The thermal energy recovered in the blanket is transferred to turbines through the steam generators to generate **electricity**.

Why it is worth pursuing electricity from fusion?

In an era with an increasing energy demand, a progressive exploitation of conventional energy sources and visible climate changes, the fusion technology looks to be a good option to provide large amount of electricity:

1) despite consuming small amount of fuel (~3.4*10^{11} J/g, 10^7 times more than coal)
2) while producing small amount of radioactive waste
3) and avoiding CO_2 emission.

According to the European fusion research community schedule, the first commercial power plant will enter the market in **2050**.

Fusion electricity for a sustainable energy mix

What is a sustainable development?

Economic Sustainability

Economic growth, financial stability, low inflation, …

Environmental Sustainability

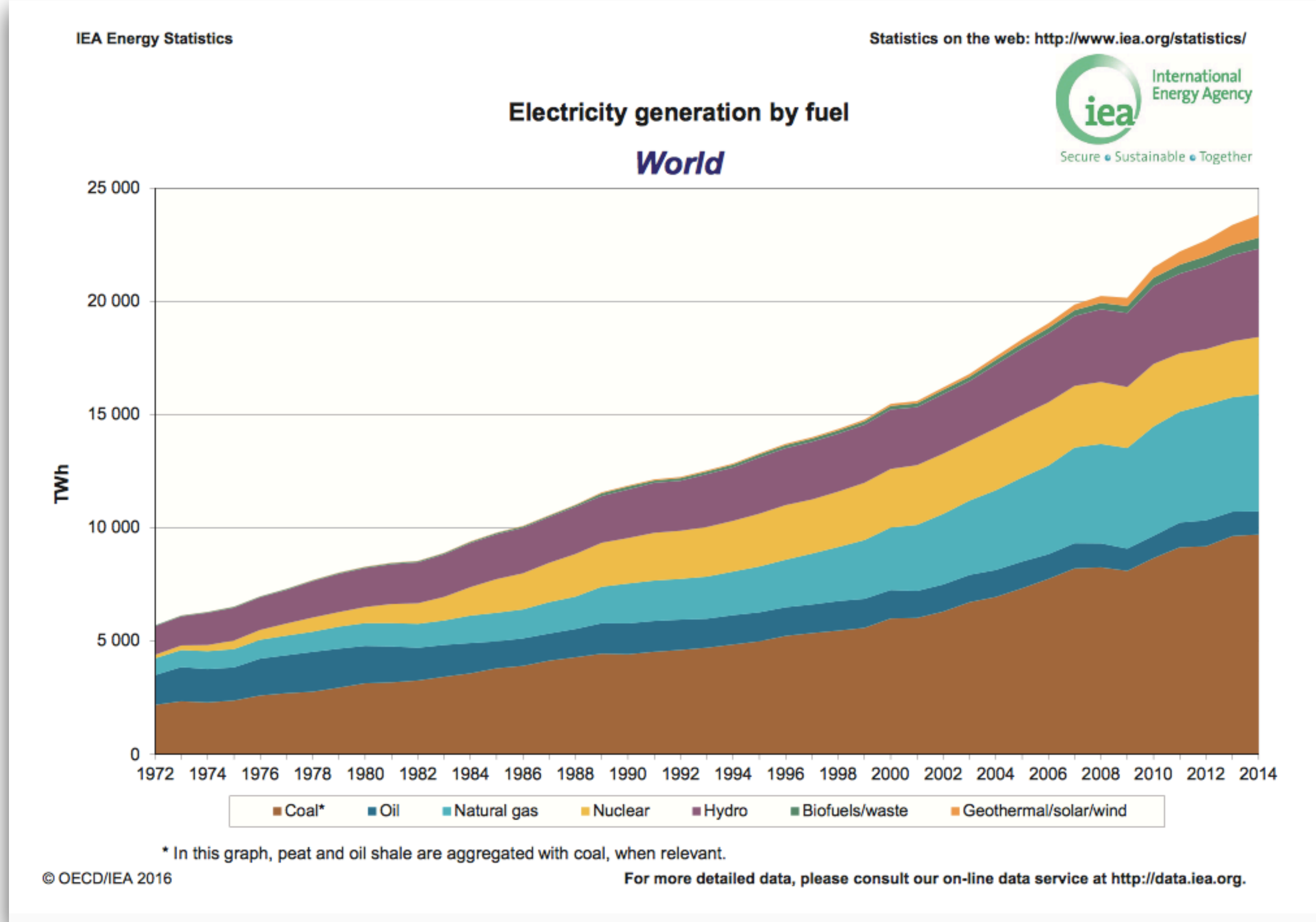
“Clean” soil, weather and air, global climate, biodiversity, …

Social Sustainability

Wide range of parameters: social equity, high level of employment, education, democracy, …

Global electricity generation in 2014

IEA Energy Statistics



Energy scenarios to look into the future

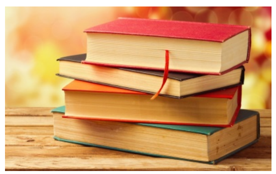
- Fusion will be available after 2050.
- Through scenarios you can look into the future and shape now your decisions to ensure the desired future (e.g. a sustainable electricity generation system) will really happen
- Be careful: Scenarios **are not** forecasts!

Forecast = prediction of some future event or condition usually as a result of study and analysis of available pertinent data (e.g. weather forecast)

Scenario = a description of *possible* actions or events in the future.

How will I spend the week end?

