

PRIMES MODEL

VERSION 2018

Detailed model description

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A.History



The PRIMES (Price-Induced Market Equilibrium System) energy system model is a development of the Energy-Economy-Environment Modelling Laboratory at National Technical University of Athens in the context of a series of research programmes cofinanced by the European Commission. The model has been successfully peer reviewed in the framework of the European Commission in 1997 and in 2012. The techno-economic parameters of the PRIMES model were recently reviewed by a broad range of stakeholders within an ASSET project study.¹

From the very beginning, in 1993-1994, the design of the PRIMES energy model focused on market mechanisms and aimed at explicitly projecting prices, which influence the evolution of energy demand and supply as well as technology progress. The model structure is modular. The modules differ by sector in an aim to represent agent behaviours and their interactions within the markets as close as possible to reality. The model design combines microeconomic foundation of behaviours with engineering and technology details. The mathematical specification focuses on simulation of structural changes and long-term system transitions, rather than short term forecasting.

From mid-90s until today, the model is regularly extended and updated. Numerous studies have been performed using PRIMES, and numerous third party studies have used projections produced using PRIMES. The majority of these studies focused on medium and long term restructuring of the EU energy system, aiming at reducing carbon emissions. PRIMES supported analysis for major energy policy and market issues, including electricity market, gas supply, renewable energy development, energy efficiency in demand sectors and numerous technology specific analysis, such as on CCS, nuclear, etc. The PRIMES model has quantified energy outlook scenarios for the EU (Trends publications since 1990), the latest being the "Reference scenario 2016", impact assessment studies for the EC, including for the Clean Energy Package for all Europeans, as well as the work for the Mid-century Strategy (forthcoming end 2018). PRIMES also supported national projections for governments, companies and other institutions including for EURELECTRIC, EUROGAS and many others.

¹ https://ec.europa.eu/energy/en/studies/review-technology-assumptions-decarbonisation-scenarios



B.General Overview

General aims of PRIMES modelling:

- Market orientation
- Focus on behaviors
- Economics and Engineering combined
- Long-term restructuring of energy systems
- Explicit price and costs projections
- Full coverage of all energy sectors and markets, including ETS
- Individual modelling of all European countries and EU trade

PRIMES provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions for each individual European country and for Europe-wide trade of energy commodities.

The distinctive feature of PRIMES is the combination of behavioural modelling following a micro-economic foundation with engineering and system aspects, covering all sectors and markets at a high level of detail.

PRIMES focuses on prices as a means of balancing demand and supply simultaneously in several markets for energy and emissions. The model determines market equilibrium volumes by finding the prices of each energy form such that the quantity producers find best to supply matches the quantity consumers wish to use.

Investment is generally endogenous in PRIMES and in all sectors, including for purchasing of equipment and vehicles in demand sectors and for building energy producing plants in supply sectors. The model handles dynamics under different anticipation assumptions and projects over a long-term horizon keeping track of technology vintages in all sectors. Technology learning and economies of scale are fully included and are generally endogenous depending on market development.

PRIMES model design is suitable for medium- and long-term energy system projections and system restructuring up to 2070, in both demand and supply sides. The model can support impact assessment of specific energy and environment policies and measures, applied at Member State or EU level, including price signals, such as taxation, subsidies, ETS, technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies and technology standards. PRIMES is sufficiently detailed to represent concrete policy measures in various sectors, including market design options for the EU internal electricity and gas markets. Policy analysis draws on comparing results of scenarios against a reference projection.

The linked models PRIMES, GEM-E3 and IIASA's GAINS (for non-CO₂ gases and air quality) perform energy-economy-environment policy analysis in a closed-loop.



C. Overview of Methodology

Basic methodological ideas:

- Modular organization
- EPEC with explicit prices
- Micro-economic foundation
- Concurrent energy and nonenergy inputs
- Hybrid model, embedding technologies in economic decisions

The PRIMES model comprises several sub-models (modules), each one representing the behaviour of a specific (or representative) agent, a demander and/or a supplier of energy. The sub-models link with each other through a model integration algorithm, which determines equilibrium prices in multiple markets and equilibrium volumes meets balancing and overall (e.g. emission) constraints.

Mathematically PRIMES solves an EPEC problem (equilibrium problem with equilibrium constraints) which allows prices to be explicitly determined.

The agents' behaviours are sector-specific. The modelling draws on structural microeconomics: each demand module formulates a representative agent who maximises benefits (profit, utility, etc.) from energy demand and non-energy inputs (commodities, production factors) subject to prices, budget and other constraints. The constraints relate to activity, comfort, equipment, technology, environment or fuel availability. The supply modules formulate stylised companies aiming at minimising costs (or maximising profits in model variants focusing on market competition) to meet demand subject to constraints related to capacities, fuel availability, environment, system reliability, etc.

PRIMES is a hybrid model in the sense that it captures technology and engineering detail together with micro and macro interactions and dynamics. Because PRIMES follows a structural modelling approach, in contrast with reduced-form modelling, it integrates technology/engineering details and constraints in economic modelling of behaviours. Microeconomic foundation is a distinguishing feature of the PRIMES model and applies to all sectors. The modelling of decisions draw on economics, but the constraints and possibilities reflect engineering feasibility and restrictions.

The model thus combines economics with engineering, ensuring consistency in terms of engineering feasibility, being transparent in terms of system operation and being able to capture features of individual technologies and policies influencing their development. Nevertheless, PRIMES is more aggregated than engineering models, but far more disaggregated than econometric (or reduced form) models.

The model performs analytical cost estimations and projections by sector both in demand and supply, as well as for infrastructure. Supply-side modules determine commodity and infrastructure prices by end-use sector (tariffs) by



Prices and Equilibrium:

- Tariffs and prices are endogenous, reflecting costs and market conditions
- Closed-loop between demand and supply
- System-wide constraints influence all sectorial submodels
- Self-supply of energy services is also priced
- Perceived costs
 and uncertainty
 factors are
 included and are
 related to
 policies

applying various methodologies by sector as appropriate for recovering costs depending on market conditions and regulation where applicable.

Prices influence demand and demand influences in turn supply. Thus, a closed-loop between demand and supply solves simultaneously for all markets. Both demand and supply modules may be subject to system-wide constraints, mirroring overall targets for example on emissions, renewables, efficiency, import dependency, etc. The demand and supply modules are subject to system-wide constraints, which when binding convey non-zero shadow prices (dual values) to the demand and supply modules. Therefore, the PRIMES model has overall a mixed-complementarity mathematical structure. The overall convergence algorithm simultaneously determines multi-market equilibrium while meeting the system-wide constraints.

The agents are a priori price-takers when being energy demanders and price-makers when being energy suppliers. Optionally the model can handle non-perfect market competition regimes. The electricity and gas market modules optionally include explicit companies (or stylised companies) and apply Nash-Cournot competition with conjectural variations.

In the demand sub-models, the agents are simultaneously self-producers of energy services (e.g. using a private car, heating using a residential boiler, etc.) and purchasers of marketed energy commodities. The pricing of self-supplied energy services is endogenous and reflect average total costs. The mix of self-supply and the purchasing from external suppliers (e.g. private cars versus public transportation, residential boiler versus district heating) derives from agent's optimisation.

Pricing and costing include taxes, subsidies, levies and charges, congestion fees, tariffs for use of infrastructure etc. Usually these instruments are exogenous to the model and reflect policy assumptions. The model handles endogenously cap and trade policies and policies reflecting obligations. The cap and trade policies (for example trading of emission allowances, green certificates and white certificates) involve issuance of certificates (or permits) and trading rules. The model projects certificate prices of equilibrium as result of simultaneous equilibrium of all markets. The model represent obligations, such as renewables or energy efficiency targets, as constraints. The model estimates the shadow prices associated to such constraints, and includes them in demand and supply sub-models where appropriate.

Some cost components are subjective reflecting uncertainty and perception about performance and cost of advanced, not yet mature, technologies.



Dynamics and technology:

- Dynamic model
- Usually perfect foresight, but other options are available
- Investment and equipment choice is endogenous in all sectors
- Technology vintages are traced
- Technology progress develops through the vintages and is endogenous
- Infrastructure influences and constraints decisions but is exogenous to the model

PRIMES follows a descriptive approach concerning factors which influence decisions by private entities where perceived costs and uncertainty factors play a significant role. Policy measures can reduce uncertainty and decrease perceived costs: such a mechanism in the model is often used to simulate policy inducing higher uptake of advanced technology or investment enabling accelerated energy efficiency progress.

The PRIMES model is fully dynamic and has options regarding future anticipation by agents in decision-making. Usually, PRIMES assumes perfect foresight over a short time horizon for demand sectors and perfect foresight over long time horizon for supply sectors. The sub-models solve over the entire projection period in each cycle of interaction between demand and supply and so market equilibrium is dynamic and not static. Other options are available allowing the model user to specify shorter time horizons for foresight.

All economic decisions of the agents are dynamic and concern both operation of existing equipment and investment in new equipment, both when equipment is using energy and when it is producing energy.

Capital formation derives from economically driven investment and follows a dynamic accounting of equipment technology vintages: equipment invested on a specific date inherit the technical-economic characteristics of the technology vintage corresponding to that date. Capital turnover is dynamic and the model keeps track of capital vintages and their specific technical characteristics. The agent's investment behaviour consists in building or purchasing new energy equipment to cover new needs, or retrofitting existing equipment or even for replacing prematurely old equipment for economic reasons.

All formulations of agent behaviours consider technologies, which are either existing at present or expected to become available in the future. The technology selection decisions depend on technical-economic characteristics of these technologies, which change over time either autonomously (exogenous) or because of the technology-selection decisions (learning and scale effects). Perceived costs associated to technologies may change in synchronised manner with technology uptake and learning.

The outcomes of decisions by sector generally depend on availability of infrastructure and the usage tariffs. The model projects infrastructure tariffs for cost recovering using regulated discount rates. Availability of infrastructure influences technology uptake where applicable.



Capital budgeting decisions:

- Capital budgeting decisions at various levels
- Capital stock accounting depends on investment, possible premature scrapping and eventual retrofitting
- Discount (interest) rates based on WACC reflecting private investor's perspective
- Technology and market related risk premium
- Social discount rates apply on calculation of present value of system-wide costs over time

Investment in network infrastructure is exogenous to the model but it can vary by scenario. It includes electricity grids, smart systems, gas infrastructure, CO_2 transportation and storage, refuelling and recharging infrastructure in transport sector.

The agents' investment for energy production, the purchasing of durable goods by consumers and the energy saving expenditures in buildings and houses are simulated as capital-budgeting decisions for new investment, possible premature scrapping of old equipment or for retrofitting old equipment. Retrofitting depends on specific costs and scrapping depends on maintenance and variable costs, which increase over time because of ageing. Investment and scrapping decisions are included in accounting for the dynamics of capacity stocks in all sub-models.

The capital budgeting decisions refer to choices with different distributions of fixed and variable costs over time. The choices depend on annuity payments for investment expenditures, which in turn depend on interest rates, which are specific to each agent (sector).

PRIMES follows a descriptive approach to the modelling of interest rates based on the opportunity cost of drawing funds from individuals or private companies. Interest rates are calculated based on the concept of WACC (weighted average cost of capital), which involve a basic risk-free interest rate applied on equity capital, a bank lending interest rate applied on the part of capital borrowed and a risk premium. All rates are net of inflation.

The interest rates applied on equity capital reflect agent-specific subjective rates and are sector-specific. Risk premiums apply with two components: one specific to each sector and one specific to the candidate technology. For the latter the model considers that innovative technologies that may not be sufficiently mature or that may not dispose a sufficiently broad maintenance service support are more risky than market-established technologies.

Different scenarios quantified using PRIMES may imply different distributions of costs over time. To compare them and to aggregate system-wide costs over time a present value method applies as a calculation external to PRIMES. The comparison of performance across scenarios uses aggregation of costs over time, which by default uses a social discount rate. This rate differs in nature from the interest rates used by sector to annualise investment expenditures and to compare choices from a private investor perspective. The sector-specific interest rates reflect opportunity costs of raising funds by private entities and the social discount rate reflects opportunity costs of raising funds



Energy Demand sectors:

- Demand for energy derived from microeconomic optimization
- Detailed and transparent demand formation from end-use services up to final energy and use of equipment
- Endogenous choice of technology and energy savings investment
- Focus on materials, efficiency and processing in industrial submodels
- Focus on efficiency and renovation of buildings/house s and on appliances

by the public sector. The discount rates are exogenous and can vary by scenario.

For each sector, representative agents optimise an economic objective function: utility maximisation for households and passenger transport and cost minimisation for industrial, tertiary and freight transport sectors.

To optimise, the model firstly considers useful energy demand (end-use energy services) and then a nesting of further decisions. At the upper level of the nesting, energy is a production factor or a utility providing factor and competes with non-energy inputs. Useful energy, as derived at upper level, decomposes into uses and processes (e.g. water heating, motor drives, industrial processes, etc.). Useful energy (e.g. air conditioning, lighting, motive power) fulfils by consuming final energy, which derives from optimisation involving self-supply, purchasing of marketed commodities and investment in equipment. Each demand model involves an internal demand and supply loop formulated in mixed complementarity mathematical structure. The self-supply is dynamic over time involving endogenous choice of equipment (vintages, technologies and learning), endogenous investment in energy efficiency (savings), endogenous purchase of associated energy carriers and fuels (demander is price taker). Mathematics based on discrete choice theory captures heterogeneity within each representative agent. Decisions at each nesting level uses relative costs based on equivalent perceived cost, reflecting actual costs, utility (e.g. comfort) and risk premium.

Industrial energy demand modelling starts from projecting physical output; the model focuses on materials, process flow and efficiency potential. The process flows include a variety of stylised industrial processes. The model distinguishes between scrap/recycling processes and basic processing for iron and steel, aluminium, copper, glass and cement (own production of clinker versus import of clinker). The process flows recycle industrial by-products such as black liquor, blast furnace gas, etc. Energy saving possibilities depend on capital turnover, which his dynamic and endogenous. The possibilities are specific to the current and future technologies, which are available for each type of industrial process. The model includes possibility of shifts towards more efficient process technologies and horizontal processing measures. Interaction with Power and Steam sub-model for industrial CHP and boilers performs through the model-integrating module. Substitutions are possible between processes, energy forms, technologies and energy savings.

For residential and tertiary sectors, multiple substitutions are possible. Useful energy demand depends on behavioural characteristics partly influenced by



Supply system operation and networks:

- Simulation of system operation in supply-side
- Demand varies over time and season for electricity, gas and distributed heat/steam
- Intermittent RES are simulated
- Trade in the European internal market is endogenous
- System operation depends on network infrastructure
- Cogeneration, industrial units and highly distributed production are represented simultaneously with utility

costs and prices. The model includes a distinction of households types according to energy consumption, it further distinguishes agriculture and services which are broken down by sub-sector (e.g. market services, trade); electric appliances are treated separately in all sectors. Final energy demand depends on thermal integrity of buildings, with consideration of renovation investment (several categories) and vintages. The model includes heat pumps and direct use of RES.

Demand-related decisions at all levels depend on a large variety of policies, which are explicitly represented.

PRIMES is very detailed in energy supply sub-models aiming at representing system operation aspects, related to interoperability between production units and transportation infrastructure over networks and other means including storage, and reliable delivery of energy to time-varying demand when storage is limited, such as for electricity, gas and distributed heat/steam.

Load curves (chronological covering typical time-periods by year) for each carrier (electricity, gas, distributed heat/steam) with time-varying demand derive in the model in a bottom up manner depending on the load profiles of individual end-uses of energy. Smart metering and other load and demand management measures are included aiming at influencing demand variability.

In the simulation of electricity system operation PRIMES takes into account the intermittency features of renewable sources. Although it represents renewable sources in a deterministic manner, the model captures balancing, flexibility and reserve-power requirements.

PRIMES models in detail trade of electricity and gas across countries deriving from simulation of Europe-wide interconnected systems including full modelling details by individual country.

PRIMES synchronises demand variability between electricity and distributed heat/steam and captures operation of cogeneration units, which produce both electricity and heat depending on both markets.

The simulation of power and heat/steam markets includes competition between plants for different purposes (pure electric, CHP, industrial boilers), takes into account networks in power and steam/heat markets and represents plant economics by scale and aim, distinguishing between utilities, industries and highly distributed generation. Self-production (by industries or individuals) is an endogenous possibility among the options and has distinct plant economics and dependency on grids.



PRIMES represents competing storage technologies and simulates their operation in the supply systems. Investment in storage is endogenous driven by economics.

PRIMES includes all other fuel supply sectors, including extraction, imports, briquetting, liquefaction/gasification, bio-energy conversion, synthetic gas, hydrogen and refineries. PRIMES generally involves non-linear formulations:

- Useful energy demand involves saturation levels and uses non-linear formulas
- The energy demand models formulate nested budgeting and involve non-linear indifference and isocost curves
- Models of discrete technology choices are non-linear (e.g. using Weibull or logit functions)
- Economics of scale and learning-by-doing are non-linear by nature
- Costs related to potentials of resources (e.g. renewables) or to possibilities of energy savings (e.g. energy efficiency measures) are represented as non-linear cost-quantity functions
- In power system optimisation non-linear cost-curves represent fuel supply, renewable potentials and limitations on development of new power plant sites, where applicable (e.g. nuclear plant sites, wind sites, etc.)
- Similarly storage potential including for CO2 storage involve non-linear cost curves
- Cost of infrastructure depends on features such as integration of RES, high distribution etc. in a non-linear manner.

PRIMES Modelling Scheme

Demand = function of Price

Through fairly complex energy demand projection models by sector

Supply = Demand

Through complex energy supply models with system operation and network details

Price = function of Supply

Through a finance and pricing model which reflects costs, market competition regime and regulation

System-wide targets

They influence all sub-models which see shadow prices associated to targets

Iteration on Prices and shadow prices until reaching equilibrium
Iterations follow a Gauss-Seidel algorithm



Summary of PRIMES modelling approach

Exogenous

- Economic Activity
- World energy prices
- Technology parameters
- Policies and measures

Sequence of model interactions

- Agents (representative household, industry per sector, services, power generation, etc.) act individually optimizing their profit or welfare, influenced by habits, comfort, risk, technology, system reliability, etc. using individual (private) discount rates for capital-budgeting choices
- Accordingly they determine energy flows, investment and choice of explicit technologies in vintages
- Demand and supply of energy commodities interact with each other over a market with assumed competition regime
- Simultaneous energy (and emissions or certificate) markets are cleared to determine prices that balance demand and supply
- Commodity tariffs reflect costs and apply a Ramsey-Boiteux methodology to recover fixed costs and determine a distribution of tariffs across sectors
- Market equilibrium spans over the entire time horizon with investment being endogenous
- Overall or sectorial restrictions apply, for example on carbon dioxide emissions or for other targets

Mathematically, the model solves as a concatenation of mixed-complementarity problems with equilibrium conditions and overall constraints (e.g. carbon constraint with associated shadow carbon value); this is an EPEC problem.

Foresight is built in the agents' decision-making representations, depending on lifetime of equipment with market equilibrium being intertemporal.

Explicit technologies are included in all demand and supply sectors

- Technology dynamics
- Vintages
- Penetration of new technologies
- Inertia from past capital stocks and in future from capital turnover



D. Stylized Mathematical Description

Summary of PRIMES modelling approach

- Consumers get utility using energy and non-energy goods and services, including energy
 efficiency as a means of meeting useful energy demand.
- Producers of energy carriers such as electricity, gas, distributed heat or hydrogen mix through optimization fossil fuels and clean energy forms (e.g. renewables, nuclear or carbon capture and storage) to produce the amounts demanded by consumers.
- They set prices of energy carriers to reflect total production costs. Consumers are price takers but price-elastic.
- The primary energy sources, which are the fossil fuels, the clean energy forms used by consumers and those used by energy carrier producers, use prices depending on cost-supply curves with a positive slope and exhaustible potential.
- The consumers of primary energy forms are assumed price takers.
- Demand and supply behaviours are balanced in simultaneously clearing markets at primary, carrier and final energy levels
- Overall and sectoral policy constraints may apply, e.g. regulations, emission targets, renewable targets, energy efficiency targets
- The consumers and producers see the constraints through their associated shadow values (e.g. marginal costs) which are found different from zero if they are binding at equilibrium
- All decisions also involve capital budgeting choices, hence determine investment using technologies with features changing over time (vintages); capital stock is dynamically updated exerting capacity constraints on flows
- Thus, decisions depend on anticipation about future evolution; the model applies perfect or partial foresight.

D.1. Stylized Model

Consumers (problem (1)) maximize utility (U) under budget constraint (r is given disposable income) and choose the mix of final energy (FE - the energy bundle), further split in fossil fuels (FFE), energy carriers (EC) and clean energy forms (CFE), and non-energy inputs (NE). Consumers perceive emission costs depending on a shadow carbon price (cp), termed as carbon value, which is the dual variable of an emission cap (4), but they do not actually incur carbon payments (this corresponds to the concept of carbon value, as opposed to carbon price). Energy carrier producers (problem (2)) minimize production costs (C) to meet given demand (EC) increased by distribution losses (los denotes the rate of losses). They mix fossil fuels (FEC) and clean energy forms (CEC) through a production function. They price energy carriers (3) so as to recover fixed and variable costs also depending on market competition regime; tariff setting is denoted by function \mathcal{H} , depending on production costs (C) and volume of demand (EC); this function is a complex financial sub-model in PRIMES. Tariffs may (optionally) include passing through of carbon costs to consumer prices, depending on carbon price (cp) which is the dual variable of (4), if producers are assumed to incur carbon payments (e.g. ETS). Total emissions, depend on unit emissions (e_{FFE} , e_{FEC}) of fossil fuel consumption and have to be lower than a given



cap (cap). Policy may impose a system-wide clean energy obligation (e.g. RES obligation) expressed by (5) as share of gross final energy consumption (res is the target and rv is the shadow price of the constraint, called RES value). Constraint (6) introduces an energy saving (or efficiency) obligation, restricting final energy consumption by a given upper bound (sav); shadow price to this constraint is ev called efficiency value.

In the formulation, \aleph is the utility function, $\mathcal F$ is a production function. Their structure define the substitution possibilities between fossil fuels, energy carriers and clean energy forms at the consumers' level, with $\mathcal G$ being a production function mixing fossil fuels and clean energy forms to produce energy carriers. $\mathscr O_{FFE}$ and $\mathscr O_{FEC}$ denote the cost-quantity curves for fossil fuels addressed to consumers and energy carrier producers, respectively. $\mathscr O_{CFE}$ and $\mathscr O_{CEC}$ are the cost-quantity curves of clean energy forms used at consumer and producer levels respectively. All these functions are in PRIMES complex sub-models and not analytical functions; similarly the pricing/tariff equation is a complex sub-model. The cost-quantity curves (representing cost-supply locus of a resource) apply in all demand and supply models to represent non-linear resource constraints and price-responsiveness in relation to potentials. The concept of resource cost curves apply on all possible potentials including energy efficiency, RES, technology progress, storage, fuel supply, etc. The formulation below shows the complex sub-models as simple functions for illustration purposes.

Structural form of PRIMES model formulation

$$(1) \quad \begin{bmatrix} \max_{FFE,EC,CFE,NE} U = \aleph[\mathcal{F}(FFE,EC,CFE),NE] \\ \mathscr{O}_{FFE}(FFE) \cdot FFE + p_{EC} \cdot EC + \mathscr{O}_{CFE}(CFE) \cdot CFE + p_{NE} \cdot NE \leq r \end{bmatrix}$$

- (3) $p_{EC} = \mathcal{H}(C, EC)$
- $(4) \quad e_{FFE} \cdot FFE + e_{FEC} \cdot FEC \le cap \quad \bot \quad cp$

(5)
$$CFE + CEC \ge res \cdot \left(FFE + \frac{EC}{(1 - los)} + CFE \right) \perp rv$$

(6) $\mathcal{F}(FFE, EC, CFE) \leq sav \perp ev$

We firstly transform the optimisation problems (1) and (2) into equivalent mixed-complementarity problems, to solve the EPEC problem. We take the derivatives of Lagrange functions assuming that both demanders and suppliers see shadow prices associated to system-wide constraints and that demanders are price takers. The transformed problem is as follows (λ_u is the marginal utility of income and λ_c is the marginal cost of energy carrier production):



Mixed complementarity form of PRIMES model formulation

(6)
$$\lambda_{u} \cdot \left(\frac{\partial \wp_{FFE}}{\partial FFE} \cdot FFE + \wp_{FFE}\right) \perp FFE \ge 0$$
$$+cp \cdot e_{FFE} + rv \cdot res + ev \cdot \frac{\partial \mathcal{F}}{\partial FFE} + cp \cdot e_{FFE} \ge \frac{\partial \aleph}{\partial \mathcal{F}} \cdot \frac{\partial \mathcal{F}}{\partial FFE}$$

(7)
$$\lambda_u \cdot \frac{\partial \mathcal{H}}{\partial EC} + rv \cdot \frac{res}{1 - los} + ev \cdot \frac{\partial \mathcal{F}}{\partial FFE} \ge \frac{\partial \aleph}{\partial \mathcal{F}} \cdot \frac{\partial \mathcal{F}}{\partial EC} \perp EC \ge 0$$

(8)
$$\lambda_u \cdot \left(\frac{\partial \mathcal{D}_{CFE}}{\partial CFE} \cdot CFE + \mathcal{D}_{CFE}\right) + rv \cdot (res - 1) + ev \cdot sav \ge \frac{\partial \aleph}{\partial \mathcal{T}} \cdot \frac{\partial \mathcal{F}}{\partial CFE} \perp CFE \ge 0$$

(9)
$$\lambda_u \cdot p_{NE} \ge \frac{\partial \aleph}{\partial NE} \perp NE \ge 0$$

$$(10) \quad r \geq \wp_{FFE}(FFE) \cdot FFE + p_{EC} \cdot EC + \wp_{CFE}(CFE) \cdot CFE + p_{NE} \cdot NE \quad \bot \quad \lambda_u \geq 0$$

$$(11) \quad \frac{\partial \wp_{FEC}}{\partial FEC} \cdot FEC + \wp_{FEC} + cp \cdot e_{FEC} \geq \lambda_c \cdot \frac{\partial \mathcal{G}}{\partial FEC} \quad \bot \quad FEC \geq 0$$

$$(12) \quad \frac{\partial \wp_{CEC}}{\partial CEC} \cdot CEC + \wp_{CEC} - rv \ge \lambda_c \cdot \frac{\partial g}{\partial CEC} \quad \bot \quad CEC \ge 0$$

(13)
$$g(FEC, CEC) \ge EC/(1 - los) \perp \lambda_c \ge 0$$

(14)
$$p_{EC} = \mathcal{H}(C, EC) \perp p_{EC} free$$

(15)
$$cap \ge e_{FFF} \cdot FFE + e_{FFC} \cdot FEC \perp cp \ge 0$$

(16)
$$CFE + CEC \ge res \cdot (FFE + EC/(1 - los) + CFE) \perp rv \ge 0$$

(17)
$$sav \geq \mathcal{F}(FFE, EC, CFE) \perp ev \geq 0$$

The system of complementarity conditions (6) to (17) is representative of the entire PRIMES model.

D.2. Using PRIMES to meet policy targets: illustration

Assuming usual convexity conditions for problems (1) and (2), the consumers exhaust disposable income and producers exactly meet demand. Thus, conditions (10) and (13) lead to equality and the associated multipliers are strictly positive. As the system-wide targets (15 to 17) entail increasing costs for being met, maximising welfare suggests that they are exactly met in equilibrium when the bounds cap, res and sav are sufficiently stringent. It is possible that some or even none of the target constraints bind at equilibrium, in which case the associated shadow prices are zero. As all cost-supply functions (\wp) are monotonically increasing, and so consumers and producers use all kinds of inputs at equilibrium. In such case, all conditions (6) to (14) are equalities in the optimal solution and the associated unknown variables are strictly positive. The optimum use of utility enabling inputs (see conditions 6 to 9) is determined at a level where marginal utility is equal to marginal costs including marginal impacts on system-wide targets. Similarly, inputs to energy carrier



production are determined at a level where marginal productivity equals marginal costs including impacts on system-wide targets. Thus, meeting the system-wide targets implies shifting away from inputs implying largest marginal deviation from targets.

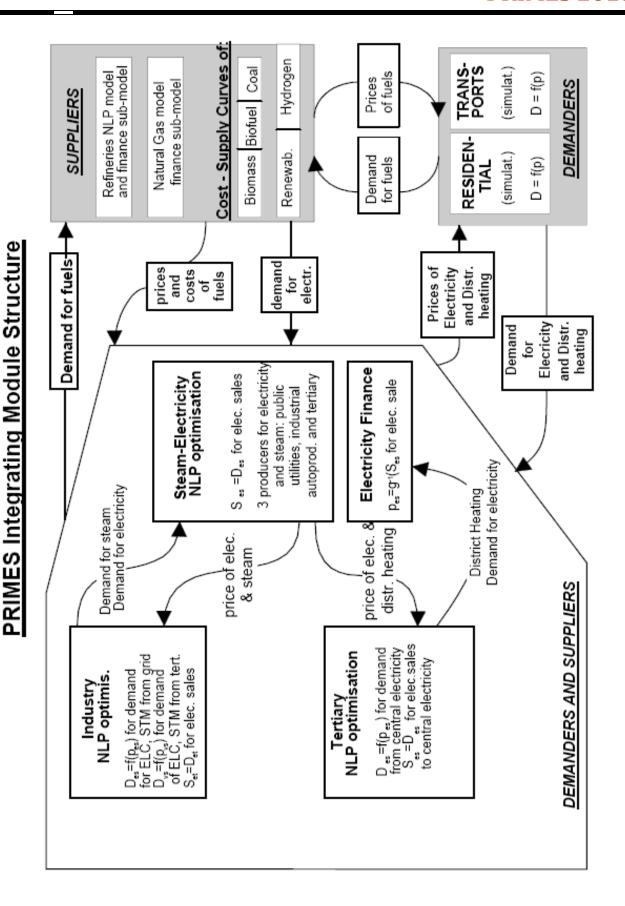
When policies set stringent targets, the demand for fossil fuels decreases but also fossil fuel prices tend to decrease (due to the increasing fuel cost-supply curve). At the same time unit costs of clean resources tend to increase, since their cost-supply curve indicates that their use approaches maximum potential and therefore increased marginal costs occur. The gradients of the cost-supply (or cost-quantity) influence consumers and producers in their optimising behaviour.

Electricity prices are set through (14) at a level sufficient to recover all costs. According to (10) the consumers do not pay directly for carbon emissions (unless carbon pricing is implemented through cap and trade or via a tax), but they do take into account shadow carbon prices in the choice of input mix charges on fossil fuels, through (8), to determine their energy mix. They indirectly incur additional costs and the purchasing power of income decreases; hence utility level decreases, when the emission constraint (15) is binding. To compensate for this utility loss, additional income would be necessitated, which correspond to valuation of disutility costs. Similarly, consumers and producers are incited to meet the renewables and/or the efficiency obligation as the renewables and efficiency values influence their optimising behaviour in (6), (7), (8) for consumers and in (12) for producers. When constraints (16) and (17) are binding, the renewable and efficiency values are non-zero (positive) and the input mix is influenced both for consumers and producers, and so indirectly costs increase.

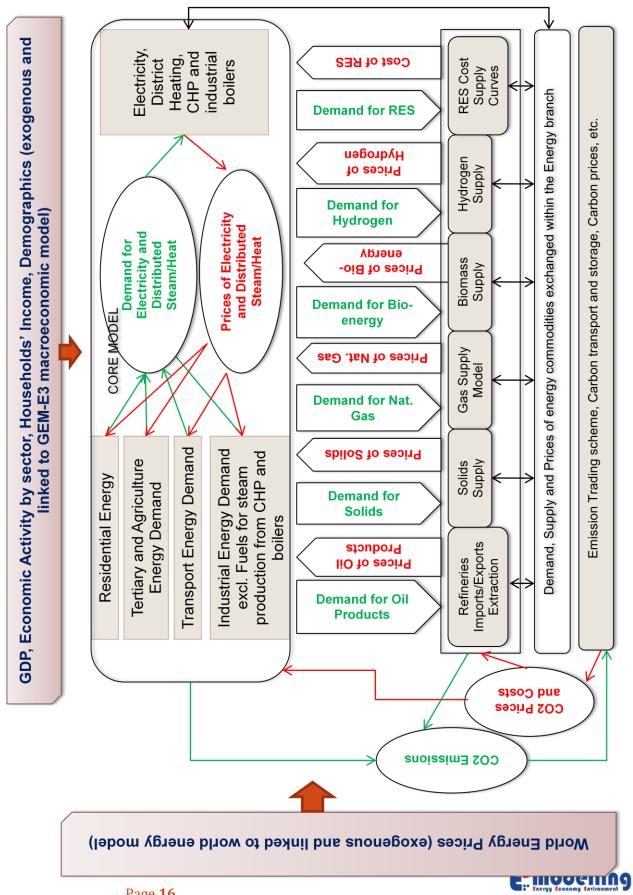
When the policy constraints entail lower marginal costs in production of energy carriers than in final consumption, then the consumers will tend to use more energy carriers to the detriment of fossil fuels. This holds true if the change in energy carrier price (p_{EC}) driven by carbon price is lower than the increase of marginal cost of clean energy forms (\wp_{CFE}) used directly by final consumers. An example is growing electrification of demand.

Energy efficiency improvement is reflected also through substitution between the energy bundle and the non-energy input to utility; example are more efficient use of materials, change in habits, use of materials and equipment to increase efficiency of building structures and factories and more efficiency in mobility. If substitution to non-energy is less costly than substitution within the energy bundle at the final energy demand level, then energy savings dominate and so the decarbonisation possibilities in energy carrier production are of less importance. Conversely, if substitution within the energy bundle is flexible enough and if emission reduction in energy carrier production is flexible, then the energy carrier gets a higher share in final energy demand and helps achieving lower emissions. Such a case occurs mostly when time lags are sufficient to allow for renewing the capital stock in energy carrier production; in the short term the impossibility to renew the capital stock imply low adaptation flexibility in energy carrier production. The absence of flexibility in the substitution between energy and non-energy at final demand level may lead to very high compliance costs, as employing only substitutions within the final energy bundle and within energy carrier production may imply high use of clean resources entailing high nonlinear costs.









E.Policy focus

Modelling of policy measures:

- Wide coverage of policies
- Targets
- Policies inducing effects on costs and prices
- Market-focusing instruments
- Regulations
- Standards
- Infrastructure
- Complex settings enabling higher effectiveness of structural changes
- Policy measures or targets can be specified by sector, by country or EUwide

PRIMES includes a rich representation of policy instruments and measures. Based on long experience with using PRIMES in major policy analysis and impact assessment studies of the European Commission, national governments and industrial institutions, detailed mechanisms have been built in the model to represent a large variety of policy measures and regulations. Scenario construction assumptions about the inclusion of policies can be made in close collaboration with the authority getting the modelling service because the modelling detail is high allowing for mirroring policies close to reality.

The policy instruments classified in groups are as follows:

Targets: they can be directly included in the model at various level, by sector, by country, and EU-wide; they may concern emissions, renewables, energy efficiency, security of supply, fossil fuel independence, and others. Performance against targets derives from projection data. The PRIMES reporting facility includes calculation of indicators according to regulations (e.g. RES shares).

