Prometheus Model

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Model description

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Overview of the model

The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system.

PROMETHEUS contains relations and/or exogenous variables for all the main quantities, which are of interest in the context of general energy systems analysis. These include demographic and economic activity indicators, primary and final energy consumption by main fuel, fuel resources and prices, CO_2 emissions, greenhouse gases concentrations and technology dynamics (for power generation, road transport, hydrogen production and industrial and residential end-use technologies).

PROMETHEUS can also represent policy instruments for emission reduction. These include both market based instruments such as cap and trade systems with differential application per region and sector specific policies and measures focusing on specific carbon emitting activities.

Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World).

PROMETHEUS is designed to provide long term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology and energy efficiency promoting policies, RES supporting policies, environmental policies and technology standards.

General aims of PROMETHEUS modelling:

- *Long-term restructuring of energy systems*
- *Fossil fuel resources and computation of international fuel prices*
- *Measure uncertainty pertaining to the evolution of the energy system*
- *Full coverage of all energy sectors globally*
- *Individual modelling of the main global carbon emitters*

Key features of PROMETHEUS

PROMETHEUS is a self-contained large-scale world stochastic energy demand and supply model consisting of a large set of stochastic equations describing the time evolution of key variables, which are of interest in the context of a general analysis of the energy-environment-economic system.

Equations in PROMETHEUS represent the model's endogenous variables as a function of other endogenous variables, exogenous variables, parameters and residual terms. All endogenous variables are stochastic and display co-variance, whose origins are analytically traceable using the model itself. The output of PROMETHEUS consists of empirical joint distributions of all endogenous variables obtained by applying the Monte Carlo method[1].

PROMETHEUS incorporates a recursive dynamic (partial equilibrium energy system) model with annual resolution currently serviced to run up to the year 2050. It has a triangular structure in order to avoid contemporaneous simultaneity. On the other hand, simultaneity is modelled through lagged instances of endogenous variables. Most of the model equations are specified in difference terms in order to avoid excessive early variability and adequately represent accumulation of uncertainty in the longer term.

The model simulates both demand and supply of energy, interacting with each other to form market equilibrium at different regional scales: detailed regional balances are aggregated in order to simulate world energy markets. Apart from international fuel prices, regional energy systems influence each other particularly through trade, technical progress and network effects including changing patterns of consumption and spillover effects with regard to technology diffusion.

PROMETHEUS is a world model and identifies ten country/regions.

EU15+NO+SW	The old EU-15 member states, plus Norway and Switzerland
New Member States	The New EU Member States that joined the union after 2000
North America	The USA and Canada
OECD Western Pacific	Japan, South Korea, Australia and New Zealand
China	China and Hong-Kong
India	India
FSU	The former Soviet Union excluding the Baltic Republics

[1] A standard run of PROMETHEUS involves 2048 Monte Carlo experiments, although of course this number can be varied.

General features

- *PROMETHEUS is organized in modules*
- *The resources for fossil fuels are modelled*
- *RES potentials and costs are included*
- *Projections of international prices for fossil fuels*
- *Detailed final energy demand projections*
- *Competition of power generation technologies to cover electricity demand*
- *Hydrogen production, storage and infrastructure is modelled*
- *Endogenous technology dynamics*

MENA	The Middle East and North Africa region
Emerging Economies	All other countries that had more than 3,000 '05 $ PPP per capita in 2000.
RESTW	All other countries. Essentially this region contains the poorer economies mostly in Africa and Asia.

The PROMETHEUS model is organized in sub-models (modules), each one representing the behaviour of a representative agent, a demander and/or a supplier of energy. The figure below presents a summary flow chart of the PROMETHEUS stochastic model. The main modules are:

1) The demographic and economic activity module, which projects population and activity growth for each region.

2) The fossil fuel supply module that emphasizes oil and gas resources, while coal is assumed to have abundant supplies relative to production prospects in the projection time horizon

3) The biomass supply module, which contains technical and economic potential for biomass per region and their effects on biomass costs.

4) The cost-supply curves for renewable energy sources (RES) module.

5) The fuel prices module projecting both international and final consumer prices, with the latter being differentiated for each demand sector.

6) The final energy demand module, projecting energy demand and fuel mix in three main sectors; industry, transport and residential/services/agriculture sector. The following energy forms are considered as options in the final demand sectors: natural gas, oil, coal, biofuels, electricity, steam and hydrogen. The private passenger cars sector is modelled in detail, by distinguishing the following types of passenger cars: internal combustion engine cars (using gasoline, diesel, biofuels or hydrogen as a fuel), conventional and plug-in hybrids, electric cars and fuel-cell cars (using hydrogen or gasoline as a fuel).

7) The electricity generation module, identifying 26 power generation technologies and their competition to cover electricity demand for base, medium and peak load.

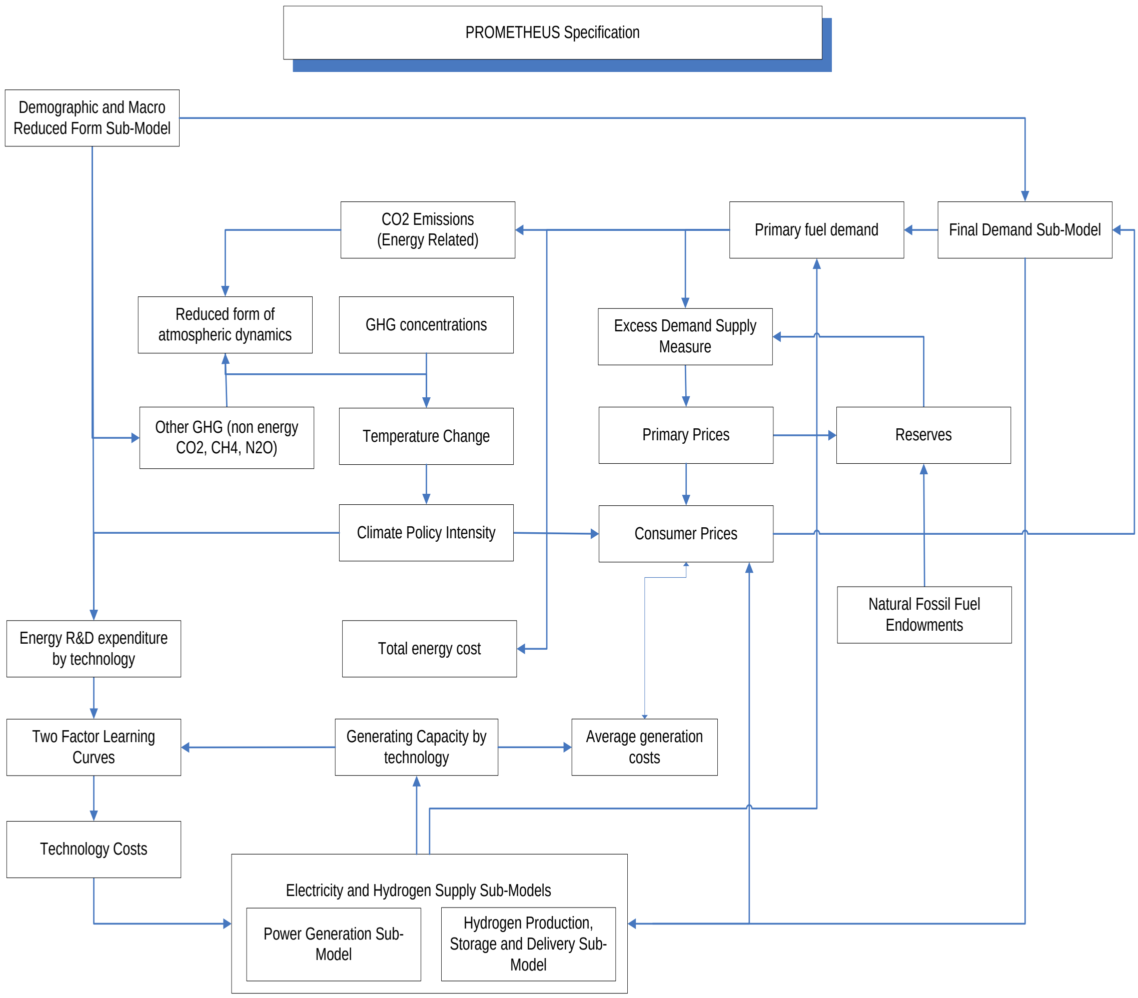
8) The hydrogen production sub-model, identifying 18 hydrogen production options.

9) The hydrogen storage and delivery module, including 16 different technological options in order to represent in detail the development of hydrogen infrastructure.

10) The climate change module, which uses reduced form stochastic equations to represent atmospheric dynamics, following the IPCC Third Assessment Report in order to calculate GHGs (CO2, CH4 and N2O) emissions and concentrations and the consequent global average temperature change.

11) The technology dynamics module, which endogenises technical progress through both learning by research and learning by experience mechanisms.

12) The technology diffusion module incorporating network effects accelerating spillovers between regions in cases where technology uptake attains critical levels.