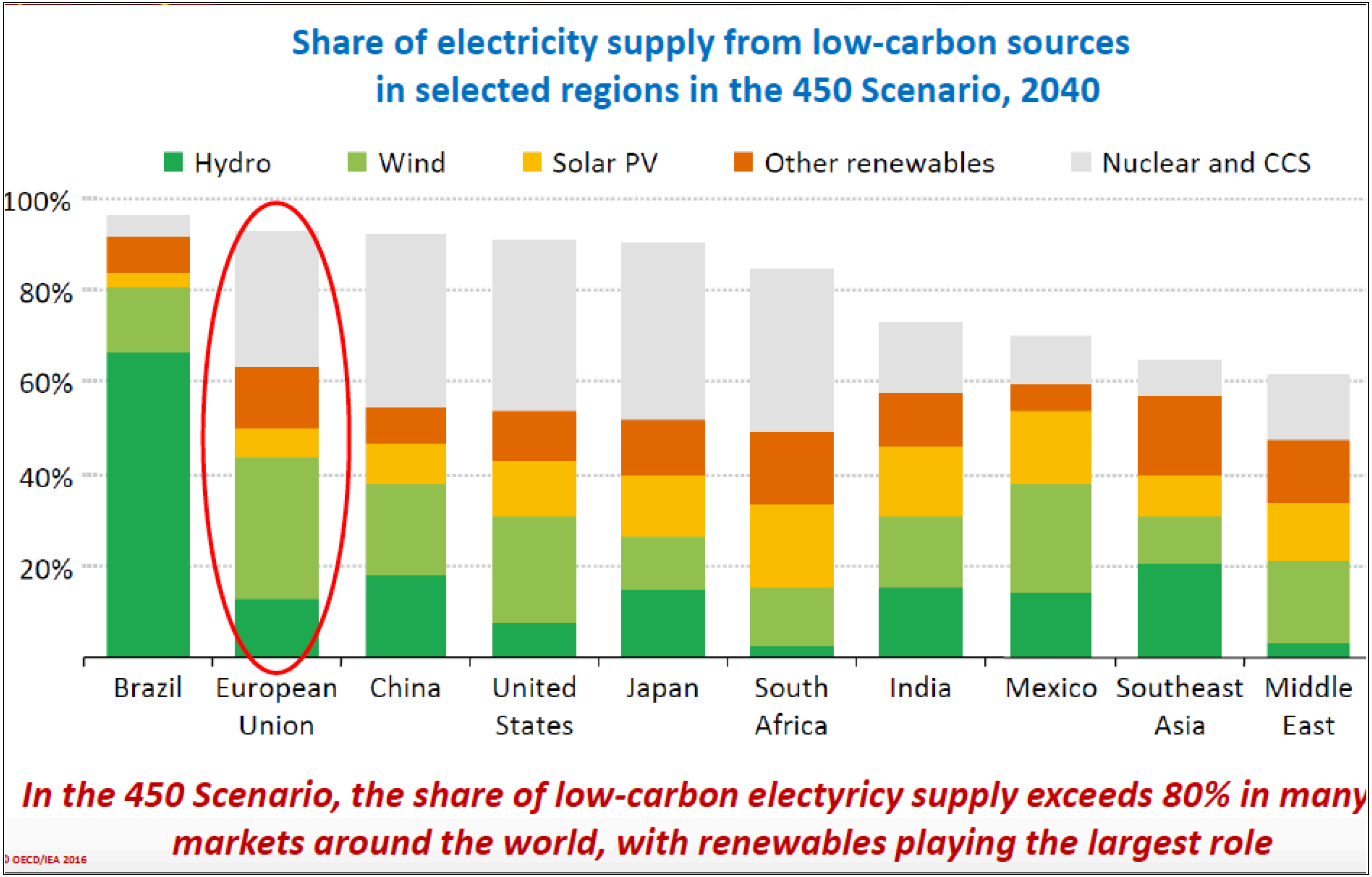
...if rainy



..if sunny

World Energy Outlook 2016

OECD/IEA

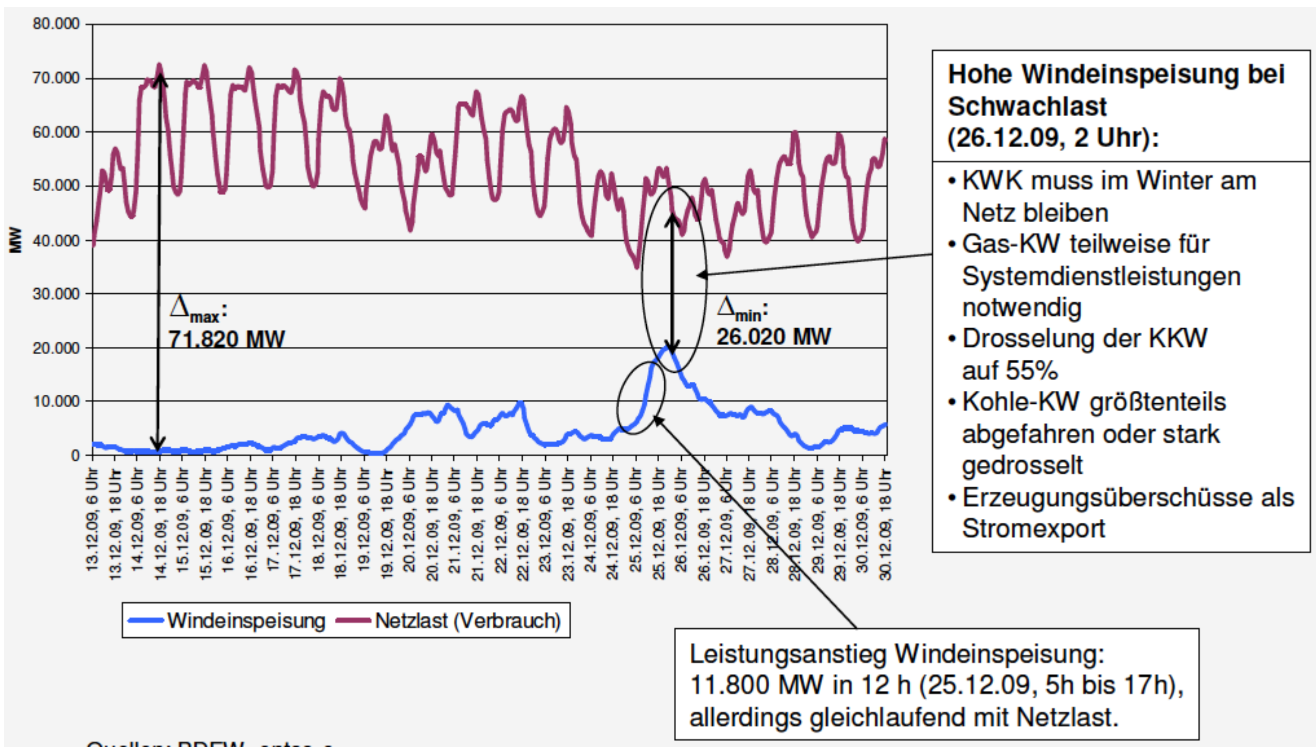


The actors of a sustainable future energy system.

Renewable Energy

- Intermittent energy source.
- Thus RES needs to be coupled with Storage Systems if they are supposed to provide the great part of the energy demand.
- Upper bounds (technical and/or economical) on capacity to be installed.
- Large land use.

GERMANY : ABSENCE OF WIND FOR **SIX** CONSECUTIVE DAYS



The actors of a sustainable future energy system.