Price or cost driving policies:

- Taxation is exogenous and follows the level of detail of regulations, being specific for fuels, sectors and countries. The data draw from the EU taxation directives. Additional information determine values for subsidies and other forms of state supports.
- Cap and trade mechanisms and tradable certificate systems, including
 Emission Trading Scheme, green and white certificates; the model
 represents a variety of regimes and regulations, including grandfathering
 and auctioning with different regulations by sector, and can handle floor
 and cap prices as well as various assumptions about allowances and their
 composition. Trade of certificates or allowances can be handled over the
 EU or by country (or other grouping of countries) and also over time
 including consideration of influence of foresight and risk-related
 behaviours
- Feed-in tariffs and other renewable support schemes: treated in great detail in PRIMES including historical data and projection of consequences over time; inclusion of possible budget constraints and modelling of individual project developments on RES based on project-based financing depending on support schemes totally or partially and the eventual involvement of the RES project in the market.



Combination of policies:

- Market-oriented instruments can be combined with bottom-up command and control measures
- Cap and Trade certificate systems are modelled in detail and various regimes can be mirrored
- Policies having indirect effects on risk and cost perception of actors, or inducing higher technology progress and uptake
- Focus on infrastructure development and its influences on technology possibilities and on structural

- Institutional mechanisms and regulations that may induce lower interest rates and lower perception of risks by individual investors; largely applied for modelling energy efficiency policies and other policies addressed to numerous individuals.
- Contract for differences and purchasing agreements backed by the state aiming at securing return on investment
- Regulations and policies that address market failures and/or enable tapping on
 positive externalities (e.g. technology progress) which induce reduction of cost
 elements (technology costs) and improve perception by consumers leading to
 lower subjective cost components.

Regulations on standards and command-and-control measures: they are explicit in the model and depending on specification they are showing to eliminate certain technologies or options in the menu in technology choices in various sectors modelled

- Eco-design standards in detail
- Best Available Technology regulations
- Emission standards or efficiency standards on vehicles and other transport means
- Large combustion plant directives
- Emission performance standards
- Energy performance standards
- Reliability and reserve standards (power and gas sectors)
- Policies regarding permitting power plant technologies at national level, for example regarding nuclear, CCS etc., including constraints applicable to new site development or expansion in existing sites. Also, policies regarding possibility of extension of lifetime of power plants (e.g., nuclear) and retrofitting (e.g. to comply with emission regulation)

Infrastructure policies and development plans in various sectors can vary in scenario assumptions and influence possibilities of technology deployment and system costs. Coverage for infrastructure:

- Power interconnectors among countries, including expansion to remote areas for RES development purposes, and different options about management and allocation of capacities
- Power grids and smart systems within countries, which are not spatially represented but only through reduced-form cost-possibility curves in which parameters mirror development plans with influences on future technology development (for RES, highly distributed generation, metering, demand response, etc.)
- Gas transport, LNG, storage and liquefaction infrastructure
- Refuelling and recharging infrastructure in all transport modes
- CO₂ transport and storage infrastructure



Complex design of policy scenarios:

- Explicit focus on technologies, systems and infrastructure combined with market functioning influenced by measures
- Assumption of background policies enabling technology, options and resource availability for energy purposes
- PRIMES
 reporting and
 ex-post
 calculations, as
 well as through
 linkages with
 other models,
 provides rich
 numerical
 projection data
 for feeding costbenefit and
 impact
 assessment
 studies

- Transport infrastructure parameters influence mobility and modal shifts but modelling does not include spatial information (limited to urban, semi-urban and inter-urban)
- Hydrogen transport and distribution infrastructure (reduced form spatial modelling)
- Heat-steam district heating infrastructure (no spatial modelling)

Enabling settings: direct policies as mentioned above or other policies (e.g. R&D) combined together may induce effects on technology costs or on perceived costs and risk factors or on actors' behaviours thus enabling faster uptake of advanced or cleaner technologies thus making possible structural changes to happen in various sectors. Examples are ambitious renovations of buildings and houses, electrification in transport, development of alternative fuels, supply of new generation bio-energy commodities, etc. The assumptions about enabling settings mainly influence perception of costs, technology uptake and technology progress.

ETS market simulation is explicit in PRIMES. However, the projections based on PRIMES are compatible with the 5-year time resolution of the model and the model algorithm only approximates the arbitration of allowances holders over time. Nonetheless, PRIMES can handle multi-target analysis, for example, simultaneously for ETS, non-ETS, RES and energy efficiency, where the aim is to determine optimal distribution of achievements (targets) by sector and by country. PRIMES has successfully provides results for that purpose in the preparation of the 2020 Energy and Climate Policy Package (2007-2008) and recently for the 2030 Policy Analysis (2013).

Detailed reporting and ex-post calculations: to support *impact assessment studies* PRIMES provides detailed reports of scenario projections. The reports calculate cost indicators (with various levels of detail distinguishing between cost components and sectors), as well as for numerous other policy-relevant indicators. Topics covered include environment, security of supply and externalities (e.g. noise and accidents in transport). Thus, the model provide elements and projections to support cost-benefit analysis studies, which are the essential components of impact assessments. When PRIMES links with the macroeconomic model GEM-E3, the coverage of projection data for the purposes of cost-benefit evaluations is more complete and comprehensive. Similarly, linkages with GAINS (from IIASA) provide wider coverage of cost-benefit projections regarding atmospheric pollution, health effects, etc.



F. Typical Inputs and Outputs of PRIMES

Inputs

- GDP and economic growth per sector (many sectors)
- World energy supply outlook world prices of fossil fuels
- Taxes and subsidies
- Interest rates, risk premiums, etc.
- Environmental policies and constraints
- Technical and economic characteristics of future energy technologies
- Energy consumption habits, parameters about comfort, rational use of energy and savings, energy efficiency potential
- Parameters of supply curves for primary energy, potential of sites for new plants especially regarding power generation sites, renewables potential per source type, etc.

Outputs

- Detailed energy balances (EUROSTAT format)
- Detailed demand projections by sector including end-use services, equipment and energy savings
- Detailed balance for electricity and steam/heat, including generation by power plants, storage and system operation
- Production of fuels (conventional and new, including biomass feedstock)
- Investment in all sectors, demand and supply, technology developments, vintages
- Transport activity, modes/means and vehicles
- Association of energy use and activities
- Energy costs, prices and investment expenses per sector and overall
- CO₂ Emissions from energy combustion and industrial processes
- Emissions of atmospheric pollutants
- Policy Assessment Indicators (e.g. import dependence ratio, RES ratios, CHP ratios, efficiency indices, etc.)

Coverage of PRIMES inputs and outputs

- 38 European countries (individual projections)
- 2010 2070 by 5-years steps
- Trade of electricity, gas and other fuels between the European countries and with the rest of the World



G.Comparison to other models

What PRIMES can do

The distinctive feature of PRIMES is the combination of micro-economic foundations with engineering at a high level of detail, compatible with a long-term time scale and sectoral detail of available statistics for Europe

Designed to provide long-term energy system projections and system restructuring up to 2050, in both the demand and the supply sides. Projections include detailed energy balances, structure of demand by sector, structure of power system and other fuel supplies, investment and technology uptake, costs per sector, overall costs, consumer prices and certificate prices (incl. ETS) if applicable, emissions, overall system costs and investment.

Impact assessment of specific energy and environment policies, applied at Member State or EU level, including price signals, such as taxation, subsidies, ETS, technology promoting policies, RES supporting policies, efficiency promoting policies, environmental policies

The linked model system PRIMES, GEM-E3 and IIASA's GAINS (for non-CO2 gases and air quality) perform energy-economy-environment policy analysis in a closed-loop

What PRIMES cannot do

No forecasting but scenario projections. PRIMES is not an econometric model. Cannot perform closed-loop energy-economy equilibrium analysis, unless linked with a macroeconomic model such as GEM-E3.

PRIMES has more limited resolution than engineering electricity, refinery and gas models dedicated to simulating system operation in detail. Although rich in sectoral disaggregation, PRIMES has limitations due to the concept of representative consumer per sector, as it does not fully capture the heterogeneity of consumer types and sizes.

PRIMES lacks spatial information and representation (at a level below that of countries) and so it does not fully capture issues about retail infrastructure for fuels and electricity distribution, except for electricity and gas flows over a country-to-country based grid infrastructure, which is well represented in the model

PRIMES is an empirical numerical model with emphasis on sectoral and country specific detail; it has a very large size and so some compromises were necessary to limit computer time at reasonable levels.

PRIMES differ from overall optimization energy models, qualified by some as bottom-up approaches, as for example MARKAL, TIMES, EFOM. Such models



formulate a single, overall mathematical programming problem, do not include explicit energy price formation and have no or simple aggregate representation of energy demand. PRIMES formulates separate objective functions per energy agent, simulates in detail the formation of energy prices and represents in detail energy demand, as well as energy supply.

PRIMES differ from econometric-type energy models, such as POLES, MIDAS and the IEA's World Energy Model. These models use reduced-form equations that relate in a direct way explanatory variables (such as prices, GDP etc.) on energy demand and supply. These models have weak representations of useful energy demand formation. They are usually poor in representing in detail capital vintages and technology deployment in energy supply sectors and lack engineering evidence, as for example the operation of interconnected grids and detailed dispatching.

PRIMES is a partial equilibrium model as opposed to general equilibrium models, such as GEM-E3.

Obviously, PRIMES differs substantially from accounting-type models, which usually focus on specific sectors, such as MEDEE, MAEDS (on energy demand), GREEN-X (renewables), BIOTRANS (biofuels), etc.

The distinguishing feature of PRIMES is the representation of each sector separately by following microeconomic foundations of energy demand or supply behaviour and the representation of market clearing through energy prices. Similar models developed in the USA, include PIES, IFFS and mainly the NEMS model, which is currently the main model of USA DOE/EIA.

These models are qualified as generalized equilibrium models because they formulate the behavioural conditions for economic agents and combine a variety of mathematical formulations in the sub-models, represent different market clearing regimes. These models are also qualified as hybrid models because they combine engineering-orientation with economic market-driven representations.



H. Overview of PRIMES model resolution

REGIONS: The PRIMES model is operational for all EU28 individual member-states and for the Western Balkans countries (Albania, Bosnia-Herzegovina, FYR of Macedonia, Serbia, Kosovo and Montenegro), the EFTA countries (Switzerland, Norway, Iceland) and Turkey. It projects also the flows of electricity and gas among all countries. A simple version of the model runs on data for 11 North African and Middle East countries.

FUEL TYPES: PRIMES projects energy demand and supply balances distinctly for 45 energy commodities and forms. The list is:

- coal, lignite, coke, peat and other solid fuels;
- crude-oil, feedstock oil, residual fuel oil, diesel oil, liquefied petroleum gas, kerosene, gasoline, naphtha, other oil products; bio-fuels (several types);
- natural and derived gasses (blast furnace, coke oven and gas works, as week as oil and solids gasification outputs);
- thermal solar (active, high enthalpy and low enthalpy), geothermal low and high enthalpy;
- steam/heat (industrial and distributed heat);
- electricity, nuclear energy;
- biomass and waste (5 bio-energy types and several feedstock types);
- solar PV electricity, solar thermal electricity, wind onshore, wind offshore, hydro lakes, hydro run of river, tidal and wave energy
- Hydrogen, e-fuels (synthetic gas and liquids).

The model projects volumes and prices by fuel type and by sector.

RESIDENTIAL: The residential sector includes 54 building types by age, location, and building type. The model includes 29 space heating and cooling equipment types, water heating and cooking. The electric appliances (several categories) for non-heating purposes reflect technology vintage dynamics, eco-design regulations and follow stock-flow relations. There is no distinction between rented and owned dwellings.

SERVICES & AGRICULTURE: The model distinguishes between two commercial sectors and one public sector, further split into 8 subsectors. At the level of each sub-sector, the model calculates energy services (useful energy), which are further subdivided in energy uses (several types) defined according to the pattern of technology. Service buildings are also categorised by age. The model includes in total more than 30 end-use technology types.

INDUSTRY: The industrial model formulates 10 industrial sectors separately and 31 subsectors, namely iron and steel, nonferrous (several sectors), chemicals subdivided in basic chemicals, petrochemicals, fertilizers, cosmetics/pharmaceuticals, non-metallic minerals subdivided in cement, ceramics, glass and other building materials, paper and pulp subdivided in pulp, paper and printing, food drink tobacco, engineering, textiles, other industries and non-energy uses of energy products. For each sector different subprocesses are defined (in total about 30 sub-sectors, including focus on materials and on recycling; sectors are subdivided in sub-sectors based on whether processing is based on primary or scrap feedstock). At the level of each sub-sector a number of different energy uses are represented (the model includes in total about 235 types of energy process technologies).

TRANSPORT: The transport sector distinguishes passenger transport and goods transport as separate sectors. They are further subdivided in sub-sectors according to the transport mode



and mean (public, private, road, rail, maritime, air, etc.). At the level of the sub-sectors, the model structure defines several vehicle types and categories including distinction by size by purpose or trip type and by technology type. Within modes like road transport there is a further subdivision, e.g. for road passenger transportation the model distinguishes between public road transport, metro, other rail, fast trains, motorcycles and many types of private cars. The model considers several alternative technologies and fuels for each transport mean. The model also projects activity by typical area (urban, semi-urban and inter-urban) and by trip type. In total, the model includes 15 transport modes, 103 vehicle types for road and non-road transport, 4 stylized geographic areas, distinction between peak and off-peak and 3 freight categories.

ELECTRICITY AND STEAM PRODUCTION: Very detailed model including 72 different plant types per country for the existing thermal plant types; 150 different plant types per country for the new thermal plants; 3 different plant types per country for the existing reservoir plants; 30 different plant types per country for the intermittent plants. In total the database includes approx. 13000 power plants. Chronological load curves for electricity and steam/heat distributed, 3 voltage types for the grid, interconnecting European system in detail (individually for all interconnectors, present and future, including ENTSOe development plans), network capacity and electric characteristics of interconnectors. The power/steam model represents three stylised activities with distinction between utilities, industrial production and highly distributed scale as well as for self-power generation. Cogeneration of power and steam (12 generic technologies), district heating, industrial boilers by sector, and distinction between plants in industrial sites and merchant CHP.

NATURAL GAS: Very detailed sub-model covering regional supply detail (Europe, Russia, CIS countries Middle Africa, North Sea, China, India for pipeline gas and global market for LNG). Detailed representation of gas infrastructure (field production facilities, pipelines, LNG Terminals, Gas Storage, Liquefaction Plants).

BIOMASS SUPPLY: Very detailed sub-model covering supply of biomass and waste energies including a wide variety of feedstock types and transformation processes into bio-energy commodities including bio-refineries. The model covers several land categories, resources (crops, forestry, aquatic biomass and wastes) and of more than 35 transformation processes. Covers life-cycle calculations.

REFINERIES: Simple oil refinery type with typical refinery structure defined at the level of each country; 5 typical refining units (cracking, reforming etc.)

HYDROGEN: Detailed hydrogen production and transportation sub-model with 18 H2 production technologies, 8 H2 transport/distribution means and several types of H2 using equipment.

PRIMARY FOSSIL FUEL PRODUCTION: Simple Cost – Supply curves limited by available resources covering all primary energy extraction activities including conversions to briquetting, liquefaction and gasification.

EMISSIONS: CO₂ emissions from energy combustion, process-related in industry, Atmospheric Pollutants (SO₂, NO_x, PM, VOC), ETS and non-ETS split, and non CO₂ GHG abatement cost curves provided by GAINS (IIASA).



I. Data Sources and Model Linkages

I.1. Data sources

EUROSTAT: Energy Balance sheets, Energy prices (complemented by other sources, such IEA),
Macroeconomic and sectoral activity data (PRIMES sectors correspond to NACE 3-digit
classification), Population data and projection, Physical activity data (complemented by other
sources), CHP surveys, CO2 emission factors (sectoral and reference approaches) and EU ETS
registry for allocating emissions between ETS and non ETS

TECHNOLOGY DATABASES: MURE, ICARUS, ODYSEE – demand sectors, VGB (power technology costs),
TECHPOL – supply sector technologies, NEMS model database, IPPC BAT Technologies IPTS

OTHER DATABASES: District heating surveys, buildings and houses statistics and surveys (various sources), IDEES, BSO, BPIE,

POWER PLANT INVENTORY: ESAP SA and PLATTS

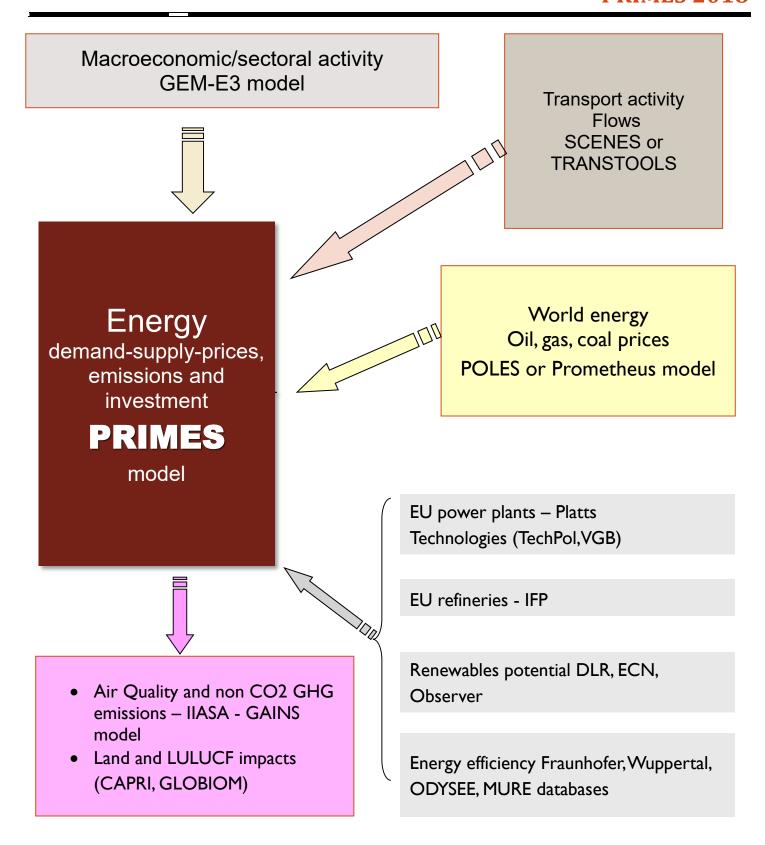
RES POTENTIAL: ECN, DLR and EURObserver

NETWORK INFRASTRUCTURE: ENTSOE, ENTSOG, GIE, TEN-T (transport infrastructure)

I.2. Model Linkages

- *GEM-E3:* Linkage to GEM-E3 to take projections of activity by sector/country and GDP and to send energy projections to GEM-E3 in order to carry out closed-loop macroeconomic impact assessment studies
- **PROMETHEUS OR POLES:** Linkage to these global energy models to take projections of world fossil fuel prices
- *GAINS:* Linkage to GAINS to take marginal abatement cost curves for non-CO2 greenhouse gases and to convey energy projections to GAINS in order to evaluate impacts on atmospheric pollution
- *CAPRI, GLOBIOM:* Linkage to send to these models detailed biomass supply projections in order to evaluate land use and LULUCF impacts
- *TRIMODE:* Linkage to a spatial transport flow model to take activity projections for mobility in order to calibrate a reference projection (PRIMES provides its own activity projection in scenarios)
- MODELS CALCULATING POTENTIALS: PRIMES uses detailed bottom-up information on energy efficiency and renewable potential (databases and models including DLR, GREN-X and several others)







J. Stationary Energy Demand Sub-models

Main Features

- Energy demand based on individual optimizing behaviour of representative agents by sector
- Choices follow a tree with useful energy on top and choice of fuels at the bottom
- Detailed decomposition in several processes and uses of energy
- Focus on materials in industry and explicit modelling of recycling
- Explicit
 representation of
 equipment using
 fuels and distinction
 between purchasing
 of fuels and self production

J.1. General Methodology

For each energy demand sector a representative decision-making agent operates, who optimizes an economic objective function. For households and passenger transport, the model formulates a utility maximisation problem. The model uses a profit maximisation (or cost minimisation) function for industrial, tertiary and freight transport sectors. The decision on fuel and technology mix follows a nested budget allocation problem.

Firstly **useful energy demand** (services from energy such as temperature in a house, lighting, industrial production, etc.) is determined at a level of a sector. At the upper level of the nesting, energy is a production factor or a utility providing factor and competes with non-energy inputs. At this level a macroeconomic econometrically estimated function is used which combines energy and non-energy inputs and considers saturation dynamics. Saturation depends on income for households and the saturation factor exhibits a sigmoid curve which indicates income elasticity of energy above one if useful energy at low levels (less developed countries) and elasticity values lower than one (and decreasing) when useful levels are high.

Useful energy, as derived, decomposes into uses and processes (e.g. space heating, water heating, motor drives, industrial processes, etc.). The separation in uses and processes follows a tree structure which is formulated mathematically so as optionally to allow either for complementarity or substitutable relationships among uses/processes. For example to produce a certain product, the model activates a certain chain of process flows: in this case, they are complementary with each other. However, it may be that the product can equally go through electro-processing or thermal processing in which case the processes are substitutable to each other. For some sectors, the model distinguishes between sub-sectors in order to get a more accurate representation of the stylised agent. For industrial sectors, the model puts emphasis on materials and recycling and so it distinguishes between subsectors, which involve basic processing (e.g. integrated steelwork, clinker in cement, primary aluminium, etc.) and sub-sectors which use recycled and scrap material. The possible substitutions between such sub-sectors is endogenous, and depend on prices, policy measures, macroeconomic demand factors and maximum potential of recycling possibilities, which are captured through increasing cost-potential curves. The choice of elasticity values and specific functional forms expresses the a priori considerations about



Main Features

- Equilibrium between energy demand and (self) supply is modelled in each sector
- Useful energy demand depends on energy saving/efficiency investment and behaviour; tapping on saving potential induces non-linearly increasing costs
- Self-supply derives from dynamic least cost optimization which involves technology choice depending on perceived costs and on subjective discount rates
- Policies are explicitly represented and influence choices, technology economics, perception of costs and discount rates

complementarity and substitutability structure among subsectors/uses/processes in each final energy demand sector.

Useful energy requirements at the level of sub-sectors/uses/processes (e.g. space heating, air conditioning, lighting, motive power, etc.) links to consumption of **final energy**.

The representative agent in each sector or sub-sector makes choices among fuels, technologies and energy savings to minimize costs in meeting the useful energy requirements. The formulation includes the possibility of choice between purchasing ready-to-use fuels or energy carriers and self-producing energy where this is possible. Examples are cogeneration versus district heating, etc.

The least cost choice is dynamic and involves endogenous choice of equipment (vintages, technologies and learning), endogenous investment in energy efficiency (savings), endogenous purchase of associated energy carriers and fuels (demander is price taker). These are capital budgeting decisions which may involve trade-offs between upfront costs and variable-running costs. Capital decisions use weighted average cost of capital (WACC) and subjective discount rates to annualise (levelized) costs to compare with variable-running costs, which by definition are annual. The model for all demand sectors dynamically tracks capital accumulation with endogenous investment, tracking of vintage characteristics and endogenous premature scrapping.

The aim of the modelling is to mimic decisions by individuals as realistically as possible. Subjective discount rates and business WACC include risk premium factors, which reflect opportunity costs of drawing funds by the private sector. They also reflect uncertainty, lack of information and probably limited access to capital markets. For this reason, the model relates the individual discount rates with a policy context, in order to mirror how certain policy instruments may reduce uncertainties or decrease financing costs in order to make economic decisions for technologies with high upfront costs. To mimic reality, the model also includes several non-engineering cost facts which represent technical uncertainty, risk of high costs of maintenance in case of not-yet mature technologies, easiness of technology application, easiness to comply with permits and regulations, etc. The terminology used is that the user sees perceived cost values for technologies and solutions where some of the cost components can reduce over time as technology becomes commercially mature. This is one of the ways for representing endogenous learning-by-doing mechanisms in the model. Thus, decisions at each nesting level use equivalent perceived costs to reflect actual costs, utility (e.g. comfort), and uncertainty



Main Features

- Detailed representation of various energy efficiency promoting policy instruments
- Heat pumps and directly used renewables are represented
- Several dwelling types and several services sectors
- Dynamic modelling of technologies tracking vintages and including endogenous learning
- Investment, use of existing stock and possible premature scrapping are endogenous decisions
- The demand submodels are solved as non-linear mixed complementarity problems

and risk premiums. The decisions depend on policy measures, such as: taxes and subsidies, promotion of new technologies (reducing perceived costs), and promotion of energy efficiency, including standards -e.g. CO₂ regulations for passenger car or regulations on minimum performance of lighting, policies that ease financing, etc.

For industrial energy demand, PRIMES follows a formulation that allows for full integration with macroeconomic production functions. Sectorial value added derived from GEM-E3 projections (general equilibrium macroeconomic model), link to PRIMES measurement of activity in physical units. Substitutions between energy and non-energy (capital) inputs is handled at the upper level of PRIMES nesting and can coordinate with GEM-E3 projections. A large number of industrial processes (e.g. different for scrap or recycling processes and for basic processing) as well as a mix of technologies and fuels, covering the use of self-produced by-products (e.g. black liquor, blast furnace gas) provides higher resolution of industrial processing in PRIMES than in GEM-E3.

Energy savings possibilities follow engineering representations, including the possibilities of shifting towards more efficient process technologies. Substitutions are possible between processes, energy forms, technologies and energy savings. The adoption of technologies depends on standards, emission constraints, pollution permits and is dynamic keeping track of technology vintages and stock-flow investment. The actual lifetime of existing equipment is endogenous driven by relative costs.

The industrial model considers explicit ways of producing steam, for example using boilers or CHP. The model distinguishes between boiler steam, CHP steam from onsite plants and distributed CHP steam. Interaction with Power and Steam sub-model for industrial CHP and boilers is an integral part of the model. The choices at industrial scale consider steam-driven CHP and CHP driven by electricity-market. The model has a database on onsite CHP, which are cogeneration units with no access to steam distribution. The official statistics do not include these onsite plants. A special routine in the PRIMES database combines Eurostat statistics on energy balances and CHP surveys, isolates in the data the on-site CHP, and reconstitute inputs and outputs for such installations.

PRIMES represents possible substitutions and energy efficiency at various levels in the residential and tertiary sectors and includes special routines for the building stock and its renovation. The model tracks the dynamics of the building stock, split by categories, and formulates demolishment decision, construction of new buildings and renovation with distinction of various



Main Features

- Efficiency obligations and white certificates are included
- Standards influence the menu of technology choice
- Engineering details for industry capture processing of materials and choice between processing technologies
- Cogeneration versus industrial boilers are closely linked to electricity and heat markets; on-site CHP is explicitly represented

degrees of renovation for energy saving purposes. These decisions derive from economics and are simultaneous with the nested decisions on useful energy demand, fuel mix choice, equipment choice, and energy efficiency investment. Rebound effects stemming from cost savings due to energy efficiency are present and derive simultaneously with the rest of decisions. For example, useful energy demand may increase because of high energy efficiency gains. The decisions related to buildings also depend on behavioural characteristics and are influenced by perceived costs, subjective discount rates and prices. Policy measures and instruments, and standards such as the building codes influence the decisions. The model includes heat pumps and direct use of renewables (biomass, solar, geothermal, etc.). The related decisions are simultaneous with the rest of decisions, including the dynamic track of technology vintages.

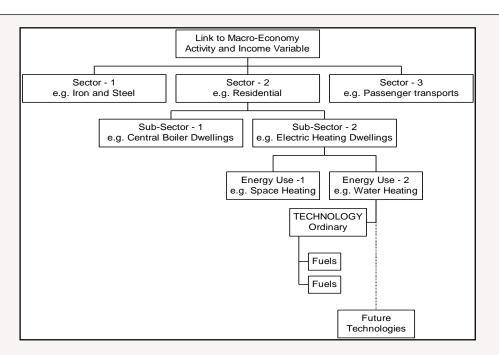
Surveys have shown that the substitution possibilities and the energy efficiency investment depend on the main pattern of space heating method, which is a goof dimension to classify the various behavioural types. For this purpose, the model includes a distinction of five dwelling types according to space heating pattern; one of the categories group partly heated houses. PRIMES also distinguishes agriculture and services sectors which are broken down by sub-sector (e.g. market services, non-market services, trade); electric appliances and lighting are separately treated in all sectors.

The following diagram illustrates the tree decomposition of each energy demand sector in sub-sectors, further in processes and in energy uses. A technology operates at the level of an energy use and utilizes purchased energy forms (fuels and electricity) or self-produces energy. The calculation starts from activity or income, then it computes useful energy and then by using technology equipment it meets useful energy by converting purchased or self-produced energy forms (final energy). The mathematical formulation of the nested decisions solves as a whole, including the least-cost choice of technologies and fuels and the dynamic investment process.

The demand models solve as mixed complementarity problems, which concatenate the individual optimization problems written in the form of Kuhn-Tucker conditions.



Summary of energy demand modelling methodology



The model evaluates consistently the potential of new technologies, by considering simultaneously four types of mechanisms: a) economic optimality, b) dynamics, i.e. constraints from existing capacity, c) gradual market penetration depending on relative costs and risk perception, d) endogenous technology learning and commercial maturity.

The non-linear optimization per agent (sector) performs dynamically in a time forward direction with foresight limited to 10 years. In a given period a set of lagged values up-dated dynamically by the single-period optimization results reflect adaptive expectation over 10-years. Choices are constrained dynamically by the existing energy-use equipment stock, which may change through investment while existing equipment can be retired based on retirement rates, or by premature replacement decisions. Technology (energy equipment that converts purchased energy to useful energy) and energy savings equipment (e.g. insulation) is considered to evolve over time, and is categorized in vintages (generations) presenting different cost and performance features.

The upper level functions which project useful energy demand (services provided by using energy or by saving energy) are of econometric nature and are based on complex functional forms relating demand with macroeconomic drivers so as to capture possible saturations, rebound effects and comfort depending on income growth. The useful energy demand functions are dynamic and depend on evolution of unit cost of energy services, which aggregate costs of equipment for operation and investment in various energy uses and for saving energy. Investment enabling energy efficiency progress at useful energy level concerns improvement of thermal integrity of houses and buildings, horizontal energy management systems in industry or offices, etc. Such investments are determined together with useful energy demand to fully capture rebound effects and depend on investment costs, energy prices, carbon prices and policies supporting or facilitating such investments. Stock turnover dynamics, including for renovation, are explicit in the model. Costs related to energy saving potentials are non-linear assuming exhaustible potentials and cost gradients increasing with volumes of energy savings due to upper level investments. Discrete choice theory formulations capture heterogeneous situations regarding house/building types and conditions. Heterogeneity also justifies the non-linear costs but are difficult to represent analytically due to lack of statistics. The non-linear cost-saving possibility curves are estimated using micro and bottom-up sources based on surveys and available databases.



PRIMES handles in great detail energy

industry and the ways of reducing

energy demand and shifting away from GHG

intensive processing in

emissions

J.2. Industrial energy demand sub-models

In PRIMES, industry consists of ten main sectors, which split in 31 different sub-sectors. Each sub-sector includes a series of industrial processes and energy uses totalling 234 uses; additionally, 22 different fuel types are available for the industrial sectors. Technologies are explicit, firstly at the process level where different process types are included and secondly at the levels of energy uses where technologies use different types of fuels. The model distinguishes between low enthalpy heat and steam. Heat and steam can be either self-produced using boilers or CHP or purchased from the steam or heat distribution markets, which depends on other industries' CHP or boilers.

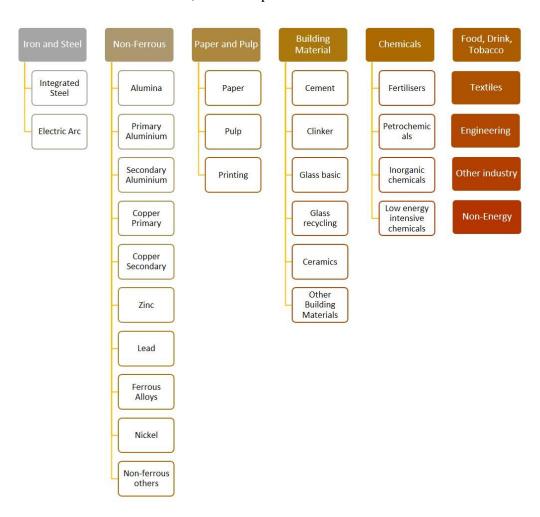
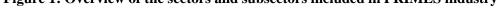


Figure 1: Overview of the sectors and subsectors included in PRIMES industry

The structure of processes and uses in the industrial sector can be seen in the figures at the end of this section. The current model version splits alumina production from primary aluminium production (previously grouped into one), clinker from cement production (particularly important, as clinker



imports tend to increase over time) and includes a large list of sector-specific processes. In particular, it further includes significant details for pyrometallurgy, fire refining, and electro-refining options used for the production of non-ferrous metals. The database of the techno-economic data for the split of process and technologies has been updated –for the last Reference scenario published 2016- based on extensive literature research (IEA-ETSAP, industrial surveys, etc.). The energy saving possibilities from technologies included in the eco-design directive (e.g. air compressors, etc.) were verified, emerging technologies such as gas and liquid membrane technologies for separation in the chemical industry are included and are taken into account in the industrial module of PRIMES.

The scope of the industrial demand sub-model of PRIMES is to represent simultaneously:

- the mix of different industrial processes (e.g. different energy intensity for scrap or recycling processes and for basic processing);
- the mix of technologies and fuels, including the use of self-produced byproducts (fuels) and renewable energy forms;
- the links to self-supply of energy forms (e.g. cogeneration of electricity-steam, steam by boilers, use of by-products (fuels), heat recovery);
- the explicit and engineering-oriented representation of energy saving possibilities;
- the satisfaction of constraints through emission abatement, pollution permits and/or energy savings, and
- the rigidities of system change evolution because of existing capacities or dynamic technical progress
- Possible substitutions between processes, energy forms, technologies and energy savings
- CO₂ capture and process related emissions are included in the model

Energy efficiency improvement in industry is linked to technology choices at process and energy use levels, and in addition derives from direct investment on energy savings; all options are fully included in the modelling.

- *Direct investments in energy savings* are modelled as horizontal energy management systems and as specific interventions mainly for heat recovery. The saving possibilities follow cost-quantity curves, which have limited potential and non-linear increasing costs.
- Choice of process technologies and energy use technologies (equipment) involve a variety of possibilities, which differ in upfront costs and in variable costs depending on energy performance. Processing and energy using equipment stock turnover is dynamic, keeping track of technology vintages; both the choice of technologies as well as the stock turnover can be influenced by policies which are represented in the modelling.



Similarly, to the energy efficiency the model includes a variety of options for the **mitigation of CO**₂ **emissions**, these are linked to the choice of technologies and fuels at process and energy use level. Obviously the emission savings deriving from reduced fuel consumption thanks to energy efficiency measures are automatically taken into account in the model.

- Fuel switching: the model allows for fuel switching towards e.g. gas or electricity (for the latter see next bullet), where the processes allow to move from more carbon intensive fuels to less carbon intensive fuels, such as switching from coal to gas. The model allows also for the use of **hydrogen** where this is technically feasible (e.g. co-firing of hydrogen in high temperature furnaces), as well as the use of waste, **biomass** and **e-fuels** (hydrogen or methane, as well as "synthetic" liquid fuels).
- *Electrification of processes/uses:* electrification often leads to energy savings, as well as CO₂ mitigation. The PRIMES model includes a variety of options for the electrification of processes, including processes available today such as electric boilers, electric arc furnaces and microwave heating, as well as processes which are expected to be commercially available in the future such as mechanical drives to replace steam drives or high temperature heat pumps.