More particularly in terms of variables of special interest in the context of projections of prices for internationally traded fossil fuels (coal, oil and natural gas), security of supply and technological development, PROMETHEUS specification includes:

PROMETHEUS includes

- *Oil reserves and resources in the Middle East, the Rest of the world and unconventional oil (extra heavy oil and tar sands)*
- *Conventional and unconventional resources of gas*
- *Gross additions to the reserves of oil and gas are endogenously determined and depend on resources, demand and international fuel prices*

- Oil reserves and resources in the Middle East, the Rest of the world, Venezuela's extra heavy oil and Canada's tar sands.
- Gross addition to the reserves of conventional oil in the world, which are composed of the reserves of oil in the Middle East and the Rest of the world, and are equal to the reserves of the previous year of each region increased by the difference between the gross additions to the reserves, the growth of which depends on the international price of oil, and the production of oil that took place in the previous year.
- Recovery rates of non-conventional oil sources (Venezuela's extra heavy oil and Canada's tar sands) that are price-dependent, acting as a crucial "backstop" preventing frequent occurrences of very high world oil prices.
- Gross additions to the reserves of conventional gas that are a function of the yet-to-find gas, which is based on the natural gas endowments, the gross additions to the reserves of gas and the gross additions to the world reserves of conventional oil. Unconventional gas resources in each region of the world (in the form of shale, tight and CoalBed Methane gas) are also identified in the model.
- Coal is assumed to have abundant supplies, thus its international price is demand driven and it is only weakly linked to the prices of other fuels.
- The production of oil, composed of the production in the Middle East, non-conventional oil production in Venezuela and Canada and the production in the Rest of the World, is based on the world demand for oil, the international price of oil and oil reserves.
- The oil production capacity in the Middle East is driven by production trends but is also subject to random disruptions determined from historical data
- The international price of oil depends on the production and the capacity of oil in the Middle East, as well as the world level of production and reserves of oil. The spot prices of heavy fuel oil, gasoline, diesel and other petroleum products are linked to the international price of oil (Brent crude oil price)
- The international price of gas depends on the reserves and production of conventional and unconventional gas and on the international price of oil. The primary price of gas in each region is linked to the international price of gas.
- Consumer prices of heavy fuel oil, light fuel oil, and gasoline in each of the ten regions depend on the spot prices of these fuels and on the carbon price.
- The consumer price of gas (different for each region and for industrial and residential consumers in each region) is based on the primary price of gas and on the carbon price.

- The consumer price of coal in each region is linked to the international price of coal and to the carbon price.
- Industrial and residential consumer electricity prices depend on the generation cost of electricity, which is the total cost of electricity generated (electricity generated by each technology times the technology cost for the production of electricity) divided by the total electricity generated, and on grid and power system costs.
- The capital cost of each technology is calculated using two-factor learning curves. The learning-by-doing component is the growth rate of capacity of the technology raised to a power that is based on the floor values of the capital costs, and the capital costs of the previous year. The learning-by-research component is the growth rate of cumulative R&D for each technology raised to a power that is based on the floor values of the capital costs, the capital costs of the previous year, and the cumulative R&D for each technology.
- Both Fixed Operating & Maintenance (FOM) and Variable Operating & Maintenance (VOM) costs of each technology are linked to the growth rate of capital costs. The technology cost of each technology for the production of electricity is based on the capital cost, FOM and VOM costs, the price of the fuel used by each technology, and its efficiency.
- Power generation from each technology depends on the overall cost of each technology used for the production of electricity and the generating cost of electricity.

Typical Inputs and Outputs of PROMETHEUS

Inputs

- Population
- GDP and economic growth per region
- World fossil fuel reserves and resources (for conventional and unconventional oil and gas resources)
- Taxes and subsidies
- Environmental policies and constraints
- Technical and economic characteristics of future energy technologies
- Parameters of supply curves for primary energy, potential of sites for new plants especially regarding power generation sites, renewables potential per type, etc.

Outputs

- Energy demand and supply balances for ten global regions
- Demand projections by sector (industry, residential, transport)
- Transport activity, fuels and passenger vehicles
- Power generation from different types of power plants
- Production of fuels (conventional oil and gas, unconventional oil, shale gas, tight gas, coal, biomass feedstock)
- Energy prices per region and sector
- CO_2 Emissions from fossil fuel combustion
- Policy Assessment Indicators (e.g. carbon intensity ratio, RES shares, efficiency indices, etc.)

Coverage of PROMETHEUS inputs and outputs

- Global coverage
- 10 countries/regions are identified
- 2012- 2050 by annual steps

Energy Demand

General Methodology

Main Features

- *PROMETHEUS identifies three main energy demand sectors (industry, transport and residential)*
- *Useful energy demand in each subsector depends on the evolution of activity indicators, energy prices and on efficiency progress*
- *Policies are explicitly represented and influence technology costs and choices of energy consumers*
- *Explicit representation of technological equipment in different subsectors using fuels*

Final energy demand in PROMETHEUS comes from three main sectors: industry, domestic (which includes households, services and agriculture) and transport.

Within these broad categories the model identifies subsectors: in industry heat, electricity and non-energy uses of fuels; in the domestic sector demand that is subject to fuel substitution (space and water heating, cooking) and specific electricity demand; in the transport sector road, air and marine bunkers. For each energy demand sector a representative decision making agent is assumed to operate.

In PROMETHEUS useful energy demand (services from energy such as temperature in a house, lighting, industrial production, etc.) is determined at a level of a sector/subsector. In the typical useful energy demand equation, the main explanatory variables are activity indicators and energy costs.

$$\ln\left(\frac{DEM_{i,t}}{DEM_{i,t-1}}\right) = \alpha + \beta \ln(\mathrm{ACT}_{i,t}/\mathrm{ACT}_{i,t-1}) + \sum_{l=0}^{p} \gamma_l \left(\ln\left(\frac{\mathrm{AVCOST}_{i,t-l}}{\mathrm{AVCOST}_{i,t-l-1}}\right)\right) + u_{i,t}$$

$DEM_{i,t}$ is the useful energy demand by subsector i in year t, $ACT_{i,t}$ is the appropriate activity indicator (e.g. industrial production, disposable household income, number of vehicles), $AVCOST_{i,t}$ is the weighted sum of the costs of different options (including fixed costs, fuel and non-fuel variable costs), α is a trend parameter, β represents the elasticity with respect to the activity indicator and $\sum_{l=0}^{p} \gamma_l$ is the elasticity with respect to the average cost. Equation (1) captures both short and long term reactions to fuel prices. Finally, $u_{i,t}$ is an error term representing variables that are not explicitly modelled, their sum is assumed to follow the normal distribution with zero mean and a constant variance and in some cases it displays serial correlation, which is modeled through an autoregressive scheme.

The PROMETHEUS model also considers saturation dynamics that depend on the income of households and the saturation factor exhibits a sigmoid curve which indicates income elasticity of energy above one if useful energy at low levels (developing regions) and elasticity values lower than one (and decreasing) when useful levels are high (developed regions).

Activity indicators are derived from the demographic and economic activity module which has a hierarchical structure with variables depending partly on a more general stochastic trend and an independent random term. The demographic module is relatively simple and it is calibrated to reproduce as a mean the UN medium fertility variant scenario.

Autoregressive specifications for the GDP per capita growth have been estimated for all regions and their covariance has been taken into account. Very long term GDP per capita series have been utilized in order to carefully measure the variability in underlying growth. GDP movements are also subject to short term (cyclical) variation displaying strong covariance between regions. The levels of overall economic activity as measured by GDP have a strong bearing on many variables of the model. On the other hand, there is virtually no feedback from the energy system on GDP (with the exceptions of the FSU and MENA regions where the effect of international fuel prices on their export revenues is taken into consideration).

The demographic and economic activity module of PROMETHEUS also determines other activity variables such as industrial production, household disposable income and car ownership as direct or indirect functions of GDP. Regarding car ownership per capita the model distinguishes between short term and long term penetration curves with a stochastic transition between the two. For the deterministic reference scenario, PROMETHEUS uses the activity indicators (GDP, consumption, investments, disposable income) as projected by the Computable General Equilibrium model GEM-E3 for each of the ten regions.

In general, stochastic transitions have been implemented in PROMETHEUS to model structural change occurring when a developing region attains levels of income typical for a developed country. In such a case, it is assumed that the specific demand equation for this region is gradually replaced by the corresponding equation for developed regions.

Useful energy requirements at the level of sectors and sub-sectors (e.g. space heating, water heating, specific electricity uses, etc.) have to be met by consumption of final energy. The representative agent in each sector or sub-sector is formulated to choose among fuels, technologies and energy savings. Final energy demand is met by a number of options characterised by the fuel used and specific technologies. Notable among the latter are: for space heating fossil fuel boilers, electrical options (resistance and heatpumps) and fuel cells; for road transport conventional vehicles (using gasoline, diesel, biofuels or hydrogen), hybrids (both stand-alone and plug-in), electric vehicles and fuel-cell powered (with or without reformer).

Main features

- *Electricity prices for industry, prices of fossil fuels and industrial value added impact the evolution of energy demand in industry*
- *Fuel/ technology competition is driven by the cost of the competing options*
- *Changes in end-user prices (removal of fossil fuel subsidies) are taken into account*
- *Increases in energy prices, technological progress and energy savings induce energy efficiency improvements*

Industry

PROMETHEUS models separately industrial demand for electric and non-electric uses.

The evolution of industrial demand for electricity is a function of electricity prices for industry and industrial value added in each region (that is exogenously specified using the GEM-E3 model). Demand for electricity is covered by the electricity grid or combined heat and power (CHP) facilities or, finally, by fuel cells that use hydrogen or natural gas. The gap in supply is calculated (with the substitution mechanism described below) and the ensuing competition between these options determines their shares in covering electricity demand for industries.