Fission power plants

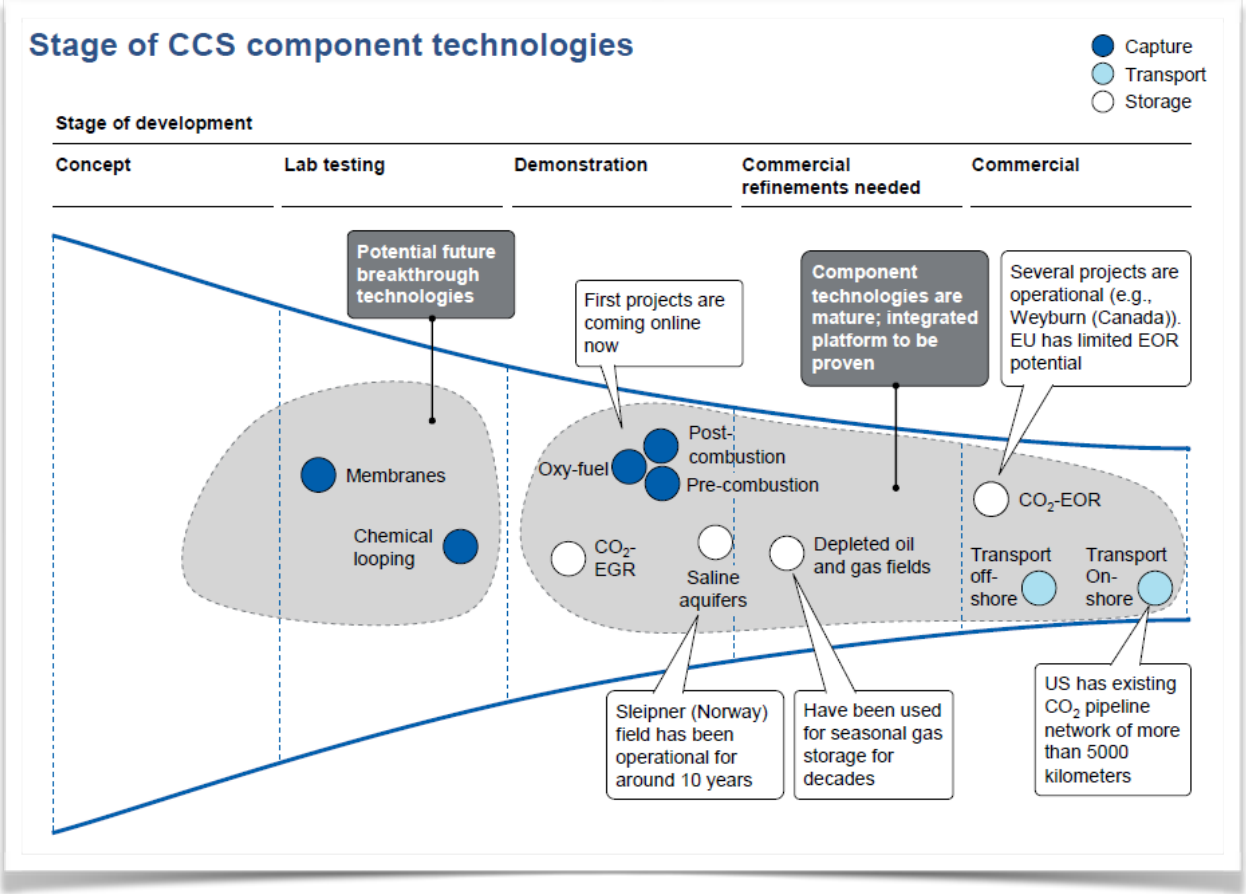
- Reduced social acceptability after Fukushima disaster,
- even if the Gen III+ reactors ensure higher safety and security level.
- The deployment of Gen IV reactors (~2030) would reduce the uranium consumption and long term waste thus helping fission sustainability.
- The cost of electricity is low (~6 c€/kWh)

A PWR fuel assembly

The actors of a sustainable future energy system.

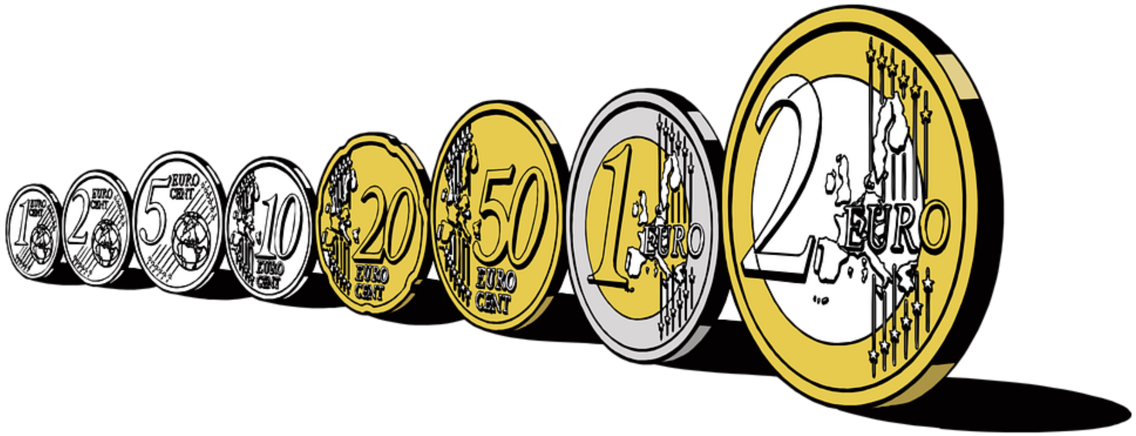
Carbon Capture and Storage Systems.

- Would help reducing the emission of industry sector as well (contribution as large as that of the energy sector ~20%)
- But most of the capture and storage technologies are still at demonstration phase.



CCS power plants could be seen in the market if they are required for fossil fuel facilities **by regulation or** if they become competitive with their unabated counterparts, for instance, if the additional investment and operational costs, caused in part by efficiency reductions, are compensated by **sufficiently high carbon prices** (or direct financial support). [IPCC 2015]

The economics of a fusion power plant



Studies about fusion economics.

Studies about the economics of fusion started in the late '70s.

Currently they are carried out by U.S. (ARIES team), Europe (EUROFusion) and Japan (JAEA and some Universities).

They all aim at estimating investment and running costs of a fusion power plant cost as well as its availability factor in order to estimate the **levelized cost of electricity**:

Carbon Emission allowance

Operation and maintenance

Decommissioning

Fuel

Investment cost

Discount rate

$$LCOE = p_{elc} = \frac{\sum_t (I_t + O\&M_t + F_t + C_t + D_t)(1-r)^{-t}}{\sum_t \left(E_t (1-r)^{-t}\right)}$$

Electricity produced

Expenditures included in Investment Costs

Direct Costs:

- Costs of structure and site facilities
- Costs of the *reactor* components (first wall, blanket, shield, divertor, magnets…)
- *Power plant* components (turbine plant equipment, electric plant equipment, energy storage system etc…

Indirect costs:

"expenses resulting from the support activities required to accomplish direct cost activities. They include Engineering Procurement Construction (EPC) costs, owner's costs (land, cooling infrastructure, administration and associated buildings, site works, switchyards, project management, licences, etc) and contingency cost, which is generally intended to compensate for uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology."

The uncertainties on Investment Costs

Financial issues.

Being fusion a capital intensive technology, it needs founding. The financial rules of the country where the power plant is built affects the Interest During Construction (IDC) amount and thus the Investment Cost which leads the LCOE.

Lead time.

The lead time is quite difficult to forecast especially in case of first-of-a-kind power plant (see as example the EPR construction in Europe). It also largely affects the IDC and thus the final Investment cost.

Cost of materials.