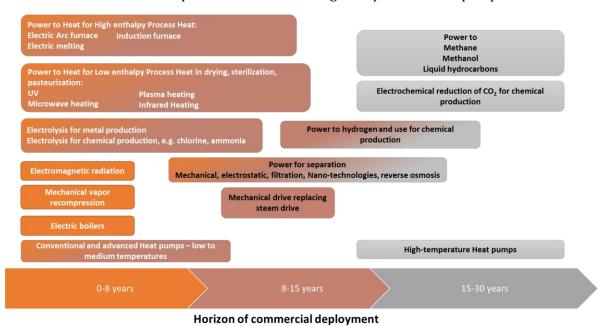


Figure 2: Horizon of commercial deployment for electrification options in industry

The PRIMES model has been recently updated to include several options to allow for deep decarbonisation of the industrial sector including:



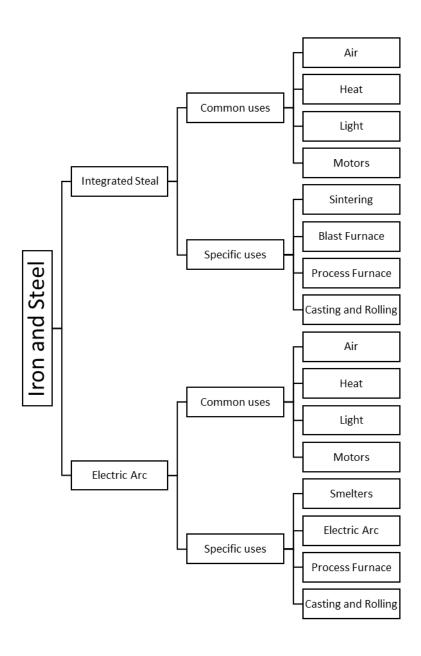
- Use recycled or renewable carbon instead of fossils as feedstock to produce complex molecules in chemicals (electro-chemical reduction technologies);
- Negative emissions in carbon feedstock to polymers;
- Integration of low carbon solutions for combustion with process emissions;
- Industrial symbiosis exchange to recycle carbon, syngas and others;
- Circularity: increase recycling of materials and products;
- Use electricity in separation, heat uses and low enthalpy heat electrification (UV, infrared, microwave, induction, etc.);
- Direct reduction of iron ore for steel;
- New cement chemistries:
- Capture of CO₂ and syngas from steel and cement (and other processes) to reuse for recycled carbon feedstock;
- Efficient separation of CO₂ from flue gas and process flows;
- Electricity for vapour recompression (electrical steam);
- Electricity-driven separation;
- Medium to High temperature heat pumps;
- Heat recovery;
- Recovery of low concentration compounds.

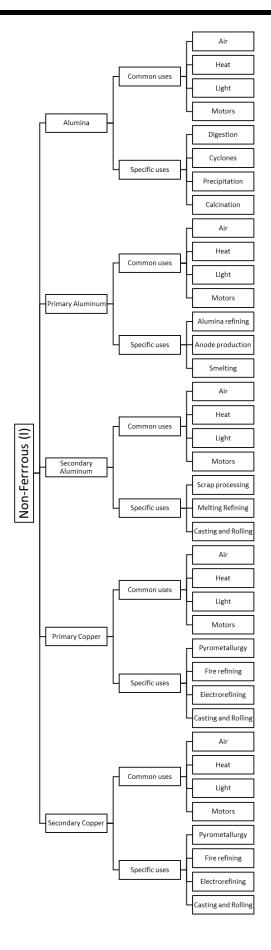
The representation and reduction options for CO₂ from process emissions have recently been improved in the PRIMES model. They are computed through relationships driven by the physical production of the relevant industrial commodities (e.g. cement) and the process type used for the production (e.g. direct ore reduction vs. blast furnace) and by the fuel use (hydrogen co-firing in furnaces). Remaining emissions may be reduced through Carbon Capture techniques, which apply on the processing of industrial commodities. The representation includes capital and variable costs of CCS, as well as electricity consumption associated with capture, which adds up to total demand for electricity. The model allows for both storage and utilization of the captured carbon emissions, as well as storage in chemical materials (plastics).

Industrial Boilers and cogeneration (CHP) are covered in a separate module of PRIMES, where they are included by sector to allow for representing the specificities of industrial sectors in an accurate manner. The steam required by different industries differs in quality (temperature-pressure ratios), implying that the boilers are "calibrated" to the specific industry which requires them, making boilers specific

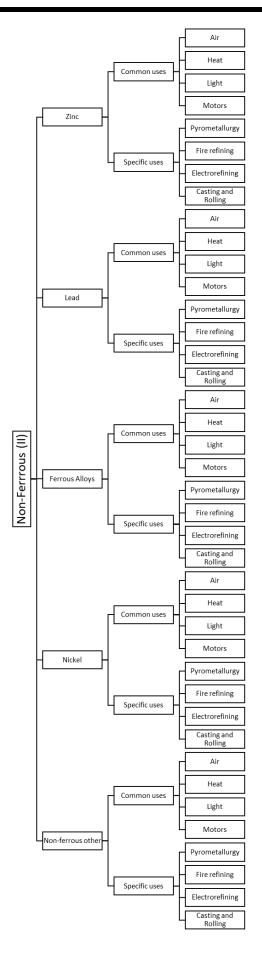


for certain industries and not easily substitutable e.g. with supply through steam distribution networks. The inclusion of boilers and CHP by industrial sector allows for the representation of the heterogeneity and inertia of behaviour, both captured through discrete choice modelling techniques. The boilers and cogeneration units each have different fuel options which can be influenced by prices or through policies, thus allowing for emission reductions; the model also allows for switching between boilers and CHP to enhance overall system efficiency.

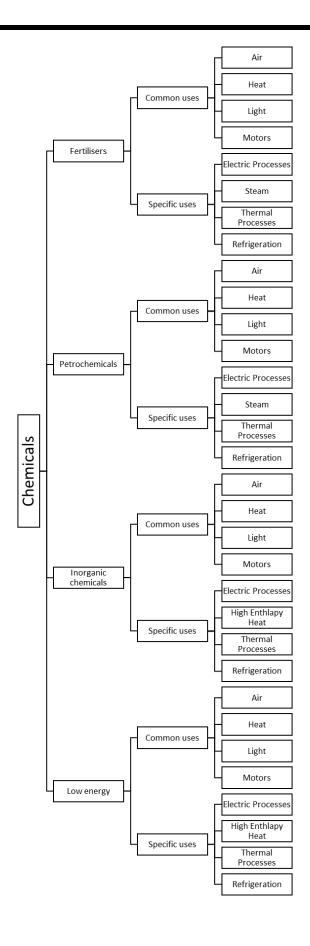




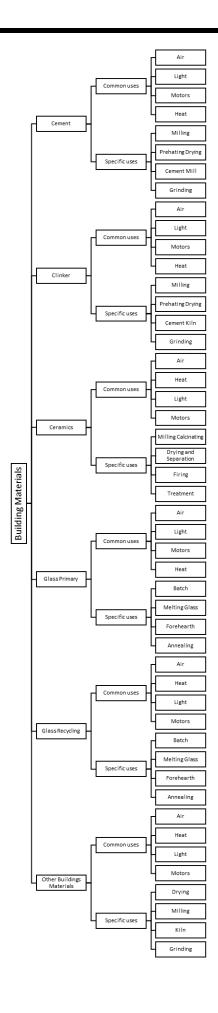




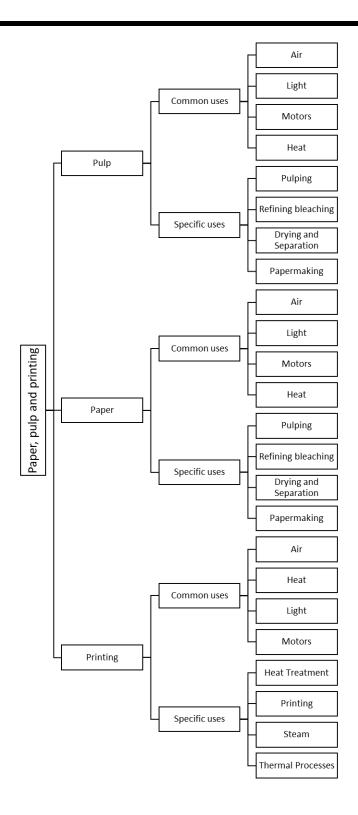


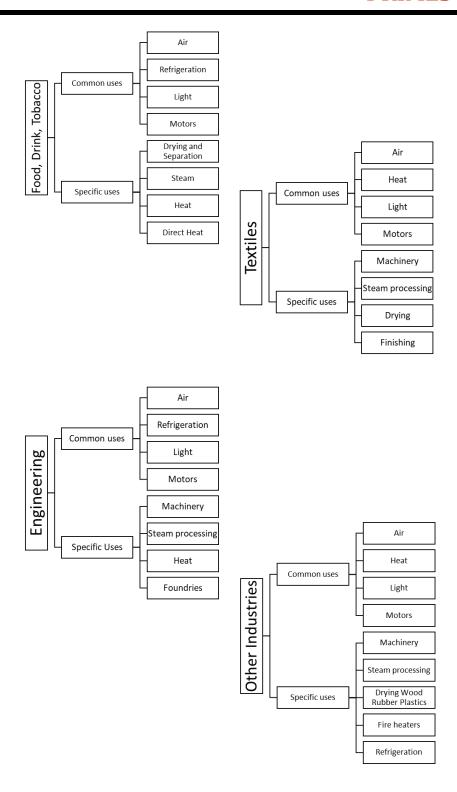












J.3. Steam and heat generation

The current version of PRIMES splits the modelling of steam and heat generation into sub-models covering boilers and cogeneration for each industrial sector, district heating including heat extraction from cogeneration and separately the rest of the power market. The three main modelling blocks communicate with each other by exchanging flows (power, heat and steam) and by exchanging money transfers based on prices for the respective commodities. The split of the models is beneficial for representing specificities of industrial sectors in a more accurate manner. It is also beneficial for introducing heterogeneity and inertia of behaviours, both captured through discrete choice modelling techniques. The enhanced model has better stability than before in the simulation of cogeneration which is more dependent on industrial sector circumstances than on conditions prevailing in the power market.

The split of the model, allows the introduction of higher resolution in terms of technologies. For example, in district heating the model includes electric boiler, heat pumps and in detail the various biomass and waste technologies and feedstock types, for example with distinction between landfill, sewage, solid waste, wood and wood waste, and biogas facilities.

Distributed steam is a small fraction of total steam consumption; however, the statistics provide very poor steam generation information by sector. Even the cogeneration surveys, carried out by Eurostat, discontinued after 2010 and anyway they were not available by year in full detail. The PRIMES model has a method for this disaggregation of steam heat production, which will be maintained until better data is available. The enhanced method combines information from the CHP surveys, the power plant inventory (as further processed to identify sector origins), engineering information on stylised process flow by type of industry (30 industries in total) and the power generation statistics which include the fuels corresponding to the electricity generation from cogeneration, nonetheless without split between pure electric and CHP generation. The data for the time series from 2000 until 2015 has been constructed through algorithms for matching and consistency checking, which generally follow cross-entropy methodology. The engineering templates of process flows draw on a large set of reports from JRC (IPPC directive), from industrial associations, specialised handbooks, IEA technology reports and the analytical surveys by sector, which are available in the USA (EIA).

In industrial sectors, practice suggests that industry does not replaces the boilers homogeneously at the end of a specified technical lifetime, but often they remain in place after refurbishment also for backup purposes. The industrial sectors use a large variety of different specific boiler technologies, with different daily load profiles, and different ways of using them. To capture heterogeneity, the model uses sector-specific survival functions coupled with economically driven premature replacement or lifetime extension. In addition, the model uses discrete choice theory formulations for the mix of fuels and technology types.

The model uses a long list of sectors, subsectors and processes and a specific list of CHP and boiler plants by sector. This allows capturing CHP dynamics at sector-specific level and detailed representation of energy savings potentials.





The energy efficiency potential in houses is great. Tapping on potential is challenging as it depends on decisions by millions of heterogeneous consumers.

J.4. PRIMES BuilMo: a detailed residential and services sector model

In the residential sector (and similarly in the services 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 decision about the level of energy consumption is related to the need for services covered by energy and depend on efficiency as well as on economics, notably relative costs and prices. Income drives demand for services from energy. Electricity demand for electric appliances is modelled separately by type of appliance and by efficiency class.

As fuel mix in thermal purposes mainly depends on the equipment technology and the type of dwelling, PRIMES decomposes the dwelling stock in different categories. The number of dwellings in each category changes over time and by country depending on demolishment, renovation and new buildings as well as on relative costs and prices of energy. Income growth combined with socioeconomic factors influences the projection of population by type of dwelling. The fuel mix possibilities for water heating and cooking depend on the fuel mix in space heating and the dwelling category. For example using gas in water heating is more common when gas is also used in space heating. Substitution possibilities thus depend on the main energy pattern of the dwelling and influences the hierarchy of fuel choices. These are well captured in the model.

Energy performance is largely depending on the characteristics of the dwelling (thermal integrity) and the technology of the equipment which uses energy. Thus, spending money to improve energy efficiency is represented at top level where it takes the form of investment improving thermal integrity of new and old dwellings and at the equipment choice level where the model represents a choice between technologies belonging to different energy efficiency classes. Both choices involve a capital budgeting decision and the model compares annualised capital costs using discount rates against variable costs; solutions with upfront costs and utilisation performance leading to reasonable pay-back periods are selected. Costs of investment in thermal integrity depends on technological possibilities but also on a large variety of specific features of the dwelling under renovation. Energy performance of new technologies and buildings follows standards and codes and for some of the eco-design regulations and labelling interventions the model shows the effects by reducing perceived costs of more efficient technologies. Utility obligations, white certificates and ESCOs allow reducing discount rates, which can be captured in values as assumed for model inputs.

Long-term responses to policies and energy price movements depend on renewal of dwelling and equipment stock, which is generally a slow process. The model tracks vintages of technologies in the dynamic simulations, and takes into account normal scrapping functions by type of equipment and dwelling and endogenously driven premature replacement and renovation which depends on economics and policy.



Energy efficiency progress saves on variable costs and frees up income resources, which may be consumed back in purchasing various commodities and in increasing energy demand as well. Therefore, net energy savings are less than expected due to energy saving upfront expenditures. This is commonly a rebound effect, which is fully captured in the model as the formulation solves simultaneously for useful energy demand, fuel mix, and energy saving investment while being subject to budget constraints.

Short-term responses to policies and energy prices are also possible. They are modelled as behaviour-driven changes, notably as modifications of the level of useful energy services. Reducing temperature level of the heating thermostat, switching-off lighting, reducing stand-by time of appliances etc. are such behavioural responses, which imply lower demand for energy but also higher disutility costs that the model explicitly includes in cost accounts.

Not only energy prices but also specific tariff forms are explicit in the model. For example it is possible to distinguish between average pricing tariffs and time-of-use tariffs for electricity, the latter having larger effect on demand for electricity in peak load times.

Useful energy demand depends also on socio-economic factors. The model includes number of persons per household and income per capita as drivers of energy requirements in a house and as determinants of diffusion pace of electric appliances. Saturation effects as well as income related elasticities depend on these drivers. Useful energy demand also depends on climatic characteristics, which are represented as uniform by country, since PRIMES lacks spatial resolution below country levels.

Energy meets fundamental needs of households. In developed economies income elasticity is expected to be less than one, while substitutions by nonenergy commodities are rather limited. However, in partially heated houses (which is one of the dwelling categories included in the model) income elasticity can approach or exceed one, at least over a limited period of time. In specific uses such as cooling and some of the electric appliances income elasticity may exceed one. Econometrics are used to estimate such elasticity value by use and by country in the PRIMES model; the estimated parameters are used at the upper level of the nesting, which corresponds to useful energy demand. In developed countries the share of energy in total consumption is close to saturation (taking account of price variations), a fact that explains the observed asymmetry in price elasticities with respect to positive or negative shifts. It should be noted, however, that PRIMES is not solely based on such overall elasticities but on a structural representation of demand and supply. Nonetheless, the PRIMES results also show asymmetry of responses for decreasing or increasing energy costs and prices.

It is important to note that the influence on useful energy demand is via not only the prices of purchased energy forms but also a cost-price index, which



capture all kinds of costs for energy purposes including annualised costs of investment in equipment, thermal integrity of buildings and energy savings.

The fuel shares, for each category of end-use in which substitution between fuels are possible, are represented as fuel choice frequencies (which express the percentage of households that choose a specific fuel to serve the end-use). These frequencies can change depending on economics but the flexibility of change depends on turnover of equipment stock and on the type of dwelling. The probability that a given appliance (for space heating, water heating and cooking) is chosen to be installed in a dwelling is calculated as a function of a total perceived cost and of the maturity of equipment (so that inter-fuel substitution is constrained) and the possibilities depend on the type of dwelling. The total perceived cost is a function of capital, maintenance and fuel (operating) cost of the equipment, as well as of the income of households. Especially, for cooking and water heating it is assumed that the total perceived cost also depends on the fuel choice made for space heating following a hierarchical decision-tree approach. Generally, nested Weibull and nested logit models are used to model choices. The fuel shares obtained are implemented for new dwellings and for the installation of new equipment due to normal replacement. As a result, updated fuel shares by end-use are computed, concerning both existing and new dwellings.

Specific electricity use is considered as an end-use not allowing substitutions. Demand depends on the projection of number of appliances by type, which is driven by socio-economic factors, and on efficiency performance, which depends on technology choice which is modelled using discrete choice modelling.

J.4.a. Model database

PRIMES BuilMo includes a very detailed database for buildings which has been constructed by combining a number of sources – see Box 1. The high resolution of the model allows to better simulate policies and the way they effect the building stock, as well as increasing the understanding of how higher energy efficiency targets can be achieved.

Residential sector

The building stock is split into the following categories:

- Single or multi-storey buildings
- Age of construction: the existing building stock has been divided into nine age bands covering the period 1920-2015
- Spatial Allocation: three regions have been selected urban, semi-urban and rural, for each Member State

This implies that there are 54 possible building categories for each of the 28 EU Member States.



Each building category is characterized by its own heating/cooling characterization (kWh/m2) which represent the average value of buildings in that category. The values are calculated based on average engineering characteristics of each building in each category and are calculated based on bottom-up engineering calculations.

The buildings are further characterized by the equipment they use and the fuel consumption. The model therefore now has 54 different possible building types for which energy consumption is calculated according to country characteristics which include size of dwellings, heating degree days and thermostat settings which are also differentiated by income class.

The classification thus achieved allows to analyse the effect of policies on the building stock and the barriers which energy efficiency progress faces: e.g. renovating very old houses leads to high energy savings however it can be difficult because many of these houses are historic buildings and therefore renovation can be very expensive; renovating newer buildings is easier however energy savings are lower. Further different costs and barriers apply to renovation of single vs. multi-family houses: high cost for single family, lower costs but difficulties in coordinating multiple owners/tenants in multi-family houses. Following the logic of PRIMES the model includes both true costs as well as perceived costs which simulate the barriers faced by the actors.

Services

Also in the services sector the database has been enhanced; the existing three sectors have been split into the following eight sub-sectors:

- Trade
 - Commercial Buildings
 - Warehouses
 - Cold Storages
- Market Services
 - o Private offices and other buildings in market services
 - o Hotels and Restaurants
- Non Market Services
 - Public Offices
 - o Hospitals and Health Institutions
 - o Schools an Educational Buildings

Different attributes and characteristics apply for each sub-sector with regard to the condition of the building stock (age, U-values), internal temperature set-points,



ventilation demands; further the entire building stock has been divided by the type of ventilation into mechanically and naturally ventilated.

Similarly, to the residential sector the high resolution allows to capture the specificities of the different sectors including the different operating hours, number of occupants for the various building types. The higher split can also represent incentives given to public building renovation more efficiently.

Sources database:

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CIBSE, CIBSE Guide A: Environemental Design, 2007

EN 13790:2008 Energy performance of buildings - Calculation of energy use for space heating and cooling, 2008

Guide to the design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages: BS 8558:2015

2013 ASHRAE Handbook: Fundamentals, ASHRAE, 2013

J.4.b. Equipment and electric appliances

The new model version includes a significant higher amount of options for equipment (boilers for space and water heating, cookers, air conditioning) and electrical appliances (TVs, etc.) both for the residential and services. Also the fuel options for the different options has increased. Different kinds of heat pumps (air to air, water to air...) for space heating and cooling are included in the database.

The higher amount of detail allows to more accurately reflect the eco-design directive and Regulations as additional equipment/appliances are now explicitly modelled.

The list of appliances now includes:

Refrigeration



- Freezing
- Dish Washers
- Washing Machines
- Dryers
- Lighting
- Information and communication
- Entertainment
- Vaccuum Cleaners
- Ironing
- Small Appliances

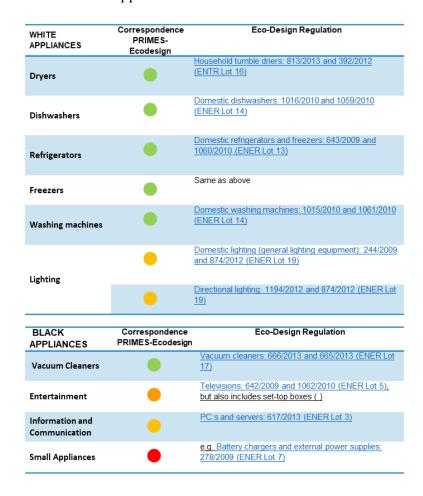


Figure 3: Correspondence of PRIMES and eco-design categorisation for appliances



J.4.c. Renovation strategies

Sources:

The Entranze Project, http://www.entranze.eu/accessed on 10 April 2017.

Cost-Effective Climate Protection in the Building Stock of the New EU Member States: Beyond the EU Energy Performance of Buildings Directive, ECOFYS

Andreas Uihlein, Peter Eder, Towards additional policies to improve the environmental performance of buildings Part II: Quantitative assessment European Commission Joint Research Centre Institute for Prospective Technological Studies 2009

Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries Final Report Fraunhofer-Institute for Systems and Innovation Research 2009

Renovation strategies are defined as the subsequential choices of, first, a renovation type, followed by the possible choices of new equipment for the different needs (first space heating, then water heating, cooling and cooking). Renovation types are classified into 8 types and refer to the changes undertaken in the buildings: R1 is the lightest renovation possible and implies the replacement of windows only, whereas R8 is the deepest form of renovation which requires, aside from window replacement, also addition of thick insulation to the building in order to reduce air permeability levels and leads to consumption below2 40kWh/m2.

Depending on the renovation type chosen, the probability of changing the equipment for space heating – before the end of lifetime - changes: if only windows are replaced synchronous change of the boiler is not deemed any more or less probable than without renovation, whereas with increasing renovation depth the probability of changing the equipment, particularly to heat pumps increases. The choice of the equipment technology for water heating, cooling and cooking is conditional on the choice of the space heating equipment.

Finally a combination of 1000s of strategies is obtained which are ranked according to performance; only feasible options are included, also options which are deemed highly unlikely are excluded from the possibilities.3 The exclusion of options is undertaken to obtain a balance between available strategies and reasonable computational time.

The choice of renovation type and larger equipment with long life time is intertemporal, not myopic: this implies that the system is optimised over the entire time period to 2050/2070. Contrarily to the choice of electric appliances like a TV, renovation choices imply large capital investment and long term benefits in terms of reduction of fuel expenditures, an intertemporal optimisation is assumed to be the better modelling option.

Fuel switching is possible when changing equipment or when renovating, however the more accurate representation of the sector in the new model accounts for the inertia of the system. Fuel switching often implies costs which go beyond the "simple" choice of the boiler. Availability of the option is crucial

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³ E.g. a fuel switch from natural gas to solids is not available, as it is not assumed to be likely under any scenario condition.

for example possibility to connect to the natural gas or to the district heating grid: as the model has no explicit geographic resolution this is approximated through the knowledge of country specificities and this availability is considered higher for urban areas than rural.

Hidden costs of fuel switching are also taken into account, for example the requirements for additional space for storing solids or biomass. Moving away from district heating is also linked to additional costs. The incorporation of all the costs for fuel switching make the system rather inert and more stable to (short term?) fuel price changes, better reflecting reality.

Levels of Renovation Intensity	Details
R0	No Renovation
R1	Light Renovation (Windows Replacement -U value 2.7 W/m2K)
R2	Light Renovation (Windows Replacement -U value 2.7 W/m2K- and addition of a 5 cm layer of insulation)
R3	Light Renovation (Windows Replacement -U value 2.7 W/m2K- and addition of a 5 cm layer of insulation and achievement of air permeability of 27 m3/m2h)
R4	Medium Renovation (Windows Replacement -U value 1.7 W/m2K- and addition of a 5 cm layer of insulation and achievement of air permeability of 27 m3/m2h)
R5	Medium Renovation (Windows Replacement -U value 1.7 W/m2K-,addition of a 10 cm layer of insulation and achievement of air permeability rate of to 27 m3/m2h)
R6	Medium Renovation (Windows Replacement -U value 1.7 W/m2K-, addition of a 10 cm layer of insulation and achievement of air permeability rate of to 9 m3/m2h)
R7	Deep Renovation (Windows Replacement -U value 1.7 W/m2K-, addition of a 20 cm layer of insulation and achievement of air permeability rate of to 9 m3/m2h)
R8	Deep Renovation (Windows Replacement -U value 1.0 W/m2K-, addition of a 20 cm layer of insulation and achievement of air permeability rate of to 5 m3/m2h)

J.4.d. The heterogeneous consumer/actor

Income classes are included in the model to simulate the heterogeneity of actors and the idiosyncratic behaviour of consumers. Instead of having one single actor the model foresees now a variety of actors each with their own behavioural characteristics. The behavioural characteristics are simulated by including differentiated discount rates: each income class has its own specific discount rate with the highest income class having the lowest discount rate and the lowest income class having the highest discount rate, representing the difficulty for such users to apply for financing.-

The population has been split into five income classes; for each Member State the shares and definitions of the different income classes by MS differ.

This modelling feature allows to better represent the barriers faced for the renovation within a Member State and among Member States: lower income classes would benefit most from a reduction of running costs –i.e. from higher EE in their dwellings,however, they often do not have the financial means to renovate the buildings as this is a capital intensive investment.

The higher detail of the modelling both in representing the building stock, the available equipment/appliances and heterogeneity of consumers allows for a more realistic representation of the barriers faced when implementing policies aimed at increasing energy efficiency in the residential and services sectors.

J.4.e. Mathematical structure and model concept

Mathematically the model is based on the concept of dynamic discrete choice, where representative agents decide among a finite set of choices the ones that are economically more cost efficient. This concept applies to renovation and equipment. The agents are defined as classes and the available choices are considered renovation strategies in the model.

A strategy includes the timing and the intensity of the renovation and/or equipment alternation. The agents have perfect? foresight over the whole projection period and as a result the decisions made are intertemporal. Each strategy has a certain economic performance depending on the amount of upfront investment and the annual spending for the energy bill; a discount rate specific to the characteristics of the agent –therefore the class- and the inclusion of possible barriers or hidden costs also influence the computation of economic performance of each candidate strategy.

The model assumes that within each class the agents who decide about building strategieshave idiosyncratic behaviour and because they have heterogeneous preferences do not adopt a single best strategy. Instead a probability density function is used which assigns probabilities of adoption of the strategies within the set of the most cost-efficient ones. Possible criteria used for the evaluation of the strategies are the maximisation of the payback period or the minimization of the levelized cost of energy.

In particular for the decision on renovation, the cost of each strategy is the result of a non-linear cost function, which mimics the interaction of the agents with the market: the high probability of taking up a strategy and the subsequent uptake of the strategy by many classes or within a class implies that the strategy becomes more expensive (due to limited availability of labour and materials for the particular strategy within a particular time span). The increase in the cost of the strategy makes the specific strategy less popular. As a result the probability of the uptake of the strategy is modified and another strategy will also enter the market. Thus a more realistic picture of the uptake of renovation is obtained.

J.4.f. Policy representation in the new buildings model

The model allows as previously the possibility to include and exclude policies in order to achieve anything from a baseline to a policy scenario with high energy efficiency or emissions reduction target.

The new improved model allows for a better and more detailed reflection of policies.

Overarching policies

Energy Taxation: as in the main PRIMES, taxation is explicit in the composition of the end user fuel prices; it can be modified as required, by fuel and by end-user; the standard model includes the obligations stemming from the current Energy Taxation Directive, as well as the latest taxes from the DG TAXUD tables

Carbon pricing: carbon pricing as a means to reduce emissions can be implemented in the model in many different forms: a CO2 tax, inclusion in the ETS of non-ETS sectors, a carbon value, etc.

Renewable energy directive: the model shows how the overall targets set in the RES directive are achieved in the H&C sector; incentives for RES put in place by MS to achieve contributions from the H&C sector to these targets can be explicitly represented. The inclusion of different types of heat pumps (ground source and air source), allows for a more precise calculation of RES-shares according to the latest methodology for calculating RES shares.4

Energy Efficiency policies

EPBD & Building codes at national levels: are now explicitly represented in the model for new, as well as for renovation, when these are clearly defined; building specifications follow engineering based calculations for the determination of energy requirements.

Eco-design and labelling directive: the higher number of equipment and appliances allows for a more precise representation of the eco-design regulations; each category of appliances in the model now includes fewer different types of appliances. Minimum energy performance standards can be explicitly implemented.

Subsidies/financing: discount rate modification or explicit reduction of costs for fuels or equipment can be represented explicitly.

EED: the EED includes many aspects which have to be differentiated in order to correctly reflect them in the model. Some examples include⁵:

- energy distributors or retail energy sales companies have to achieve 1.5% energy savings per year through the implementation of energy efficiency measures: this aspect can be verified through the model by undertaking the quantification of a baseline scenario (defined e.g. by the exclusion of any new policies after a specific year), and then comparing it to a scenario where additional policies are included to verify the energy savings
- the public sector in EU countries should purchase energy efficient buildings, products and services: this can now explicitly be modelled
- every year, governments in EU countries must carry out energy efficient renovations on at least 3% (by floor area) of the buildings they own and occupy: this can now also explicitly be modelled and set as constraint in the model

⁴ Share of renewable energy based on Directive 2009/28/EC (SHARES tool)

⁵ Selected from: http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive

The energy efficiency value (EEV) still exists as a tool in the modelling, however it is used as a shadow value (marginal benefit) derived from energy efficiency gains of an energy efficient constraint (target). Bottom-up defined policies and EEVs can co-exist in the model. As the model formulates equilibrium conditions, and not an overall optimization, the shadow value of energy efficiency acts as a dual variable of a virtual energy efficiency constraint. By varying the level of the energy efficiency value one can increase or decrease the stringency of the constraint. In the buildings model, the energy efficiency value measures EUR/toe saved perceived as an extra benefit by the decision makers. The value applies to all cost comparisons which lead to the choice of house renovation options and equipment type options. Consequently the value increase the competitiveness of efficient options and incite the decision maker to select them.

SPACE HEATING	Correspondence PRIMES- Ecodesign	Eco-Design Regulation
Boilers Gas	•	Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1)
Boilers condensing Gas	•	Same as above
Boilers Oil	•	Same as above
Boilers condensing Oil		Same as above
Wood stoves or Boiler pellets	•	Solid fuel boilers:2015/1187 and 2015/1189 (ENER Lot 15)
Heat Pump Air	•	Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1)
Heat Pump Hydro		Same as above
Heat Pump Geothermal		Same as above
Heat Pump Gas	•	
SPACE HEATING	Correspondence PRIMES- Ecodesign	Eco-Design Regulation
SPACE HEATING Electric Resistance		Local room heating products; 2015/1188, 2015/1185 and 2015/1186 (ENER Lot 20)
	PRIMES-	Local room heating products; 2015/1188, 2015/1185
Electric Resistance	PRIMES-	Local room heating products; 2015/1188, 2015/1185
Electric Resistance Gas individual	PRIMES-	Local room heating products; 2015/1188, 2015/1185 and 2015/1186 (ENER Lot 20) Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1) *(referred to as cogeneration – not specific technologies)
Electric Resistance Gas individual Solar Thermal	PRIMES-	Local room heating products; 2015/1188, 2015/1185 and 2015/1186 (ENER Lot 20) Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1) *(referred to as cogeneration – not specific
Electric Resistance Gas individual Solar Thermal CHP ICE	PRIMES-	Local room heating products; 2015/1188, 2015/1185 and 2015/1186 (ENER Lot 20) Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1) *(referred to as cogeneration – not specific technologies)

Figure 4: Correspondence of PRIMES and eco-design categorisation for space heating

WATER HEATING	Corresponden ce PRIMES- Ecodesign	Eco-Design Regulation
Water heating boiler (diesel)	•	Water heaters: 814/2013 and 812/2013 (ENER Lot 2)
	•	Space and combination heaters: 813/2013 and 811/2013 (ENER Lot 1)
Water heating boiler (electricity)		Same as above
Water heating boiler (natural gas)		Same as above
Solar collector	•	Same as above
Water heating heat pump		Same as above
Water heating boiler (heat)	•	

AIR COOLING	Corresponden ce PRIMES- Ecodesign	Eco-Design Regulation
Electric Air Conditioning	•	Ecodesign regulation in force in March 2012. Labelling regulation in force in July 2011.
Electric Air Conditioning central	•	Regulation in force 2016.

Figure 5: Correspondence of PRIMES and eco-design categorisation for water heating and air cooling

J.7. Mathematical Illustration of Modelling Energy Demand of Stationary Energy Use Sectors in PRIMES model

J.7.a. First Level: Aggregate demand for energy service be sector

For each sector we first identify the level of demand by a sector h for energy service ES_h in a way to link the energy system to the macro-economic system. The concept of the energy service is similar to that of useful energy and its measurement is deprived of any effect of energy or technology efficiency.

The energy service is directly linked to a macro-economic activity or income variable X_h . The relationship between the energy service and the activity variable represent the increase (or decrease) of the volume of energy service as a function of time or economic development. For example this relationship may represent improvement of comfort enabled by time or income growth.

We assume that this relationship is of logistic type (S-curve) by introducing a fixed upper limit $\frac{\overline{ES_h}/\chi_h}{\chi_h}$ expressing maximum comfort from an energy service per unit of activity (or income). In the case of industry, the logistic curve may be decreasing to express technology trends that improve the productivity of the energy service. In this case, the limit denotes a lower bound of productivity improvement.

$$ES_{h} = \frac{\overline{ES_{h}/X_{h}} \cdot X_{h}}{1 + \exp(\alpha_{0h} + \alpha_{1h} \cdot \varphi(X_{h}, RP_{h}, \tau) \cdot \tau^{\varepsilon})} \cdot Tp_{\tau}$$

where τ denotes a time index.

If α_{1h} is negative, the logistic process is increasing, expressing an improvement of comfort from the energy service, while if it is positive, the logistic process is decreasing expressing an improvement of productivity of energy.

The function φ represents the steady-state relationship between the energy service and the explanatory factors, such as economic activity or income, time and the relative profitability of the energy service.

Therefore, the function φ may be written as:

$$\log(\varphi_h) = \beta_{0h} + \beta_{1h} \log(X_h) + \beta_{2h} \log(RP_h) + \beta_{3h} \cdot \tau$$

where RP stands for relative profitability and τ is a time index. The parameters $\alpha, \beta, \varepsilon$ can be econometrically estimated or determined as a result of a calibration. The relative profitability of the energy service may be defined along the concept of opportunity cost and may be determined as a weighted sum of prices and costs of energy uses and processes contributing to form the corresponding energy service.

J.7.b. Formulation of allocation decisions of the consumer

To meet the demand for energy service, the decision maker (i.e. the consumer who is representative of a sector) faces allocation decisions. For example, he must decide about the mix of processes and technologies.

Penetration of new technologies

Some of these processes or technologies are mature in the market, with known economic and technical characteristics, some other may be new or anticipated to be present in the future.

For the latter, two types of costs are identified: the engineering cost, which is the technical cost for delivering a given technology or process, and the perceived cost for the consumer. For a mature technology these may be identical, but for an emerging one, with a small market share, the perceived cost can be much higher. The concept of the perceived cost reflects consideration about the supply of the technology to the consumer, including costs of maintenance and operation of the technology choice when this is diverging from the dominant choices in the market.