The total non-electric energy demand for industrial processes requiring steam and heat is determined by industry value-added and the "steam price", which is defined as the weighted average of fuel prices (coal, oil, gas, CHP, fuel cells) for industry consumers (using their shares in non-electric industrial energy demand of the previous year as weights). Coal, natural gas and oil together with CHP facilities and fuel cells (that can use hydrogen or natural gas) compete for gaining shares in the demand-supply gap for industrial non-electric uses. The inclusion of CHP and fuel cells in the set of competing technologies for non-electric uses is based on the rationale that their utilization for electricity production results in the co-production of a certain amount of heat which is subtracted from the gap for non-electric uses.

Energy efficiency improvement is induced by increases in energy prices, technology/fuel choice at the energy use level and can be also obtained by direct investment on energy savings. The saving possibilities are seen as cost-quantity curves which have limited potential and non-linear increasing costs. PROMETHEUS explicitly takes into account fossil fuel subsidies and taxes in the ten regions of the world and can simulate changes in end-user prices for individual energy consumers, e.g. removal of fossil fuel subsidies for residential purposes in the Middle East and North Africa (MENA) region.

The choices of energy use technologies involve a variety of possibilities which differ in upfront investment costs and in variable costs depending on energy performance and efficiency. The scope of the industrial demand sub-model of PROMETHEUS is to represent simultaneously:

- the mix of technologies and fuels, including the use of CHP and fuel cells
- the links to self-supply of energy forms (e.g. cogeneration of electricity-steam);
- the representation of energy saving possibilities;

- the satisfaction of constraints through emission abatement, pollution permits and/or energy savings, and
- Possible substitutions between energy forms, technologies and energy savings

Residential

Main features

- *Energy meets fundamental needs of households*
- *Demand for non-substitutable electricity is driven by income growth and residential electricity price*
- *Fuel/ technology competition for heating purposes is driven by the cost of the competing options*
- *Responses to price shifts and environmental policies usually involve long lags*

In the residential sector, energy is consumed as input in processes that provide services to the households, such as space heating, water heating, cooking, cooling, lighting and other needs. The model distinguishes between residential sector's (which, as was noted above, includes households, services and agricultural sectors) demand for specific electric uses (e.g. electric appliances for non-heating purposes, air-conditioning, lighting etc.) and useful energy demand for space and water heating.

Demand for non-substitutable electricity is driven by economic activity and income growth and residential electricity price, while useful energy demand for heating purposes is related to income growth and the evolution of fuel prices.

Residential and tertiary consumers decide about the level of energy consumption taking into account their need for heating, which is further related to changes in income and fuel prices. Different iso-elastic demand equations are estimated for each type of residential sector's demand and for each region. As the pattern of energy consumption is not usually controlled directly by the consumer, but is determined by the installed technology and is largely embodied in the characteristics of the durable equipment, responses to price shifts and environmental policies usually involve long lags. Changes in consumption patterns for developing regions are also modelled through a gradual convergence procedure to developed countries' consumption patterns.

The competition between technologies to cover energy demand for space and water heating is modelled using the substitution specification described below. The model differentiates between "cold" and "warm" regions (like India, Emerging economies, the Middle East and North Africa and the Rest of the World region), as in the latter energy demand for space heating is relatively insignificant, i.e. energy demand for water heating dominates. Useful energy demand depends on regional climatic characteristics.

Energy demand for heating purposes is covered by natural gas, oil, coal, electric resistances, fuel cells (using hydrogen or natural gas as a fuel) and heat-pumps. Substitution between fuels and technologies is triggered by their total cost, which includes capital, fixed O&M, variable O&M and fuel cost, their transformation efficiency, the scrapping rates of their equipment and their relative "maturity" factors. Technological trends and stochastic infrastructure and social network effects that influence technologies' maturities, especially for fuel cells and heat-pumps, are incorporated in the decision mechanism, in order to represent in a realistic way the consumption patterns, the evolution of technology and fuel mix and the rigidities involved in the decision mechanism.

Energy performance largely depends on the characteristics of the dwelling (thermal integrity) and the technology of the equipment which uses energy. Individual energy consumers can spend money to improve energy efficiency and select solutions with upfront costs and utilisation performance leading to reasonable pay-back periods. Energy efficiency progress implies high upfront cost but saves on variable costs during the lifetime of the energy equipment.

Energy meets fundamental needs of households. In developed economies (like North America, OECD Western Pacific and the EU) income elasticity is expected to be less than one, while in developing regions income elasticity can exceed one. Econometrics are used to estimate such elasticity value in all PROMETHEUS regions.

Transport

Main features

- *PROMETHEUS projects in detail the evolution of passenger car stocks*
- *The penetration of electricity and hydrogen depends on their relative costs compared to internal combustion engine cars*
- *Energy efficiency improvements are endogenous in the model*

The transport sector is considered among the most important energy related GHG emitters, while the emission reduction options in this sector are rather limited (compared to the power generation sector). A detailed representation of the transport sector allowing projection of activity, final energy and carbon dioxide emissions to the future and policy and impact analysis is thus very important.

The PROMETHEUS transport module projects to the future (up to 2050) the entire transport sector for the ten regions of the world identified in the model. The module projects the evolution of passenger car stocks and demand for transport, based on economic and technology choices of transportation; PROMETHEUS also projects the derived fuel consumption (diesel, gasoline, natural gas, biofuels, electricity and hydrogen) and CO_2 emissions from fuel combustion.

The PROMETHEUS model is equipped with a detailed mechanism to project the evolution of passenger car stocks in each region, which depends on the exogenous socio-economic projections (mainly population and GDP) and on the average cost of passenger transportation (depending on the evolution of fuel prices, especially for diesel, gasoline, biofuels, electricity and hydrogen). The formulation used in PROMETHEUS can also capture changes in consumption patterns (when a developing region reaches income levels typical for a developed one) and the possible saturation effects in developed regions (when passenger vehicles per inhabitant reach a certain high threshold).

The private passenger cars sector is modelled in great detail in the PROMETHEUS model, by distinguishing thirteen types of passenger cars:

- Internal combustion engine cars, using gasoline, diesel, hydrogen (liquid or gaseous) or bio-fuels as a fuel
- hybrid cars (conventional hybrids, plug-in hybrids, hybrids using bio-fuels, plug-in hybrids using bio-fuels)
- pure electric cars
- Fuel cell cars, using hydrogen (gaseous or liquid) or gasoline (with on-board reformer).

The road transport module projects transport activity, in terms of car ownership per capita, and the penetration of new car types in the market. The model first determines the total car stock that is necessary to satisfy the increased transport activity, by using stochastic equations of GDP and average fuel price for road transport. Short term, long term and very long term effects on road transport activity are thoroughly modelled, in order to project transport activity.

Very long term equations are estimated using a pool of developed countries that have already reached or they are approaching saturation levels. Transitions from one specification to another are modelled using stochastic weights. PROMETHEUS then calculates the new registrations required to meet the increased demand by taking into account the scrapping of the cars reaching the end of their lifetime.

Market penetration of road transport technologies is not pre-defined but is a result of the model depending on economics and behaviours. The share of each car type in new registrations is determined by its total cost per km (that includes capital, fixed O&M, variable O&M and fuel costs) and stochastic relative maturity factors through a Weibull specification (already described in the “Substitution mechanism” section).

Then, fuel consumption (gasoline, diesel, bio-fuels, electricity or hydrogen) is calculated using efficiencies, which are determined endogenously by the two factor learning curves module, and average mileages. Infrastructure and social network effects are thoroughly modelled and play a crucial role, especially for new technologies, like electric and fuel cell cars.

Improvements in energy efficiency also impact final energy consumption in the road transport sector. Reduction in energy intensity of road transport activity can be a result of increases in fuel prices, technological choices (e.g. hybrid vehicles substituting for gasoline internal combustion cars), reduction in the utilisation rates of vehicles as motorisation increases, changes in consumption patterns, technological improvements and imposition of energy efficiency (or CO_2) standards.

PROMETHEUS incorporates stochastic equations for the calculation of final energy consumption for non-road transport activity, including aviation, internal navigation and railways, estimated as a function of GDP and average fuel price. The main technologies that compete to satisfy non-road transport demand are oil and biofuels (there are only limited opportunities for electricity and fuel cells to penetrate in the non-road transport sector). Competition between technologies to cover non-road transport demand occurs in terms of shares in new demand (calculated using the substitution mechanism described the previous section) and heavily depends on the relative competitiveness of oil products (mainly diesel, gasoline and kerosene for aviation) with biofuels. GTL (Gas-to-Liquids) and CTL (Coal-to-Liquids) technologies are also modelled in PROMETHEUS to cover both road and non-road transport demand.

Marine bunkers are treated separately at the world level, due to the fact that CO_2 emissions from bunkers are not included in climate policy targets, as described in Kyoto Protocol. Oil products dominate in final energy demand for marine bunkers, but the model also includes biofuels as an alternative to petroleum products.

The Substitution Mechanism

Main Features

- *PROMETHEUS explicitly models the substitution between different fuels and technologies in final demand subsectors*
- *New capacity is determined by the increase in final energy demand in each sector and the scrapping of old capacity*
- *Both normal and premature scrapping of technologies are included*

The substitution between different fuels/technological options in PROMETHEUS is modelled through a mechanism that is similar for both final demand and supply (power generation and hydrogen production that are discussed in sections below respectively). It is therefore presented here as it applies to final demand; a similar formulation is applied to define the mix of the supply options.