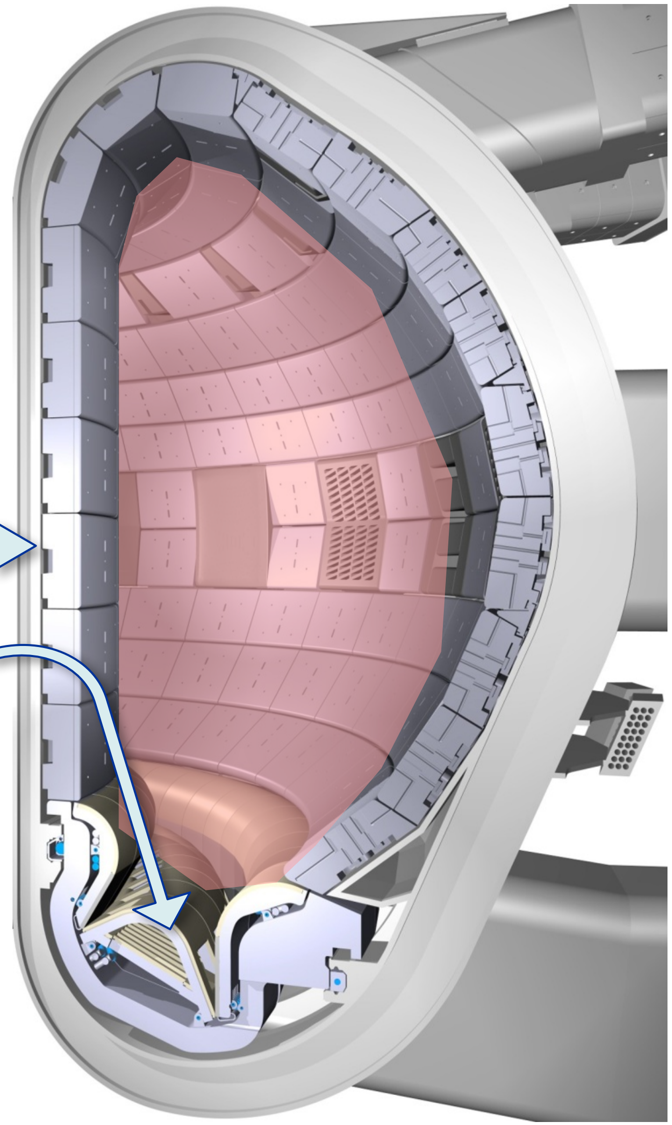
The cost escalation of raw materials already experienced with ITER could affect the Investment Cost estimation of a FPP.

The uncertainties on Investment Costs

Learning factor.

As much experience is acquired in producing specific components, as much lower is the production cost. For this reason the 10th of a kind is likely to be cheaper than the first. But *how much* cheaper?

Replaceable components.



- How long will be the life of blanket and divertor?
- How much time will be needed to replace them?

These aspects largely affects the power plant *availability factor*. The lower is the power plant availability factor (hours of operation/ hours in a year), the lower is the annual electricity production and thus the higher is the cost of electricity.

Working with System Codes

- A systems code is a comprehensive, though necessarily simplified, **model of an entire (fusion) power plant**.
- The systems code is used **to develop many conceptual designs** with a range of materials and technology assumptions. The internal models must be simple (but accurate enough) so that each execution can be fast.
- **It can be used to determine power plant costs and ultimately cost of electricity, for conceptual design and economic studies.**
- Once a conceptual design is settled, full engineering and physics analysis can be carried out using more detailed models.
- The aim of the systems code is to ensure that no substantial conflicts arise between engineering and physics needs.

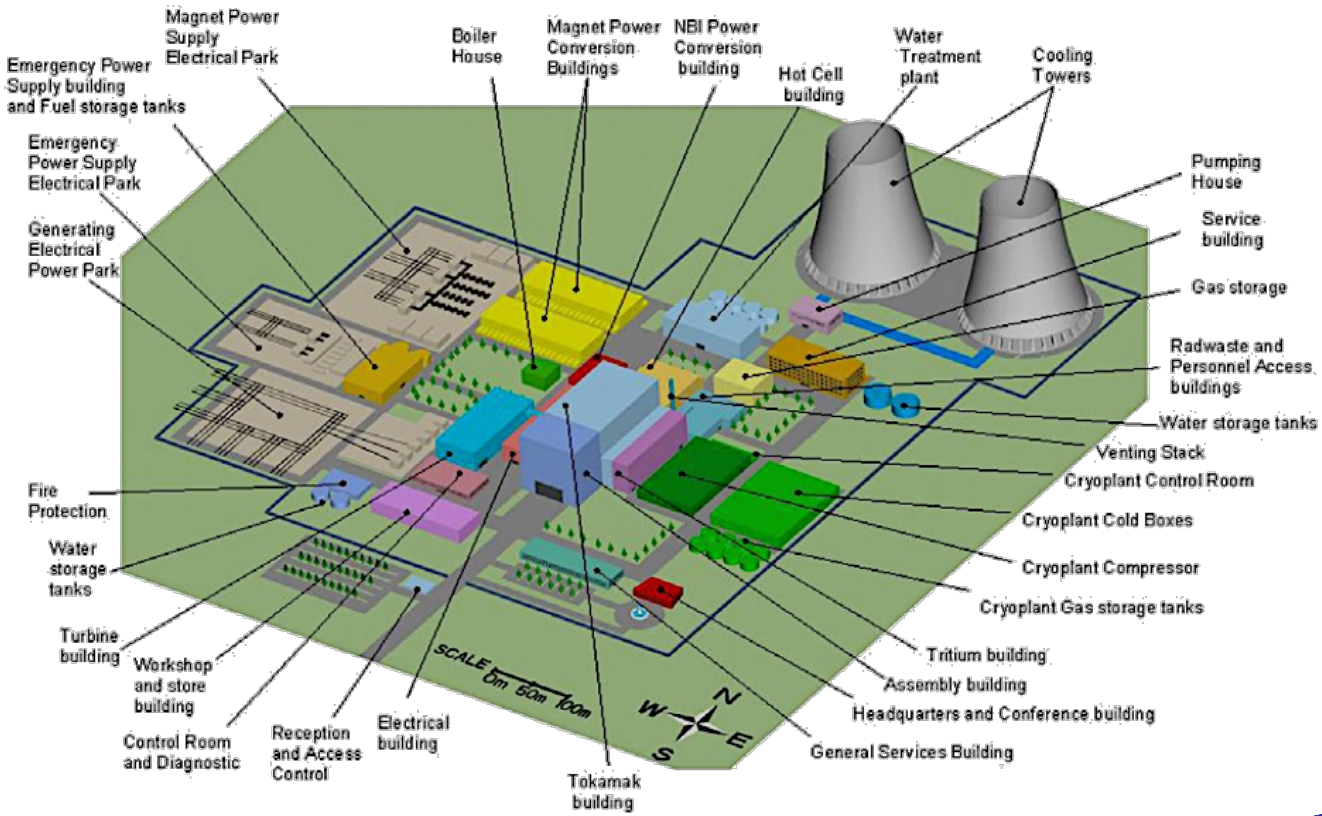
FRESCO - Fusion Reactor Simplified Cost

developed at Consorzio RFX - Project started in 2010

AIM Economic assessment of a future fusion power plant equipped with a TOKAMAK reactor with a HCLL or HCPB blanket, operating in steady state, inductive or partially inductive modes

APPROACH 0-D as for plant model, stochastic as for economic assessments, genetic as for optimisation

Fusion power plant, general layout.



What does FRESCO calculate?