Similar technology supply considerations can be introduced in the formulation, to reflect situations in which a mature technology losing market share beyond some level, enters into a decline process with perceived costs increasing. This could reflect for example, supply-side deviations from the efficient scale of technology production.

The question then is, how the model dynamics can accommodate the introduction of a new technology, or new energy form. A new technology starts from a very high perceived cost. Exogenous shifts, such as subsidisation of a start-up cost, an accelerated technical progress or the investment in infrastructure (e.g. for a new fuel) provides an initial push that allows an increase in the market "acceptability" of the technology. The lower perceived costs will increase the market share of the technology, thereby further reducing the perceived cost (due both to technology supply and demand side effects) so that the penetration of the new technology will accelerate.

The specification can allow several situations such as: more than one technologies prevailing in the market; a technology entering the market only when reaching a critical competitiveness; or even simulating avalanche effects in technology penetration..

Diversity of consumer decisions in a sector

Any energy model accepts the notion of the "representative" consumer which is well known in economic modelling. The decomposition by sector or sub-sector or energy use, aims at defining decision cases in which the discrepancy of decision conditions becomes smaller, but this decomposition is limited by available statistics.

Therefore, even within each sector the optimality of the shares of technologies or fuels may vary across the individual decision-makers operating in that sector. This of course is due to the varying conditions of energy use for each individual case.

To represent the fact that a number of decision makers with varying conditions operate in a sector, we must introduce a way of aggregating individual decisions to derive the overall "average" choice of the representative consumer. This way, even unlikely choices of seemingly higher costs will have a small share. A number of consumers will choose to adopt them, because they have welfare or cost gains from deviating from the "norm", due to their special conditions.

We propose two alternative formulation to accommodate this aggregation of individual behaviours:

- We introduce a probability distribution expressing the probability to make a choice that is different from the average. We interpret the average choice as determined along engineering cost concepts. An individual decision maker may have an optimal share that differs from the average, but frequency of such choices decreases as it moves away from the average. For the representative consumer, this situation leads to a U-shaped average cost curve, having as minimum the average choice (share). The problem in this formulation, is that the average engineering shares are exogenously projected to the future and therefore the penetration of completely new technologies cannot be easily simulated.
- An alternative approach, is to introduce the diversity in the function that aggregates the choices. While the individual consumers do make discrete choices (the corresponding shares add to unity) the representative consumer is more likely to choose a mix. This means that at

the level of the representative consumer a concave indifference curve reflects the aggregation of the individual choices. Therefore the aggregation of the choices is not linear. Following the Dixit/Stiglitz approach⁶, we specify a CES-type (constant elasticity of substitution) aggregation function of the shares for the representative consumer.

In both the economic problem of the representative consumer is to minimise cost of meeting the total energy service by allocating energy flows to alternative processes or technologies.

$$\min z_h = \sum_p c_{p,h} \left(Q_{p,h} - Q b_{p,h} \right) \cdot Q_{p,h}$$

subject to

$$f(Q_{p,h}) \ge ES_h$$

$$\sum_{i} a_{i,j,p,h} \cdot Q_{p,h} \le b_i$$

where $c_{p,h}$ is the unit cost function, that depends on the difference between the choice $Q_{p,h}$ and the engineering "optimum" $Qb_{p,h}$.

The first of the constraints is the demand constraint, with f being the aggregation function that can be either linear (first formulation above), or a constant elasticity of substitution (CES) function (second formulation above). The second set of constraints represents any technical restrictions on the possible choices.

To introduce the new technology penetration mechanism, we may formulate the perceived unit cost $\overline{c_{p,h}}$ as a logistic function involving the engineering cost $c_{p,h}$, the market share $2^{p,h}/ES_h$ and an exogenous factor indicating the maturity or acceptability of the technology $\mu_{p,h}$.

$$\overline{c_{p,h}} = c_{p,h} \cdot \frac{\mu_{p,h}}{\exp\left(a - b \cdot \frac{Q_{p,h}}{ES_h}\right)}$$

J.7.c. Second level: Uses or processes

The uses or processes may be organised in the form of a network of flows. For simplicity we assume here that they are organised as a set per sector.

Each use or process addresses a demand for useful energy. The uses or processes $\mathcal{Q}_{p,h}$ corresponding to a sector deliver the energy service to that sector. We assume that the allocation of energy flows to the uses or processes within a sector may involve competition, in which case the uses/processes are substitutable to each other, at least to a certain degree. Alternatively, the uses/processes may be complementary to each other, in which case energy flows depend on technical parameters and involve all uses/processes for a given sector.

At this stage, the objective is to determine the optimal shares of each use or process in a sector, that minimise total cost of delivering the energy service. Constraints on the mix of uses/processes are included to reflect varying degrees of competition among the uses/processes.

⁶ "Monopolistic competition and optimum product diversity", Dixit and Stigliz, 1977.

For this allocation decision we propose the first of the two alternative formulation presented in the previous section. As the alternative uses/processes are known from an engineering point of view and are complementary at some degree, this formulation is more suitable (the aggregation function is known). Through the cost function appearing in the objective function, the formulation introduces the diversity of the decision context. It may also involve the emergence of new processes or uses (e.g. introduction of natural gas equipped homes) through the market penetration mechanism.

The representative decision maker (in a sector) minimises total cost of delivering the energy service:

$$\min z_h = \sum_{p \in map(p,h)} CP_{p,h} \cdot Q_{p,h}$$

The unit cost $CP_{p,h}$ is generally non-linear involving the normative engineering cost $CPEng_{p,h}$ the engineering "norm" $Qb_{p,h}$, the degree of discrepancy σ , the market maturity of technology $\mu_{p,h}$.

$$CP_{p,h} = CPEng_{p,h} \cdot \exp\left(\frac{\left(Q_{p,h} - Qb_{p,h}\right)^{2}}{2 \cdot \sigma^{2}}\right) \cdot \frac{\mu_{p,h}}{\exp\left(a_{p,h} - b_{p,h}Q_{p,h} / ES_{h}\right)}$$

The network equilibrium states that:

(1)
$$ES_h = \sum_{p \in map(p,h)} Q_{p,h} \cdot \varepsilon_{p,h}$$

Bounds can also be incorporated in the above scheme:

(2)
$$lo_{p,h} \le \frac{Q_{p,h}}{ES_h} \le up_{p,h}$$

The problem (3) to (6) decides the optimal shares of processes and uses.

J.7.d. Third level: Demand for technologies and fuels

At a next level for each process or use, the sector can decide between alternative technologies and ultimately fuels that can be used for each. This is also an allocation decision problem in which the sector minimises the cost of serving energy demanded by the process or use and thereby decides the optimal allocation to technology $Q_{t,v,h}$ and fuel $Q_{f,t,v,h}$.

As at this stage we seek two represent two phenomena: the fact that the technologies are strongly competing and only a few of them will ultimately survive in the market; the fact that the substitutability possibilities between technologies or fuels should reflect a preference mapping of the decision maker (for example coal cannot be considered as a perfect substitute of natural gas in space heating). Even if the diversity of situations can explain the existence of a small share of consumers using for example coal for space heating, at the level of the representative consumer the relative fuel prices provide insufficient explanation. The phenomenon can be captured by introducing concave indifference curves that aggregate technologies and fuels. We therefore adopt the second formulation presented above for this case.

New technologies, or new energy forms for a given technology can again emerge in the model dynamics. A new technology starts from a very high perceived cost. An exogenous shift, as explained above, may provide the initial push to trigger a mechanism that accelerates the penetration if the technology proves to be competitive.

The sector again minimises total costs of fuels subject to the technical restrictions. The cost function is non-linear as explained above. A non-linear aggregation function (constant elasticity of substitution or CES) is used to indifference curves between choices.

$$\min z_{p,h} = \sum_{f,t \in map(f,t,p,h)} \left(Cf_{f,t,p,h} \cdot Q_{f,t,p,h} + Ct_{t,p,h} \cdot Q_{f,t,p,h} \right)$$

 $Cf_{f,t,p,h}$ is the fuel cost and $Ct_{t,p,h}$ is the non-linear cost function of implementing a given technology.

$$Ct_{t,p,h} = CPEng_{t,p,h} \cdot \left(\frac{Q_{t,p,h}}{Q_{p,h}}\right)^{-\alpha_{t,p,h}} \cdot e^{\beta_{t,p,h} \left(\frac{Q_{t,p,h}}{Q_{p,h}}\right)} \cdot \frac{\mu_{t,p,h}}{\exp\left(a_{t,p,h} - b_{t,p,h} \cdot \frac{Q_{t,p,h}}{Q_{p,h}}\right)}$$

for all $t \in map(t, p, h)$.

 $\alpha_{t,p,h}$ represents the effect of market penetration on the reduction of the perceived cost for a new technology, or for an existing technology, the increase of the perceived cost when its' market share declines.

 $\beta_{t,p,h}$ represents diseconomies of scale as a function of the market share and $\mu_{t,p,h}$ is again the market acceptance or maturity of the technology. $CPEng_{t,p,h}$ is the engineering cost of the technology

A CES transformation function links fuels and technologies to meet demand by processes and uses:

$$Q_{p,h} \leq \sum_{t \in map(t,p,h)} \left(\alpha_{t,p,h}^{1/\sigma} \cdot \left(Q_{t,p,h} \right)^{\sigma - 1/\sigma} \right)^{\sigma/\sigma - 1}$$

$$Q_{t,p,h} \leq \sum_{f \in map(f,t,p,h)} Q_{f,t,p,h}$$

Upper and lower bounds for flows can again be included both at the level of technologies and at the level of fuels.

$$lo_{f,t,p,h} \leq \frac{Q_{f,t,p,h}}{\sum\limits_{f \in map(f,t,p,h)}} \leq up_{f,t,p,h}$$

$$lo_{t,p,h} \leq \frac{\displaystyle\sum_{f \in map(f,t,p,h)} Q_{t,p,h}}{Q_{p,h}} \leq up_{t,p,h}$$

Energy savings are one of the possible combination of inputs that can be used for any given technology. These may include direct energy saving measures, but also other techniques like for example heat recovery. We introduce a non-linear cost curve with an upper bound which is the maximum potential that can be achieved for a given process or use.

$$Q_{Sav,t,p,h} = \frac{Q_{Sav,t,p,h}^{\text{max}}}{1 + \exp(a - b \cdot Cc_{Sav,t,p,h})}$$

solved for the cumulative cost (investment in energy saving) $Cc_{Sav,t,p,h}$ which is linked to the objective function through

$$Cf_{Sav,t,p,h} = \Delta Cc_{Sav,t,p,h}$$
.

The demand models compute the demand for each fuel $Q_{f,t,p,h}$ and the supply for by-products (as these have no explicit supply function from the supply side). Some of the fuels (electricity, steam and probably gas) demanded by the consumers are defined by time segment τs . This notation has been omitted from the above for simplicity.

K. Transport Energy Demand (PRIMES-TREMOVE)

The transport sector has a key role in climate change strategy and for oil independence policies. Large restructuring is required towards alternative fuels and technologies.

K.1. Introduction

Energy consumption for transportation purposes generates very significant amount of greenhouse gases and emission abatement is particularly inelastic in this sector. Transport is by far the largest consumer of oil products. Expenditures for transportation purposes represent a significant percentage of GDP.

Because of its importance, PRIMES devotes particular focus on transport and includes very detailed modelling which covers the energy and mobility nexus and can handle a large variety of policy measures addressing the transport sector.

PRIMES-TREMOVE Transport sub-model produces projections of transport activity, stock turnover of transport means, technology choice, energy consumption by fuel and emissions and other externalities. PRIMES-TREMOVE is a very detailed partial equilibrium simulation tool used for scenario projections and impact analysis of policies in the transport sector. The model design focuses on long-term simulation of conditions, which would drive restructuring of the sector towards new, cleaner and more efficient transportation technologies and fuels. For this purpose, the transport model fully handles possible electrification of road transport, high blending of biofuels in all transport sector and market penetration of alternative fuels including hydrogen. The simulation of dynamics of changes combines modelling of consumer choices, technology change, refuelling and recharging infrastructure and policy instruments, which enable the changes.

K.2. Model overview

PRIMES-TREMOVE Transport Model produces projections covering the entire transport sector by 5-year steps up to 2050. The model projects mobility for passengers and freight, allocation of mobility by transport mode, projection of mobility by type of trip, allocation of mobility by mode in transport means, investment and scrapping of transport means, energy consumption and emissions of transport means and costs and prices of transport. Choices among alternative options and investment are specific to each by agent, being a representative of classes of transport consumers. The choices derive from economics and utility from mobility and depend on policies, technology availability and infrastructure. The projection includes details for a large number of transport means technologies and fuels, including conventional and alternative types, and their penetration in various transport market segments. The projection also includes details about greenhouse gas and air pollution emissions, as well as impacts on externalities such as noise and accidents. Operation costs, investment costs, external costs, tax revenues or subsidy costs, congestion indirect costs and others are included in the model reports.

Agent choices derive from structural microeconomic optimisation, in which technology features and transport activity allocation possibilities are embedded.

Coverage by PRIMES-TREMOVE transport model

Model simulation run: Stand-alone or linked with the entire PRIMES energy system model and the PRIMES-Biomass model

Time horizon: 2005 to 2050 by 5-year time steps; 2005 and 2010 are calibrated base years and 2015-2050 being projections.

Countries: Individually all EU 28 Member-States

Transport modes: Private road passenger (cars, powered 2 wheelers), public road passenger (buses and coaches), road freight (HDVs, LDVs), passenger rail (slow and high-speed trains, metro), freight rail, passenger aviation (split into distance classes), freight and passenger inland navigation and short sea shipping, bunkers. Numerous classes of vehicles and transport means with tracking of technology vintages.

Regions/road types: No spatial resolution below country levels. For trip classes distinction between Urban areas (distinguished into one metropolitan and other urban areas) and inter-urban areas (distinguished into motorways and other roads).

Time of day/trip types: off peak and peak time travelling relevant for congestion; passenger trips are distinguished into non-working, commuting and business trips; freight split into bulk, cargo and unitized.

Trip distances: stylized histogram of trip types according to distance, representing different agents' travelling habits per trip and region type.

Energy: all crude oil derived fuels (total and separated by the different grades), biofuels (bioethanol and biodiesel blends, bio-kerosene, bio-heavy oil and DME), CNG, LNG, LPG, electricity and hydrogen. Linkage to refueling/recharging infrastructure by trip type.

The exogenous scenario assumptions are as follows:

E S n

- Transport activity for passengers and freight
- Fuel prices, taxation of fuels
- Availability of alternative fuels and regulations on blending
- Other costs and taxations in transport
- Development of refuelling and recharging infrastructure and coverage
- Cost parameters influencing public transport tariffs and infrastructure fees where applicable
- Regulations on technologies, standards on CO₂ or on energy efficiency performance of vehicles
- Measures and infrastructure influencing modal shifts and modal efficiency
- Taxations to internalise external costs (for example for air pollution, noise, accidents, etc.)
- Technical improvements and cost changes for various vehicle technologies
- Driving range for battery equipped and hydrogen fuel cell vehicle technologies
- Market coordination assumptions between infrastructure, technology learning and perception of fuel/technology maturity by consumers.

The model can run as either a stand-alone tool or can run as fully integrated in the rest of the PRIMES energy systems model. In the integrated run mode, the transport model takes from the rest of PRIMES projection of prices for fuels, biofuels, electricity and hydrogen, as well as carbon prices where applicable. The transport model transmits projection of fuel, electricity and hydrogen consumption to the rest of PRIMES model. The model linkage supports life cycle analysis of emissions of fuels used in transport, covering the entire well to wheel calculations. The possibilities, costs and prices of biofuel supply are assessed using the dedicated PRIMES-Biomass Supply Model which is also linked with the core PRIMES model and the transport model, taking from them demand figures and conveying to them bio-energy commodity prices. Thus, lifecycle analysis of emissions and energy is performed for all fuel types including alternative fuels.

PRIMES-TREMOVE Transport model can also link with TRANSTOOLS a network transport model with spatial information. A module handles transformation of TRANSTOOLS mobility projections in transport activity variables handled by PRIMES.

K.3. Policy analysis focus of PRIMES-TREMOVE

PRIMES-TREMOVE Transport model includes a large variety of policy measures, to mirror in scenarios. Policy targets, for example on future emissions in transport, are constraints in scenario projections. The model endogenously determines drivers, which influence restructuring in transport and substitutions enabling achievement of the target. The model can handle multiple targets simultaneously. Market penetration of technologies is not pre-defined but is a result of the model depending on economics and behaviours. Technology learning is explicit and depends on volume of anticipated sales.

Market penetration of alternative technologies and fuels in transport heavily depends on successful market coordination of various agents having different aspirations. At least four types of agents are identified:

- developers of refuelling/recharging infrastructure aiming at economic viability of investment depending on future use of infrastructure;
- fuel suppliers who invest upstream in fuel production the economics of which depend on market volume;
- providers of technologies used in vehicles and transport means who need to anticipate future market volume to invest in technology improvement and massive production lines in order to deliver products at lower costs and higher performance;
- consumers requiring assurance about refuelling/recharging infrastructure with adequate coverage, and low cost fuels and vehicle technologies in order to make choices enabling market penetration of alternative fuel/technologies.

The PRIMES model supports explicit analyses of dynamics of market coordination with individual focus on stylised agents allowing for development of complex scenarios, which may assume different degrees of success in effective market coordination. Thus, projections of market penetration of alternative fuels/technologies are fully transparent and include the entire spectrum of interactions between consumer choices, technology learning, infrastructure economics and fuel supply.

The policy measures, which are in the model, can be grouped in soft, economic, regulatory and infrastructure measures.

Soft measures include the coordination between the public and the private sector, information campaigns, certification of services and labelling, partnerships between the public and the private sector aiming at enhancing knowledge and at using resources more efficiently. These kind of measures can be mirrored as factors improving the perceived cost of technologies by consumers, thus allowing for faster adoption of new or more efficient, but also more expensive, technologies. In the absence of such measures, the model assumes higher perceived costs in the form of risk premiums for new technologies, which discourage consumers. Policies that decrease uncertainty or risk (technical, financing, regulatory. etc.) surrounding consumer choices can be mirrored by reducing risk premium factors and by lowering discount rates which are involved in capital budgeting decisions simulated by the model. The perceived cost parameters also reflect anticipation by consumers and can vary in order to mirror the anticipation confidence by consumers of commercial maturity of new technologies.

Economic measures

Economic measures aim at influencing consumer choices by modifying relative costs and prices of fuels and technologies. They include subsidies and taxes on fuels, vehicles, emissions, congestion and other externalities such as air pollution, accidents and noise. Certificate systems such as the ETS are also explicit in the model. The level of the ETS carbon price is determined in the core PRIMES model. Measures supporting R&D influence costs and performance characteristics of new technologies. Taxation or subsidisation policies reflect policies at relatively high resolution. They are specific to individual technologies (e.g. subsidies to BEVs), apply to new versus old vehicles, can vary by size of vehicle, can link to vehicle performance in terms of efficiency or emissions, can handle tax exemptions (e.g. exemption from registration tax for new alternative vehicles), can on fuels, or can vary by vehicle age etc. Economic measures are also modelled for public transport (for example to influence ticket prices) and for non-road transport. Fuel taxation is modelled through the standard excise taxes which can be defined either in standard form, or in proportion to emissions (direct or life cycle) or energy efficiency.

Regulatory measures

Regulatory measures include the setting of targets and technology standards. EU regulations No 443/2009 and No 510/2011 setting emission performance standards for new passenger cars and new light commercial vehicles respectively as part of the European Union's integrated approach to reduce CO₂ emissions from light-duty vehicles are explicit in the model. Tailpipe CO₂ emission standards measured in gCO₂/km, which apply on new vehicle registrations are constraints influencing the consumers' choices upon purchasing new vehicle. In a similar way, energy efficiency performance standards for all road transport modes have been integrated in the model; these standards set an efficiency constraint on new vehicle registrations. The current, as well as future, EURO standards on road transport vehicles are explicitly implemented and are important for projecting the future volume of air pollutants in the transport sector and determining the structure of the fleet. The model includes a special routine, which simulates how the regulations imposing standards influence supply (structure by technology and vehicle prices) by vehicle manufacturers in order to influence consumer choices therefore allowing compliance with standards. Technology standards are also handled in the model for non-road transport technologies. Targets on emissions or energy can be imposed by transport sector or overall. Targets influence consumer choices through shadow prices (associated to each target type) which are perceived by the consumers as costs or benefits. Such shadow prices, including carbon values, can be coordinated with the rest of PRIMES model.

Infrastructure policies

Development of refuelling/recharging infrastructure for alternative fuels (electricity, hydrogen, LNG, CNG, etc.) is policy driven. Geographic coverage is determined as part of the policy assumption and concern road and maritime transport. The model

simulates perception of infrastructure availability by consumers and depending on the matching between geographic coverage and trip types availability influences consumer choices. Investment cost recovery options are included. Transport infrastructure changes and improvements (e.g. intelligent systems, improved logistics) are not explicitly represented in the model but it is possible in scenario design to mirror cost, efficiency and modal shift impacts of these policies.

Comparison to TREMOVE model

K.4. Novel Model Features

The PRIMES-TREMOVE Transport model is a completely new design. It has substantially drawn from TREMOVE model but compared to this model the new design has included significant new developments, which are summarised below:

- Endogenous mileage distribution against various trip types
- Modelling of several additional alternative technologies, fuel types (including several bio-fuel types) and energy carriers and better representation of vehicle vintages
- Inclusion of cost-performance (or cost-efficiency) possibility curves for deriving endogenous technology improvement for conventional and new technologies in all transport modes
- Detailed modelling of standards on specific CO₂ emissions and alternatively on energy efficiency performance of road vehicles applying on vehicle manufacturers and influencing supply hence choice of vehicle types
- Integration of multiple parameters in a perceived cost formulation which captures several factors influencing consumer choice, including "range anxiety" related to availability of refuelling/recharging infrastructure, commercial maturity of new technologies and anticipation of policies and targets
- Formulation of more general discrete choice mathematical functions which allow representation of consumer heterogeneity through frequency distributions (histograms)
- Expansion of representation of stylised trip types by type of geographic area and connection to infrastructure
- Expansion of the modelling of non-road transport, including fast trains, and maritime transport
- Connection of transport infrastructure development with modal shifts, as well as with cost and performance characteristics of transport modes
- Endogenous formulation of public transport economics, ticket price derivation and infrastructure economics including derivation of infrastructure fees
- Lifecycle analysis of energy and emissions by fuel type through linkage with the entire PRIMES energy systems model

Spatial features

The model does not calculate spatial allocation of mobility as the TRANSTOOLS model which has resolution over a detailed spatial network; spatial coverage in PRIMES-TREMOVE is stylised and is included for better modelling vehicle choice in relation to availability of refuelling/recharging infrastructure and thus for treating trip distance and vehicle ranges as factors influencing choice of vehicle types. PRIMES-TREMOVE and TRANSTOOLS can interact with each other and exchange data to produce coordinated scenario projections.

Refueling infrastructure and vehicle choice

An important feature implemented in the PRIMES-TREMOVE transport model is the representation of vehicle range possibilities and the different refuelling infrastructure development, which influence the choice of vehicle technology by consumers. Literature indicates that among the barriers for the introduction of alternative fuels such as electricity or hydrogen are the "range anxiety" and the lack of refuelling/recharging infrastructure. Such barriers do not entail direct cost implications to the consumers; they rather imply losses to their utility function. Conventional technologies like ICEs do not neither have range limitations nor face scarcity of refuelling infrastructure. Vehicles with limited range capability and lack of refuelling/recharging infrastructure are then endogenously penalised in the model and thus the corresponding perceived costs by the consumers are increased.

Barriers to rational technology choice

Other barriers are captured through discount rates, which are meant to be subjective and vary by consumer class to capture different perceptions of opportunity costs of drawing funds by individuals. Such barriers combined with representation of uncertainties surrounding new technologies discourage consumers in opting for cleaner and more efficient technologies, which have higher upfront costs and lower variable running costs. The model can build scenarios in which policies are supposed to remove such barriers and accelerate market diffusion of cleaner technologies/fuels. By varying such policies, in intensity and over time, the model can analyse impacts on diffusion pace and costs arising from eventual lock-ins.

Trip types, "range anxiety", and heterogeneity

PRIMES-TREMOVE distinguishes a number of different trip types varying according to purpose, geographic area and time. Average distance by trip type has been estimated using statistical surveys and depends on area type (metropolitan, motorway, etc.) and other factors. Comparing the range possibilities of a vehicle technology against only the average trip length of a typical representative consumer is not sufficient to capture the large variety of situations that exist in reality. Approaches based on averaging fail to represent the true effects of range limitations on consumer choices. For this purpose, the model representation of trip categories was extended by introducing a distribution of trip lengths for each trip category of the model.

Heterogeneity is captured by assuming that a frequency distribution applies on each trip type showing different frequencies of various trip distances (short, long, etc.). The distributions have different shapes and standard deviations depending on the trip nature. By taking into account the distributions, the model compares the range possibilities of vehicle technology against each class of trip length within a trip category and derives cost penalties in case of mismatch; an example of a trip distribution histogram for motorway trips is shown in figure. The cost penalties are aggregated as weighted sums for each consumer type, depending on the involvement in the various trip categories and the relative distribution shapes in each category. The numerical parameters of the model reflect strong aversion for trip cases with high

40% | 35% | 30% | 25% | 20% | 15% | 20% | 25% | 20% | 25% | 20% | 25% | 20% | 25% | 20% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% | 25% |

discrepancy between trip lengths and range possibilities of the technologies. The purpose of the formulation of heterogeneity in representation of trips is to assess the mileage performance of specific vehicle technologies (e.g. BEVs) over a fine resolution of trip distances. Because vehicles of consumers serve various trip types and various trip distances, vehicle choice is associated to availability of refuelling/recharging infrastructure. Range anxiety is modelled as cost penalising factors, which are endogenously calculated at a fine resolution level. The model can thus assess cost and technology diffusion implications of recharging infrastructure development limited to urban centres versus development with wider coverage.

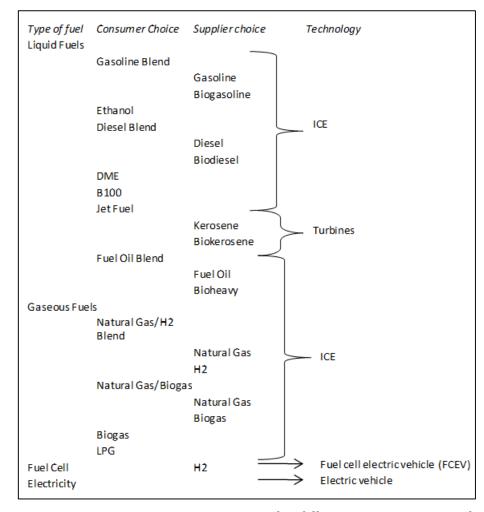
Lack of adequate refuelling/recharging infrastructure is considered among the major barriers of large deployment of alternative energy carriers. Insufficient density of filling stations or public recharging plugs prevents consumers from using vehicles in all trip distances and in some geographic areas, which implies additional costs for the consumer if a vehicle with such limitations is chosen. PRIMES-TREMOVE model captures this mechanism through modelling of cost penalties related to infrastructure, which enter the economic choice modelling of consumers. The aim is to perform cost-benefit analysis of developing new infrastructure: cost of investment would be compared to benefits in terms of externalities made possible by wider use of alternative fuels/technologies, which require the infrastructure. The modelling includes the following:

- The "spatial infrastructure" module features exogenous assumptions as regards refuelling/recharging infrastructure development and distinguishes between different areas and trips (urban/inter-urban/short/long distance). Trip types are represented through frequency distributions, as mentioned above.
- The "infrastructure finance" module performs financial analysis of refuelling/recharging infrastructure, evaluates investment and O&M costs of the infrastructure by category, and determines fees which optionally applies on users of infrastructure or are socialised..
- The "market" module dynamically estimates the rate of use of infrastructure simultaneously with projection of market penetration of alternative fuels/technologies, depending on availability of infrastructure and its cost of use. The model projects mileage for each road vehicle type and its distribution over trip types and regions. Mileage estimation is simultaneous with distribution of mobility across transport modes and is fully embedded in the utility/cost optimisation of consumer behaviour. Mileage distribution depends on fuel type, vehicle age, variable/fuel costs, perceived costs and cost penalties related to availability of refuelling infrastructure, range limitation and uncertainty surrounding new technologies. The aim is to capture "real life" driving patterns of potential users of new technology vehicles (e.g. commuting urban trips). The availability of refuelling/recharging infrastructure implies that the user cannot use his vehicle in all areas but only at those covered with adequate density of filling stations.

Endogenous vehicle mileage

PRIMES-TREMOVE represents a large set of alternative vehicle technologies, including conventional IC engines with various fuel possibilities, plug-in hybrid electric vehicles (PHEVs), BEVs and fuel cell electric vehicles (FCEVs). PHEVs and BEVs include technology variants with various electric ranges depending on battery capacity (e.g., PHEVs distinguishes between 20, 40, 80 km electric range categories and types with range extenders). Flexible fuel vehicles (FFVs) being able to run on high ethanolgasoline blends, vehicle types that can use low blends of biofuels (e.g. E10, B20 etc.), other biofuels such as biogas, bio-kerosene in aviation, bio-heavy oil in inland navigation are in the list of alternative technologies represented in the model. Electricity and hydrogen have been included in road transport for all transport means and LNG for road freight transport and inland navigation.

Vehicle technologies and vintages



Additionally, a fuel choice module has been developed simulating the choice of the consumer between different substitutable fuels upon refuelling the vehicle. For example, a diesel car is represented as being able to run either on conventional diesel (with low bio-fuel blending) or on various higher blends of biofuels (e.g. B20, B100). The fuel choice lies within the context of minimizing expenses allowing policy measures to influence the choice towards cleaner fuels. Not all technology and fuel options are available in base year, but are assumed to become available gradually over time and reach commercial maturity at various degrees and at different future times, depending on market uptake. PRIMES-TREMOVE fully keeps track of technology vintages for transport means. New vintages incorporate the latest technologies and have to meet standards and regulations, such as the EURO standards. Second hand cars are included among the possible choices of consumers: they

are represented to follow previous vintage technologies and their availability and prices are calibrated to real market characteristics by country. Trade of second hand cars between countries is not included in the model.

CO2 Car Standards and Car Efficiency Standards Aiming at reducing vehicle tailpipe CO₂ emissions the regulations No 443/2009 and No 510/2011 have set emission performance standards for new passenger cars and new light commercial vehicles. The standards apply on average sales of car manufacturers. PRIMES-TREMOVE modelled these standards as a constraint on weighted average emission performance of new cars in each period simulated by the model. A CO2 emissions label is associated to each car type, as included in the model. Using projected new car sales by type as weights, the model calculates average emission performance of the new car fleet, which is compared against the standard. If average performance exceeds the standard, a cost penalty applies on car costs proportionally to the CO₂ label for cars with labels exceeding the standard. Thus, consumers are incited to modify the mix of car types in their choices; cost penalties increase until the standard is exactly met in each period. The modelling method is equivalent of assuming that car manufacturers define high car prices to car types with label exceeding the standard in order to obtain a mix of car sales, which on average complies with the standard. The car labels defined as specific CO₂ emission performance (in gCO₂/km) are based on the NEDC test cycle. In a similar way, PRIMES-TREMOVE implements energy efficiency standards (with labels expressed in toe of final energy per vehicle-km) and can also handle efficiency standards based on primary energy or emission standards (for various pollutants) based on lifecycle emission calculation. The model can also handle co-existence of multiple car standards. The same methodology applies also on heavy duty vehicles and other transport means to capture the effects of new regulations which may apply in the future.

Efficiency-Cost Curves for all transport means

Energy efficiency improvement possibilities as an increasing function of unit cost are represented for all types and technologies of transport means. The cost-efficiency curves are shown to change over time because of autonomous (market-driven as opposed to policy-driven) technical progress. Depending on scenario context, the projected carbon prices or other shadow prices associated to policy targets are modelled as drivers of consumer choices towards more efficient transport means, which have nonetheless higher unit costs. Therefore, the level of efficiency progress is endogenous in the model and is derived simultaneously with other variables from economic optimisation of consumer choices. The inclusion of efficiency-cost possibility curves is an important mechanism for representing progress of conventional road vehicle technologies and for capturing efficiency improvement possibilities for trucks, trains, aircrafts and ships. The model does not include details about how efficiency improvement is obtained but instead it uses a reduced-form functional representation of progress enabled by several possible changes, such as engines that are more advanced, lighter materials, aerodynamic designs, etc. The numerical estimation of the reduced-form efficiency-cost curves has been based on a series of engineering studies and laboratory testing reports, which are available in the literature. The efficiency-cost curves are also fully integrated in the dynamic representation of technology vintages. For example if assumptions drive early efficiency progress then future technologies will be at least equally efficient.

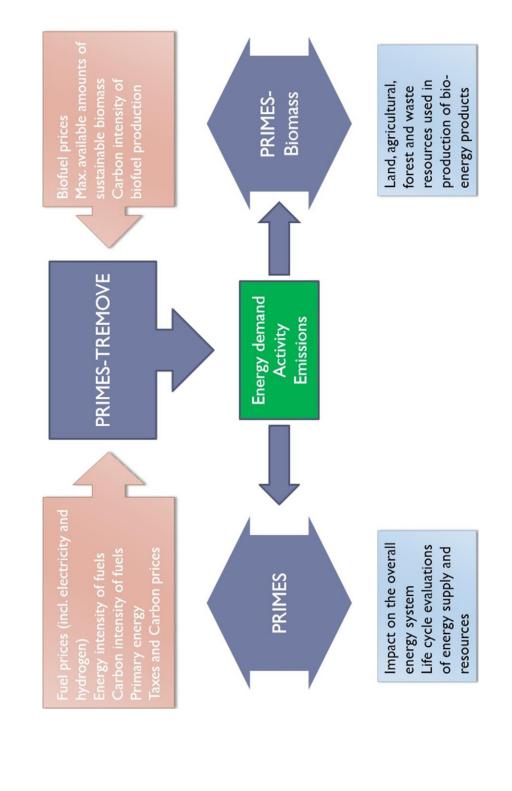
PRIMES-TREMOVE transport model is linked with the entire PRIMES energy systems model and the PRIMES-Biomass Supply model. The linkage calculates lifecycle energy and emissions of fuels and energy carriers used for transportation.

Lifecycle analysis of energy and emissions

The PRIMES projects the entire energy balances and thus calculates primary energy requirements, which correspond, to the final energy amounts by fuel consumed in transport. Thus, policy analysis and targets focusing on primary energy or energy imports can be handled. PRIMES also projects greenhouse gas emissions related to energy covering the entire chain of energy transformations. Therefore, it can calculate energy-related lifecycle emissions of transport fuels. Similar lifecycle calculations can be handled for air pollution. More enhanced air pollution calculations can be carried out using PRIMES model suite linked with GAINS model (IIASA).

The PRIMES biomass supply model covers the entire lifecycle of bio-fuels and calculates greenhouse gas and air pollution for the entire chain of transformations, including cultivation, imports, pre-treatment, transport and conversion of biomass feedstock into biofuels. So, calculations of sustainability indices can be performed for all types of fuels used in transport, including mineral oil and bio-fuels (of various types and based on feedstock of various technology generations).

The entire PRIMES model suite is able to perform calculations of well to tank, well-to-wheel and tank-to-wheel energy requirements and emissions and to handle policy targets, standards or taxation associated to such lifecycle indices. The PRIMES suite is also designed to simulate emission-trading markets (e.g. ETS) which can include parts or the entire transport sector. Actually, aviation is included in the EU ETS; effects from that inclusion on costs, prices and efficiency improvement are fully captured in the model and obviously depend on ETS carbon prices.