Central to this mechanism is the notion of the "gap". It is defined in terms of the difference between energy demand and the amount of energy that can be satisfied using existing equipment. The generic specification for the gap in demand is:

$$GAP_{i,t} = TOTDEM_{i,t} - CAP_{i,t}$$

In the above equation, $CAP_{i,t}$ represents the total capacity of the equipment of each subsector i which has been installed by the year t-1 and is not scrapped until t:

$$CAP_{i,t} = \sum_{k} (1 - SCR_{i,k,t}) * DEM_{i,k,t-1}$$

where the summation includes all competing technologies k, $DEM_{i,k,t}$ stands for the demand satisfied by technology k in year t and $SCR_{i,k,t}$ is the overall scrapping rate of technology k, which includes normal scrapping, due to plants reaching the end of their lifetimes, and premature scrapping, due to changes in variable and fuel costs which render the continuation of the plant's operation economically unsustainable.

The inclusion of the latter form of scrapping is important in order to enable the modelling of rapid technical transformation in case of strong action against climate change or rapidly rising fossil fuel prices, as the renewal of equipment stock accelerates. The general algebraic formulation for the premature scrapping rate is[2]:

$$prescr_{k,t} = 1 - \frac{vom_{k,t}^{-\gamma_t}}{h_{k,t} * \sum_{j \neq k} \left(totcost_{j,t}^{-\gamma_t} \right) + vom_{k,t}^{-\gamma_t}}$$

[2] In equations (4)-(6) the subscript of the sector i is omitted for purposes of legibility.

where $prescr_{k,t}$ is the pre-mature replacement rate of technology k, $vom_{k,t}$ is the variable (including fuel) cost of technology k and $totcost_{j,t}$ is the total cost of using technology j including capital and variable costs (index j represents all competing technologies in a sector i including technology k). Factor $h_{k,t}$ is stochastic and is used for scaling purposes and γ_t (also stochastic) is a measure of sensitivity of investment decisions to cost considerations.

Allocation of new investments

- *is modelled as a quasi cost-minimizing function driven by the total cost of the competing options*
- *The market share of each technology in new investments depends on its total costs and on its relative "maturity" factor"*

In most cases demand does not fall faster than total scrapping and the gap is therefore positive[3]. Competition between technologies occurs in terms of market shares within the gap. The allocation of new investments is modelled as a quasi cost-minimizing function and is driven by the total cost of the competing options. The total cost of technology k at time t is expressed as:

$$totcost_{k,t} = \frac{\left(\frac{dr_t * e^{dr_t * lft_k}}{e^{dr_t * lft_k} - 1}\right) * cc_{k,t} + fc_{k,t}}{ur_{k,t}} + vom_{k,t} + \frac{fuelprice_{k,t}}{eff_{k,t}}$$

$cc_{k,t}$ is the capital cost, $fc_{k,t}$ is the fixed cost for operation and maintenance (O&M), $vom_{k,t}$ refers to the variable costs of O&M, $eff_{k,t}$ is the efficiency factor, $ur_{k,t}$ is the utilization rate, $fuelprice_{k,t}$ is the price of the energy source used by technology k, dr_t is the discount rate, which is a function of long term interest rates derived from the economic activity module, and lft_k is the economic lifetime of technology k. Capital costs, fixed and variable O&M costs and the efficiency factor are calculated in the technology dynamics module and endogenous technical progress leads to an overall improvement in each of them.

The shares of each option k in the gap for the year t are calculated as follows:

$$sh_{k,t} = \frac{w_{k,t} * totcost_{k,t}^{-\gamma_t}}{\sum_k w_{k,t} * totcost_{k,t}^{-\gamma_t}}$$

The above equation (Weibull specification) determines the market share in the gap of technology k based on its total cost $totcost_{k,t}$. In this specification, the stochastic parameters γ_t represent the sensitivity of the share in the gap with respect to the total cost of each technology, while the stochastic weights $w_{k,t}$ can be interpreted as reflecting the relative "maturity" factor of each technology in terms of readiness of consumers to adopt them. These factors play an important role in modelling the process of technology diffusion.

[3] If the equation (2) produces a negative value, the gap is assumed to be zero and no competition between technologies takes place

- *Technological uptake is interconnected between regions through costs*
- *Technological diffusion in also influenced by mimetism, trade and network effects, which are modeled implicitly in PROMETHEUS*
- *The radical energy system transformation towards a predominantly electric paradigm and to a hydrogen-based economy are included in the modelling*

Uptake is of course interconnected between regions through costs that are strongly related across the world, but apart from economic considerations, diffusion is also influenced by a host of other factors including mimetism, information, trade, infrastructure development and network effects. In PROMETHEUS the maturity coefficients follow a stochastic path that is determined by a world component and an independent regional component. The maturity of technologies belonging to some clusters also display statistical dependence on other technologies belonging to the same cluster. Notable cases where this applies are: electric and plug-in hybrid vehicles; different types of fuel cells meeting requirements in transport, industry and the residential sectors; in power generation the acceptance of CO_2 storage influences the penetration of alternative and otherwise technologically distinct CCS technologies.

In two cases stochastic dependence has been taken a step further in order to analyse probabilistically the prospects of a radical transformation of the world energy system. They concern: the case of transformation towards a predominantly electric paradigm with deep penetration of electricity in the space heating and road transport sectors; a transition to a hydrogen-based energy system involving the evolution of a distinct energy production, distribution and use paradigm. For these two cases, apart from the stochastic dependence that characterises technological clusters, logistic penetration curves simulate stochastically take-off and saturation depending on non-deterministic thresholds attained by the technologies involved as a whole at a world and regional level.

The detailed specification of stochastic dependence in technology diffusion allows for a better representation of the distribution of the penetration of the technologies themselves but also contributes to the distribution of a host of other variables, which is influenced by the statistical dependence of the various factors determining them.

Power Generation

Main Features

- *Total electricity generation is determined by electricity demand, own-consumption of power plants and distribution losses*
- *PROMETHEUS model is equipped with an enhanced portfolio of 26 power generation technologies*
- *Competition between technologies to cover electricity demand occurs in terms of market shares within new capacity requred*
- *Competition is driven by the relative cost of the power generation options*
- *Both normal and premature scrapping of technologies are included*

PROMETHEUS incorporates a detailed module for the representation of the power generation sector. Total electricity generation is determined by electricity demand for the industrial, residential and transportation sectors, own-consumption of power plants and transmission and distribution losses in each region identified in the model. The PROMETHEUS model is equipped with an enhanced portfolio of power generation technologies. Overall, twenty six electricity generation technologies compete to satisfy electricity requirements.

	Power Generation technologies		
1	Conventional coal thermal	14	Nuclear PWR
2	Conventional lignite thermal	15	Nuclear 4th generation
3	Supercritical pulverised coal	16	Large hydro
4	Integrated coal gasification	17	Small hydro
5	Conventional gas thermal	18	Wind on-shore
6	Open cycle gas turbine	19	Wind off-shore
7	Gas turbine combined cycle	20	Photovoltaics
8	Combined heat and power	21	Concentrated Solar Power
9	Conventional oil thermal	22	Conventional biomass thermal
10	Open cycle oil turbine	23	Biomass gasification
11	Supercritical pulverised coal with CCS	24	Biomass gasification with CCS
12	Integrated coal gasification with CCS	25	Fuel-cells using hydrogen
13	Gas turbine combined cycle with CCS	26	Fuel-cells using natural gas

Plant scrapping (normal and premature) and competition of alternative technologies in new capacity installations follow the pattern of the substitution mechanism described in the previous chapter. PROMETHEUS also accounts for already decided investments in specific power plants and the firmly adopted plans for decommissioning of old and inefficient ones in each region, as obtained from a wide literature review.

The utilisation of the capacity of power plants for each time segment (dispatching of power plants) is endogenous in the model and is determined by the annual load duration curve together with variable O&M and fuel costs and the installed capacities of the different technologies.

The year is divided into nine hour segments, which are symbolized by the index i, i=0,..,8. The annual load duration curve is approximated by a rectangular section representing base load and an exponential section

Load curve

- *The annual load duration curve is approximated by a rectangular section representing base load and an exponential section accounting for the shorter durations*
- *Power plant dispatching in each time segment is endogenous*
- *When load profile in a region becomes smoother, capital intensive technologies (like RES and nuclear) are favoured*
- *Electricity prices are determined by the long term average generation costs and are differentiated between industries and households due to different sectoral load profiles*

accounting for the shorter durations. Total electricity production for the year t is then approximated ($TOTPROD_t$) using the formula:

$$TOTPROD_t = \sum_{i=0}^{8}[\,(M_t - B_t) * e^{-\lambda_t*(0.25+i)}] + 9 * B_t$$

where M_t is the peak load demand, B_t is the base load demand and the parameter λ_t is calculated implicitly from the equation:

$$\frac{1 - e^{-8.76*\lambda_t}}{\lambda_t} = \frac{PROD_t - 8.76 * B_t}{M_t - B_t}$$

where $PROD_t$ represents electricity generation.

The extent to which the various power plant types k are used in each hour segment i (i=0,..,8) is determined from the following relationship:

$$\sum_k CAP_{k,t} * e^{-\frac{\alpha_{u,t}}{disp_{k,t}}} = (M_t - B_t)e^{-\lambda_t*(0.25+i)} + B_t$$

which, for each time segment i, is solved implicitly for $\alpha_{u,t}$. In this specification, $CAP_{k,t}$ is the installed capacity of technology k in year t and $disp_{k,t}$ represents the share of technology k in meeting power generation requirements in each time segment on the basis of its short term marginal cost[4].

The model associates a demand fluctuating profile to every use of electricity included in the demand sector modules (industry, transport, households). Regional load profiles change over time and in scenarios, depending on the relative shares of various electricity uses, the prices (which are higher for sectors with poor load factors), the degree of energy savings (and the use of more efficient equipment) and special demand side management measures including smart metering, which in the transport sector are supposed to motivate battery recharging at off peak hours. When load profiles become smoother, capital intensive power technologies are favoured (like RES and nuclear) and reserve power requirements are lower, implying lower overall costs.