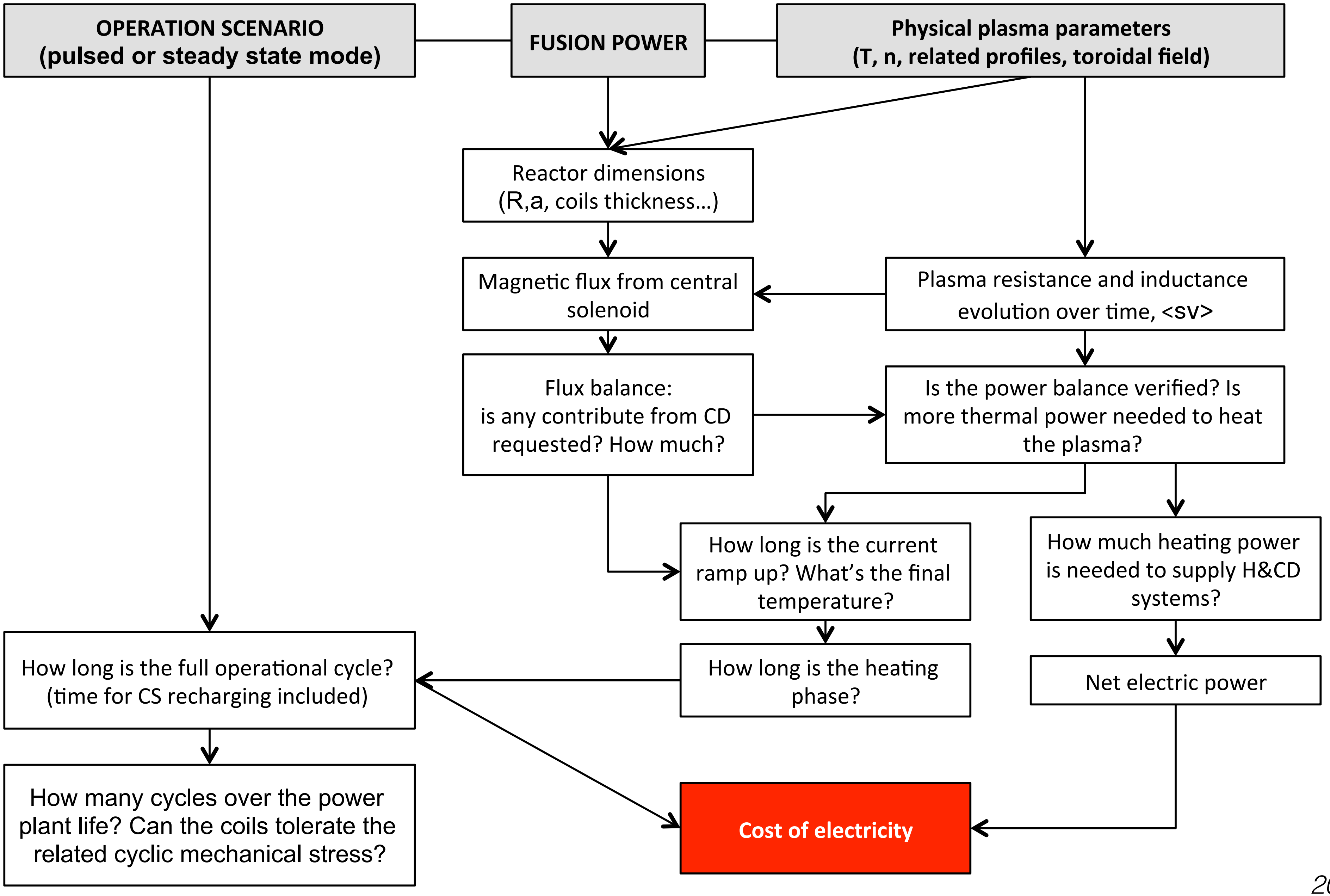
Physical & Technical parameters:

- Plasma current, plasma inductance and resistivity
- Beta-parameter
- Central Solenoid electromagnetic parameters and size
- Magnetic flux balance (from which the need of auxiliary power for current drive is derived)
- Plasma power balance (from which descends the plasma temperature evolution)
- Reactor radial building and mechanical stress on coils
- Balance of the Plant (BoP)

Economics paramenters:

- cost of reactor component (including the thermal storage in case of pulsed mode), mainly trough scalings from ITER costs
- cost of electricity (levelized cost of electricity method)

FRESCO in a nutshell.



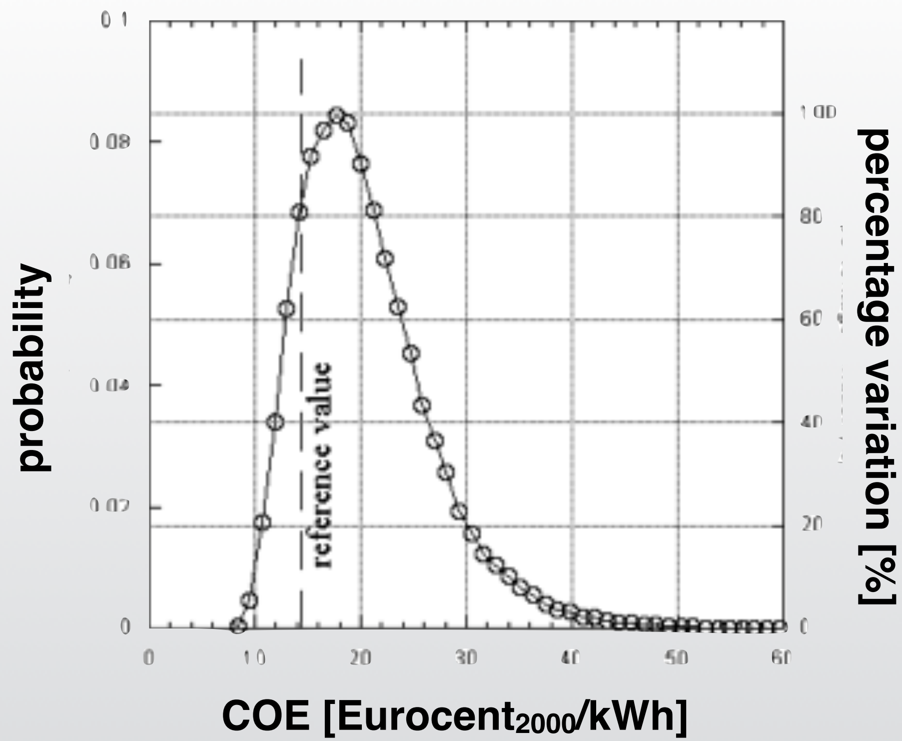
The Monte Carlo approach to the economics of a fusion power plant

The FRESCO code is here used to generate the technical, physical and economic model of a **steady state DEMO-like power** plant whose features are derived from the current European research activities on the DEMO design definition.

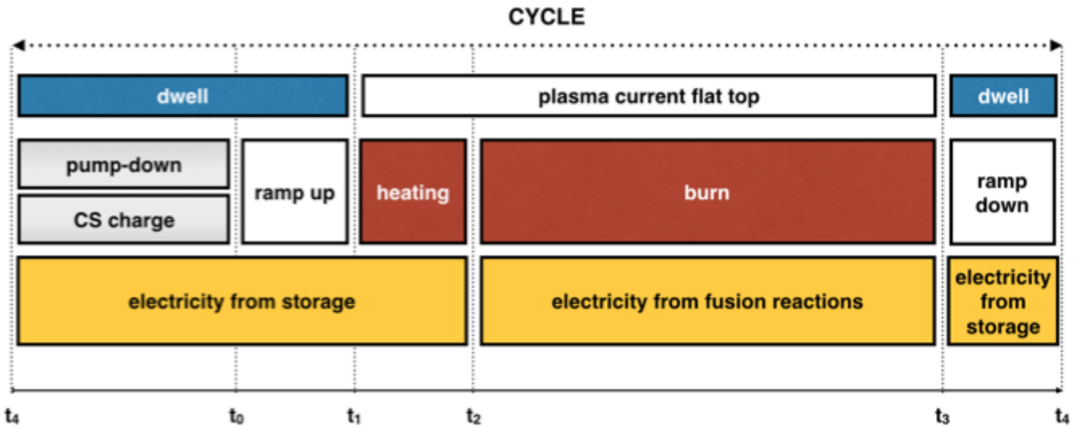
The Monte Carlo method is used to perform **stochastic analyses in order to assess the weight on the cost of electricity (COE) of the uncertainties that currently affect the future technical and economical parameters of a fusion power plant.**

Table 3
Reference, minimum and maximum values of the parameters accounted as stochastic variables.