K.5. Demand and supply equilibrium in the transport model

K.5.a. Overview

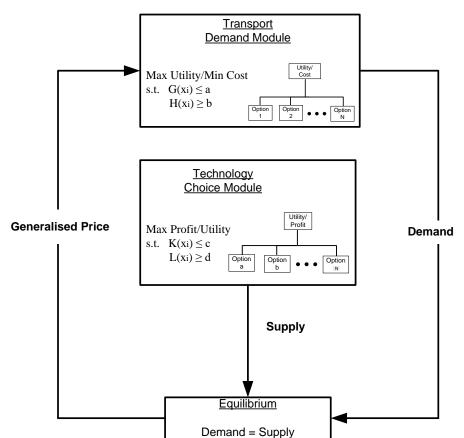
PRIMES-TREMOVE solves a sort of market equilibrium between demand for transport services and supply of transport services.

Equilibrium between
demand and supply of
transport services,
with distinction
between selfproduction and
business production of
transport services

The model fully captures the features of demand and supply matching which prevail in transport sector: part of the supply of transport services is carried out by the same person who is a demander for such services; in other words, supply is split between self-supply of transport services and the purchasing of transport services from transportation companies.

There are fundamental differences between self-production of transport services and purchasing from transport businesses: to self-supply the service, the consumer (individual or firm) faces both capital and variable costs, where capital costs correspond to the purchasing of transportation means, whereas when purchasing transport services from transport suppliers the consumer faces only variable costs (corresponding to ticket prices). Transportation companies also face capital and variable costs but sell services at transport tariffs (ticket prices, etc.).

In addition, there is no capital rent in self-supply of transport services and the consumer chooses between alternative self-supply solutions by comparing total costs,



assuming average cost pricing of alternative solutions. This contrasts prices as set by transportation companies, which are often based on marginal costs, which may allow for capital rents (e.g. aviation). Other transportation companies owned by the state and subject to strong price regulation, apply average (instead of marginal) cost pricing rules to determine transportation tariffs.

To find the equilibrium between demand and supply of transport services, PRIMES-TREMOVE considers transport prices as a pivot influencing both demand and supply.

To include external costs and also other costs, such as congestion, the model includes additional components in the equilibrium enabling prices which is termed "generalised price of transportation" and is calculated both for self-production and for business supply of transport services.

Based on the above-mentioned

approach, PRIMES-TREMOVE solves an equilibrium problem with equilibrium constraints (EPEC) simultaneously for multiple transport services and for multiple agents, some of which are individual consumers and other are firms, which demand for transport services or produce transport services. The EPEC formulation also includes overall constraints which represent policy targets (e.g. on emissions, on energy, etc.) which influence both demand and supply. Mathematically the model solves as a non-linear mixed complementarity problem.

The transport demand module simulates mobility decisions driven by macroeconomic drivers, which distribute transport activity over different transport modes and trip types, to calculate transport services by mode for both individuals and firms. The decision process is simulated as a utility maximisation problem under budget and other constraints for individual private passengers and as a cost minimisation problem for firms.

The transport supply module determines the mix of vehicle technologies (generally the transportation means), the operation of transport means by trip type and the fuel mix so as to meet modal transport demand at least cost. In case of supply by transportation companies, the module calculates transportation tariffs (ticket prices). Consumer or firm choices at various levels of the supply module use total costs, inclusive of capital costs, or only variable costs, as appropriate. For example purchasing a new car involves total cost comparisons among alternative solutions, but choice of fuel type for an existing car, if that is possible, or determining the rate of use of an existing car naturally involves only variable costs. The choice of technology is generally the result of a discrete choice problem, which considers relative costs, which optionally include factors indicating impacts on externalities.

Solving for equilibrium also includes computation of energy consumption, emissions of pollutants and externality impacts related to the use of transportation means. Optionally, policy targets related to externalities (or overall efficiency or overall emissions) may become binding in equilibrium; through the mixed complementarity formulation of the model, such overall constraints influence all choices in the demand and supply transport modules.

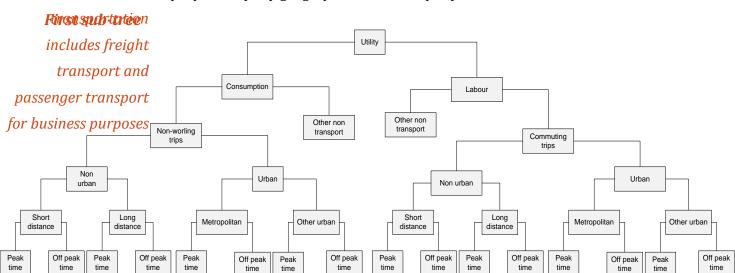
Both the demand and supply modules are dynamic over time, simulate capital turnover with possibility of premature replacement of equipment and keep track of equipment technology vintages. Foresight assumptions are optional and by default foresight is limited to two 5-year time periods.

K.5.b. The transport demand module

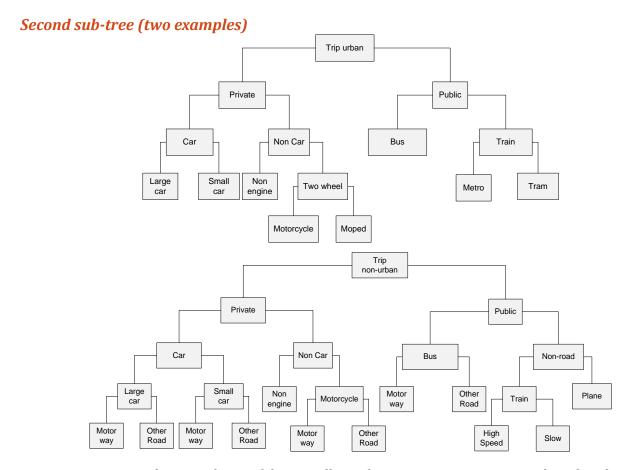
The transport demand module simulates the decision process of representative agents in defining total mobility and allocating mobility to a predefined set of transport modes and of trip types by mode. The model distinctly treats private passenger transportation and transportation driven by economic activity, such as movement of products and business trips. The former involves individuals deriving utility from mobility, whereas the latter involves firms needing mobility for business purposes.

Representative individuals, i.e. passengers, are formulated to maximise a utility function subject to income constraint. Utility is derived from transport activity and by consumption of goods and services not related to transportation. Thus, substitutions are possible between transportation and non-transportation expenditures, when for example relative costs of transportation increase. Allocation of income to expenditures in transportation services and non-transportation goods and services is derived from optimisation. The projection of income is exogenous and is based on macroeconomic growth scenarios. Allocation of income to different utility inputs is organised as a tree involving choices at consecutive levels.

Utility formation is formulated using a nested Constant Elasticity of Substitution (CES) function. Concerning transportation-related choices, a first part of the tree involves trip types, which are organised as a sub-tree, which consecutively deals with trips, by purpose, trips by geographic area and trips by distance classes.



Business



The second part of the overall tree for passenger transport involves distribution across transport modes of mobility by trip type. The corresponding sub-tree, allocates nobility between aggregate transport modes, such as public and private, and further down it allocates activity to more disaggregated transport modes such as private cars (disaggregated by size), two wheelers, buses for urban trips, coaches for inter-urban trips, aviation, rail, inland navigation, metro and trams where applicable.

Activity of business transportation derives from cost minimisation under constraints, which represent mobility requirements associated to macroeconomic activity, which is exogenously projected. A nested constant elasticity of substitution (CES) production function is formulated to simulate substitutions at consecutive levels of a tree structure. The top level of the tree applies a Leontief decomposition of business mobility in passenger transportation for business purposes (transport to go to work places – commuting trips – is included in the transport tree of individuals) and freight transport. The next levels of the tree decompose mobility by trip type, distinguishing between geographic area types and trip distance classes. In the following tree levels decomposition starts from aggregate transport modes (bulk-private and public), which are further allocated to transport means such as trucks (with size differentiation), freight trains, maritime, etc.

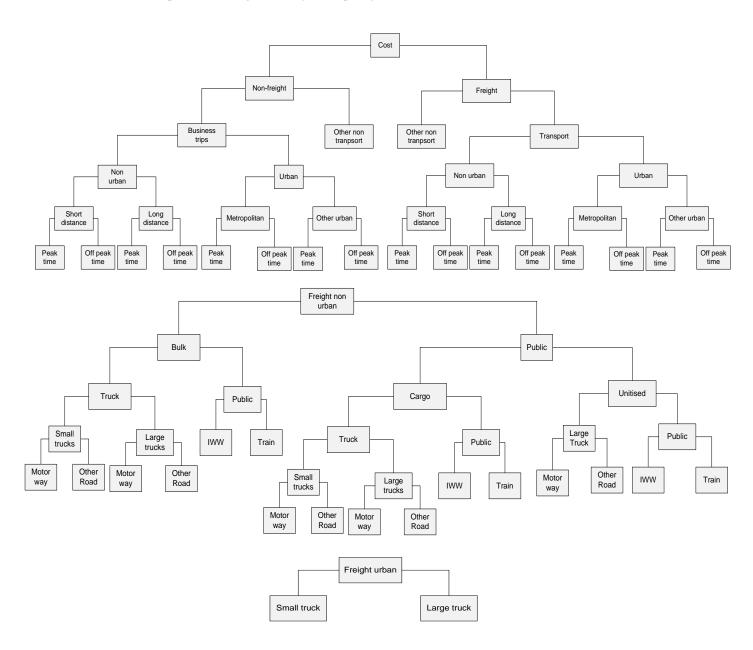
For both passenger and freight, transport mobility allocation differentiates trips between trip at peak or at off-peak times. The level structure of the trees allows specifying different values of elasticity of substitution by level to capture the degree of substitutability between mobility choices. A low elasticity corresponds to choices that are close to be complementary to each other (in other words allocation is based on almost fixed proportions), whereas a high elasticity value signify that choices are substitutable to each other.

The constant elasticity of substitution functional forms are calibrated to past year statistics. The official statistics of transport activity (e.g. EUROSTAT and DG MOVE Pocketbook) include aggregate decomposition of activity. Disaggregation up to the tree structure of the model has been based on transport surveys, on TREMOVE model data and on accounting techniques (Excel-based models). Validation of the calibrated transport demand model has been performed consisting of running the model over a large set of different assumptions about exogenous parameters, calculating aggregate elasticities and comparing them to econometrically estimated elasticity values as reported in the literature.

Generally the values of elasticity substitutions in the CES transport activity functions are small, which implies that modal shifts are rather inflexible, as confirmed by several empirical studies found in the literature. Aiming at simulating long-term structural changes, including in the mix of transport modes, the model includes a "shifting" technique, which applies on the scale parameters of the CES functions and allows to represent the effects of policies and infrastructure investments driving modal shifts at higher degrees than observed in the past. Intelligent transport systems, new transport infrastructure, congestion management policies acting in favour pf public transport in the cities, inter-modal facilitation techniques, improved logistics, etc. are examples of interventions that can accelerate modal shifts, in particular in favour of public transport and rail. PRIMES-TREMOVE does not represent these interventions in an explicit manner, because it lacks appropriate spatial resolution, but it can mirror their effects on modal shifts in scenarios, if detailed transport studies have measured these effects.

The optimisation models for passenger and for business transport activity uses unit prices/costs, which are associated to each node of the bottom level of the trees and refer to specific transport modes for specific trip types. These prices/costs are calculated in the model of transport services supply. The unit costs of upper tree levels are calculated from minimum cost functions derived from the optimisation.

Business transport activity trees (examples)



K.5.c. The transport services supply module

Overview

The transport services supply module determines the mix of transport means technologies, the mix of fuels and the rate of use of transport means to meet demand for transport services as given by the transport demand module. To do this a cost minimisation model is solved which incorporates discrete choice behavioural models at various levels. Based on the results of cost minimisation, unit prices/costs are calculated following explicit pricing and cost accounting rules, which are appropriate for each transport mode. These unit prices/costs may optionally include external costs. Demand for transport services depend on these unit prices/costs, and so a loop is established between demand and supply of transport services.

A specific transport means can serve for more than one trip, which have different characteristics in terms of geographic area, peak or off-peak time and distance. This is taken into account in establishing how supply matches demand for transport services. The unit price/cost by mode depends on the characteristics of the trips served by this mode.

Stock-flow relationships are fully captured in tracking evolution of transport means fleet (vehicles, trains, vessels, aircrafts). The model considers stock of transport means inherited from previous periods, calculates scrapping due to technical lifetime, evaluates the economics of possible premature scrapping and determines the best choice of new transport means, which are needed to meet demand. The model also calculates the degree of using the transport means by trip type and so it calculates the unit costs of trips. To do this, the fuel mix is also chosen endogenously. The calculation involves all steps and options simultaneously. Balancing of demand and supply is obtained for each period. The choices are based on cost minimisation, which include anticipation factors.

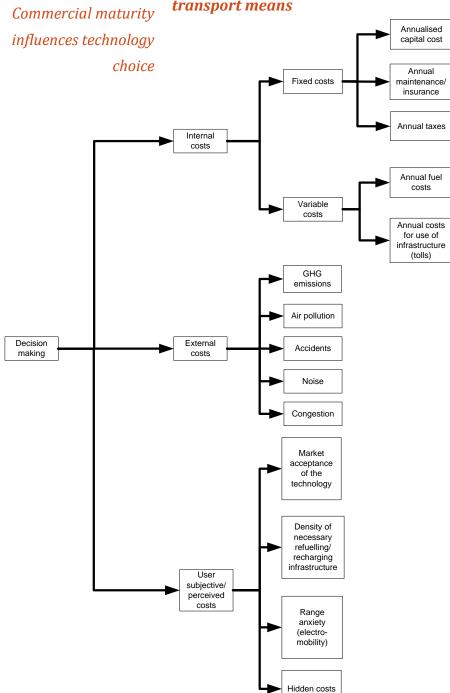
The choices involve adoption of specific technologies and fuel types; technical and economic characteristics of adopted technologies are inherited in future times when using the adopted technology. The model follows a vintage capital approach for all transport means, which means that dynamically it keeps track of technology characteristics of transport means according to vintages. Not only latest technologies are available in the choice menu in a given time period; the model allows choice of older technologies, if that is permitted by legislation, which may have lower costs; thus the model capture behavioural inertia and also market features, such as the possibility of purchasing second hand vehicles.

Choice of new transport means.
Costing methodology

There are several factors influencing the choice of a new transport means. They include payable and non-payable elements. The former include true payments (internal costs) and external costs (when internalised); the latter include indirect costs as perceived by decision makers.

True payable costs include all cost elements over the lifetime of the candidate transport means: purchasing cost, which is interpreted as a capital cost; annual fixed costs for maintenance, insurance and ownership/circulation taxation; variable costs for fuel consumption depending on trip type and operation conditions; other variable costs including congestion fees, parking fees and tolled roads.

Schematic representation of factors influencing choice of new transport means



To compare candidate transport means, a total cost index is calculated which aggregates all cost elements on an annual basis. Only capital costs are upfront costs and so they are transformed in annuity payments. The transformation uses a discount rate. which is conceived as opportunity cost of drawing funds by the decision maker. It is calculated as a weighted average cost of capital, which adds equity capital valued at a subjective discount rate (which is higher for individuals and lower for business) and borrowed capital valued at lending interest rate.

Risk premium is also added which has several components differentiating sectors (private versus public), type of decision maker (higher risk for individuals) and type of technology (higher risk for yet immature technologies). The capital cost parameters can be changed by scenario and over time so as to mirror policies and evolutions which affect risk premium factors.

The purchasing costs of new technologies are assumed to evolve dynamically, according to learning curves which depends on cumulative sales and to technology support policy (varying by scenario), reflecting economies of scale from mass production. Similar learning curves are included for car components such as batteries or fuel cells.

Multiple external cost categories are due to transportation. They refer to congestion, accidents, noise and air pollution and they are evaluated in physical and monetary terms by the

model. Monetary values are based on the Handbook of Internalisation of External Costs, published by the European Commission.

Other factors, which do not necessarily, imply true payments by the user but may imply indirect costs are influencing decisions about choice of new vehicles (and generally transport means). The model includes perceived cost factors reflecting: technical risk of yet immature technologies, acceptance factors representing market penetration (this factor serves to simulate accelerated market diffusion), density of refuelling/recharging infrastructure applicable to technologies using alternative fuels and those that have range limitations.

Market acceptance factors are used to simulate circumstances where consumers have risk avert behaviours regarding new technologies when they are still in early stages of market deployment. Perception of risk usually concern technical performance, maintenance costs and operation convenience. When market penetration exceeds a certain threshold, consumers imitating each other change behaviour and increasingly accept the innovative technologies giving rise to rapid market diffusion. Both stages of market deployment are captured in the model through appropriate values of market acceptance factors, which are part of scenario design. Therefore, the model can simulate reluctance to adopt new technologies in early stages of diffusion and rapid market penetration, often leading to market dominance, in later stages.

Infrastructure influences technology choice The decision-making is also influenced by the availability of infrastructure and the range provided by each vehicle technology; these features are particularly important when new fuels or new technologies enter the market. In order to represent in a more refined manner the true effects of the range limitations of some vehicle technologies and the lack of adequate infrastructure of alternative fuels, the trip categories represented into the model are assumed to follow a frequency distribution of trip distances. The model assumes that decision makers compare the range possibilities of each vehicle technology and the availability of refuelling/recharging infrastructure for all classes of trip types and trip distances and apply cost penalties in case of mismatches between range limitations or non-availability of refuelling and trip types or trip distances. Thus, a vehicle or fuel type may not becoming competitive because of mismatches compared to other options, which do not present such limitations. The mismatching considerations do not apply to conventional technologies such as the ICEs and are relevant for BEVs and FCEVs, as well as for alternative fuels such as electricity, hydrogen, methane, LNG, biofuels, etc. The refuelling/recharging infrastructure applies to road and to maritime transport networks and ports, respectively.

Specific fuel consumption

Specific fuel consumption of each vehicle type is endogenously determined by the model and is calculated based on the COPERT⁷ methodology. The COPERT methodology enables calculation of fuel consumption of road vehicles as a function of their speed, which is determined by the endogenously calculated travelling time and the average mileage of trips per type of road transport mode. The complete COPERT methodology has been integrated into the model providing a strong analytical tool for the calculation of the consumption of various fuels and consequent calculations of costs. For other technologies not included in COPERT such as BEVs and FCEVs, data from literature and other studies are used. Similar approaches have been followed in the model to calculate specific fuel consumption by vehicle type and by trip type for bus/coaches and for heavy-duty vehicles.

The COPERT methodology enables calculation of fuel consumption of road vehicles as a function of their speed, which is determined by the endogenously calculated travelling time, the average mileage of trips per type of road transport mode, the occupancy factor for passenger trips and the load factor for freight transportations. The complete COPERT methodology as fully integrated into the model also serves to calculate emissions of pollutants, including NO_x , CO, SO_2 , PM and VOC.

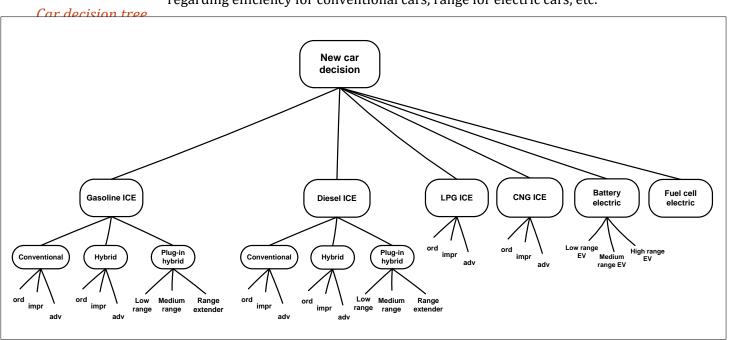
The calculation of fuel consumption for hybrid vehicles has been modelled in such a way that takes into account the region in which the vehicle is moving. For urban regions the fuel savings are significantly higher than in non-urban ones because of traffic congestion and the slower average speeds that lead to more braking and thus to more energy regenerated by the hybrid powertrain.

⁷ COPERT is a software program for calculation of air pollutant emissions from road transport (EEA and JRC).

Scrapping pfyehiclese

As far as plug-in hybrid cars are concerned, they are assumed to operate both as pure electric vehicles and as hybrids. The electric operation depends on the battery capacity, which indicates an average pure electric mileage between charges. When the battery supplies are exhausted, the vehicle switches to a hybrid mode burning conventional fuel. Plug-in hybrid types with range extending engines are also included. The model includes pure electric vehicles as following a single all electric operation equipped with high capacity batteries. Electricity consumption for plug-in hybrids and pure electric vehicles is being calculated using efficiency figures drawn from literature.

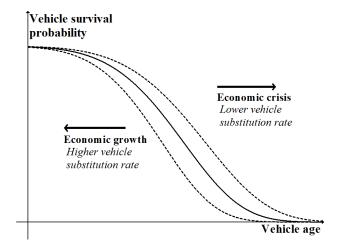
The choice of technology and fuel type when purchasing a new vehicle is represented in the model as a discrete choice model following a nested Weibull formulation. The upper level of the decision tree includes ICE types, battery-based electric cars and fuel cell cars. The next level distinguishes between conventional, hybrid and plug-in hybrids. Each of these car types is further disaggregated in technology types, regarding efficiency for conventional cars, range for electric cars, etc.



The model includes possibility of fuel choice for some vehicle technologies. The choice depends on relative fuel costs of vehicles. Cost penalties apply for fuels with poorly available refuelling infrastructure. A logistic function is used to calculate the frequencies of alternative fuel choices. For example, a diesel vehicle can refuel with diesel blend or pure biodiesel if technically feasible.

The capital vintage model includes normal scrapping and possibility of premature scrapping for economic reasons.

Normal scrapping is represented using a distribution function (two parameters Weibull reliability function) with calibrated parameters by country. The distribution function indicates the survival probability of a vehicle type as a function of time after date of purchase. The model includes dependence of parameter values on income expectation, to capture scrapping rates reducing in periods of low economic growth and increasing in periods of sustained growth. For low-income countries scrapping rates are high but they may reduce rapidly with economic growth.



Low usage rates of yet not scrapped old vehicles is endogenous in the model through the determination of annual mileage by type of vehicle and by vintage. The driver in the model is economic cost of using a vehicle; obviously costs (fuel and environmental) increase with age and mileage decreases.

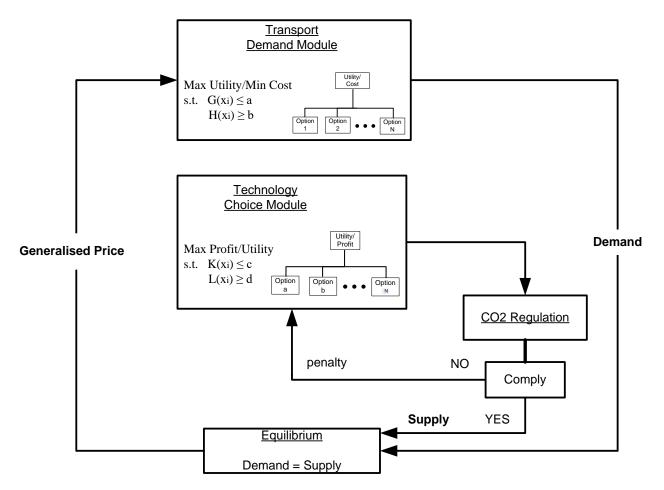
Premature scrapping of a vehicle is endogenous and occurs when fixed and variable operating costs are higher than total costs (including annuity payment for capital) of a new vehicle. To capture other drivers, related to behavioural features, the model uses a logistic function to calculate the frequency of premature scrapping.

The model includes several present and future regulations, which influence choice of vehicle technologies. The EURO standards on pollutant emission performance are explicitly represented in the model for all types of vehicles. The model relates EURO standards with vehicle vintages and it specifies that only vehicle types, which are compliant with the applicable EURO standard, are available for choice in each period.

The standards on specific CO_2 emissions (e.g. EU regulations No 443/2009 and No 510/2011) are modelled as constraints applying on average emission performance over all new vehicles that are available for choice. It is assumed that average specific CO_2 emissions of the fleet sold by manufacturers in a period must not exceed the specific emission standard as applicable, otherwise a high penalty applies. The specific CO_2 emissions of each vehicle are measured through the New European Driving Cycle (NEDC). A CO_2 label is thus associated to each vehicle type.

Regulations influencing choice of vehicles

Average label for new registrations is computed by weighting labels by vehicle type using the shares of each vehicle type in new registrations. These shares are endogenous in the model and depend, among others, on the costs of purchasing new vehicles. If the average label is higher than the applicable standard, the model applies a cost penalty on the purchasing costs of each vehicle type proportionally depending on the difference between the vehicle's label and the standard. As the purchasing costs of vehicles are modified, consumers are simulated to change the decisions and so the mix of new registrations is modified towards a lower average label. This process continues until average label is exactly equal to the standard.



The model also represents other labelling policies and standards, as policy options. Energy efficiency labels and standards is such an example. They can be measured either in final energy or in primary energy terms. Mixed labelling and standards are also possible.

Obviously, the choice of standards influence future mix of vehicles and this is fully captured in the model. For example, very strict end-of-pipe CO_2 standards would equally incite battery-based and fuel cell cars, but strict final energy efficiency standards would promote battery-based rather than fuel cell cars.

Moderate CO_2 or efficiency standards can be met also by conventional car technologies if they become more efficient. Cost-efficiency curves are modelled for all conventional technologies (and for various technologies and vehicle types in road transport) to represent a locus of efficiency improvement possibilities. The cost-efficiency curves have a time dimension and have increasing slopes, which signify that purchasing costs increase with efficiency but the incremental costs decrease over time.

Cost of time influences transport costs

Cost of time represents a monetary valuation of travelling time, which differs between individual and business passengers, and also differs among transport modes depending upon temporally and geographically features. Cost of time is subdivided into cost of time for non-road and road transport. Cost of time is expressed as the product of travelling time and the value of time, used to represent the value of travel time, which differs between the trip types. Travel time is directly influenced by traffic congestion and for road transport, a congestion function is used. For public transport, cost of time also includes waiting time, which is also influenced by congestion.

The travelling time is calculated with distinction between metropolitan, other urban, motorway and other road areas, and depends on allocation of mobility to different

trip types as calculated in the transport demand module. Travelling time also depends on exogenously defined parameters denoting infrastructure investment and expenditures for the creation of parking places. Travelling time for non-road transport is exogenously defined, taking into account average mileage and speed.

Cost of time is included in the calculation of generalised price of transportation.

Demand for rail transport (passengers and freight) as well as substitutions between rail and road transportation are covered in the transport demand module. The transport supply module aims at finding the mix of train types and fuel types to meet demand. For this purpose, a discrete choice methodology determines the structure of the train fleet, by distinguishing between metro, tram, urban and non-urban trains as well as high-speed rail. A capital vintage approach is implemented also for rail. Choice of new types of rail transport is simulated through a logistic share function that depends mainly on total operational costs and takes into account capital costs, fuel consumption, emissions etc. The stock of existing rail infrastructure is taken into account through an aggregate indicator, which influences the degree of renewal of the train fleet. The model endogenously calculate mileage per vehicle technology, rail type and train vintage by taking into account relative variable costs and the influence of regulations. The model includes engineering-based formulas to calculate specific fuel consumption by train type and vintage and thus it derives total fuel consumption and emissions. Cost-efficiency curves, conceived as reduced-form representations of various efficiency improving techniques, are included for train technologies.

Air transport

Rail transport

Demand for air transport distinguishes between trip distance classes and between domestic, intra-EU and international flights. The air transport supply module determines investment in new aircrafts, finds a mix of stylised aircraft technologies, and calculates fuel consumption and emissions. The model includes a few stylised aircraft technologies, namely ordinary, improved and advanced which have in that order have higher investment costs and higher energy efficiency. The efficiency possibilities draw on aggregate costefficiency curves, which are parameterized based on

Airplane distance classes
< 500
500 - 1000
1000 - 1500
1500 - 2000
>2000

literature data. Specific fuel consumption is based on engineering-type formulas, drawn from literature, and the calculation distinguishes between distance classes of flights. The only alternative fuel possibility is to use blends with bio-kerosene. The blending rates are exogenously defined and are depending on emission reduction objectives (signalled through carbon prices) and assumptions about biofuel supply possibilities (which are included in the biomass supply and bio-fuel blending models). Inclusion of aviation in the EU ETS is explicitly modelled.

Maritime transport refers to inland navigation and distinguishes between short sea shipping and inland water ways, as well as between freight and passenger transport. Vessel types refer to stylised technologies (ordinary, improved, advanced). Costefficiency curves capture possible energy efficiency improvement is relation to capital costs. Choice of fuels include conventional mineral oil, blended bio-fuels and LNG.

Maritime transport

A separate model projects activity and energy consumption for international maritime bunkers. Activity is projected using a simplified world trade model covering EU import exports with distinction of ships carrying hydrocarbons, bulk cargo and containers. Separate drivers are considered for each category and for energy bulk cargo the model links to energy imports-exports of the EU. Allocation to EU ports is based on exogenous parameters and time trends. Energy consumption is based on specific fuel consumption functions, which use cost-efficiency curves to summarise efficiency possibilities. Alternative fuels include bio-fuels and LNG.

K.5.d. Generalised Price of Transportation

As mentioned before, the transport supply module projects the structure of the vehicle, train, aircraft and vessel fleet together with fuel consumption and emissions. The calculations are based on simulated decisions, which can be grouped as follows:

- Normal scrapping
- Premature scrapping of old stock of vehicles
- Requirements for new vehicle registrations
- Allocation of new vehicle registrations into different technologies
- Fuel choice
- Annual mileage per vehicle type and vintage, which is further distributed by trip type.

At this stage fuel consumption and emissions are calculated. Policy driven regulations and standards influence the simulated choices.

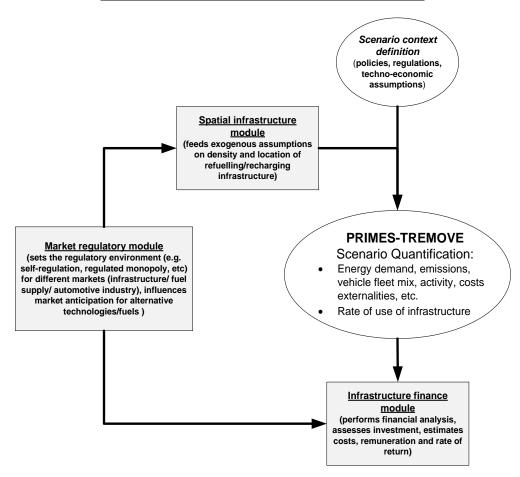
The above-mentioned decisions imply expenditure for purchasing transport means, for fixed and variable operating costs and for externalities if and where applicable. The model calculates an indicator of unit cost of transportation by mode and trip type, inclusive of all cost elements, the cost of time and external costs if applicable.

The unit cost is based on average costs for self-supply of transportation services and on tariff setting rules for business supplied transportation services. The rules mirror current practices and regulations concerning ticket and tariff setting by transportation businesses and generally combine marginal cost and average cost pricing. For aviation, marginal cost pricing is assumed to prevail. For rail and road public transport, average cost pricing is assumed with partial recovery of fixed capital costs, depending on assumptions about subsidies. Fixed cost recovery is distributed across customer types using a Ramsey-Boiteux methodology.

The calculated unit cost of transportation by mode and trip type is termed "generalised prices of transportation" and is conveyed to the transport demand module where it influences demand for transportation services. The interaction through the generalised prices of transportation ensures equilibrium between demand and supply of transport services.

The transport demand and the technology choice modules reach an equilibrium through the generalised price of transportation. The generalised price is determined once the structure of the vehicle fleet is defined (at minimum cost) by the technology choice module to meet the projected demand derived from the transport demand

Area	Distance classes
Metropolitan area	-
Other urban areas	-
	Short distance coverage (< 100 km)
Motorway	Medium distance coverage (100-300 km)
	Long distance coverage (> 300 km)
Other roads	Short distance coverage (< 100 km)
	Medium distance coverage (>100 km)



module. The generalised price of transportation differs among the transport modes and across the various trips and regions. It is also endogenously defined as a result from an interaction between the demand and the technology choice modules.

K.6. Refuelling/recharging Infrastructure

As mentioned above, the availability of refuelling or recharging infrastructure has an impact on vehicle and fuel choices. Aiming also at supporting cost-benefit analysis, PRIMES-TREMOVE includes a block of modules on refuelling/recharging infrastructure development.

The refuelling/recharging infrastructure is represented for urban, semi-urban and inter-urban categories per country, as a density of refuelling/recharging points. The projection of densities is exogenous and is part of scenario design.

The density of infrastructure of different fuels in various areas is connected to agents' travelling habits (represented through stylised histograms of trip distances). The combination is modelled as a driver of vehicle/fuel choice.

The fuel types with explicit infrastructure modelling are grid electricity, hydrogen, CNG gas, LNG gas, LPG, biogas and liquid bio-fuels (when there are separate dispensers for bio-fuels). Specific infrastructure assumptions are included for larger and heavier vehicles like HDVs and buses and for vessels (e.g. LNG in ports).

The infrastructure finance module calculates investment and 0&M costs of the infrastructure by category, as well as revenues, which depend on the scenario specification about infrastructure tariff method, funding and remuneration. Using model-derived rates of use of the infrastructure, the module calculates infrastructure remuneration and capital cost recovery in case exogenously assumed tariffs are applied only to users of infrastructure. Alternatively, if tariffs are socialised (i.e. applied on all consumers), the module calculate the level of the tariff as required to recover capital costs.

K.7. Calculation of external costs

The main external costs in transport are congestion, accidents, noise and air pollution. Physical and monetary valuation are projected by the PRIMES-TREMOVE model.

The external costs of congestion denote the additional social cost incurred to the other users of the road infrastructure by an additional car. The model captures congestion impacts as changes from base year values due to vehicle activity depending on exogenously assumed changes in infrastructure. The calculation has limitations due to limited spatial coverage (stylised geographical areas) of the model. The aim of the model is to include a monetary valuation of congestion in the cost of time indicator, which influences choices in demand and in supply of transport services.

Similarly, the model includes a simple calculation of impacts on accidents, which is based on total activity of vehicles and on exogenous time trends. The impacts on noise are based on exogenous parameters that are differentiated by type of vehicle and technology.

The model calculates air pollution emissions as a function of fuel consumption, depending on vehicle and technology types and depending on standards. Diffusion of pollution is not included.

Monetary valuation of externalities is based on average values drawn from literature and from the impact assessment handbooks published by the European Commission. The model includes possibility to internalise externality impacts in various forms, such as inclusion of specific constraints (e.g. upper limits on physical evaluation of impacts) or as taxation on fuels or on vehicle types defined so as to reflect impacts on externalities. Obviously, the internalisation influences vehicle and fuel choices and affects cost of transportation.

K.8. Measuring disutility costs

The PRIMES-TREMOVE model has a microeconomic foundation and solves a utility maximisation problem for the individuals. When unit price of transportation increases for any reason, consumer's utility (as well as the transportation activity) may decrease if substitutions are imperfect. Fuel price rises, taxation increase, emission constraints etc. are among the causes, which drive reduction in transport activity.