Electricity prices are determined by the long term average generation costs and are calculated separately for the final electricity demand sectors (industry and domestic sectors). Differences in electricity prices between sectors mostly arise from the fact that different technologies supply different segments of the

[4] that includes the variable O&M cost and the fuel cost of each technology.

load duration curve and from differential distribution and grid costs. The electricity prices in PROMETHEUS are calculated in order to recuperate all costs, including capital and operating costs, costs related to schemes supporting renewables, grid costs and supply costs.

Investments in RES

- *Regional stochastic cost-supply curves are introduced for all RES technologies*
- *Cost-supply curves imply that additional RES deployment increases RES costs*
- *RES support schemes are modelled and influence investments in RES technologies*
- *RES facilitation policies include subsidies, feed-in tariffs and RES targets*

Investment in RES based electricity is dominated by the consideration of capital costs. On the other hand such technologies are generally characterised by limitations as to their potential. In most cases this is taken into account by incorporating reductions in availability as such potentials are approached (i.e. the most suitable sites being exploited earlier and less suitable ones increasingly sought). This effectively results in a supply curve where costs increase non-linearly with the gradual exhaustion of potential. The cost-supply curve implies that additional RES deployment is accompanied by a reduction in availability and hence increase in RES costs for electricity production due to the depletion of suitable sites, the difficulty of getting access to resource and grid connection difficulties. In establishing such curves, a wide range of bibliography is used. Of course in order to fit into the specifications and purpose of PROMETHEUS the potential and general shape of the curves are stochastic. The modelling also simulates the site retaining factor, i.e. the cost incentive to install a new renewable power plant in the same place where an old one existed.

PROMETHEUS can take into account support for RES technologies in each of the ten regions identified in the model by assuming different levels of feed-in tariff and other supporting schemes for renewables in the alternative scenarios simulated. The main RES facilitation policies that can be simulated with the PROMETHEUS model include subsidies for RES technologies, feed-in tariffs and obligation/target for specific RES deployment.

In constructing the supply curves for biomass, a number of studies were taken into account which include technical and economic assessment of biomass potential. However, their estimates vary significantly, implying high uncertainty regarding biomass economic potential. Such uncertainty is introduced explicitly in the specification of the biomass cost equations, according to which the deployment of biomass technologies is constrained by limited land and waste energy resource availability.

Driven by emission reduction targets or by carbon pricing, CCS competes with other emissions reduction options, such as carbon free power generation (renewable energy, nuclear), the fuel switching towards low emitting forms and the reduction of energy consumption. The power plants that are equipped with CCS are more expensive in terms of capital and O&M costs and have lower net thermal efficiency compared to similar plants without carbon capture. Non-linear cost-supply curves are simulated for underground storage of carbon dioxide. Public acceptance issues can be modelled through parameters lowering CCS potential and making the technology more expensive.

Nuclear deployment depends on the evolution electricity demand, load profiles, economic features of competing technologies and carbon prices (and other energy and climate policies assumed in each of the ten regions identified in the model). The unit cost of investment depends on the nuclear technology: nuclear PWR and fourth generation technologies are represented in the model. The unit cost of investment take into account costs for future decommissioning (15% provision). Variable and fuel costs of nuclear power take into account waste recycling and disposal costs. Nuclear costs are revised upwards following the Fukushima accident. Due to the long construction times for new nuclear power plants, the increasing public acceptability concerns and the difficulty to licence and build new nuclear plants, the development of nuclear power is calibrated until 2020 taking into account the already decided investments and the firmly adopted plans for decommissioning of nuclear power plants in each region identified in the model.

The building of equipment in the electricity and steam system usually requires several years. This has important implications for planning and plant type choice. The model considers the financial costs associated to the construction period but ignores the fact that the plant types differ in construction time, which may influence plant selection in particularly uncertain circumstances.

Hydrogen Production and Infrastructure

Hydrogen

- *18 hydrogen production options compete for the centralized H_2 production*
- *Hydrogen can be used for vehicle propulsion and for production of steam or heat and electricity*
- *Hydrogen powered cars compete with other vehicle types to gain share in vehicle stock*

PROMETHEUS includes 18 hydrogen (H2) production options, which compete for the centralised production of hydrogen. Investments in hydrogen-supply technologies are based on the production cost of each technology. In each year, the model determines the required new investments, by taking into account scrapping and pre-mature scrapping rates of technologies, and then calculates their shares in new investments (using a Weibull function similar to the one used in the power generation module).

	Hydrogen Production technologies		
1	Gas steam reforming	10	Biomass pyrolysis
2	Gas steam reforming with CCS	11	Small scale biomass gasification
3	Solar methane reforming	12	Large scale biomass gasification
4	Coal partial oxidation	13	Large scale biomass gasification with CCS
5	Coal partial oxidation with CCS	14	Solar high temperature thermochemical cycles
6	Coal gasification	15	Nuclear high temperature thermochemical cycles
7	Coal gasification with CCS	16	Water electrolysis from dedicated nuclear plant
8	Oil partial oxidation	17	Water electrolysis from dedicated wind plant
9	Oil partial oxidation with CCS	18	Water electrolysis from electricity grid

On the demand side, hydrogen is introduced in the competitive market of distributed electricity production (through stationary fuel cells) and in the road transport sector. The hydrogen and electricity systems are connected and interact in the energy system in two points: in the hydrogen production through the electricity price in grid electrolysis and in the demand side through the competition between the decentralized fuel cell electricity production and the electricity from grid.

The major end uses of hydrogen in PROMETHEUS are for vehicle propulsion and for production of steam or heat and electricity. Two kinds of vehicle propulsion engines that use hydrogen are included in PROMETHEUS: fuel cells and internal combustion engines. The fuel cell engine is further differentiated into stack and system components. Moreover, the stacks and systems themselves are varying depending on the fuel used in the fuel cell cars (hydrogen or gasoline). On the other hand, the internal combustion engines technically are not different from the internal combustion engines that are used today in oil-powered vehicles.

For automotive on-board hydrogen storage, two options are included in the model: hydrogen in liquid form and hydrogen in gaseous form. These two options compete in the model, since each of them needs its own specific infrastructure to support it. On-board gasoline reformers are also included in PROMETHEUS, in order to allow for on-board hydrogen production. These reformers are used in the fuel cell vehicles, bypassing in this way the need for hydrogen distribution infrastructure.

In total, the hydrogen related technologies (incorporated in the model) for mobile applications are two types of fuel cell stacks, two types of fuel cell systems, two types of on board hydrogen storage, one type of on-board reformer and a hydrogen IC engine. All these result in eight different hydrogen related technologies in road transport. These components are combined together to define five vehicle types in the model:

- Fuel cell cars powered with liquid hydrogen
- Fuel cell cars powered with gaseous hydrogen
- Fuel cell cars with on-board reformer powered with gasoline
- Internal combustion engine cars fuelled with liquid hydrogen
- Internal combustion engine cars fuelled with gaseous hydrogen

The hydrogen powered cars compete with the rest of the car types that are included in the model in order to gain share in the new market. The decision is based on the cost per vehicle kilometre of each car type.

In PROMETHEUS hydrogen is also used for the combined production of heat and electricity. The fuel cell CHP plants are distinguished according to their size and the fuel that they use. Small scale stationary fuel cell CHP plants (1-5Kw) are directly linked with low voltage grid (small scale applications), while fuel cell CHP plants of a size of up to 300KW are used for the combined production of low enthalpy steam and electricity in the industrial sectors (medium voltage). Regarding the fuel that they use, two types are considered, one which is fuelled directly with hydrogen and one which uses natural gas and onsite steam reforming. For a more accurate characterisation of the fuel cell CHP plants, the fuel cell stacks, the fuel cell systems and the onsite reformers are defined individually.

In total, six hydrogen related technologies are considered for stationary applications in the residential/commercial and industrial sectors:

- Fuel cell stacks and fuel cell systems for small scale CHP
- Fuel cell stacks and fuel cell systems for large scale CHP