Stochastic variables	Ref	Min	Max
DV life (year)	3.2	2	12
BLK life (year)	4.5	2	17
DV replacement time (months)	4.5	2	12
BLK replacement time (months)	8	4	24
Power plant life (year)	40	30	60
Discount rate (%)	5	5	10
Lead time for construction (year)	6	5	12
Construction payout skewness (%)	1.36	1.36	1.94
Cost of EUROFER (EUR/kg)	110	110	280
Cost of tungsten (EUR/kg)	15	15	38
Cost of beryllium (EUR/kg)	600	600	1200
Cost of lithium orthosilicate (EUR/kg)	60	60	120
Cost of zirconium hydride (EUR/kg)	80	80	160
Cost reduction factor	0.65	0.5	1



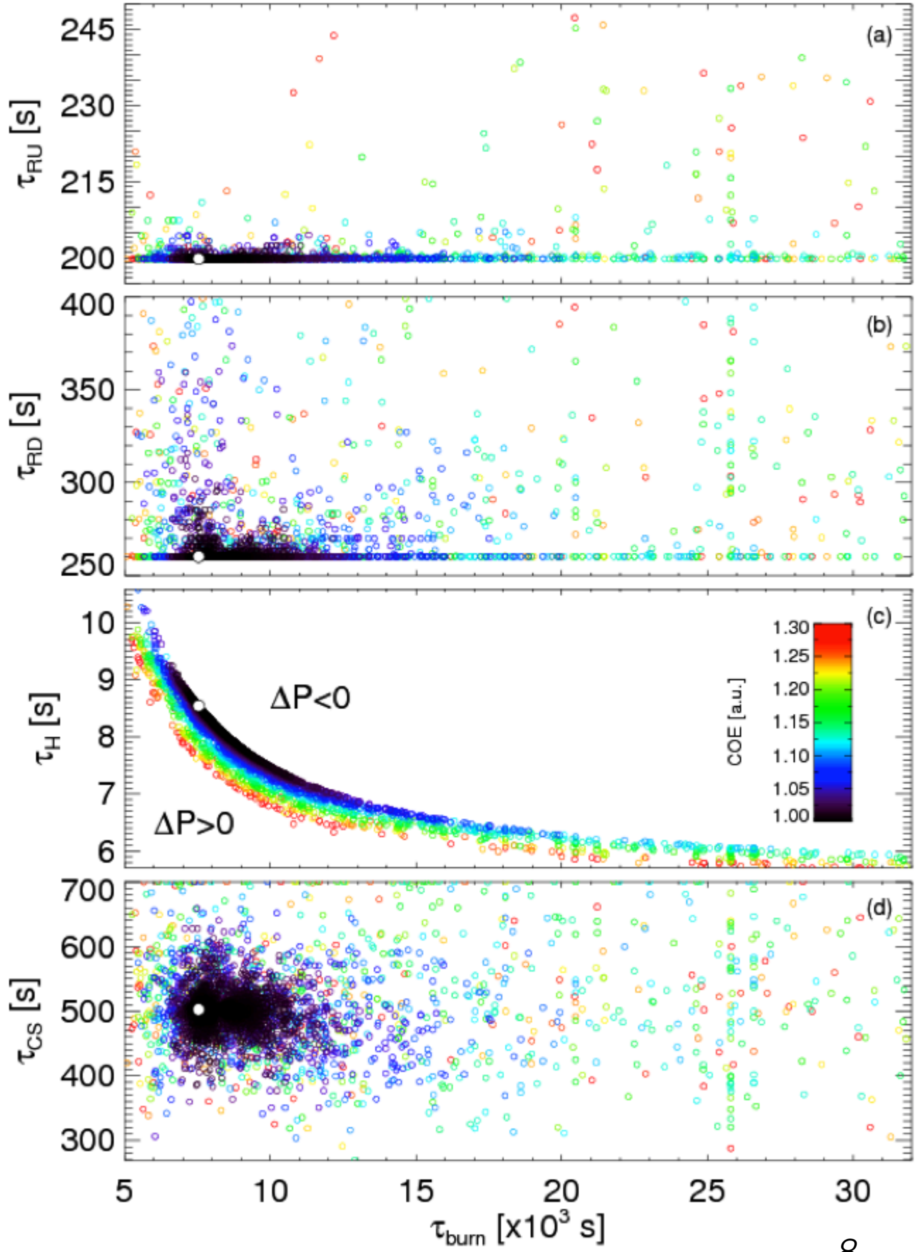
Economic assessment of different operational reactor cycle structures in a pulsed DEMO-like power plant.



A pulsed DEMO-like power plant is modeled with the FRESCO code and the optimization of the operative cycle structure is carried out with a genetic algorithm in order to find the economic optimal solution.

It is achieved with the minimum dwell time allowed by constraints on the number of cycles the reactor can cope with.

The optimal burn time length is a function of the cost of the H&CD power system.

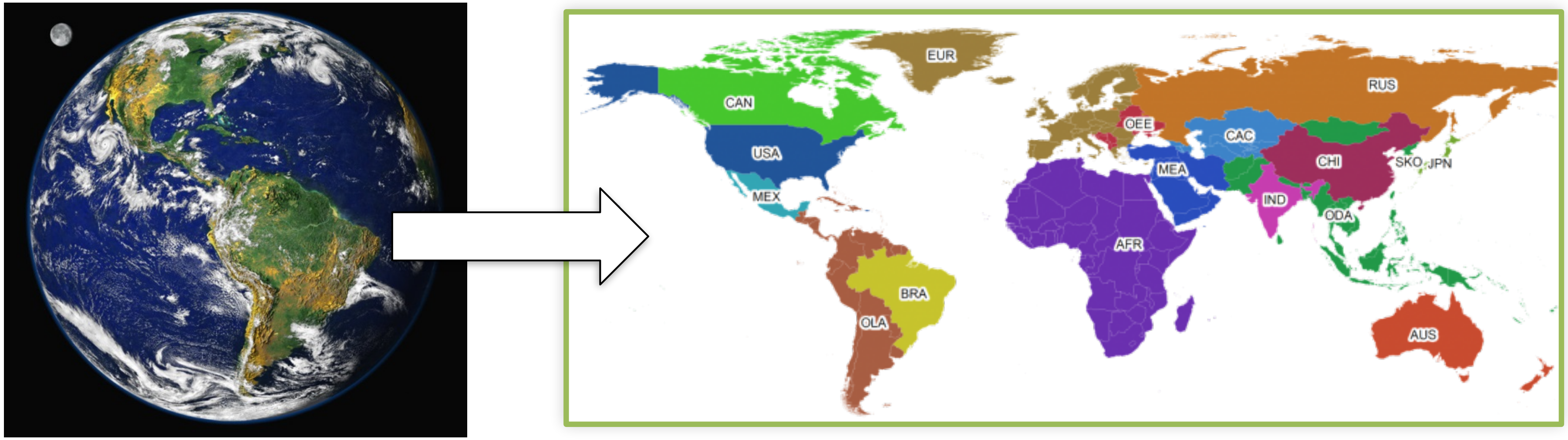


World energy scenarios

EUROfusion

The EUROfusion TIMES model

ETM is a **simplified** model of the real current World energy system as proposed by EUROfusion scientists.