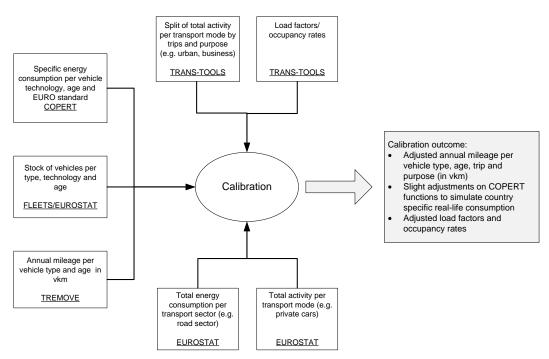
In monetary terms, the utility level changes are measures following the income compensating variation method. This calculates the additional amount of income that

consumers would require to allow increase in transport activity to compensate for the loss of utility due to the rise of unit price of transportation.

The disutility costs thus reflect the losses in utility (due to lower transport activity) of consumers in the context of a counterfactual scenario compared to a baseline scenario.

K.9. Source of data and calibration to statistics

PRIMES-TREMOVE transport model is calibrated to 2005 and 2010 historical data. The main data come from statistics on passenger and freight transportation activity as available in EUROSTAT databases. Energy consumption is calibrated to EUROSTAT energy balances. Vehicle stock for road transport is calibrated to FLEETS database and to EUROSTAT. Rail data come from EXTREMIS database. Initial values for occupancy, load factors and average vehicle annual mileages are derived from TRANS-TOOLS and TREMOVE databases; these initial values are further modified using special routines to calibrate to EUROSTAT more aggregated data. Data on vehicle purchasing costs draw on "Car prices within the European Union" reports. Excise taxes derive from DG TAXUD excise duty tables. Aviation draws data from EUROCONTROL databases and maritime from IMO databases and other sources.



The split of transport activity by transport mode, by transport means and the allocation to trip types is a complex datatreatment task. We use a special routine that uses data from EUROSTAT (aggregate figures), TRANS-TOOLS (split of activity of each transport mode by stylised area, such as metropolitan, motorway etc., by purpose such as commuting, nonworking, business, etc. and time such as peak, off-peak. The splitting routines also draws from TREMOVE data.

Load factors for freight transportation and occupancy rates for passenger transportation are simultaneously derived in the splitting routine using data from surveys and minimum-maximum limits to capture differences by trip type. The stock of vehicles provided by the FLEETS database is at high level of disaggregation (vehicle size, fuel, engine size for cars and motorcycles, vehicle gross weight for trucks, EURO standard). The specific energy consumption is retrospectively calculated using the COPERT methodology, which considers average speed of vehicles at same level of disaggregation as the vehicle stock. To calibrate annual mileage of vehicles at high resolution of vehicle types and vintages, expert-driven values are used to reflect that for example older cars are less used than new cars.

K.10. Classification of transport means

Category	Classification of trans	Technology
dutegory	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Bio-ethanol blend, E85 FFV
	Hybrid Gasoline	Euro IV-VI
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Euro IV-VI
Small cars	Bio-diesel	Blended Bio-diesel
(<1.4 l)	Synthetic fuels	Synthetic fuels
	Hybrid Diesel	Euro IV-VI
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	Hydrogen	Hydrogen fuel cell
	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Blended Bio-ethanol, E85 ethanol car
	Hybrid Gasoline	Euro III-V
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Pre ECE, ECE, Conventional, Euro I-V
	Bio-diesel	Blended Bio-diesel
Medium Cars	Synthetic fuels	Synthetic fuels
(1.4 - 2.0 l)	Hybrid Diesel	Euro III-V
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	LPG	Conventional, Euro I-V
	CNG	Euro II-V
	Hydrogen	Hydrogen fuel cell
	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Blended Bio-ethanol, E85 ethanol car
	Hybrid Gasoline	Euro III-V
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Pre ECE, ECE, Conventional, Euro I-V
Large Cars	Bio-diesel	Blended Bio-diesel
(>2.0 l)	Synthetic fuels	Synthetic fuels
	Hybrid Diesel	Euro III-V
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	LPG	Conventional, Euro I-V

Category	Туре	Technology
	CNG	Euro II-V
	Hydrogen	Hydrogen fuel cell
	2-stroke technology, Gasoline, biofuels	Conventional
Motorcycles	Capacity 50-250 cc	4-stroke technology using gasoline/biofuels
	Capacity 250-750 cc	or electric motors
	Capacity 750cc	of electric motors
Mopeds	Moped Conventional, Gasoline, biofuels	Conventional, Euro I-V
	Electric mopeds	Pure electric technology
	Gasoline	Conventional, Euro I-V
	Hybrid Gasoline	LDV gasoline hybrid technology
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Conventional, Euro I-V
Light Duty	Hybrid Diesel	LDV diesel hybrid technology
Vehicles	Biofuels	Biofuels
(<3.5 ton)	LPG	LPG
	CNG	CNG
	Synthetic fuels	Synthetic fuels
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	Hydrogen	Hydrogen fuel cell

Category	Туре		Technology	
	Capacity 3.5-7.5 ton, Conventional			
	Capacity 7.5-16 ton, Conventional	D'andre de	Methane trucks (LNG)	LPG trucks
Heavy Duty	Capacity 16-32 ton, Conventional	Diesel trucks		
Trucks (> 3.5 ton)	Capacity >32 ton, Conventional			
	Capacity 3.5-7.5 ton, Hybrid	Truck diesel hybrid technology , biofuels, synthetic fuels Electric trucks, Hydrogen fuel cell trucks		oiofuels,
	Capacity 7.5-16 ton, Hybrid			
	Capacity 16-32 ton, Hybrid			
	Capacity >32 ton, Hybrid			I trucks
Busses-Coaches	Diesel	Conventional, I	Euro I-V	

Category	Туре	Technology
	CNG	CNG thermal
	LPG	LPG
	Busses only Hybrid Diesel	Hybrid Diesel technology
	Battery electric	Battery electric technology
	Biodiesel	Biodiesel technology
	Synthetic fuels	Synthetic fuels
	Hydrogen	Hydrogen fuel cell
Metro	Metro Type	Metro Technology
Tram	Tram Type	Tram Technology
	Language	Locomotive diesel
	Locomotive	Locomotive electric
Passenger Train	D d	Railcar diesel
	Railcar	Railcar electric
	High speed train type	High speed train technology
	Locomotive	Locomotive diesel
		Locomotive electric
Freight Train	D. C.	Railcar diesel
	Railcar	Railcar electric

K.11. Model outputs

The PRIMES-TREMOVE model as the whole PRIMES suite gives standardised outputs independently if the requirements refer to a baseline, scenario or variant; the set of information delivered, the excel files delivered, are the same and an overview of the model outputs may be found below. The projections cover a time horizon up to 2050 by 5-years steps.

Model output	Level of detail
Transport activity	By transport mode, type of transport means, by
	purpose, by agent and by stylised geographic area and
	by trip type
Final energy demand	By transport mode and vehicle type and by fuel type
Specific energy consumption	Efficiency indicators for all transport means
CO2 emissions TTW	By transport modes, vehicle type and fuel
CO2 Emissions WTW	By transport mode, vehicle type and fuel
Vehicle stock	By vehicle type and fuel type, as well as by vintage
New vehicle stock	By vehicle type
Refuelling/recharging infrastructure	Density by fuel and by geographic area type; linkage to trip types
Infrastructure costs for charging and refuelling	Ex-post calculation based on modelling results, related to the level of penetration of the different vehicle/fuel types and analysis of cost recovery
Investment expenditures	By transport means, by mode and by agent
Capital costs related to transport equipment	By transport means, by mode and by agent in annual payment terms. In addition, calculation of additional capital costs for energy and emissions purposes based on an incremental cost method.
Fixed operation costs	By transport means, by mode and by agent
Fuel costs	By transport means, by mode and by agent
Excise duty payments	By transport means, by mode and by agent
VAT on fuel payments	By transport means, by mode and by agent
CO2 tax payments	By transport means, by mode and by agent
Ticket prices for public transport	By transport mode and finance balances by mode
Registration and circulation tax payments	By transport mode distinguished between household and business expenditures
EU Emission Trading Scheme	By transport mode distinguished between household
payments	and business expenditures
Variable non-fuel operation costs	By transport mode and vehicle type
Disutility costs	For passenger and freight transport
Pollutant emissions (CO, NOx, PM2.5,	By transport mode and distinction by trip area
SO2)	(urban/inter-urban)
External costs (congestion, accident, air pollution, noise)	By mode vehicle type and trip area

The model output is presented in the forms of excel sheets for all the modelling tools. The PRIMES-TREMOVE model includes two excels files available for each country, as well as the EU15, NM12 and EU28 aggregates.

K.12. Transport activity modelling using econometrics in v. 6 K.12.a. Transport activity projections

Within the elaboration of the Reference 2015 scenario, a more sophisticated approach for deriving the transport activity projections by each MS until 2050 compared to the previous Reference 2013 was developed and this is the methodology for version 6 of PRIMES. It employs a combined econometric and engineering approach for deriving transport activity by transport mode. A considerable enhancement in the transport sector is that it follows the territoriality principle for the heavy-duty trucks activity (in both the past and the future years), reflecting transportation activity of vehicles circulating in the territory of the country irrespective of the nationality of the vehicle.

The econometric methodology employs a two-stage error-correction model, which correlates transport activity with GDP, fuel prices, length of motorways and total length of railways. Equations (1) and (2) given below show the basic structure of the two-stage error-correction model.

$$\log(transport)_{i,t} = \alpha_0 + \sum_{i=1}^n \alpha_i \log(X_{it}) + u_{i,t}$$
 (1)

$$\Delta \log(transport)_{i,t} = \beta_0 + \sum_{i=1}^n \beta_i \Delta \log(X_{it}) + \gamma u_{i,t-1} + v_{i,t}$$
 (2)

The term (transport) i,t refers to transport activity of country i for year t, the term $X_{i,t}$ refers to the respective explanatory variables (e.g. GDP) correlated with each activity and the terms $u_{i,t}$ $v_{i,t}$ are the error terms. The coefficients α_i , β_i are the respective estimated short and long-term elasticities used in transport activity projections and the coefficient γ represents the gravitation towards the long-run equilibrium relationship (1).

The activity projections have been validated using typical indicators such as activity per capita and, where necessary, they were adjusted to yield realistic values. Regarding the split of passenger railways into conventional and high-speed rail, we followed an engineering approach using as an input the expected development of the high-speed railways network within each MS along the guidelines of the TEN-T core and comprehensive network.

Regarding, aviation, the new method provides a split into international intra-EU and international extra-EU aviation. The new econometric methodology treats separately the two alternative types of trips due to the different dynamics and the expected increase of the international extra-EU trips to emerging economies (e.g. China). The activity projections for aviation have been validated against the most recent forecasts provided by EUROCONTROL.

Sea freight and bunkers activity is correlated with GDP, fuel prices and international trade. The total trade for each EU country is an additional key driver of maritime activity. For the bunkers activity projections a panel estimation approach is applied. The EU-28 countries are being split into 6 regions and as a consequence 6 different panel estimations are being produced. These estimated coefficients for the countries that belong to the same region are used for the country-specific projections. The panel estimation approach is being chosen in this sector, since the bunkers activity in each EU country is mostly affected by regional (panel specific) instead of country specific macroeconomic characteristics.

K.12.b. Data update and calibration of the transport sector

The transport sector database has been considerably updated for the purposes of the Reference 2015 scenario. It includes the most recent very detailed TRACCS database that provides the most up-to date information regarding the split of the vehicle fleet for each EU MS. Apart from the update of the vehicle fleet numbers for the past years, an update on vehicle taxation, maintenance and insurance has been performed. Various sources were used to update the model database drawing from the TRACCS and ACEA databases, the MS replies to the questionnaires and other open access sources.

The database for the techno-economic assumptions has also been updated to reflect the most recent changes and the expectations of the vehicle manufacturing industry. The latter refer, in particular, to the expected evolution of the capital costs of advanced vehicle powertrains such as battery electric vehicles and plug-in hybrids. The battery costs for battery electric vehicles and plug-in hybrids have been reduced in the medium and long-term due to the technical progress and steep learning curves observed in the recent years in the battery manufacturing industry. In addition, the additional capital costs for improvements in the conventional technologies have been slightly modified downwards due to the fact that manufacturers tend to absorb engineering-related costs in the final vehicle price.

During the calibration phase of the model, complex routines calculate transport related indicators such as the vehicle mileage or the occupancy and load factors such that the EUROSTAT energy balances and transport activity figures are respected. For the purposes of the Reference scenario, the calibration routines have been modified to include additional constraints on the actual activity of heavy-duty trucks in vehicle-km. The new constraints, even though they increased the computational complexity of the model, yield more realistic figures regarding the activity of heavy duty trucks.

K.13. PRIMES-Maritime transport model

K.13.a. Introduction

The aim of the PRIMES-Maritime model is to perform long-term energy and emission projections, until 2050, for each EU MS separately. The coverage of the model includes the European intra-EU maritime sector as well as the extra-EU maritime shipping.

PRIMES-Maritime focuses only on the EU MS, therefore trade activity between non-EU MS is not part of the model. Aggregate trade with non-EU countries by non-EU geographical zones permit modelling of extra-EU flows. The model captures competition between short-seas shipping and road freight transport. The demand for maritime services depends on fuel prices and relative costs.

PRIMES-Maritime comprises a demand module projecting maritime activity for each EU MS by type of cargo and by corresponding partner. Econometrical functions relate future demand for maritime transport services with economic drivers including GDP, energy demand (oil, coal, LNG), international fuel prices, and bilateral trade by type of product.

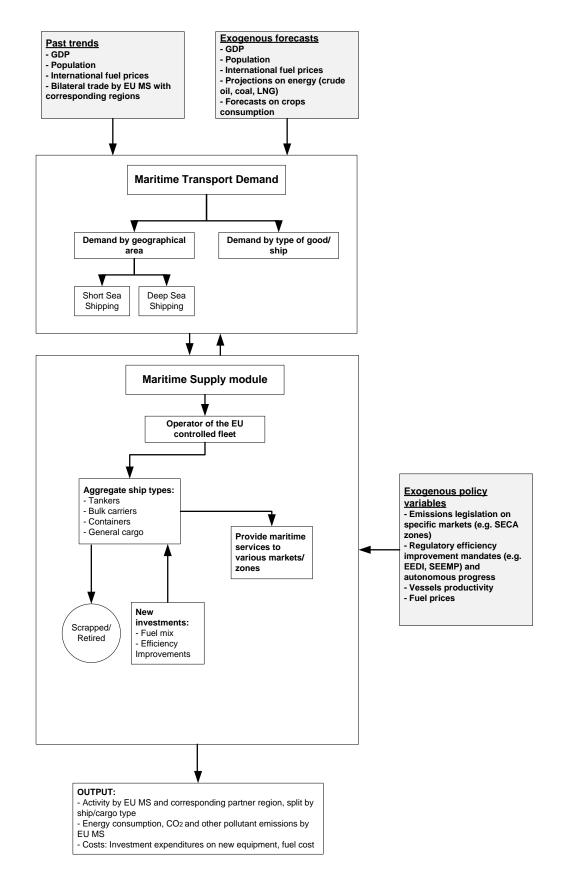
The supply module simulates a virtual operator controlling the EU fleet, which performs the requested maritime transport services and allocates the vessels to activities in the various markets (the EU MS and the extra-EU area) where different regulatory regimes may apply (e.g. environmental zones). The fleet of vessels disaggregates into several categories depending on cargo types. PRIMES-Maritime utilises stock-flow relationship to simulate the evolution of the fleet of vessels throughout the projection period.

PRIMES-Maritime solves for a balance between demand and supply of maritime services, with the demand and supply modules interacting dynamically. The allocation depends on policy measures such as fuel standards or efficiency improvement regulations. The PRIMES-Maritime model reports both the volume of trade (in tons) and the maritime transport activity (in tkm) disaggregated by EU MS, by cargo type and by geographical region. The model also calculates energy consumption by fuel type and cargo type as well as CO_2 and other pollutant emissions. The model projects investment costs, which mainly includes new vessel purchases and fuel costs.

The PRIMES-Maritime model operates in two modes, namely: (1) the *forecasting* mode and (2) the *simulation* mode. The running modes particularly refer to the demand module, which determines maritime activity.

When operating in the *forecasting* mode, PRIMES-Maritime performs a forecast of the maritime transport activity by EU country following a bottom-up methodology. Forecasting draws on econometric estimations of trade activity, in tons, between the EU countries and each aggregate geographical area. Explanatory factors include GDP, imports and exports of products such as crude oil, dry bulk products, crops, and others. The evolution of oil prices is an additional critical *variable since fuel costs represent about half of total* operating costs⁸.

⁸ Ferrari, C., Tei, A. and Parola, F. (2012). Facing the economic crisis by cutting costs: The impact of low-steaming on container shipping networks. Paper presented at International Association of Maritime Economists (IAME) Conference, Taipei, Taiwan, 5-8 September 2012



Schematic representation of the PRIMES-Maritime model

Geographical zones North America South central America CIS North Africa Sub-Saharan Africa Middle east East Asia South- South east Asia Oceania

The maritime activity derives from multiplying volumes transported by distance according to origin-destination matrix, with endogenous allocation coefficients, which link the ports of the trading partner countries or regions. The accounting follows the territoriality principle. Total maritime transport activity by EU country, in tkm, is the sum of activities of the specific country.

In the *simulation* mode, PRIMES-Maritime dynamically matches exogenously defined projections of maritime transport activity by EU country. The projections come either from the same model running in forecasting mode or from external sources. Further, the PRIMES-Maritime model determines the allocation of import activity among the various regions and types of ships. The methodology for allocating the overall transport activity to the various geographical regions and types of ships/ goods resembles the bottom-up methodology employed in the *forecasting* mode.

K.13.b. Processing of data input

A very extensive dataset on bilateral trade, available by EUROSTAT, is the starting point of the model's database.

The product types are one of the dimensions of the database and a mapping account for correspondence between various cargo types and the products transported, based on EUROSTAT. The expanded dataset provides additional information regarding the types of goods transported between the EU MS and the corresponding partner regions and is the basis for deriving future forecasts of transport activity by cargo type. The product types in most countries follow the NST 2007 classification. However, in some countries (e.g. France, Netherlands) the distinction of product types follows the NSTR/24 classification due to data limitations.

Types of products: NST 2007 classification

	NST
Product types	2007
Products of agriculture, hunting, and forestry; fish and other fishing products	01
Coke and refined petroleum products	07
Secondary raw materials; municipal wastes and other wastes	14
Food products, beverages and tobacco	04
Metal ores and other mining and quarrying products; peat; uranium and thorium	03
Basic metals; fabricated metal products, except machinery and equipment	10
Machinery and equipment n.e.c.; office machinery and computers; electrical machinery and apparatus n.e.c.; radio, television and	
communication equipment and apparatus; medical, precision and optical instruments; watches and clocks	11
Unidentifiable goods: goods, which for any reason cannot be identified and therefore cannot be assigned to groups 01-16.	19
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products;	
printed matter and recorded media	06
Chemicals, chemical products, and man-made fibres; rubber and plastic products; nuclear fuel	08
Other goods n.e.c.	20
Goods moved in the course of household and office removals; baggage and articles accompanying travellers; motor vehicles being	
moved for repair; other non-market goods n.e.c.	17
Transport equipment	12
Coal and lignite; crude petroleum and natural gas	02
Other non-metallic mineral products	09
Equipment and material utilized in the transport of goods	16
Furniture; other manufactured goods n.e.c.	13
Grouped goods: a mixture of types of goods which are transported together	18
Mail, parcels	15
Textiles and textile products; leather and leather products	05
unknown	XXX

Types of products: NSTR/24 classification

Types of products: 110111/24 elassification		
Product types	NSTR/24	
miscellaneous articles	G24	
metal products	G13	
transport equipment, machinery, apparatus, engines, whether or not assembled, and parts thereof	G20	
cereals	G01	
foodstuffs and animal fodder	G06	
oil seeds and oleaginous fruits and fats	G07	
petroleum products	G10	
potatoes, other fresh or frozen fruit and vegetables	G02	
wood and cork	G04	
textiles, textile articles and man-made fibres, other raw animal and vegetable materials	G05	
crude petroleum	G09	
iron ore, iron and steel waste and blast furnace dust	G11	
cement, lime, manufactured building minerals	G14	
crude and manufactured minerals	G15	
chemicals other than coal chemicals and tar	G18	
glass, glassware, ceramic products	G22	
leather, textile, clothing, other manufactured articles	G23	
live animals, sugar beet	G03	
manufactures of metal	G21	
solid mineral fuels	G08	
natural and chemical fertilizers	G16	
coal chemicals, tar	G17	
paper pulp and waste paper	G19	
non-ferrous ores and waste	G12	

The initial detailed dataset from EUROSTAT includes bilateral trade (denoted trade) by type of cargo type k (measured in tons) between the corresponding countries (i and j denoting an EU MS and a corresponding trade-partner, respectively). However, the activity indicators (Act measured in ton-km) are essential for PRIMES-Maritime to calculate energy and emissions. Therefore, to obtain the maritime activity in PRIMES-Maritime, the volume of goods transported from an origin point to a destination point multiplies the average distance between the two points. However, the only available data regarding maritime activity per EU MS are available for 2005 and 2010 and split into international-intra EU and international-extra EU transport activity per EU MS. National maritime is part of the PRIMES-TREMOVE model.

PRIMES-Maritime adopts the territoriality principle for the allocation of the maritime activity per EU MS, based on some assumptions. As regards the trade of goods between EU 28 MS (i.e. international intra-EU maritime), the transport performance attribution is 50% to the origin country and 50% to the destination country. The same "50-50" principle allocation also applies to the EFTA countries (i.e. Iceland, Norway, Liechtenstein and Switzerland) and the candidate countries. As regards the international extra-EU maritime, where the corresponding partner is outside EU-28 and is not an EFTA or candidate country, the maritime activity is attributed 100% to the declaring EU MS country.

A calibration procedure of PRIMES-Maritime ensures retrospective simulations in accordance with activity statistics. The calibration involves assignment of average distances to match statistics by trading region based on an origin-destination matrix. For the international extra-EU maritime, the assignment of typical distances uses geographic information for stylised trips linking the main ports of the EU country and the ports of major extra-EU countries⁹ that perform the majority of trade. Knowing the typical distances, total maritime activity by EU MS disaggregates into international intra-EU and extra-EU maritime shipping.

⁹http://www.searates.com/reference/portdistance/ (accessed on 5th March 2015)

The calibration adjusts average distances between each EU MS and the various region partners to match activity statistics. For validation purposes, the obtained distances compare to actual distance data obtained either from maps or from other sources (e.g. EUROSTAT). The validation performs at the level of grouped activities: Ro-Ro mobile self-propelled units, Ro-Ro mobile non-self-propelled units, liquid bulk goods, large containers, other cargo not else specified. The splits by region or country are specific to each cargo type.

Additional calibration procedures further split the maritime activity into Short Sea Shipping and Deep Sea Shipping.

The international intra-EU maritime activity lies within the category of Short Sea Shipping. However, a part of international extra-EU maritime transport activity categorized as Short Sea Shipping refer to the movement of cargo that takes place along coastlines on the enclosed seas bordering Europe. The calibration procedure solely focuses on the international extra-EU maritime shipping between the EU MS and the various worldwide regions.

Measuring the volume of the vessels by EU MS is not straightforward. According to a study¹⁰ by Oxford Economics, there are a number of ways to measure the volume of the EU fleet. The "**EU controlled**" fleet includes ships that their operational activity lies within the EU even though that they might be flagged elsewhere. Secondly, measuring the fleet by the flag nationality is another principle, which determines under which state/country the ship falls under.

Following the "EU controlled" principle of measuring the fleet is likely to align most closely with the purposes of the PRIMES-Maritime model, which is to simulate the maritime transport activity for the EU MS. According to the ISL study, 11 the major countries controlling the EU fleet are Greece, Germany, Denmark and Italy. However, in contrast with the general approach of EU transport modelling, the maritime model does not assign the fleet of vessels to the various EU MS but assumes an overall fleet serving the demand for maritime services for the EU MS. This is equivalent to assume that an operator determines the usage of the EU controlled fleet to serve the maritime activity of all EU MS. Data regarding the volume of the EU controlled fleet draw from the Shipping Statistics Yearbook 2013 database (ISL, 2013). The base year regarding the fleet of vessels is 2010 based on the ISL study, which provides data for 2009 and 2012; the data for 2010 derive from linear interpolation.

The ISL study provides a disaggregation of the vessel fleet into four cargo categories. The four main categories are the tankers carrying liquid cargo, the bulk carriers transporting dry bulk cargo, the containers ships and general cargo vessels. Tankers further split into oil, chemical and liquefied gas tankers depending on the type of the liquid transported. The general cargo ships also include the Ro-Ro vessels, which carry roll-on and roll-off cargo. This further disaggregation has been possible to introduce in PRIMES-Maritime by using data from the study by Oxford Economics on the EU controlled fleet by type of vessel and by gross tonnage.

The available deadweight tonnage by type of vessel is also an important variable for the purposes of the modelling, apart from the fleet of vessels. Deadweight tonnage represents the maximum permitted load of the fleet of vessels and denotes the maximum carrying capacity of the ships.

The ISL database provides the distribution of the total available fleet of vessels and the deadweight tonnage by age. The distribution of the EU controlled fleet by age

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¹⁰ http://www.safety4sea.com/images/media/pdf/Oxford-Economics-ECSA-Report-FINAL.pdf

¹¹ ISL Shipping Statistics Yearbook

shows a differentiation depending on the cargo type of the vessel. Indeed, the age of the bulk carriers is relatively low, compared to the other vessel types.

The evolution of the future fleet of vessels also depends on the evolution of the fleet productivity throughout the projection period. Fleet productivity, which denotes the amount of transport work per deadweight tonne per vessel type, is measured in tkm/deadweight tonne. Activity by vessel type comes from the calibration of PRIMES-Maritime to 2010, whereas the values for the available deadweight tonnes come from the ISL study. The productivity values for the base year (2010) in PRIMES-Maritime model differentiate according to the various vessel type categories. The average productivities by type of vessel are relatively lower than the values reported by the IMO report. This implies that part of the EU controlled fleet and the available DWT, in reality, provides transportation services outside Europe. Technical features of vessels

The available fleet of vessels has technical features, which refer to average speed of vessels and to days at sea spent annually for travelling purposes. The assumptions presented draw from the IMO GHG Study (2014). The data restrict the mileage that vessels can perform per year for maritime services.

The low sulphur limits, established in the Emission Control Areas (ECA) to minimize sulphur and other pollutant emissions from ships, would drive a significant penetration of alternative vessel engine types using LNG. LNG vessel engines are part of the model among the alternative technological options. Capital costs for LNG vessels draw from literature, but may reduce in the future depending on the expected installed engine capacity. The model includes data on capital cost of the various vessel types disaggregated by size and engine type. The capital costs increase with the size of the vessel and the power of the engine. The values of capital costs assumed in PRIMES-Maritime model refer to new-built vessels. Vessel costs related to energy efficiency progress add on top of the vessel capital costs.

K.13.c. Supply- Fleet module

A virtual supplier controlling the EU fleet of vessels provides the transportation services to the various markets (e.g. country specific). The equilibrium ensures that supply balances the demand for transportation services in every period. The available stock of vessels evolves dynamically through investment and retirement.

PRIMES-Maritime employs a scrappage function to determine the fleet of vessels of a specific age that are retired. The scrappage function differentiates by type of vessel, as average lifetime can be different. The volume of scrapped vessels depends on the vessel type, the age of the vessels and the total available fleet of vessels in the previous period.

The model takes into consideration the second hand vessels, which allows for a more realistic simulation of the evolution of the fleet of vessels throughout the projection period in terms of both the efficiency improvement of an average vessel, as well as the associated investment costs. Data regarding the second hand prices of vessels and contracting prices for newly built ships draw from an ISL study. The model projects a ratio denoting the share of second hand vessels in the EU controlled fleet as a function of future prices of ships.

Fuel costs derive from multiplying energy consumption by country by energy prices, which come from the rest of the PRIMES model. The costs related to capital split by MS by using an indicator reflecting the degree of operation of specific fleet types in specific EU countries. Hence, if the virtual operator purchases very efficient vessels to operate mainly on low sulphur expensive marine diesel fuel in ECA zones, then the purchasing cost correspond to the countries where most of the activity takes place.

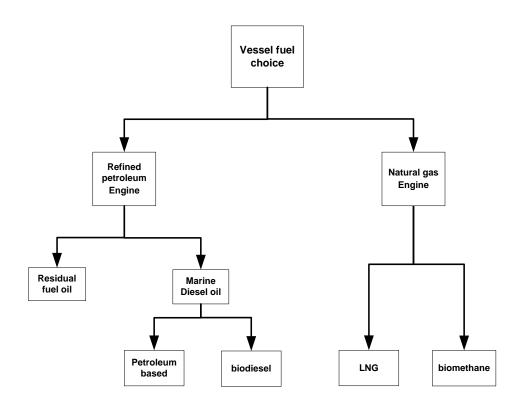
The vessel choice module in PRIMES-Maritime is based on discrete choice theory modelling. A Weibull functional form is used to determine the frequency of choice of a certain vessel engine. The choice of fuel by vessel type depend on short-term costs and the technical possibilities of the vessel type. This implies that a vessel equipped with an Internal Combustion Engine (ICE) will choose the most economic fuel (RFO). The LNG engine only uses LNG as a fuel. The higher the size of the vessel implies higher daily expenditures for operational costs; the crew wages alone account for about half of the total operational costs. However, strong economies of scale prevail regarding operational costs, especially when accounting the vessel DWT; the same also applies for fuel costs. Hence, the average unit cost of operation, inclusive of fuel and operational costs (in Euro/DWT), decreases for high vessel sizes. The operational costs in PRIMES-Maritime depend on the age of the vessel as insurance and maintenance costs change with vessel age.

The specific fuel consumption of vessels draws from relevant literature and the TRACCS database. The calibration adjust these factors to match country statistics on maritime activity and fuel consumption. A frequency- Origin-Destination matrix built for 2010, serves the calibration, showing the frequency of movements (routes) that each vessel type and size cluster undergoes.

Several alternative fuel options are included in the energy model regarding the fuel mix of the new vessels. The available fuel options are residual fuel oil, low sulphur marine diesel oil (LSMDO), natural gas and biofuels; biofuels include particularly the possibility of using biodiesel produced from advanced processing methods and biomethane. LSMDO, biofuels and natural gas are fuels that comply with the environmental regulations in ECA zones. According to the EUROSTAT energy balances, the maritime sector consumed only fossil fuels in 2010. The model can handle future changes in the fuel mix depending on relative costs and regulation.

The choice of fuel mix for new vessels based on discrete choice theory derives from a Weibul functional form, which includes relative unit operation costs of alternative technologies (mainly fuel costs) and annualized fixed costs for purchasing new vessel types. Market barriers mirroring availability of supply of various fuels or the market readiness of new vessel technologies also influence the decision. Market barriers have the form of perceived costs, which do not correspond to actual costs, but influence the agent's decision in the discrete choice modelling by increasing the costs of the relevant choices.

Regulations can influence the fuel mix. The strict sulphur regulations over the ECA zones (0.1% sulphur content mandate) would pose constraints on the use of high-sulphur fossil fuels. The model includes several alternatives to comply with the regulation, including distillates, LNG, biofuels and other gaseous fuels.



Fuel options for new vessels in PRIMES-Maritime

The supply- Fleet module of the PRIMES-Maritime model solves the problem of allocating in an optimal way the available vessels to the specified routes and transports the specified quantities between the origin country and the corresponding partner. The amount of goods to carry between trade partners is an input from the demand module of the PRIMES-Maritime model. The various vessel categories in PRIMES-Maritime (i.e. tanker, bulk carriers, containers and general cargo) can obviously transport only the relevant types of goods; meaning that a container ship does not transport dry bulk goods.

The quantity of goods that a vessel can carry depends on its load factor and its available deadweight tonnage, both measured in tons. The different vessel categories considered in PRIMES-Maritime are distinct cases of deadweight tonnage, which implies that their cargo capacity can differ substantially.

The allocation of the various vessels to the possible routes solves the problem of cost minimization under equality and inequality constraints. The objective function does not include only actual costs (e.g. fuel and operational costs), but also perceived costs which introduce penalty factors.

The penalty factors influence the possibilities and the pace of compliance with possible strict regulations in the ECA zones. For example, a vessel utilizing residual fuel oil sees significantly increased costs if it operates in the ECA zones. Given that, the optimization problem aims to minimize costs including penalties, the activity of vessels utilizing non-compliant fuels increases in trips outside these zones. In addition, an oil-powered vessel has the possibility to switch fuels, subject to technical constraints, depending on the region that the vessel is travelling.

The PRIMES-Maritime model allocates the available fleet of vessels to the various trips for the transportation of the different cargo types on an annual basis. Depending on capacity and mileage constraints, it can only provide a limited number of trips of specific distance per year. This technical constraint takes into account the distance between the corresponding partners and the average speed of the vessel. The model

assumes a number of hours per day that the vessel is travelling and the annual days spent at sea, to account for the annual distance travelled by the vessels.

The model calculates pollutant emissions (NOx, CO, NMVOC, PM_{10} , SOx). Average values draw from the TRACCS database and the IMO study.

The Energy Efficiency Design Index (EEDI) applies to the new ships and it aims to promote the use of more energy efficient equipment and engines on the vessels. This measure applies in a stepwise manner mandating specific energy efficiency improvements by vessel, which are supposed to tighten every five year. The reduction rates of the EEDI apply to a "baseline" representative vessel of the ships built between 2000 and 2010. The Ship Energy Efficiency Management Plan (SEEMP) is an additional policy, which aims to improve the energy efficiency of vessels in a cost-effective manner. This policy does not only apply to newly built vessels but also to the existing fleet of vessels when it is economically viable.

The potential efficiency improvement possibilities take the form of cost-efficiency improvement curves following the logic of the PRIMES-TREMOVE transport model. This implies that in order to obtain an additional improvement in the average specific fuel consumption of the "base" vessel, the operator of the fleet needs to invest an incremental amount of money reflecting engineering costs associated with these improvements in fuel efficiency. The actual cost- efficiency improvement potential draw from literature (IMO studies 2009, 2014). Efficiency progress is endogenous, driven by fuel prices, environmental policies and standards.

L. Power and Steam Generation and Supply Models



Power sector decarbonisation is a powerful strategy allowing electricity to substitute fossil fuels in otherwise inflexible final demand sectors

L.1. Overview

PRIMES includes a very detailed model for electricity generation, trade and supply and for steam generation and distribution. The model is dynamic, solving over multiple periods (until 2050), multi-country to capture electricity trading in the European internal market, and market-oriented as it projects electricity tariffs by sector/country and closes the loop between demand and supply.

The PRIMES power and steam model applies a sophisticated optimisation algorithm to handle long-term simulation of power system operation, power plant dispatching, investment in new or refurbished power plants, supply/distribution, trading and pricing of electricity between countries and towards customers/consumers. Power market simulation is simultaneous with simulation of steam/heat market so as to capture trade-offs between cogeneration and boilers, between CHP and pure-electric plants and between self-production and distribution of steam/heat.

The PRIMES power and steam model is rich in representation of technologies, market mechanisms and policy instruments:

- The fully endogenous investment and plant operation modelling covers all known generation technologies (more than 150 distinct technologies) and very detailed representation of renewable energy sources, including highly distributed resources. Several electricity storage technologies are endogenous, including hydro with reservoir, hydro pumping, compressed air storage and hydrogen-based storage. Several CHP technologies and their technical operation limits are also included.
- Daily and seasonal variations are captured through hourly modelling of several typical days for each year. Data for typical days include power load, wind velocity and solar irradiance. Load demand is bottom-up built from projection of energy end-uses at detailed level by the PRIMES energy demand models. Demand side management possibilities are handled at detailed level based on technical potential and costs. Highly distributed generation at consumer premises is also included and is taken into account in calculating transmission/distribution losses and costs.
- Investment decisions distinguish between green-field development, construction on existing plant sites, refurbishment and extension of lifetime of plants and the building of auxiliary equipment (such as DENOX, desulphurization, CHP, CCS-ready, etc.). Investment decisions also distinguish between utility, industrial and highly distributed scales.
- The model incorporates in detail feed-in tariff and other supporting schemes for renewables and simulates individual investment behaviour in RES following project-financing considerations.
- The PRIMES power model includes reliability and reserve constraints, such reserve margin constraints to address forced outages of plants or unforeseen demand increases. The model is deterministic and handles uncertainty of load, plant availability and intermittent RES by assuming standard deviations, which influence reserve margin constraints. Ramping up and ramping down restrictions of plant operation, balancing and reserve requirements for intermittent renewables and reliability restrictions on flows over interconnectors are also included.