- Onsite natural gas reformers

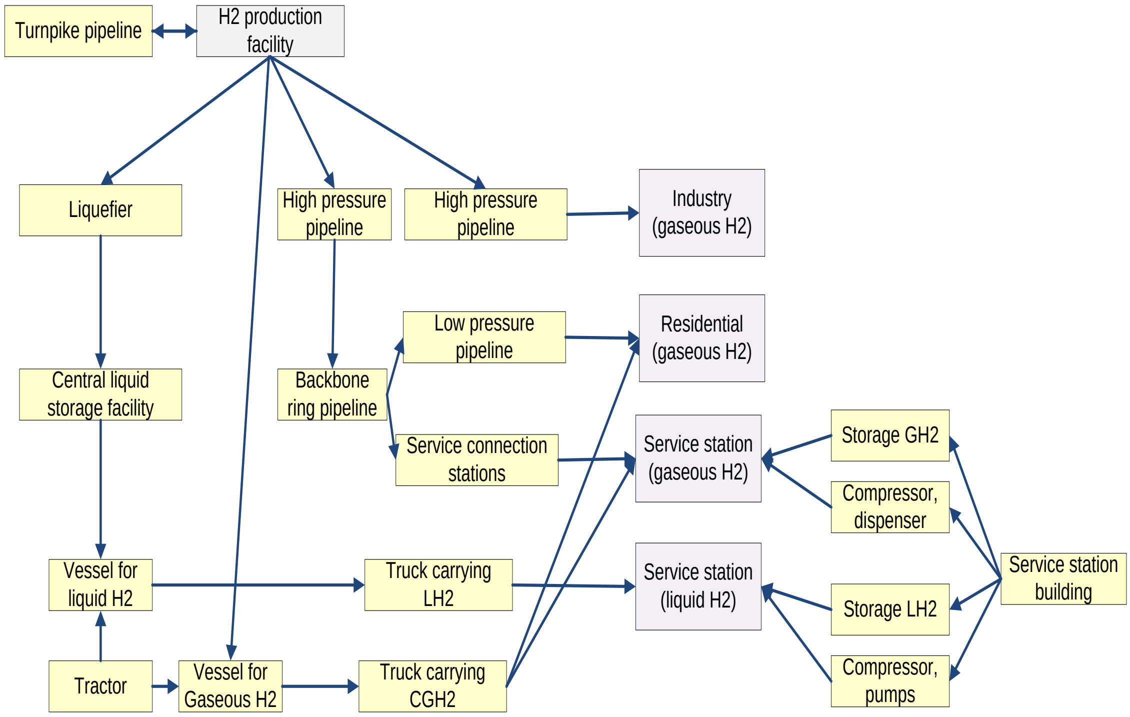
Hydrogen infrastructure

- *The extensive development of H2 infrastructure is critical for the transition towards a hydrogen-based economy*
- *It is not possible to have infrastructure developments without hydrogen demand and vice-versa*
- *The PROMETHEUS technology database contains several options for liquid and gaseous hydrogen storage, transport and distribution*

The eventual development of hydrogen economy must be accompanied by the development of an extensive hydrogen storage and delivery infrastructure. A great number of configurations of such infrastructure are possible. The PROMETHEUS technology database contains several options for liquid and gaseous hydrogen storage and distribution (pipelines, trucks, service stations) providing flexibility in the choice of the components of a future hydrogen infrastructure system as a result of the work performed in the common information base of the CASCADE MINTS project.

However, complete modelling of the hydrogen storage and distribution system is a very complex task, since it is a "chicken-egg" problem; it is not possible to have infrastructure developments without demand and vice-versa (network effects, which are modelled in detail, play a crucial role in development of such infrastructure). Therefore, a vision is needed about the future development of hydrogen infrastructure system, in which its main components will be identified and fully characterised in terms of their technical and economic performance.

The stylized configuration of PROMETHEUS refers to an "average" region supplied with hydrogen during a "take-off" period for hydrogen and contains a plant connected to a turnpike pipeline, which is used as storage medium, load management tool and emergency supply in cases of production disruption. The turnpike pipeline crosses the region and is connected with similar turnpike pipelines in neighbouring regions. Moreover, other pipelines of smaller capacity connect the plant with the urban and industrial areas (high-demand areas) of the region. The model identifies two kinds of service stations: rural stations along the roads crossing the region and urban service stations mostly concentrated on the outside ring of the urban area. It can be reasonably assumed that all rural stations will be supplied by trucks carrying gaseous or liquid hydrogen. On site hydrogen production and distribution facilities can be built where demand is high enough. Hydrogen can be stored either in gaseous or liquid form. PROMETHEUS also incorporates competition between gaseous or liquid storage options and between pipelines and trucks.


Turnpike pipeline
H2 production facility
Liquefier
High pressure pipeline
High pressure pipeline
Industry (gaseous H2)
Low pressure pipeline
Residential (gaseous H2)
Central liquid storage facility
Backbone ring pipeline
Service connection stations
Service station (gaseous H2)
Storage GH2
Compressor, dispenser
Vessel for liquid H2
Truck carrying LH2
Service station (liquid H2)
Service station building
Storage LH2
Tractor
Vessel for Gaseous H2
Truck carrying CGH2
Compressor, pumps

Fossil fuel supply

Main features

- *The evolution of oil and gas reserves is one of the most important drivers of the world energy system*
- *PROMETHEUS distinguishes between conventional and unconventional (extra heavy oil and tar sands) oil resources*
- *Unconventional gas resources (shale, tight and CBM gas) are included*
- *Gross additions to oil and gas reserves depend on the resources base, global fuel demand and international fuel price*

The uncertainty pertaining to the evolution of oil and gas reserves is one of the most crucial drivers of the world energy system. Conventional and non-conventional oil are distinguished in PROMETHEUS analysis. The former are differentiated between Gulf and non-Gulf oil, while the latter are distinguished between Venezuela's extra heavy oil, Canada's tar sands and light tight oil.

The uncertainty that surrounds the amount of oil and natural gas that is yet to be discovered has been incorporated into PROMETHEUS. Using studies conducted by USGS, stochastic analysis has been carried out in order to obtain joint distributions for the yet to be discovered oil and gas resources (endowments) at the starting year of the simulation procedure.

The rate of discovery as well as the rate of recovery of petroleum are endogenous in the model, they are both positively correlated with the international oil price and are subject to their own specific uncertainties. Gross additions to reserves of conventional oil are a function of the yet to be discovered oil in each region, the international oil price and world oil production, while the recovery rates of unconventional oil sources are price-dependent and act as a "backstop" preventing the persistence of very high oil prices.

Gross additions to conventional gas reserves are a function of the yet to be discovered natural gas and the gross additions to oil reserves, as the exploration for conventional oil increases the likelihood of gas discoveries. In addition to conventional gas, unconventional gas (shale, tight and coal bed methane) is considered in the PROMETHEUS model, the resource base of which and the uncertainty surrounding it, is derived from a variety of assessments.

Oil and gas reserves are supplemented by reserve growth arising from known deposits following assessments by USGS. Apart from statistical dependence arising from geological factors, exploration and extraction technologies, hydrocarbon reserves are also linked through their dependence on the relevant prices which are incorporated in the equations.

Oil production in the Gulf is influenced by the (lagged) reserves to production ratio in the Middle East and the world oil demand, while oil production capacity in the Middle East is driven by petroleum demand but it is also subject to random disruptions, whose variance is determined using historical data. Conventional oil production in the Rest of the world is driven by the world demand, the international oil price and reserves of this region.

Non-conventional oil production is driven by world oil demand, the international oil price and the R/P (reserves to production) ratio of conventional oil. When the international oil price exceeds a (stochastic) threshold, the production from non-conventional oil sources increases substantially, as more and more non-conventional deposits become economically recoverable.

International fuel prices

- *International oil price is demand and supply driven and depends on the oil production to capacity ratio in the Middle East*
- *International gas price depends on the world gas R/P ratio and on the international oil price*
- *International coal price is only demand driven*

International fuel prices (for oil, natural gas and coal) are endogenous in PROMETHEUS. The international oil price ($oilprice$) is demand and supply driven (equation below) and depends on the oil production to capacity ratio in the Middle East ($PRODCAPEAST_t$) and on the world R/P ratio ($\frac{RSV_t}{PROD_t}$).

$$\ln(oilprice_t) = \alpha + \beta * \ln(PRODCAPEAST_t) + \sum_{l=0}^{p} \gamma_l \left(ln\left(\frac{RSV_{t-l}}{PROD_{t-l}}\right)\right) + u_{oil,t}$$

International gas price ($gasprice$) depends on the international oil price (oil price indexing) and on the world gas R/P $\left(\frac{RSVGAS_t}{PRODGAS_t}\right)$ ratio (equation below).

$$\ln(gasprice_t) = \delta + \sum_{l=0}^{p} \zeta_l ln(oilprice_{t-l}) + \sum_{m=0}^{r} \eta_m \left(ln\left(\frac{RSVGAS_{t-m}}{PRODGAS_{t-m}}\right)\right) + u_{gas,t}$$

The importance of R/P ratios in the oil and gas price equations is a clear reflection of the oligopolistic nature of the markets for the respective fuels. At any rate, the equations have been estimated econometrically over periods when cartel power has been much in evidence and rents and other oligopolistic mark-ups are captured in all parameters including constants. The latter can be varied in order to reflect different formulations of the fossil fuel market.

The international coal price ($coalprice$) is only demand driven ($DCOAL_t$), as coal supplies are assumed to be ultimately abundant, and is also partly linked to the international oil price.

$$\ln(coalprice_t) = \theta + \sum_{l=0}^{p} \lambda_l ln(oilprice_{t-l}) + \sum_{m=0}^{r} \xi_m (ln(DCOAL_{t-m})) + u_{coal,t}$$

Endogenous technical change

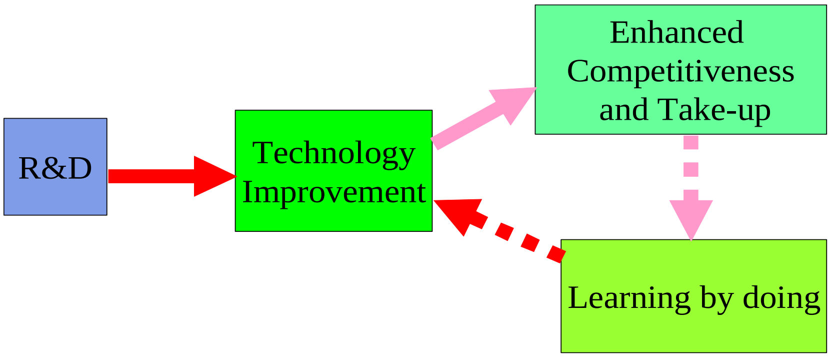
Main features

- *PROMETHEUS adopts the two factor learning curve specification*
- *Both learning by doing and learning by research are endogenous in the model*
- *Learning by doing acts as an accelerator of the impact of initial R&D effects*
- *Technical potential is included in the specification*

Traditional technology dynamics has long recognised the importance of learning by experience in the improvement of the cost and technical performance of technologies. However, it is also widely accepted that R&D can contribute directly to technological improvement and in order to address policy questions concerning the efficacy of R&D, it is clear that R&D must figure explicitly in the technology dynamics specification.