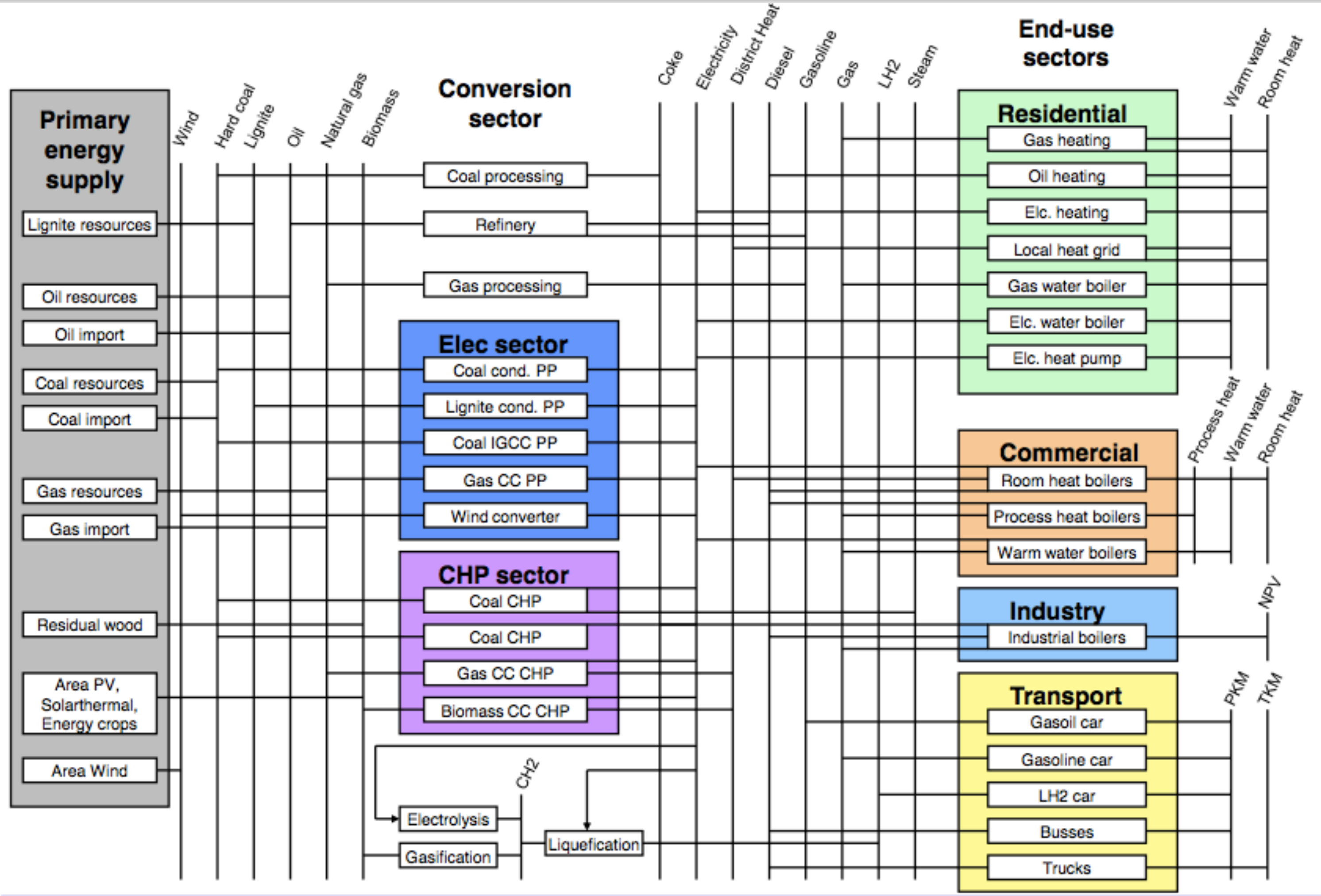


17 regions are connected by trades of “commodities”

(energy sources like coal or electricity)

To create a model, the real world and its dynamics are translated into numbers and equations.

The model of an energy system

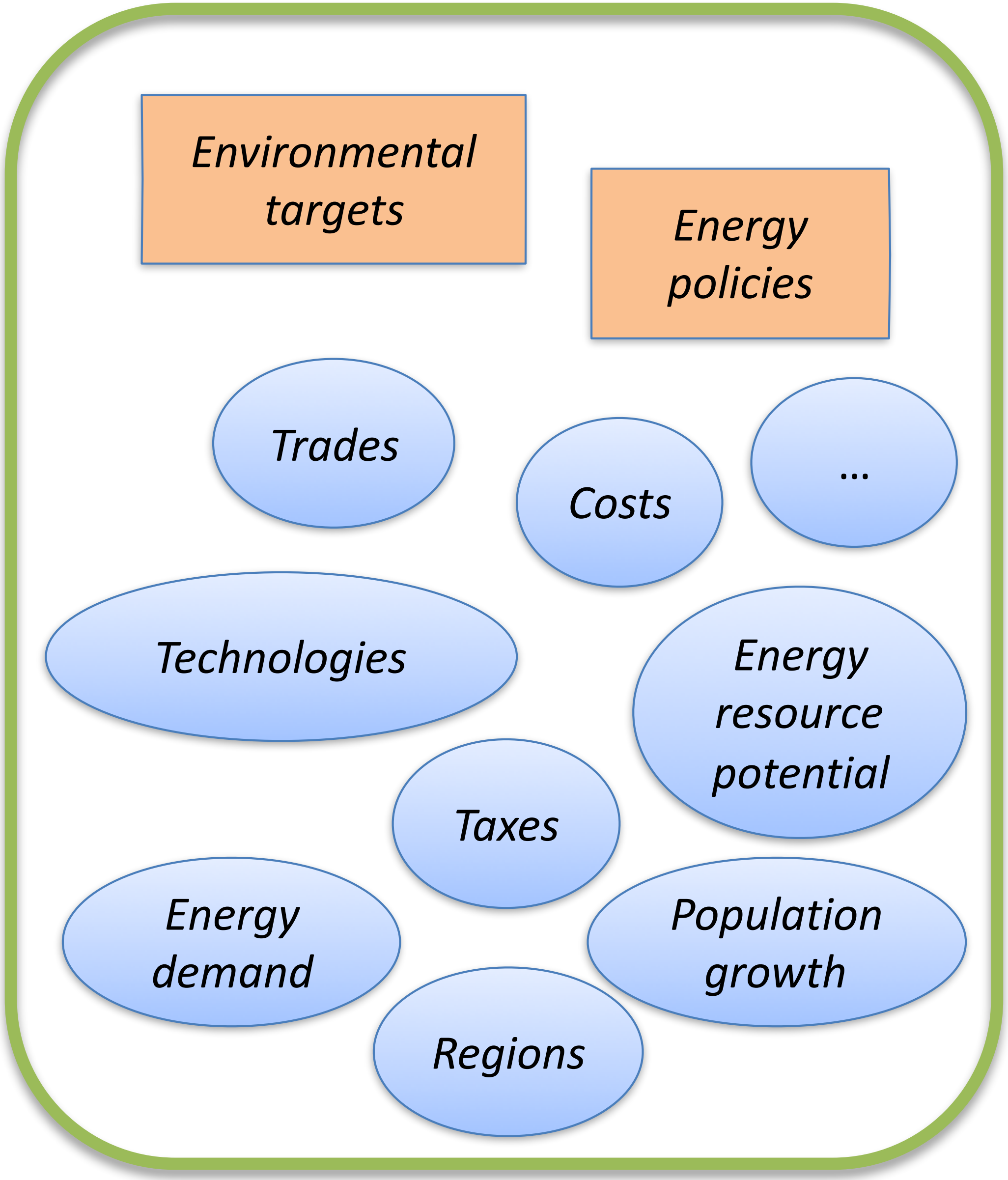


All the stages from energy sources to electricity, heat and fuels to be used in homes, shops and offices and for transport of goods and people.