- Flexibility and reserve to balance intermittency from renewables is ensured simultaneously by storage (various endogenous techniques), ramping possibilities of power plants (which influence plant technology mix) and demand response.
- Regulations such as the large combustion plant directives, the (optional) emission performance standards, the best available techniques standards, the (optional) CCS-ready recommendations, the CHP directive and the Emission Trading Scheme are fully implemented in the model.
- The PRIMES power model represents the entire system of interconnectors in Europe, as well as possible AC and DC line extensions (including optional remote connections with offshore wind power in North Sea and with North Africa and Middle East).
- The model can perform simulation of different market arrangements within the internal European market, including market coupling, net transfer capacity restrictions versus load flow based allocation of capacities and others.

A novel feature in PRIMES power model is the inclusion of non-linear cost-supply curves for all types of fuels, as well as for renewable power sources, for CCS and for nuclear plant sites.

Cost-supply curves are numerically estimated functions with increasing slopes serving to capture take-or-pay contracts for fuels, possible promotion of domestically produced fuels, fuel supply response (increasing prices) to increased fuel demand by the power sector, exhaustion of renewable energy potential, difficulties to develop CO₂ storage areas, acceptability and policies regarding nuclear site development, etc.

The non-linear cost-supply curves are fully included in the power investment and plant operation optimisation.

The PRIMES power and steam model finds technology and fuel mix by minimising total system costs over a long period of time, assuming perfect foresight (optionally myopic foresight limited to medium term).

The PRIMES power/steam financial model is a separate module, which determines electricity and steam tariffs by demand sector (and sub-sector) so as to recover power/steam costs. For this purpose, the financial model simulates wholesale markets, bilateral contracting between suppliers and customers and regulated tariff setting for grid cost recovery. Electricity/steam prices are conveyed to PRIMES energy demand models, which further recalculate demand and load profiles.

The PRIMES power and steam model reports on projection by country of power plant capacities, plant operation (gross and net output), fuel consumption, generation from renewables, grid losses, emissions, investment costs, operation costs and electricity/steam prices by sector.

L.2. Mathematical Structure

Mathematical Structure

The **optimisation** is intertemporal (perfect foresight) and solves simultaneously:

- a unit commitment-dispatching problem
- a capacity expansion problem and
- a DC-linearized optimum power flow problem (over interconnectors).

The optimisation is simultaneous for power, CHP, distributed steam, distributed heat, district heating and industrial boilers and satisfies synchronised chronological demand curves of power, steam and heat, which result from the sectoral demand submodels. Dynamically the model applies a full scale capital vintage formulation (keeps track of plant vintages until the end of the projection horizon). All types of investment in all types of plants including storage are endogenous, as well as their operation and consumption.

The unknown variables include

- capacity additions by plant type (several types of capacity investment);
- extension of lifetime of plants after refurbishment, investment in auxiliary equipment;
- generation of electricity (or steam or heat) from plants on an hourly basis;
- consumption of fuels (use of more than one fuels or blending of fuels in each plant type is permitted under constraints);
- emissions, CO₂ transportation; and storage;
- injection or extraction from storage facilities on an hourly basis; and
- investment in storage equipment.

The **input (exogenous) parameters** include

- electricity demand and elasticities,
- plant fleet as existing in the beginning of projection,
- planned capacity decommissioning,
- known capacities under construction in the beginning of projection,
- grid loss rates,
- ramping possibilities of power plants by technology,
- technical restrictions of CHP plant operation,
- unit costs of investment by technology, unit variable costs, unit fixed costs,
- fuel prices.
- site development costs,
- parameters used in non-linear cost-supply curves,
- taxes and subsidies,
- ETS carbon prices,
- feed-in tariffs and other parameters for representing RES support schemes,
- costs and potential parameters for transportation and storage of captured CO₂,
- costs and potential parameters of storage technologies,
- unit costs of investment in grids, unit operation costs of grids,
- parameters expressing policy instruments and restrictions (nuclear, CCS, environmental, efficiency, CHP, etc.),
- parameters expressing cost of development of smart grids,
- parameters on uncertainty affecting calculation of reserve margins,
- restrictions on use of interconnectors,
- capacities and electrical characteristics of interconnectors.
- reliability parameters on flows over interconnectors

Non-linear relationships regard the cost of access to resources, such as fuels, RES and plant sites. Such resources are represented as upward sloping cost-supply curves

linking unit costs to cumulative exploitation. The cost-supply curves are country and resource specific and change over time in order to reflect changing conditions about potential and technology.

The **financial and pricing model** is a recursive model, which includes mixed complementarity formulations to solve a cost allocation problem.

The equations below aim at presenting the optimization problem solved by PRIMES

$$\mathbf{Min}_{G.K.P.F.H.S} z(G_{(i,n,f,s,t)}, K_{(i,n,t)}, F_{(i,n,f,s,t)}, H_{(i,s,t)}, S_{(i,t)}) \tag{1}$$

Subject to

$$\sum_{n} \sum_{t} G_{(i,n,f,s,t)} = C_{(i,s,t)} + \sum_{b} \{M_{(i,b)} P_{(b,s,t)}\} + H_{(i,s,t)}$$
 $\forall i, s, t$ (2)

$$P_{(b,s,t)} = \sum_{i} \left\{ Y_{(b,i)} \left[\sum_{n} \sum_{f} G_{(i,n,f,s,t)} - C_{(i,s,t)} - H_{(i,s,t)} \right] \right\}$$
 $\forall b, s, t$ (3)

$$F_{(i,n,f,s,t)} = hr_{(i,n,t)}G_{(i,n,f,s,t)} \qquad \forall i,n,f,s,t \qquad (4)$$

$$0 \leq \sum_{f} G_{(i,n,f,s,t)} \leq u r_{(i,n,s,t)} K_{(i,n,t)}$$
 $\forall i,n,f,s,t$ (5)

$$P_{(b,s,t)}^{min} \le P_{(b,s,t)} \le P_{(b,s,t)}^{max} \qquad \forall b, s, t \qquad (6)$$

$$\sum_{n,s} F_{(i,n,f,s,t)} \le F_{(i,f,t)}^{max} \qquad \forall i, f, t \qquad (7)$$

$$0 \le H_{(i,s,t)} \le S_{(i,t)} \qquad \forall i, s, t \qquad (8)$$

$$0 \le \sum_{s} \{ H_{(i,s,t)} : H_{(i,s,t)} \ge 0 \} \le H_{(i,t)}^{max}$$
 $\forall i, t$ (9)

$$\sum_{n} \min_{s} ur_{(i,n,s,t)} K_{(i,n,t)} \ge rm_{(i,t)} M_{s} ax \left\{ C_{(i,s,t)} + \sum_{b} \left\{ M_{(i,b)} P_{(b,s,t)} \right\} + H_{(i,s,t)} \right\}$$
 $\forall i, t$ (10)

$$\Delta \sum_{s} G_{(i,n,f,s,t)} \leq r r_{(i,n,t)} \sum_{f} G_{(i,n,f,s,t)} \qquad \forall i,n,s,t \qquad (11)$$

$$\sum_{f,n} ef_{(i,n,f,t,j)} \sum_{s} F_{(i,n,f,s,t)} \leq E_{(i,t,j)}^{max} \qquad \forall i,t,j \qquad (12)$$

Power/Steam in a nutshell, focusing on its essence and avoiding entering into details that are not necessary for the understanding.

The indices i, n, f, s, t, b and j refer, respectively, to countries, power plants, fuels, load segments (hours), years, interconnectors and emission types. Unknown variables are the electricity productions G, the power plant capacities K, the inter-country power flows P, the fuel consumptions F, injections or extractions from storage H and storage capacities S. Equation (1) is the objective function expressing total inter-temporal system costs and involving linear and non-linear cost function, including for fuels, RES and plant

sites, where applicable. These are denoted by $z(\)$ in which discount factors (weighted average cost of capital) are used to transform investment expenditures in annuity payments for capital.

Equation (2) imposes balancing between demand and production, including injection and extraction from storage and flows over interconnections. The matrix $M_{(i,b)}$ has 1, 0 and -1 elements denoting network topology. Demand $C_{(i,s,t)}$ is exogenous at this stage, but it depends on electricity prices through solving the model as a closed loop between demand and supply. Let us note that in the actual implementation, losses and self-consumption of electricity by plants are also accounted for, but this is not shown in for the sake of presentation simplicity. Also for simplicity reasons CHP, steam/heat production plants and flows over distribution grids are not shown.

The interconnector power flows are computed in equation (3), where *Y* is a matrix of power transfer distribution factors (PTDF), connecting net country power excess/deficit with inter-country power flows.

Parameter $hr_{(i,n,t)}$ denote power plants' heat rate values, and so equation (4) defines the amount of fuels consumed. Fuel blending is not shown, for simplicity. This equation has the form of inequality constraint for intermittent renewables, with $hr_{(i,n,t)}$ denoting hourly availability of renewable resources.

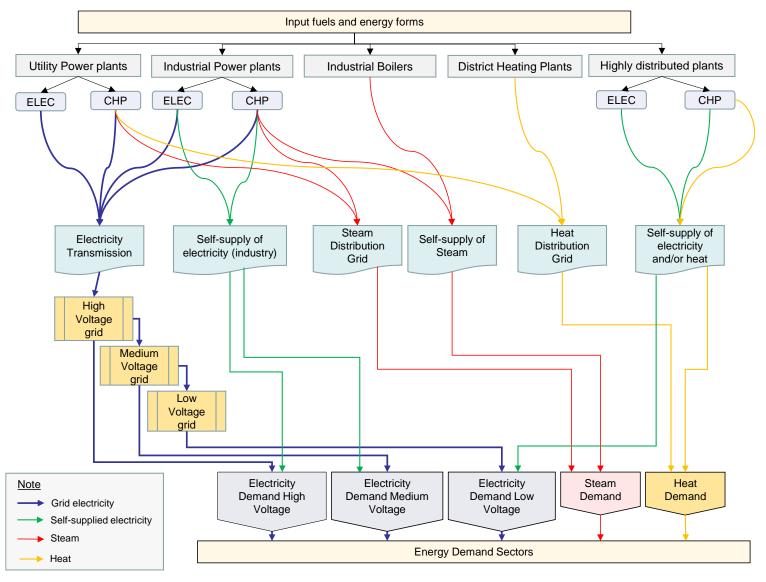
Equations (5) are the power plant capacity constraints, which use planned and forced outage rates as known parameters. For simplicity, old capacities, decommissioning, extension of lifetime with refurbishment and distinction of new investment cases (on site, new sites, auxiliary equipment, etc.) are not shown.

Equation (6) imposes upper and lower bounds on flows over interconnections to represent technical, reliability and regulatory limitations. Equation (7) makes sure that fuel consumption does not exceed maximum available fuel amounts, if applicable. Equations (8) and (9) ensure that injection or extraction from storage do not exceed injection or extraction capacity and that the amount stored in a year does not exceed storage capacity. For simplicity, losses or electricity consumption (for example in electrolysis to produce hydrogen) are not shown.

Equations (10) and (11) illustrate reserve margin and flexibility constraints respectively, where rm and rr denote system and plant-based technical parameters. Equation (12) is an example of upper bound on emissions (em being emission factors). Similarly RES obligation or security of supply constraints can be added.

Demand responses are approximated by expressing demand *C* as a function of marginal prices, which are dual to the balancing constraint. For this purpose the model is solved as a mixed complementarity problem (Kuhn-Tucker conditions).

The model formulates competition between electricity only plants, CHP, industrial boilers, district heating and between self-supply and grid supply. A stylized graph of electricity and steam/heat supply is modelled.



The above graph is modelled as follows:

- a) arrows represent flows of energy which are among the unknown model variables;
- b) boxes represent equipment with given capacities, for which investment, decommissioning and tracking of technology vintages is endogenous;
- c) demand choices between self-supply and grid-supply are endogenous based on economics and subject to upper and lower bounds expressing technical possibilities;
- d) demand choices drive supply and determine flows over the grids, hence losses of energy (losses decrease if self-supply increases);
- e) CHP plants can jointly produce electricity and steam or heat based on technical possibilities represented in the model;
- f) overall cost optimisation, subject to min and max bounds, drives competition between CHP and boilers (it is also influenced by policies).

L.3. Model Features

L.3.a. Representation of Plants

The PRIMES database includes an inventory of all power plants in Europe. The individual plants are grouped in a large number of categories, defined according to fuel type, technology, CHP and scale (utility, industrial). A calibration model determines heat rates and other operational parameters by group of plants, by simulating the structure of power generation and consumption of fuels in past years (2000-2010) aiming at matching aggregate figures with published statistics by Eurostat. So the PRIMES model data for old plants are close to reality and thus the model is validated.

Representation of Blending of fuels Plants

A power plant category in PRIMES has thermal (fuel consumption function and fuel blending possibilities), operational (gross and net capacity, ramping rates, technical minimum, planned and forced outage rates), age (commissioning date, refurbishment dates, date of planned decommissioning), cost (capital cost, fixed O&M cost, variable operating cost) and environmental (emissions, pollution prevention equipment) characteristics. These characteristics are known for plants existing in the beginning of projections and also for plants which are under construction and their commissioning date is known. For new plants, which are candidate for investment, the data for plant characteristics are drawn from a technology forecasting database and are subject to change over time reflecting technical progress. In future times, each plant preserves the characteristics as at construction date.

L.3.b. Investment modelling

Investment in new power plants distinguishes between two cases: a) construction on a new site, b) construction on an existing plant site if available area allows for. Obviously, the former is more costly than the latter. PRIMES maintains an inventory of available plant sites, by type of technology, and projects dynamically site availability depending on projected decommissioning and new constructions.

Investment modelling

Optionally the model treats power plant investment in new plants as integer multiples of generic plant sizes (which are different per plant type).

The building of equipment in the electricity and steam system 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. Furthermore, under the myopic anticipation regime, the model considers that the plants can be constructed and immediately used within the 5-years runtime period of the model. In this sense, the model operates as if the current 5-years period is perfectly known by the decision-maker.

Old plants, as well as new plants, which are projected by the model, are considered for possible refurbishment when reaching their planned decommissioning date. Refurbishment implies improvement of technical characteristics and extension of lifetime, and may include environmental upgrading. Capital costs of refurbishment are lower than cost of new investment, but the lifetime extension is limited. Exogenous parameters reflect technical possibilities, or impossibility, of refurbishment for certain plant categories (defined by country). The refurbishment decisions are simultaneous with new investment decisions and are based on economics. Fixed O&M costs are assumed to increase with plant age and this may drive premature decommissioning under certain economic circumstances.

L.3.c. Blending of fuels

The model also considers the possibility of building auxiliary equipment to an existing plant or to a new plan later than construction. Auxiliary equipment include pollution prevention facilities (for NO_x , SO_2 and/or for PM), CO_2 capture equipment and steam

CCS

cogeneration plant extension. Regulations, emission reduction policies, carbon prices and steam demand are drivers of such plant upgrades. Building auxiliary equipment implies additional capital costs and may imply reduction of heat rates of plants. Exogenous parameters are used to represent technical possibilities and restrictions about building auxiliary equipment. The model also represents plant categories, which include such auxiliary equipment at construction time. These plant types (combustion plants with full pollution prevention equipment, CHP plant with several CHP technologies and CCS plants with several technologies) are more efficient and less costly than plants for which auxiliary equipment is built at a later stage. Under good foresight conditions, it is usual that plants with auxiliary equipment at built times are preferred for economic reasons. However, in other policy circumstances, e.g., regulations such as mandatory CCS or large combustion plant directives, it may be economic to retrofit old plants by adding auxiliary equipment.

The model includes an endogenous possibility of using more than one fuel type in some plant types (both in power plants and in industrial or district heating boilers). The fuel mix decision is based on economics but the fuel mix are restricted through exogenous upper and lower bounds. Fuel blending is used in case of co-firing biomass products, or industrial by-products (e.g. derived gas) and is possible in few combustion technologies.

L.3.d. Scale of generation activity

The model put emphasis on the representation of plant efficiency, cost and performance as a function of plant typical sizes. The size classes are associated to three stylised scales of generation business, namely utility, industrial and highly distributed scales. Utilities can invest in large size plants and benefit from economies of scale, while industrial power and steam producers can invest only in relatively small size plants have better access to steam uses and markets. Distributed generation plants are very small scale and are very costly but save over grid losses and costs. The cost gap between plant sizes is considered to decrease over time and thus distributed generation gradually becomes more attractive. A similar trend has been observed for combined cycle plants compared to large-scale open cycle plants. Nuclear costs are also supposed to decrease with scale.

Scale of generation activity

L.3.e. CHP

Cogeneration is represented as an efficient frontier of possible electricity and steam combinations from a plant. The possibility frontiers are specified for various CHP. Both the choice of CHP technologies and the operation mode (mix between electricity and steam production) are endogenous in the model. The operation possibilities are restricted by feasible combination of electricity and heat output, which are different, by plant technology. The CHP operational constraints delimit maximum electric power and minimum steam combinations as a locus of an iso-fuel line.

L.3.f. CCS

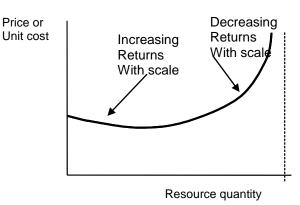
CHP

The PRIMES database includes three generic carbon capture technologies (CCS), namely capture at post-combustion stage, capture at pre-combustion stage and the oxyfuel technology (which consists in burning with oxygen instead of air). The generic carbon technologies apply to a series of power plant technologies, including conventional steam turbine plants, supercritical steam turbine plants, fluidized bed combustion plants, integrated gasification combined cycle and gas turbine combined cycle plants. The model represents transport and storage of CO_2 through reduced-form inter-temporal cost-supply curves, which are specified per country.

L.3.g. Nonlinear cost curves

The power agent's cost optimization takes into account non-linear cost supply curves of resources used in power generation, as for example for fuels, renewables, sites for nuclear investment, cost of storage of CO₂ captured, etc.

These cost supply curves incorporate information about the maximum potential of the resources or the decreasing returns of scale associated to the amount used.



Nonlinear cost curves

L.3.h. Plant dispatching and system operation

The power model can handle preference or obligations about using domestically produced fossil fuels (e.g. lignite) by assigning low cost values for some of the first steps of the cost-supply curves for such fuels. In the same way, the model can handle take-or-pay obligations, for example for imported natural gas. The low cost values would reflect a virtual "subsidy" on fuel purchase costs, which however is not accounted for in transactions but only influence economics of fuel mix. Costs used for price determination and costs reported by the model account for actual payments (fuel purchase costs, or fuel production costs). Low prices are attributed to byproducts, such as blast furnace gas, coke-oven gas, refinery gas, reflecting only variable costs

Plant dispatching and system operation The model represents demand variability for electricity and steam/heat by including hourly fluctuation of load in typical days (one for winter and one for summer in the reduced model version and nine typical days in the extended model version). Data for annual load curves, from the national TSOs and other sources, are aggregated to obtain equivalent load curves by typical day.

The operation of all modelled plants and the use of energy input resources are calculated on an hourly basis for each typical day (load segments). Hourly profiles of intermittent renewable sources are supposed to be known at country level. Load segment synchronisation also applies for electricity and steam/heat; this feature is important for capturing the operation of CHP plants and competition between cogeneration, boilers and distribution of steam/heat.

The model associates a demand fluctuating profile to every use of electricity and steam or heat included in the demand sector models and for energy demand in the energy branch. Special focus has been devoted to represent various optional profiles of recharging car batteries. By adding up the sectoral load profiles, the model determines aggregate load profiles by country.

Load profiles change over time. By scenario they also vary, depending on the relative shares of various energy uses, the prices (which are higher for sectors with low load factors), the degree of energy savings (and the use of more efficient equipment) and special demand side management measures including smart metering. The latter motivate battery recharging at off peak hours.

When load profiles become smoother, capital-intensive power technologies are favoured and reserve power requirements are lower, implying lower overall costs.

The various power plants contribute to reserve power through differentiated estimates of their capacity credits. Variable RES power plants have low capacity

credits. In order to meet reserve power constraints, the power model may require additional thermal power (evidently from low capital-intensive technologies, such as gas turbines), or may invest in pumped storage (depending on maximum possibilities and costs), or may use import-exports more intensively. Similarly, flexibility services depend on ramping possibilities of plants. Operation and investment in storage is endogenous and compete against investment in flexible power plants. Costs of developing reserves and flexibility service capacities are calculated and reflected onto electricity prices, which are set at levels to recover total cost.

The model solution with endogenous flows over interconnections simulates common balancing and/or market coupling and operation by load segment are synchronised across the countries.

L.3.i. Environmental Policies

The PRIMES model computes emissions of air pollutants, such as SO2, NOx, PM, VOC, from power generation and other types of industrial combustion.

End-of-pipe abatement is represented in the power model: auxiliary FGD, DENOx, electrostatic filters, etc. are options for investment associated to existing or new plants.

Usually in the scenarios, it is assumed that according to the Large Combustion Plant directives, all new power plants shall be equipped with such end-of-pipe abatement devices, and so they are included in new power plant investment.

Other provisions for old plants, such as transitory measures specifying maximum operating hours for old plants, are represented in the model as constraints on specific plants. Possibilities for retrofitting are endogenous.

Environmental policies

The model allows for imposing ceilings on atmospheric emissions and associating a shadow price (e.g. price of a SO2 permit). The provisions of the IPPC Directive on Best Available Technologies are reflected upon the technical (hence economic) characteristics of new technologies in all sectors. Similarly, other regulations are handled, e.g. lighting.

 CO_2 emissions from industrial processes (non-energy related) are handled in relation to industrial production of materials (e.g. cement). The model includes a marginal cost abatement curve for reducing emissions and CCS investment for more drastic emission cuts. Costs for CCS for processes are determined by accounting for capital and variable costs. Electricity consumption for capturing is determined and adds to total electricity demand. The PRIMES power/steam model is fully linked with the ETS market simulation model of PRIMES and takes carbon prices from the latter. Sector-specific carbon emission constraints as well as emission performance standards by plant type can also be handled in the model.

Data Base

L.4. Data sources of PRIMES power and steam model

The PRIMES power and steam model uses the following data sources:

- Inventory of existing power plants in all European countries (35 countries in total) which is based on Platts and on ESAP; the data base includes power plant name, location, name of owner, technology type, whether it is CHP or not, fuel burning possibilities, gross and net power capacity, pollution control, date of system commissioning, dates of possible refurbishment, indicative date of decommissioning.
- Surveys of power plants under construction, which are qualified as plants with exogenously fixed commissioning date; information by plant similar to inventory.

- Eurostat statistics (complemented using data from ENTSOE, EURLECTRIC and IEA) on power capacities, power generation by fuel or by plant type, fuel consumption.
- CHP surveys by Eurostat (complemented by various sources and studies). The CHP surveys are used in combination with plant inventory data and Eurostat energy balances data to construct a complete statistical picture of cogeneration by country. In this picture, industrial CHP including CHP on-site is fully represented; this modifies Eurostat data because Eurostat does not show steam production and fuel consumption by industrial on-site CHP separately (Eurostat shows only if CHP is selling steam to steam markets).
- District heating surveys (from associations and industry). Surveys of industrial boilers by sector (from industry)
- ENTSOe and national TSO/DSO data on electricity grids and interconnectors
- Data set of technical-economic characteristics of plant technologies that are considered as candidates for investment. The data include: overnight investment costs, fixed operation costs, variable costs, self-consumption rates, fuel efficiency curves, ramping rates, technical minimum capacity, cost of start-up/shut-down, emission factors (depending on fuel), CO₂ capture possibilities if applicable, technical maturity parameter (risk premium), distinction of scale (utility, industrial, distributed). Technical data on possible configurations of electricity and steam outputs of various CHP technologies. All technical-economic characteristics of plant technologies change over time. Data are based on surveys of several studies and databases, including IEA, VGB, etc.
- Potential of renewable energy sources for power generation. RES are classified by technology and also in intensity classes by country. Potential data are used to quantify cost-supply curves. Data come from various sources: ECN, DLR, GREEN-X, Observ'er, etc. Wind velocity and solar irradiation data by country (TSOs and private databases).
- Surveys on fuel prices, fuel procurement contracts, electricity prices by sector and by component, grid tariffs, etc.
- Data on policies: feed-in tariffs, other RES supporting schemes, environmental legislation etc.
- Underground CO₂ storage possibilities by country.

L.5. Modelling of the EU power network and market

European Internal Market PRIMES has two options for computer running: a) full optimisation including all European countries simultaneously, b) separate optimisation per country with fixed net imports, which are obtained after a full model running. The second option is used in scenario variants in order to reduce computer-running time.

The regional model optimisation fully incorporates all existing and future interconnection capacities (and Net Transfer Capacities). Electricity flows are endogenous based on solving a DC linearized optimal power flow problem simultaneously with all country optimisations. This means that an injection to a bus (in the model a country node) is propagated to all interconnecting links. When interconnection use is at capacity limit, marginal costs differ by node (country). Interconnectors have limitations based on thermal capacity and feature reactance and resistance.

The optimal power flow (OPF) problem seeks to control generation/consumption to optimise certain objectives such as minimizing the generation cost. Power flow constraints can be approximated by some linear constraints in transmission networks, and then OPF reduces to a convex program.

New interconnectors to be built in the future are projected based on planning by TSO or on exogenous plans (e.g. Super-Grid, etc.). Power flows in DC lines are treated differently than those in AC lines. The latter are linked with the countries' net power surplus or deficit by the power transfer distribution factors (PTDFs). On the other hand, flows in DC lines are set by the solver when performing the optimization without any link between each other (apart from being such that each country's balance is maintained). This reflects the fact that the link's operator can control the flow in a DC-link. Additional constraints mirroring Net Transfer Capacities or other reliability constraints can be introduced. The choice of DC stems from anticipating a possible evolution of the European grid, where a DC backbone could act as a highway network that would bring renewable energy (produced in remote sites such as in North Sea and in North Africa) to the big load centres of the continent.

This regional modelling approach can be also optionally used to study market coupling policies or common balancing with coordinated management of interconnectors. PRIMES can solve the power system model simultaneously by region (alternative regional configurations are possible, user-defined), with endogenous links between regions, which indicatively are the following:

- 1. **Central Western Europe**: France, Germany, Belgium, Netherlands, Luxembourg,
- 2. **Central South Europe**: Switzerland, Austria, Italy, Slovenia, Malta
- 3. Eastern Europe: Poland, Czech Republic, Slovakia, Hungary
- 4. **Nordic and Baltic**: Norway, Sweden, Finland, Denmark, Lithuania, Estonia, Latvia, Kaliningrad
- 5. **Iberian**: Portugal, Spain
- 6. **South East Europe**: Romania, Bulgaria, Greece, Albania, Croatia, Bosnia & Herzegovina, FYROM, Serbia-Kosovo-Montenegro, Turkey
- 7. **British islands**: UK, Ireland

External links (with exogenous or endogenous net imports): Russia, Ukraine, Moldova, Belarus, Morocco, Middle East and North Africa (by country)

L.6. List of plant technologies

Solid fuel power technologies	Gas firing power technologies	
1. Steam Turbine Coal Industrial	1. Steam Turbine Gas Industrial	
2. Steam Turbine Coal Conventional	2. Gas Turbine Gas Industrial	
3. Steam Turbine Coal Supercritical	3. Gas Combined Cycle Industrial	
4. Fluidized Bed Combustion Coal	4. Steam Turbine Gas Conventional	
5. Integrated Gasification Combined Cycle Coal	5. Gas Turbine Combined Cycle Gas Conventional	
6. Pulverized Coal Supercritical CCS post combustion	6. Peak Device Gas Conventional	
7. Pulverized Coal Supercritical CCS oxyfuel	7. Gas Turbine Combined Cycle Gas Advanced	
8. Integrated Gasification Coal CCS post combustion	8. Gas combined cycle CCS post combustion	
9. Integrated Gasification Coal CCS pre combustion	9. Gas combined cycle CCS pre combustion	
10. Integrated Gasification Coal CCS oxyfuel	10. Gas combined cycle CCS oxyfuel	
11. Steam Turbine Coal Industrial	11. Internal Combustion Engine Gas	
12. Steam Turbine Lignite Conventional	12. Peak Device Gas Advanced	
13. Steam Turbine Lignite Supercritical	13. Small Device Gas	
14. Fluidized Bed Combustion Lignite	Biomass firing power technologies	
15. Integrated Gasification Combined Cycle Lignite	1. Steam Turbine Biomass Industrial	

- 16. Pulverized Lignite Supercritical CCS post combustion
- 17. Pulverized Lignite Supercritical CCS oxyfuel
- 18. Integrated Gasification Lignite CCS post combustion
- 19. Integrated Gasification Lignite CCS pre combustion
- 20. Integrated Gasification Lignite CCS oxyfuel

Oil firing power technologies

- 1. Steam Turbine Refinery Fuels
- 2. Gas Turbine Diesel Industrial
- 3. Steam Turbine Fuel Oil Conventional
- 4. Peak Device Diesel Conventional
- 5. Steam Turbine Fuel Oil Supercritical
- 6. Fuel Oil Supercritical CCS post combustion
- 7. Integrated Gasification Fuel Oil CCS pre combustion
- 8. Internal Combustion Engine Diesel
- 9. Peak Device Diesel Advanced
- 10. Small Device Light Oil

Boilers for industry and district heating

- 1. Fuel oil boiler
- 2. Coal boiler
- 3. Lignite boiler
- 4. Diesel oil boiler
- 5. Gas boiler
- 6. Derived gas boiler
- 7. Biomass boiler
- 8. Waste energy boiler
- 9. Biogas boiler
- 10. Electric boiler
- 11. Hydrogen boiler

Storage

- 1. Hydro with reservoir
- 2. Hydro Pumping
- 3. Compressed Air Storage
- 4. Hydrogen from electrolysis using RES
- 5. Hydrogen from electrolysis to mix in gas supply
- 6. Power to gas technology

Industrial CHP Plants (by industrial sector)

- 1. Coal
- 2. Lignite
- 3. Natural Gas
- 4. Derived gas
- 5. Oil
- 6. Biomass
- 7. Waste

- 2. IG Biomass CC Industrial
- 3. Steam Turbine Biomass Solid Conventional
- 4. Peak Device Biogas Conventional
- 5. High Temperature Solid Biomass Power Plant
- 6. Peak Device Biogas Advanced
- 7. Small Device Biomass Gas
- 8. MSW incinerator CHP
- 9. Internal Combustion Engine Biogas

Nuclear technologies

- 1. Nuclear fission second generation
- 2. Nuclear fission third generation
- 3. Nuclear fission fourth generation
- 4. Nuclear Fusion

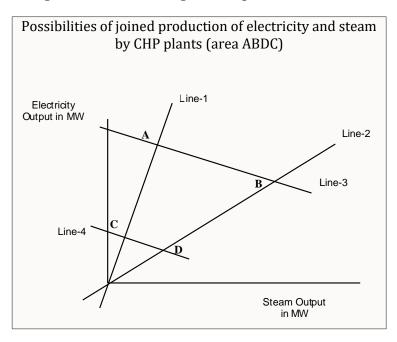
RES technologies

- 1. Wind Power Low Resource
- 2. Wind Power Medium Resource
- 3. Wind Power High Resource
- 4. Wind Power Very High Resource
- 5. Wind Offshore Power Low Resource
- 6. Wind Offshore Power Medium Resource
- 7. Wind Offshore Power High Resource
- 8. Wind Offshore Power Very High Resource
- 9. Wind small scale
- 10. Solar PV Low Resource
- 11. Solar PV Medium Resource
- 12. Solar PV High Resource
- 13. Solar Thermal
- 14. Solar PV Very High
- 15. Solar PV small scale rooftop
- 16. Tidal and waves
- 17. Lakes
- 18. Run of River
- 19. Geothermal High

Cogeneration technologies

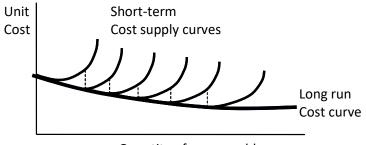
- 1. Combined cycle with extraction
- 2. Combined cycle with Heat Recovery
- 3. Backpressure steam turbine
- 4. Condensing steam turbine with post firing
- 5. Condensing steam turbine of large power plants
- 6. Gas Turbine with heat recovery
- 7. Internal combustion engine with cogeneration
- 8. Others backpressure steam for district heating
- 9. Fuel Cell
- 10. Very small scale Gas Turbine with Heat recovery

Illustration of the power-steam production possibilities of cogeneration technologies as represented in PRIMES



L.7. Technology Progress

The technical-economic characteristics of technologies are assumed to change over time (as a result of R&D and eventually economies of scale in mass production). The rate of change of technical-economic characteristics over time is an assumption of the modelling which may be altered depending on the scenario.



Quantity of a renewable resource

Depending on the scenario, learning-by-doing and economies of scale effects are introduced in the quantification of technical-economic parameters for both demand and supply-side technologies. However, the PRIMES model does not include fully endogenous learning-by-doing mechanism in the power sector model (because of non-convexity problems) but handles learning in the design of scenarios and by modifying parameters ex-post.

Technology progress is also assumed regarding the cost gap between technologies of different scales, for example small-scale wind vs. large-scale wind parks. Scale economics are also included through the representation of plants differently by stylised scale (i.e. utility, industrial, distributed). A plant at industrial scale has worse economics than plants at utility scale but benefits from possibilities of using CHP and performing self-supply. Highly distributed plants, located at consumer premises, are more expensive as they lack economies of scale, but bring benefits by avoiding grid costs and losses. These mechanisms are simulated in the model.

L.8. Investment and Renewables

RES power

Investment in new RES plants and operation of RES plants are fully endogenous. The stochastic or variable RES (wind, solar PV, solar thermal, small hydro, tidal wave) are represented as a **deterministic** equivalent power capacity: nominal capacity is reduced according to the yearly resource availability rate and is assumed to operate hourly at a share of nominal capacity according to exogenous resource availability statistics by hour.

The hydro resources are considered dispatchable but constrained by yearly available water flows: the model shows that they are used at peak hours until water constraint is met.

The stochastic or variable RES get a "capacity credit" which is much lower than nominal capacity. It varies by country and scenario depending on total deployment of variable RES: capacity credit decreases with RES quantity deployed and differs by country depending on assumptions about dispersion of RES sites. Capacity credits enter the reliability or reserve power constraints: in case of large development of variable RES, the model determines investment in low capital-intensive thermal power plants (back-up) in order to meet reliability and reserve power constraints. Thus costs increase and the competitiveness of variable RES decrease.

Flexibility of the power system to balance fluctuating RES is endogenously built and reflected on investment as ramping possibilities differ by plant technology.

Large-scale storage is endogenous in the model (hydro-based pumped storage, air compression and hydrogen-base storage): depending on economics, storage simultaneously smooth load and accommodates transfer of RES energy from times when RES availability exceeds load to times when RES is insufficiently available.

The model represents possibility for producing **hydrogen** from electrolysis and blending hydrogen with natural gas (up to a maximum share of 30-40%). In case of high RES development, hydrogen production, assumed to take place at off peak hours, helps smoothing out the load curve, relaxing reserve power constraints and hence allowing for more variable RES capacities

Regional power market operation under interconnection constraints also help development of RES capacities and is simulated by the model (common balancing).