The core in the endogenous technological change modelling adopted in PROMETHEUS, is the two factors learning curve (TFLC) specification and the endogenisation of the technical progress through both learning by research and learning by experience. Under this scheme, an R&D action leads directly to technological improvement, which in turn enhances competitiveness of a particular option and leads to increased technology take-up. This latter increase sets in motion learning by experience, which results in further technological improvement, further up-take etc. In this sense, learning by doing acts as an accelerator of the impact of initial R&D effects. Clearly, the cycle is characterised by dampening effects that result in finite overall impacts. This dampening notwithstanding, the inclusion of such mechanisms in the model does tend to introduce elements of instability, in particular "lock-in" effects –massive R&D funding on some options may lockout other options that fail to benefit from the learning by experience they could have enjoyed, had such initial R&D infusion not taken place. There is sufficient evidence that this scheme is an accurate representation of the way technical progress has occurred in the past. PROMETHEUS also incorporates the notion of technical potential (floor costs), as they emerge from perspective analysis. Such potentials are naturally uncertain and their stochasticity is explicitly modelled.

General scheme of the technology dynamics mechanism



Main features

- *The parameters of the two factor learning curves in PROMETHEUS are jointly distributed random variables and they co-vary*
- *The size and direction of R&D for energy technologies are endogenous*
- *Clustering effects are incorporated*
- *PROMETHEUS includes technology dynamics for 51 energy technologies*

Taking into account the fact that technological change is a process characterized by fundamental uncertainty, critical parameters for the effects of R&D effort, technology adoption and cost efficiency are explicitly modelled enabling the quantification of the variance and covariance associated with the adoption of particular technologies. The parameters of the two factor learning curves in PROMETHEUS are jointly distributed random variables and they co-vary. The PROMETHEUS outlook also incorporates uncertainties regarding the size and direction of R&D, which are endogenous to the model. By analysing historical observations of R&D on energy technologies and utilizing perspective analysis, relations have been established, linking R&D to economic factors and particularly measures of energy cost.

PROMETHEUS augments the traditional TFLC specification by incorporating clustering effects, which are essential in cases of a rapid transformation of the energy system .The idea is that technological progress in a specific direction enhances cost efficiency of similar technologies, to a degree which depends on the “proximity” of the corresponding technologies. A technology cluster is a group of technologies that share a common component. A technology can belong to different clusters when it is composed of different components, e.g. a natural gas combined cycle is part of the gas turbine, recovery boiler and steam turbine clusters. The common component is assumed to be the learning technology and each component has its own learning curve specifications.

Technical progress leads to the improvement of the different components and a reduction of the total cost of each technology, i.e. capital, fixed O&M and variable O&M cost and technical efficiency and consequently learning parameters have been estimated for each of the above.

More specifically, let i be a technology, and c be a cluster. Let us then define $cc_{i,t}$ as the capital cost of technology i in time t, $K_{i,t}$ as the installed capacity of technology i in time t, and $R_{i,t}$ as the cumulative R&D (both Government and business energy R&D) that has been spent on technology i by time t. The general formulation of the TFLC equations as estimated for the PROMETHEUS model is:

$$cc_{i,t} = cc_{i,t-1} \prod_{c=1}^{l} \left(\frac{cl_{c,t}}{cl_{c,t-1}}\right)^{r_{i,c}\, a_{i,t}} \left(\frac{K_{i,t-1}}{K_{i,t-2}}\right)^{a_{i,t}\,(1-\sum_{c=1}^{l} r_{i,c})} \left(\frac{R_{i,t-1}}{R_{i,t-2}}\right)^{\beta_{i,t}} e^{u_{i,t}}$$

where we have defined:

$$cl_{c,t} = \sum_{i=1}^{n} w_{i,c} \cdot K_{i,t-1}$$

as the weighted sum of lagged installed capacity for the technologies belonging to cluster c.

In the above specification the effective learning parameters are $a_{i,t}$ and $\beta_{i,t}$. $u_{i,t}$ is a white noise random disturbance. Each technology i has a weight $w_{i,c}$ in each cluster c, reflecting the importance of the generic technology defining the cluster c on the cost structure of technology i. Moreover, there is a weight $r_{i,c}$ reflecting the importance of the component belonging to cluster c for each technology i adjusted for the learning rate of the cluster.

In PROMETHEUS technology dynamics for 51 technological options for electricity production, hydrogen production/storage/delivery and passenger cars were estimated. These include:

- Capital costs parameters for 44 technological options
- Fixed O&M costs for 34 technologies; although they are basically labor costs, technical progress has been assumed based on the increased automation, reliability and the economies of scale
- Variable cost parameters for 12 technologies, adjusted for efficiency.
- Efficiency parameters for 20 technologies

The climate module

The forecasting horizon of the climate sub-model included in the PROMETHEUS world energy system model is extended by 15 years in order to take into account the “additional warming commitment”. The commitment is necessary because the climate system can be recognized as a form of “hysteresis” meaning that the current state of climate reflects not only the inputs, but also the history of how it got there. According to IPCC Third and Fourth Assessment Reports, an increase in forcing implies a “commitment” to future warming even if the forcing stops increasing and is held at a constant value. At any time, the “additional warming commitment” is the further increase in temperature, over and above the increase that has already been experienced, that will occur before the system reaches a new equilibrium with radiative forcing stabilized at the current value.

The sub-model takes as input economic activity, population and fossil fuels production from the rest of the PROMETHEUS world energy system model, and projects emissions for the following greenhouse gases: CO_2 from fossil fuel combustion and industrial processes, N_2O from industrial and land uses and CH_4 from biomass burning, landfills, livestock, rice farms, oil & gas supply and coal mining.

Based on IPCC Fourth Assessment Report, reduced form equations of the atmospheric dynamics were estimated, which take into account the uncertainty underlying the interaction of the main components of the climate system (atmosphere, hydrosphere, cryosphere, land surface and biosphere). The anthropogenic emissions constitute the main input to equations enabling the calculation of the atmospheric concentrations and the estimation of global temperature.

It should be noted that there is a feedback between the climate change and the effective climate policy. The intensity of the climate policy takes into account the change in global temperature as it averages in PROMETHEUS simulation.

Uncertainty in PROMETHEUS

General Methodology

Main features

- *PROMETHEUS generates stochastic information for key energy variables*
- *Exhaustive coverage of uncertainties*
- *The model explicitly recognizes four main sources of uncertainty*
- *Monte Carlo and Latin hypercube methods are used*
- *The basic input of PROMETHEUS is a set of distributions for all variables and parameters*

PROMETHEUS is a tool for the generation of stochastic information for key energy, environment and technology variables. It is a stochastic model that produces joint distributions for a number of variables pertaining to the world energy system with some extensions into the fields of Greenhouse Gases (GHGs) emissions, concentrations and temperature change.

In constructing PROMETHEUS the main effort has been the exhaustive coverage of uncertainty by introducing it in the generation of all parameters and exogenous variables. The model also recognises residual stochasticity arising from variables that are not explicitly included in the model specification. Furthermore considerable attention is paid on statistical dependence of model input since it is recognised that it can play a major role in determining the distribution of endogenous variables and especially aggregate ones. In some instances even the model specification is subject to random variation.

The model recognises four main sources of uncertainty:

- Uncertainty regarding assumptions and the evolution of exogenous variables
- Variation in variables that are not explicitly modelled since they are considered relatively unimportant but could cumulatively cause deviations (such deviations are usually assumed to be zero centred)
- Uncertainties arising from imperfect knowledge of the system and notably the parameters included in the model.
- Uncertainty pertaining to the model specification itself.

All the above are introduced in the model in the form of probability distributions. The inverse of the cumulative equivalent of these distributions is then used to generate experimental values by "Monte Carlo" methods.

Orthogonal Latin Hypercube Sampling is implemented for a selected set of critical parameters that dominate stochastically the growth rate of economic activity in developing regions, oil and gas resources, R&D expenditure and coal price evolution. This kind of sampling improves the statistical significance of probability statements concerning joint occurrences of these crucial variables.

Thus the basic input of PROMETHEUS is a set of distributions for all variables and parameters. Deriving the parameters of these distributions constitutes a central research task associated with building and using the model.

From econometric estimation to Monte Carlo stochastic simulations

Main features

- *Econometric estimations are extensively used*
- *Parameter estimates are stochastic but time independent*
- *Parameter estimates are not statistically independent (i.e. they co-vary).*
- *The residuals of the equations vary with time but are independent*

Econometric estimations are extensively used in PROMETHEUS, as they provide an element of objectivity and force the analyst to investigate the nature and extent of stochastic elements (why past variability occurred). They are also amenable to the analysis of co-variance. On the other hand, the main disadvantage is the excessive reliance on history. However, it is not clear whether this reliance leads to exaggeration or under-estimation of variability – therefore the method does not in itself produce systematic bias.