How we get scenarios

What do we use:

- TIMES model generator
- ETM model = Data about the current global energy system and information on future technologies
- External constraints such as upper bound on CO2 concentration in the atmosphere in 2100 or technology phase out.

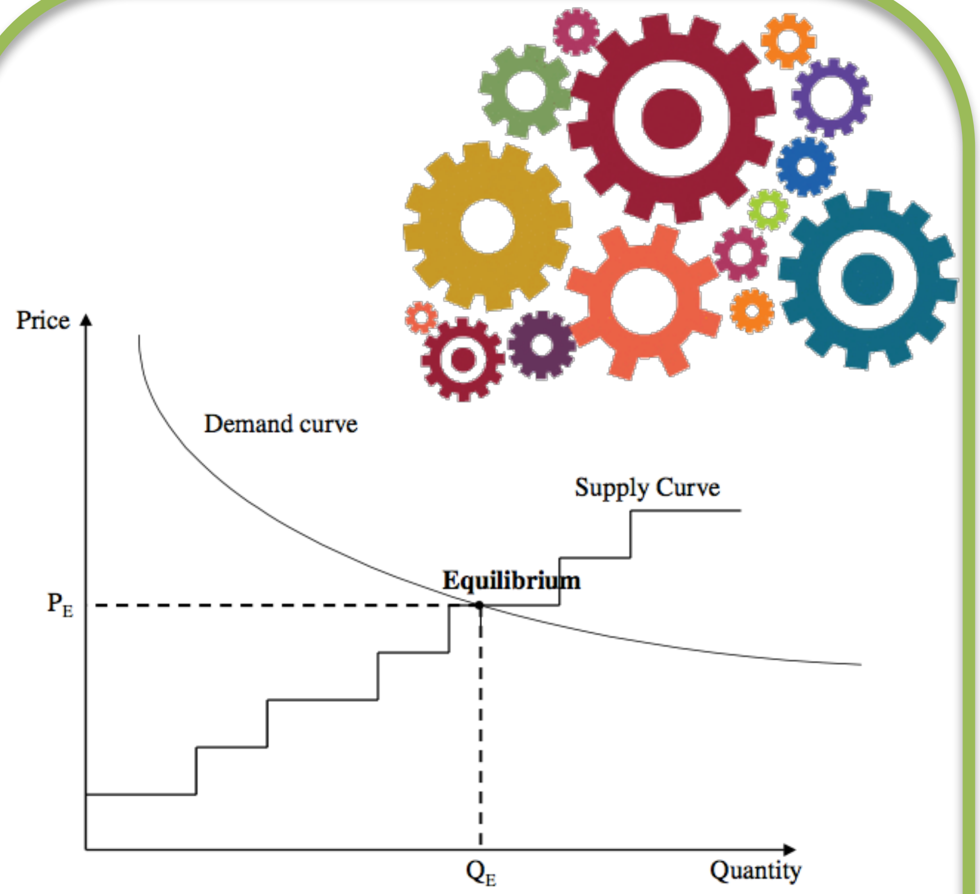


How we get scenarios

The data are processed by **TIMES**

It translates the information into an **optimization** problem to be solved by **linear programming** with a **market-based approach**.

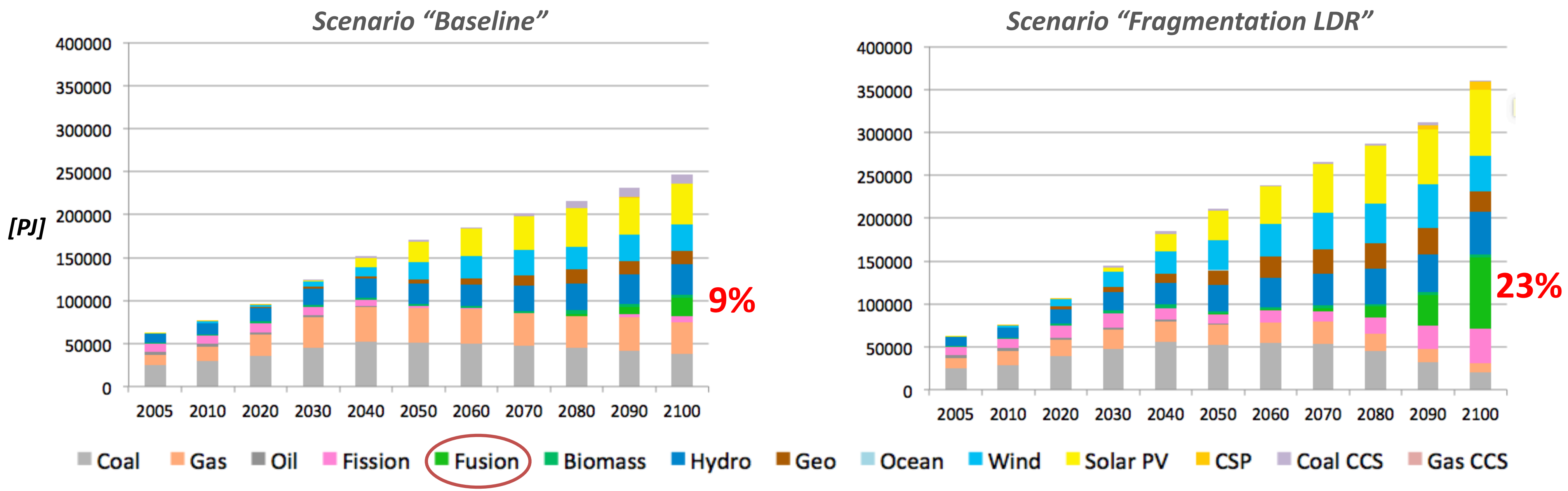
The outputs are the values which each parameter should assume in order to minimize the total cost of the system.



The market-based approach is applied to each sector of the energy system

The energy scenarios

Fusion electricity generation share in *different* future energy markets.



What does increase the market share

- Stringent environmental policy in in terms of CO2 emission
- High technology availability over the year
- High technology efficiency (electricity production vs "fuel" usage)
- **Low cost of electricity**

ETM coupled to System Codes

We can assess:

> ***If the power plant model under study might have chances to have a prominent role in a future energy market.***

Or, on the other way round:

> ***Which are the features of the power plant to be changed or the economic conditions to be ensured in order to make the fusion technology competitive.***