The classical econometric estimation model can be presented as: $y_t = f(\boldsymbol{x}_t, \boldsymbol{\theta}, \varepsilon_t)$, where y_t are the observations on the dependent variable, $\boldsymbol{x}_t$ are the observations on the independent variable, $\boldsymbol{\theta}$ is the unknown parameter vector and ε_t is an unobservable random disturbance (usually assumed Normal or Lognormal). The estimation process derives estimates for the parameter vector $\widehat{\boldsymbol{\theta}} = g(\boldsymbol{x}_t, y_t)$, error term $e_t = f^{-1}(\widehat{\boldsymbol{\theta}}, \boldsymbol{x}_t, y_t)$, the variance of ε_t and the variance covariance of the estimators $\widehat{\boldsymbol{\theta}}$. All the estimators are random variables that can be appropriately generated in order to simulate the stochastic characteristics of the equation. The derivation of stochastic elements takes into account that:

- The variance of the regression is unknown and hence itself a random variable (in the process of the implementation of PROMETHEUS this has usually proved a major source of variability especially since the samples used for econometric estimations were relatively small and the distribution of the variance skewed).
- Parameter estimates are stochastic. These parameters are used in PROMETHEUS as time independent stochastic variables. It was found that it was preferable to specify equations in dynamic form in order to avoid excessive early variability and adequately represent accumulation of uncertainty in the longer term.
- Parameter estimates are not statistically independent (i.e. they co-vary). This has often proven to be an element of stability (i.e. negative covariance between autonomous efficiency gains and activity elasticity in a demand equation). However this is not a general rule: a positive co-variance between activity and price elasticity combined with decreasing prices in the course of a Monte-Carlo run will increase variability.
- The residuals of the equations vary with time but are independent and hence their cumulative effect though it increases, it does so at a decreasing rate.

Most of the econometrically estimated equations take the form of log linear difference equations. Ordinary Least Square estimation has been found to provide an adequate estimation methodology in most cases. Three Stage Least Square estimation has been performed on some simultaneous equation blocks, notably in the technology dynamics module. Maximum likelihood regressions has also been used. Where serial correlation of error terms was found to be statistically significant an appropriate correction has been performed and the autocorrelation structure incorporated as part of the model specification.

From econometric estimation, the variance-covariance matrix of the estimated equation parameters is derived and divided by the estimated variance of the equation in order to be normalised. Then a chi-squared distributed random value for the variance for i-th experiment is generated, with the estimated mean and the sample requisite degrees of freedom and is multiplied by the variance-covariance matrix. Since the matrix that is calculated with the above procedure has real elements and is symmetric and positive definite, Cholesky decomposition is applied and the matrix is decomposed to one lower triangular and to its transpose (upper triangular matrix). A vector of standard normal variates is then generated and multiplied by the triangular matrix in order to obtain an experimental trial vector of equation parameters (they will have the required variance and covariance). Residuals are then generated for all time periods as normal random variables with zero mean and the experimental variance. The same process (called the "generation process") is repeated for all model equations and for all Monte Carlo runs. In a standard PROMETHES run 2048 Monte Carlo experiments are performed.

Latin Hypercube sampling is applied to a selected set of critical parameters (e.g. growth rate of economic activity in developing regions, oil and gas resources, R&D expenditure) in order to achieve more efficient sampling.

A major problem encountered in the procedure described above is the possibility of values that violate economic theory (i.e. positive price elasticity in a final demand equation). More specifically, the Standard Least Squares estimation and its statistical interpretation, which is extensively used in the econometric estimation of PROMETHEUS, is based on the assumption of normality of error terms. As a result, parameter estimators follow student-t distributions, which in theory implies the possibility that a parameter can change sign. While this may not always cause problems, in most cases economic theory and common sense determines a specific sign for key parameters.

The problem is aggravated by the fact that many of the PROMETHEUS equations have poor statistics (i.e. high variances) for many estimated parameters. High variances imply non-negligible possibilities for illegal values for parameters. Clearly such values cannot generally be tolerated and in PROMETHEUS could prove particularly unwelcome as in the course of Monte-Carlo runs they could be combined with extreme values of results and completely distort the experiment.

The solution adopted in the case of PROMETHEUS is to simply ignore illegal values. This method tends to alter the shape of the t distribution, but at the same time compared to alternative correction methods (e.g. scaling of the standard deviation) it introduces much smaller bias on variability. The rejection of an illegal value must be accompanied by rejection of associated (and probably legal) values for the other parameters in the specific experiment in order to maintain the desired properties of the Monte Carlo exercise.

The basic output of PROMETHEUS is a data set of Monte Carlo simulations containing values for all the variables in the model. This set can be used as strategically or analytically important information on risks and probabilities, regarding the variables incorporated in it or any pre-determined function involving them. Major applications could be in security of supply assessment environmental risk assessment, investment risk analysis etc.

Exogenous Risk information

Econometric estimation has been in many cases supplemented with risk assessment provided by scientific expertise. In all such cases, where "exogenous" risk information has been introduced in the model, care is devoted to incorporate a wide range of opinion. In PROMETHEUS, it is important that the variance and covariance of exogenous variables and parameters is unbiased to the extent possible, otherwise probabilistic statements made on the basis of model results are highly likely to be biased. Two main methods were used to supply the model with exogenous risk information: Delphi methods (questionnaires), in order to determine future climate policy stances, and specialised studies for incorporating stochasticity pertaining to fuel resources and techno-economic potential of renewable sources as well as stochastic technological perspective analysis.

Stochastic transitions

Stochastic transitions have been implemented in PROMETHEUS model. Stochastic transitions are also used to model market reform, price reform, alternative patterns of consumption and other structural changes. Transitions model structural change occurring, for example, when a developing region attains levels of income typical for a developed country. In such a case, it is assumed that the specific equation for this region is gradually replaced by the corresponding equation for a developed region (e.g. North America or the EU). It was considered important to model the uncertainty associated to both the frontier at which the transition occurs and the speed of transition. A stochastic transition process is specified as follows:

$$y_t = (1 - \lambda_t(t;\sigma)) * f_1(\boldsymbol{x}_{1t,}, \boldsymbol{\theta}_1) + \lambda_t(t;\sigma) * f_2(\boldsymbol{x}_{2t,}, \boldsymbol{\theta}_2).$$

where f_1 and f_2 represent alternative specifications of the equation, potentially containing a different set of variables ($\boldsymbol{x}_{1t,}, \boldsymbol{x}_{2t}$). f_1 and f_2 refer to the short and long-term equations respectively. The transition from f_1 to f_2 is regulated by a stochastic weight λ_t, that takes values between 0 (in the starting year of the simulation) and 1 (when the transition is completed). The stochastic weight depends on the parameter $\sigma \in \Re^+$ which is a general indicator of the "uncertainty" surrounding the process, and the time t, with $t = 0$ representing the initialisation of the process.

For example, the evolution of cars per capita in developing regions (especially in China, India, Emerging Economies and MENA) is initially assumed to follow equations estimated with historical data for these regions. These equations are gradually replaced (through a stochastically evolving weighting scheme) by equations estimated from a pool of European countries. Long term parameters (e.g. possible saturation levels for cars per capita) are treated in parallel to short term variation to obtain the path of variability: variables move in response to short term random stimuli but at the same time tend towards equally random long term states.

Projection of Energy Balances

PROMETHEUS produces Excel reports containing projected energy demand and supply balances for each of the ten regions identified in the model. The projection figures come from the various PROMETHEUS modules. The main sectors and energy forms (fuels) presented in the PROMETHEUS energy balances are shown below:

Energy Forms in PROMETHEUS Energy Balances	
Industry	Coal
	Oil
	Natural gas
	Electricity
	CHP
	Biomass & waste
	Hydrogen
Residential (households, services, agriculture)	Coal
	Oil
	Natural gas
	Electricity
	CHP
	Biomass & waste
	Hydrogen
Transport	Gasoline
	Diesel
	Bio-diesel
	Natural gas
	Electricity
	Hydrogen
Power generation and hydrogen production	Coal
	Lignite
	Oil
	Natural gas
	Nuclear
	Hydro
	Wind
	Solar
	Biomass & waste
	Hydrogen

Main Policy Indicators projected by PROMETHEUS

Energy Demand

- Energy intensity of GDP (primary and final energy)
- Energy intensity per unit of value added in industry
- Energy intensity of households' income
- Energy intensity per inhabitant
- Energy intensity per passenger car
- Electricity consumption per capita in residential sector
- Electricity generated per capita
- Transport fuels per capita
- Performance against overall energy efficiency targets (primary energy and final energy)
- Number of passenger cars per capita

Renewables

- Overall share of RES in primary energy demand
- Share of RES in total power generation
- Share of bio-fuels in fuels used in the transport sector

Power sector

- Share of electricity produced by CCS
- Share of RES in power generation
- Share of intermittent RES in power generation
- Share of nuclear in power generation
- Power generation per capita
- Average load factor of demand
- Average rate of use of power plant capacities (by type)

Security of Supply

- Overall energy dependence indicator in each region
- Evolution of import fossil fuel prices for the EU
- Share of unconventional oil (extra heavy oil and tar sands) in global oil supply
- Share of Middle East production in global oil production and reserves
- Development of unconventional gas resources (shale, tight and CBM gas)

Emissions

- Carbon intensity of GDP
- Emissions per unit of value added in industry
- Carbon intensity of households
- Carbon intensity of transport
- Carbon emissions per capita in residential sector
- Carbon intensity of power generation
- Share of emissions captured in power generation
- Carbon intensity per unit of final energy in industry
- Carbon intensity per unit of final energy in transport
- Carbon intensity per unit of final energy in the residential sector
- Carbon intensity per unit of primary energy
- Carbon emissions per capita

Costs and Prices

- Prices for internationally traded fossil fuels (coal, oil and natural gas)
- Electricity prices for industries and households
- Unit costs of electricity
- Investments in the power generation sector
- Consumer expenditures on final energy
- Carbon prices

Further Information

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