Cost of direct (shallow) connection of RES plants (wind, solar) with the grid are assumed to be included in the unit investment cost of RES technologies; this is also the case of offshore wind (assumed to develop at small distances from the coast). For remote wind offshore, the model explicitly considers grid development for connection. The model formulates impact of stochastic RES on power grid investment and costs, distinguishing between offshore wind, onshore wind, solar PV and the level of decentralisation.

Non-linear cost-potential curves for renewable resources (unit cost depend on quantity and time) reflect difficulty of getting access to resource, availability of sites, acceptance, grid connection difficulties, performance and for biomass land and waste energy resource availability. Data on Potentials from: ECN (Admire-Rebus database), DLR (database), Green-X, RES-2020, Observer, national sources, various studies and a special data collection for biomass resources.

Investment in RES is projected on economic grounds as for any other technology. The relative competitiveness of RES depend on technology progress (change of technical-economic characteristics over time) and on policies supporting RES directly or indirectly.

The unit cost of RES energy production is composed of the annuity payment for capital (depending on WACC and risk premium), the fixed O&M cost and the variable cost, where capital and fixed cost are divided by the number of yearly hours of full capacity production, which depends on the resource availability rate. The capital part of the cost of RES investment as perceived for decision making (not for actual payment) is increased by a rate reflecting the non-linearly increasing cost-potential curve, which may change by scenario according to assumptions about RES facilitation policies.

Building a RES plant on an existing site (after RES plant decommissioning) is considered to be cheaper than investing on a new site. Thus, the model captures the fact that replacement of obsolete RES plants is much less expensive than building a new RES plant.

For the biomass resources and commodities the model determines prices which span the whole chain of activities and processes for producing and transforming feedstock, reflect the possibly increasing cost of land use (for crops) and of collecting wastes and price-setting components which reflect competition (for example pricing relative to

RES Feed-in tariffs: power purchasing agreements.

RES Obligation: in power generation a certain percentage of electricity generated must come from RES (modelled as a constraint).

RES blending obligation: fixed blending rate of biofuels for transportation liquid fuels or for distributed gas.

Green certificates, Guarantees of Origin or generally RES objectives: a RES shadow value is introduced (in power generation and/or in other sectors) providing a price signal to decision makers for getting benefits from RES; the level of the RES value changes iteratively until the desired volume of green certificate or of the RES target are obtained; when iterating by keeping the same level of RES value across sectors in a country or across countries, the model can simulate RES certificate trading or other forms of RES obligation exchanges between countries. Higher RES values mirror more enabling policies for RES penetration.

RES facilitation policies: meant to include actions, scenario-specific, which increase RES potential and make cheaper the access to potential (reflected onto the parameters of the cost-potential curves).

Note: RES as % of gross final energy is handled by PRIMES as a target, either by sector, or country or EU-wide.

substitute fuels).

Direct RES subsidies reduce unit cost of capital or commodity prices (for biomass).

Feed-in tariffs are modelled as power purchasing agreements and they are subject to budget constraint (by RES or overall). Investment in RES under feed-in tariffs is modelled separately by simulating investment decision on individual projects based on pay-back period calculated given the feed-in tariff amount. The model calculates the probability of individual investment as a function of feed-in tariff level. This mimics project finance accounting for RES investment. Payment for feed-in tariffs under long-term PPA is fully accounted in the model. Revenues for these payments are based on a special RES levy, applied directly on consumer tariffs. The amount of the levy is endogenously calculated as a difference between RES feed-in tariffs and marginal system costs (known from simulation of wholesale markets) since RES displace fuels used by thermal generation.

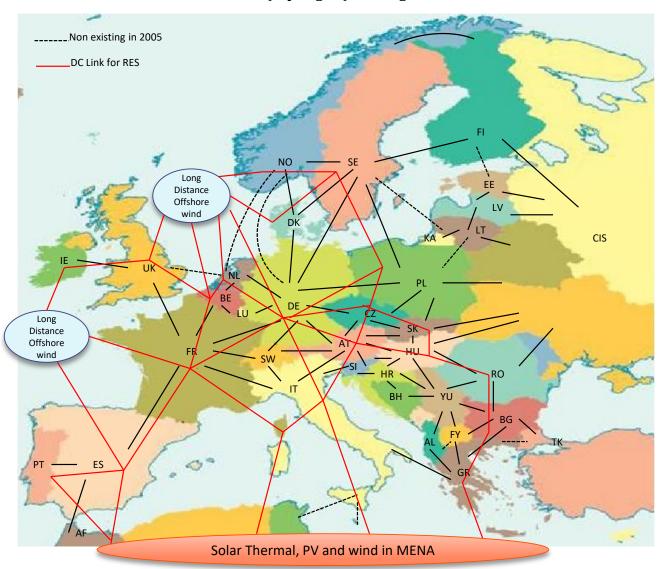
Green certificates or renewable obligations are explicitly modelled as constraints, which act on top of other support measures.

When the entire PRIMES model is used to determine distribution of a renewables target across sectors, including the power sector, the amount of generation from renewables in the power sector is unknown. To find the distribution across sector, the model introduces a shadow price of renewables obligations by sector, assumes that this shadow price is equal in all sectors and varies its level until the overall RES target is met. The shadow price of the RES obligation is called a RES-value (e.g. EUR/MWh from RES) and can be interpreted as a virtual subsidy to generation from RES.

In power generation RES investment decisions are treated simultaneously with system operation and reserve constraints, as well as with grid operations and costs, which indirectly influence RES competitiveness.

RES curtailment is endogenous and depends on economics of the system without affecting payments to RES owners under power purchasing agreements.

Illustration of using PRIMES to simulate conjoint development of renewables and the EU network (super-grid) at a large scale



L.9. Investment and Nuclear Energy

Nuclear

Investment in nuclear power is treated as an economic decision. Nuclear deployment depends on electricity demand, load profiles, economic features of competing technologies and carbon prices. Nuclear decisions, taken together with all other power plant decisions, fit within least cost capacity expansion to a long-term horizon

(under perfect foresight) and within least cost unit commitment and is influenced by policy drivers for example by carbon prices.

Investment decision on nuclear distinguish between:

- Extension of lifetime of an existing plant (involves investment cost lower than for a new plant)
- Building a new nuclear plant on an existing site, if such possibility exist (investment cost is lower than for a new site)
- Building a new nuclear plant on a new site (Greenfield development)

The unit cost of nuclear plant investment differs by country depending on economies of scale experienced in nuclear industry: it ranges from first-of-the-kind investment costs for countries that may invest in nuclear for the first time to investment cost levels corresponding to high economies of scale. The unit cost of investment depends on the nuclear technology: second, third and fourth generation technologies are represented in the model database. Regarding new nuclear plants, In PRIMES, nuclear second refers to generation II reactors until 2015 and will include after 2015 the commercially most advanced reactors (e.g. EPR, AP, VVER 1200) currently summarized under generation III and III+; nuclear third refers to the remaining set of generation III+ reactors and nuclear fourth refers to generation IV reactors. Technology progress over time is represented differently by nuclear technology. 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.

The lifetime of old nuclear plants is set as specified in their license and is extendable upon investment. New nuclear plants are supposed to have lifetime of 40 years, extendable after investment.

The model can represent the following possible policy constraints on nuclear investment:

- No nuclear in the future
- Phase-out of nuclear
- Fixed decommissioning dates for specific plants
- Permission of extension of lifetime (as economic decision or as a decided policy)
- Permission of investment only on existing sites
- Upper bounds on nuclear expansion
- No constraints on nuclear expansion

To reflect growing cost of developing new nuclear sites, the model includes site specific cost elements, which differ by country and evolve over time (or set as a scenario specific assumption). These costs are based on cost-potential curves, which apply only for Greenfield investment and are nonlinear with increasing slopes. Policies aiming at higher nuclear are represented by shifting the nuclear cost-potential curve to the right (lower cost for equal potential).

The PRIMES model database includes a detailed inventory of nuclear power plants that are in operation in Europe and their characteristics and includes new nuclear projects, which are under construction or in consideration.

L.10. Investment and CCS

 CO_2 capture, transportation and underground storage (CCS) is one of the possible means of reducing CO_2 emissions from combustion of fossil fuels in power plants and in industry. Driven by emission reduction targets or by carbon pricing, CCS (if considered available at a certain period and countries as part of scenario

CCS

assumptions) competes with other means, such as carbon free power generation (renewable energies, nuclear), the fuel switching towards low emitting forms and the reduction of energy consumption.

The power plants with carbon capture are more expensive in terms of capital investment and operation costs than similar plants without carbon capture. Moreover, their net thermal efficiency is much lower, since carbon capture needs electricity to operate.

The costs of transporting and storing CO_2 are modelled through non-linear cost curves by country, bounded by storage potential (set exogenously for each scenario per period). Costs increases with quantity stored. Data come from TNO and JRC.

It is assumed that CO_2 transportation and storage are offered by regulated monopolies operating by country (CO_2 exchanges between countries are mot modelled in the current model version). Investment is considered as exogenous and varies by scenario. Transportation and storage activities operate under strong economies of scale, bear very high fixed costs (and small variable costs) and face high uncertainty about future use of infrastructure. Prices for transportation and storage services are determined based on levelized total development costs and investments over time on an anticipated cumulative demand for the service.

Public acceptance issues and other uncertainties are expressed through parameters shifting the cost-supply curve to the left and up (making more expensive the service and lowering potential).

Scenarios involving delays in CCS development may be simulated by introducing particularly high storage and transport costs for a limited period.

The pilot CCS plants envisaged for 2020 are assumed to have reserved specific sited for CO2 storage at rather short distances with small marginal costs for storage.

The CCS investment decisions are integrated within the PRIMES sub-model on power and steam generation. The CCS technology for power plants is represented in two ways: a) as typical new power plants enabled with CCS considered as candidate for investment, b) as auxiliary technologies candidate for retrofitting existing power plants or plants built (endogenously by the model) without initially having the CCS.

This flexible representation allows assessment of various policy options, as for example the "capture-ready" options or mandatory CCS measures.

L.11. Financial and Pricing Model for Electricity, heat and steam

Financial and Pricing Model

The financial power/steam model operates after the run of the power/steam optimization model.

The first step is to calculate in detail all costs of power and steam/heat production, based on the results of the power/steam optimization model. The costs, separately for electricity, steam and heat, are calculated as time series and include:

a) Capital investment costs: total investment expenditures and annuity payments for capital calculated using a weighted average cost of capital, which mirrors business practices, and differ by plant scale, i.e. utility, industrial and distributed. Capital costs of non-yet amortized old plants are included.

- b) Variable costs which include variable operating, fixed maintenance, fuel costs and payments for fuel taxes, emission taxes and ETS auction payments¹².
- c) Costs of electricity supply and trading (by country and by voltage category)
- d) Total system payments for direct subsidies or power purchasing agreements (feed-in tariffs) for renewable plants.
- e) Other costs including for public service obligations if applicable.
- f) Grid costs, separately by grid type, calculated according to a regulated asset basis methodology, which includes capital costs of old infrastructure, cost of new investment and operating/maintenance costs.

The electricity prices in PRIMES are calculated in order to recuperate all costs, including capital and operating costs (and possible stranded investment costs), costs related to schemes supporting renewables, grid costs, and supply costs.

The next step aims at determining the electricity (and steam/heat) prices by category of customer (sectors and sub-sectors of demand). Each customer type has a load profile, which is calculated in the PRIMES demand models, and partly the customer may be self-supplied. The aim is to allocate variable, fixed, and capital costs as well as grid and other costs to each category of customers as it would be resulting from a well-functioning market in which suppliers would conclude efficient and stable bilateral contracts with each customer category based on the specific load profile of the customer.

To do this, the following calculation steps are performed:

- a) Simulation of virtual wholesale energy-only markets by country in order to estimate marginal system prices reflecting fuel marginal costs.
- b) Calculation of marginal long-run costs of the system, including capital costs by vertical time zone of the marginal plant, in order to allocate capital costs to customer-types according to their load profiles; this step can be used to estimate capacity remuneration which is eventually needed to address the "missing money problem" of the energy-only wholesale market approach performed in the first step.
- c) Allocation of costs of energy losses in transmission and distribution to customer types according to their connection to voltage categories depending also on the share of demand covered by grid electricity (self-supply is excluded).
- d) Matching of load profiles of customer-types with the duration curve of system marginal prices including long-run capital cost components with customers sorted in descending order of their load factor mimicking bilateral contracting. Calculation of payments by customer category and comparison to total recoverable costs.
- e) Calculation of fixed capital/maintenance costs not recovered from prices determined in previous step. Inclusion of possible other costs, such as costs for public service obligations, ancillary services, etc. Allocation of these remaining fixed costs to customer categories using a Ramsey-Boiteux method:

¹² In case of ETS with free allocation of allowances, the cost calculation considers that allowances have an opportunity cost, based on ETS carbon prices. Depending on the scenario, the model allows for assuming that part pf this opportunity cost can be passed through to consumer tariffs, depending on the intensity of market competition.

a mixed complementarity problem, which allocates fixed costs at inverse proportions of assumed price-elasticities by sector. At this stage, cost mark-up factors (positive or negative) are exogenously added to reflect different market circumstances and regulatory practices, including price regulations, pricing below total recoverable costs (which is the case in some countries), pricing above recoverable costs due to market power, practices of cross-subsidization between consumer categories, etc.

- f) Calculation of revenues of RES supporting schemes and comparison to payments, in order to determine a RES levy to be paid by customers. Revenues of RES are estimated based on short-term marginal system costs calculated in the first step of the process, to reflect marginal fuel costs displaced by the use of RES. The level of the RES levy may vary by customer category depending on policy assumptions.
- g) Grid costs are recovered from grid use tariffs determined by customer category, depending on connection to voltage category. The grid tariffs are calculated as levelized long-term prices as required to recover regulated asset basis, using an assumed discount rate which mirrors regulation practices in the different countries.
- h) Calculation of final end-user prices by sector based on prices of virtual bilateral contracting, allocation of remaining fixed costs, grid and losses tariffs, RES levy, etc. Recovery of total system budget is ensured depending on assumed mark-up factors on costs.
- i) End-user excise tax and VAT rates are added to electricity prices. These prices are transmitted to PRIMES demand models.

Prices of distributed steam and heat follow a similar, but simpler, methodology. Recovery of costs of steam and heat distribution networks is based on tariffs calculated as levelized prices using regulated asset basis. The price of steam produced by CHP is calculated based on opportunity costs: they reflect the marginal cost of avoided boiler use.

L.13. Simulation of Oligopoly Competition in Electricity Markets

Market Competition Model Version To study regulatory issues related to market competition at national and EU levels, the PRIMES model uses a modified version of the power/steam model.

As mentioned above, the standard power model solves least cost optimization, which corresponds to perfect long-term market competition. Electricity prices computed on this basis reflect long-run marginal costs. In these conditions, investment schedules as projected by the model exactly match demand and reserve and flexibility requirements and investors fully recover capital costs. Studying regulatory policies requires dealing with possible market imperfections and situations where investors may not fully recover capital costs unless exercising market power or receiving capacity remuneration.

The market competition version of the power/steam model introduces competition between generation and supply companies, which are explicitly represented as owners of plants and potential load serving entities in some countries. The number of companies actually competing in each national market (optionally in each regional market) indicate the intensity of competition. Each company is supposed to act according to Cournot behaviour under conjectural variations. The model finds a Nash equilibrium when solved. Conjectural variations include parameters, which can represent a variety of competition regimes, ranging between quasi perfect competition, supply function equilibrium, pure Cournot and monopoly competition.

Investors consider plant investment as a project financing problem and decide upon implementing the investment if the internal rate of return exceeds a certain threshold. The return depends on earnings based on system marginal prices and on eventual capacity remunerations. Uncertainty factors mirroring poor predictability are introduced in the investment appraisal calculations, which can be varied by scenario. The model does not allow unmatched demand and supply, as it assumes that system-driven open-cycle turbine plants become available in case of market failure to cover demand; such investments are paid as part of system charges.

Trade of electricity between countries is driven by differentiation of system marginal prices between countries (or regions) and the model formulates arbitragers (traders) which take profit from price differentiation by transferring electricity between country nodes as much as allowed by the interconnecting system, which is constrained by the Kirchhoff law, and possible regulatory/reliability restrictions. Transmission system operators are also modelled as owners of interconnectors with behaviours seeking rents from interconnection congestion. Traders and suppliers are formulated to anticipate such congestions by seeing the marginal rents.

Electricity prices are not exactly reflecting long-term costs as they depend on market competition intensity; in other words cost mark-ups are endogenous in this model. Hence, demand response is also endogenous and this constitutes in fact the main force of mitigating market power. Demand is modelled as having varying price flexibility by sector.

The market competition power model of PRIMES can handle asymmetric capacity adequacy policies in the EU as well as harmonised policies. The model has been successfully used in studies on capacity remuneration schemes for the European Commission.

L.14. Power sector sub-model of PRIMES Version 6

Enhancements in version 6 of the power sector model of PRIMES The version 6 of PRIMES includes a significantly enhanced version of the power sector sub-model of PRIMES. The improvements are mainly twofold:

- a) representation in higher detail and resolution of the existing fleet of power plants in Europe and so capturing in a better way the projection of decommissioning, refurbishment and new constructions;
- b) improvement of the model capability in simulating unit commitment in the presence of high contribution by variable renewables and so capturing in a better way the system requirements for operation of fast-ramping power resources (flexibility) and the possible sharing of such resources within the EU internal market based on cross-border trade and market coupling.

The new developments make the model considerably better placed to study policy issues for the internal market, the integration of renewables and the simulation of investment behaviour. Recent experience from the market suggests that investment in power plants relies less than before on theoretical long-term optimality of costs. System-depending operational restrictions deriving from penetration of variable RES imply forced operational cycling of plants. Ignoring them in economic appraisal of investment would be a serious drawback. In addition, the refurbishment options are highly influenced by increased regulation regarding the air pollution emissions, for fossil fuel plants, and by security regulation, for nuclear plants.

The enhancement of the model addresses these main issues in a considerably improved manner, due to higher resolution of load variation (daily and seasonal) and to higher resolution of the handling of old plants. More specifically:

- a) The model data decomposes load variation into 120 different time segments per annum. They cover typical days by season, for working days and for weekends and holidays. The decomposition took into account the variability of wind and solar by region (country level at least). The design of the time segments, based on statistical algorithm, aimed at capturing the variance of load and simultaneously the variance of solar and wind. Therefore, the distribution distinguishes typical days with for example high solar irradiation from similar days with low irradiation, and similarly for wind intensity. The data represent variability of solar and wind on an hourly basis and the aggregation by time segment takes care to capture the simultaneity of variance with load. This work drew on a vast data collection of hourly load curves and hourly wind and solar resources on geographical scales.
- b) The enhanced model performs unit commitment (dispatching) in considerably more sophisticated way than in the past, as the time resolution allows including technical details on cycling operational constraints of power plants, such as ramping rates, minimum power levels for stable generation, start-up and shutdown costs, etc. These are important to capture risk of overgeneration (with possible curtailment of renewables and low levels of wholesale prices), reliability of ramping (flexibility resources) and backup (reserve) power. Constraints also reflect reserves for ancillary services, which are also important for real time balancing in the presence of high variable renewables.
- c) As the model operates unit commitment (dispatching) over the entire European network, it captures the possibilities of sharing power resources among the system control areas, which depends on availability of interconnectors and the possible constraints arising from net transfer capacity restrictions, as opposed to flow-based allocation of interconnection capacities.

Thus, the model simulates different regimes of market coupling and their impacts on dispatching, costs, and efficiency.

- d) Obviously, investment in new power plants, as well as in storage systems, depends in a much more accurate way on the sophistication of dispatching simulation, within the enhanced model.
- e) In addition, the enhanced model includes in more detail the carious storage technologies, including pumped hydro storage (with distinction between mixed pumping and pure pumping, which is a new feature), batteries, air compression and a number of power-to-X technologies, where X stands for hydrogen, gas, synthetic liquids, etc. These latter technologies act as storage systems indirectly, and obviously also as source of electricity-based (thus possible renewables-based) new energy carriers.
- f) The model applies a sophisticated Benders decomposition algorithm to perform sequence of unit commitment over the entire European network (including simulation of wholesale markets, coupled or not) and investment decision cycles. The new algorithm is computationally more efficient and allows introducing uncertainty factors influencing specifically the investment behaviour. Limited foresight also applies, optionally, in the investment behaviour.
- g) As the new model version uses Benders decomposition, the investment decision runs separately from unit commitment. Model options are used to specify the time horizon of foresight influencing investment decisions with additional parameters handling uncertainty and anticipation, which allows for the representation of non-perfect foresight if required. The previous version of the model was solving simultaneously optimal expansion and unit commitment and thus it was impossible to introduce sophistication in the investment behaviour to capture influencing factors more realistically. Similarly, the decomposition allows capturing in more detail the specific investment behaviour subject to feed-in tariffs or other similar mechanisms including auction-based contracts for differences or power purchase agreements. This is also among the enhancements of the new model version.

Although the database of the power model includes all existing power plants in Europe on an individual basis, the simulation aggregates them in categories. Previously the categories reflected the main power technology and fuel. In the enhanced version of the model, the aggregation considered several dimensions, including location, size, technology, age of the plant, and fuel.

Thus, the number of different existing plants in the model increased considerably and the capturing of specific features improved a lot. For example the model now includes in all countries the large power plants one by one (individually) and not aggregated as before. The aggregation mostly concern small plants. The new classification of plants also puts more emphasis on disaggregating the categories by each industrial sector and in addition by technology, age, and fuel. The aim was to capture industrial cogeneration in an improved manner from a sectorial perspective. This was necessary for the enhanced industrial model on boilers and cogeneration.

The enhanced model further allows for the inclusion of cyclical operation constraints of plants, which differ by technology. As we perform unit commitment over chorological sequence of load – at hourly resolution- the model is able to include ramping constraints, minimum up time, minimum stable generation levels, etc. The model further now fully includes flexibility and secondary reserve requirements at system level; hydro power, imports and gas are the main providers of flexibility.

Operational costs of cycling operation (default) compared to forced provision of faster ramping and cycling imply higher operation and maintenance costs, which are included in the model. This kind of operation mainly applies to GT, CCGT and other plants operating under AGC control of the TSO.

The benefits of investing in flexible plants arise for system reliability purposes, which are represented as reserve requirement; the monetary benefits for investors depend on specific remuneration of the service. Within fully optimal model resolution, such remuneration is implicit as full cost recovery is assured in the modelling.

The model can be adapted in order to be able to represent failures, which can incur with such systems. It is important to note that flexibility, as well as reliability, have public goods features, this means that private investment can be subject to free riding by competitors not investing.

L.15. Special version of power sector model for the Internal European Market: The PRIMES/IEM model

L.15.a. Introduction to PRIMES/IEM model

The modelling analysis with the PRIMES/IEM aims to simulate in detail the sequence of operation of the European electricity markets, namely the Day-ahead market, the Intra-day and balancing markets and finally the Reserve and Ancillary Services market or procurement. The PRIMES/IEM modelling suite consists of four main models:

- A Day-Ahead Market simulator (DAM_Simul), which simulates the operation of the day-ahead market and is based on the EUPHEMIA algorithm¹³.
- A Unit Commitment simulator (UC_Simul), which simulates the scheduling of units occurring real-time, considering fully technical limitations of power plants.
- An Intra-Day and Balancing market simulator (IDB_Simul), which simulates the
 operation of the market for balancing services and the settlement of deviations
 which occur between the real time scheduling of units (output of UC_Simul)
 from the day-ahead (output of DAM_Simul).
- A Reserve and Ancillary Services market simulator (RAS_Simul), which simulates the reserves and ancillary services market procurement.

The PRIMES/IEM covers all EU 28 Member States individually, in detail. It also represents Norway, Switzerland and the Western Balkan countries, in an aggregate manner, in order to account for exchanges of energy between EU and these countries. PRIMES/IEM disaggregates the interconnection network, and considers more than one node for each country, in order to represent in-country grid congestions. The assumptions about the grid within each country and across the countries change over time, reflecting an exogenously assumed grid investment plan. Existing power capacity of lines and new constructions are based on ENTSOE data and the TYNDP. Technical characteristics of transmission lines (thermal limits and admittance factors) have been collected from TSOs.

The power market simulators of the PRIMES/IEM can be calibrated to projections of the standard PRIMES model for any specific scenario, and can run for any year of the projection (usually 2015 to 2050 by 5-year periods). Inputs from a scenario include:

 Load demand (hourly), power plant capacities, net imports with countries outside of EU28, capacity of the transmission lines and net transfer values NTC values.

Special version of the power sector model utilized as a market operation simulator with high resolution

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¹³ EUPHEMIA (Pan-European Hybrid Electricity Market Integration Algorithm) is the single price coupling algorithm used by the coupled European PXs

- Fuel prices, ETS carbon prices, taxes, etc.
- RES generation, however the simulators of PRIMES/IEM can determine endogenously curtailment.
- Potential of hydro production (for hydro reservoirs). Constraints on water availability have been applied on a daily basis in PRIMES/IEM. We have separated mandatory hydro-lakes production (due to excess water and other uses of water) from hydro-lakes production at peak load times. This is an important distinction for the bidding behaviour of lakes.
- Heat or steam serving obligations of the CHP units whose main product is heat or steam rather than electricity (industrial CHP and small CHP units exclusively used for steam and heat).
- Other restrictions derived from specific policies, e.g. operation restrictions on old plants, renewable production obligations, and, if applicable, support schemes of renewables, biomass and CHP.

The PRIMES/IEM incorporates a detailed database by plant, with disaggregated technical and economic data for each plant in order to be able to represent cyclical operation of plants, possible shut-downs and start-ups. Its database also includes detailed data on the technical possibilities of plants to provide ancillary services. The ancillary services represented in PRIMES/IEM include Frequency Containment Reserve (primary reserve), Automatic Frequency Restoration Reserve (secondary reserve – Automation Generation Control or AGC), Manual Frequency Restoration Reserve (spinning tertiary reserve) and Replacement Reserve (non-spinning tertiary reserve). Relevant data have been collected from the national TSOs.

Finally, the PRIMES/IEM represents typical 24-hour days, which are distinguished by season, and by working days or holidays (and weekends). For example, a typical day could be a working day in winter.

L.15.b. Modelling procedure

First, the Day-Ahead Market simulator runs (DAM_Simul), and yields with a unit-commitment schedule of power plants, including demand response and schedule of flows over interconnectors.

After the simulation of the Day-Ahead market, we use a "Random Events Generator" tool (developed as part of the PRIMES/IEM specifically for the purposes of this analysis) to generate a set of random events (experiments). The purpose of this step is to artificially introduce a deviation between the day-ahead forecasts (on load, RES generation, availability of plants etc.) and what is occurring real-time.

Considering these deviations, we run a unit commitment simulation with the UC_Simul, which is similar to the day-ahead simulation, with the difference that it includes constraints on the technical operation capabilities of plants. The outcome compares to the day-ahead simulation outcome, and the difference serves as a best forecast of deviations by the market participants.

The next step is the financial settlement of the deviations between the day-ahead schedule and the UC_Simul schedule, and is undertaken with the Intra-Day and Balancing Market simulator (IDB_Simul). The IDB_Simul runs and bids for deviations are generated.

The next step is the simulation of the market or procurement for reserve and ancillary services, conducted with the RAS_Simul tool. The simulation takes into account the commitments in the previous stages, and determines the offerings and remuneration for reserve and ancillary services, given exogenously set reserve requirements.

The table below gathers the steps of the modelling work performed. The following paragraphs describe in more detail each modelling tool of the PRIMES/IEM and the methodology followed in the simulations.

Steps of modelling work performed with the PRIMES/IEM modelling suite

Steps of the PRIMES/IEM simulations	Process	Output
Step 1: Running of the Day-Ahead Market simulator	Simulation of the DAM simultaneously for all EU countries. Basis is a PRIMES scenario (capacity, demand, must-take generation, etc.).	Plant and interconnectors operation schedule (DAM schedule), and its financial settlement
Step 2: Generation of experiments with the Random Events Generator	Generation of experiments (events), with deviations from the PRIMES scenario for wind and solar generation, demand, availability of plants and interconnections	52 cases (random events), and respective frequencies
Step 3: Running of the Unit Commitment simulator	For each random event, UC simulation considering all technical constraints of plants	Revised plant and interconnectors operation schedule (UC), deviations from the DAM schedule
Step 4: Running of the Intra-day and Balancing Market simulator	Set-up of market to settle deviations from DAM defined with the UC simulator. Eligibility by plant to bid in the IDB is determined hourly, based on output of UC.	Financial settlement of deviations and revised schedule for operation of units and interconnectors
Step 5: Running of the Reserves and Ancillary Services market or procurement simulator	Settlement of exogenously set reserve requirements, considering residual capacity after IDB settlement.	The remuneration of the resources for providing reserves
Step 6: Final cost- accounting	Calculation of financial balances (revenues and costs) for each generator, load payments (payments by consumers) and payments by the TSOs. Calculation of unit cost indicators (e.g. for reserves, etc.). Calculation of expected values of the outcomes, as average of results by case (random event), weighted by the frequency of each case.	

L.15.c. Day-ahead market simulator (DAM_Simul)

The DAM_Simul algorithm consists of a set of equations which replicate the EUPHEMIA algorithm. The core parts of the algorithm of the DAM_Simul is a balancing equation, which regulates the inflows and outflows in each node, and the objective function which is such so as to maximize the social surplus. These are complemented by network equations, which allow to simulate a flow-based allocation of interconnection capacities. The model also includes equations related to operational limitations, which guarantee that all plants should offer energy below their maximum capacity or that over-the-counter arrangements (nominations of energy) should be respected. DAM_Simul runs for all EU countries simultaneously, with every country representing a node, and determines market clearing by node and interconnection flows. DAM_Simul produces unit schedule, use of interconnectors and SMPs. It also performs the financial settlement of the DAM. DAM_Simul draws techno-economic and other data from the standard PRIMES model database, including:

- heat rate per plant,
- fuel prices,

- CO₂ emission coefficient per plant,
- cost parameters per plant (fixed and variable),
- power network topology and technical characteristics,

L.15.d. Network representation in DAM

In the DAM_Simul, every country is represented by a single bus and the network includes all current AC and DC interconnections, as well as known investments according to the TYNDP. The model simulates optimal flow-based allocation of capacities across interconnections. The flows are restricted by the first and second Kirchhoff laws and by administratively defined Net Transfer Capacity (NTC) limitations, applying to pairs of adjacent countries.

Depending on user-defined options, flows may be further restricted by over-the-counter arrangements, such as the Available Transfer Capacity (ATC) restrictions implying limitations not only by the NTCs but also by the amount of capacity engaged for cross-border nominations.

L.15.e. Bidding of power plants

Energy offers by plant in the DAM Simul can be of various types, including hourly orders, flexible hourly orders, block orders and complex orders (defined as in EUPHEMIA). We assume that plants bid in the markets (if bidding is allowed in the option under analysis) at the level of their marginal cost (which is taken from the PRIMES database) plus a scarcity mark-up. The mark-up is derived according to a scarcity bidding function (defined by plant), which takes into account hourly demand, plant technology and plant fixed costs. The use of the scarcity bidding function serves as a means of mimicking the strategic bidding behaviour of plant owners in an oligopoly. Regarding hydro-reservoir power plants (lakes), we assume that part of the generation of lakes (mandatory generation) makes zero biddings, simulating the energy that needs to be used in order to avoid overflow and/or for irrigation purposes (particularly relevant for southern EU countries). Only the non-mandatory part of lakes is bidding in the day-ahead market. Bidding is determined through a scarcity bidding function (similar to all other power plants), which takes as basis the marginal cost of gas generation and adds a mark-up that reflects scarcity during peak hours and water availability.

It should be noted that no negative bidding is assumed in the simulations, for any type of power plants. This has effects for the results of the simulations, mainly in the analysis of results regarding priority dispatch of variable RES. In particular, in policy options that assume no priority dispatch of variable RES, these capacities make offers at very low prices, as their marginal cost is close to zero, and are therefore very competitive. In case negative bidding was allowed, and given the increased variability introduced in the dispatching schedule due to the high shares of variable renewables, some inflexible units would bid negative prices in order to e.g. maintain a minimum operation level. In these hours, the close-to-zero bids of RES would seize to be competitive and thus RES generation would be curtailed. Without negative bidding, RES are still curtailed (if no priority dispatch is assumed), but not as often as they would if negative bidding was allowed.

Depending on user-defined options, the model can handle different assumptions regarding the existence of bidding zones. They can vary from national, to regional or to a fully integrated EU markets with flow-based allocation of the entire capacity of interconnections, as if there was a single bidding zone.

L.15.f. Modelling of nominations

Depending on user-defined options, the simulation with the DAM model assumes nominations of energy, i.e. scheduled and fixed generation by power plants. In particular, in the options that this assumption is activated, for example the generation

of nuclear and solids-fired power plants is treated as nominated. Part of this nominated energy can be allocated to contribute to the fulfilment of cross-border trade contracts (cross-border nominations). In-country nominated energy does not participate in the DAM solution. Cross-border nominated energy is subtracted both from supply of the country of origin and demand of the country of destination, while ATC value is reduced in their borders accordingly.

L.15.g. Modelling of priority dispatch

Depending on user-defined options, the DAM simulation can handle priority dispatch for certain power generation technologies, such as RES, industrial CHP units, district heating plants and others. In order to simulate priority dispatch for certain capacities, we assume zero biddings for fixed hourly amounts of generation of these capacities and introduce a very high penalty for curtailment, high enough so as no curtailment is occurring when we assume priority dispatch.

L.15.h. Modelling of demand response

Demand response is modelled so as to allow for endogenous shifting of demand quantities among hours. The shift comes as a response to price signals, thus shifting demand from hours of peak prices to hours of low prices, leading to a smoother demand curve. The modelling of demand response uses stepwise functions that associate amount of demand response to relevant costs, exhibiting decreasing returns of scale (i.e. the higher the amount of demand response the higher the cost). Consumers can bid for demand response, with bidding quantities being subject to potential and bidding price reflecting the stepwise costs.

L.15.i. Day-ahead market simulator version with Unit Commitment (DAUC)

The DAM model includes as an option the possibility for optimising simultaneously offering of energy and reserves. When this option is activated, the DAM model algorithm includes additional equations:

- a. Equations that represent plant-related technical constraints (e.g. technical minimum and maximum, ramping capabilities, minimum up hours of operation, etc.). This implies that the DAM simulator in these options includes the same set of equations as the Unit Commitment simulator. The fact that the DAM model becomes similar to the UC model, implies that deviations between the day-ahead market scheduling and the real-time scheduling simulated by the UC are the least possible, and attributed solely to random events occurring unexpectedly real-time.
- b. The equations of the Reserve and Ancillary Services Procurement model. In practice, when the co-optimisation option is activated, it is as if the two models run simultaneously.

The problem of co-optimising energy and reserves is a mixed integer problem, with binary variables reflecting plant operation status. In order to derive the SMP, we perform a second run, after fixing variables to the integer solution, and relaxing the integer constraints, allowing them to be linear. This is necessary, as the SMP should be able to take non-integer values.

L.15.j. Random Events Generator (optional)

Using a random events generator is basically the modelling way to represent the difference between "what is projected to happen" the day-ahead and "what is happening" real-time. The simulation of the day-ahead market starts by taking as given the hourly demand, hourly renewables generation and hourly availability, as in a PRIMES scenario. This can be seen as the projections of the TSOs for the following day, based on which the day-ahead market clears. The random event generator, generates a set of deviations for these projections trying to mimic the deviations that

could occur in reality between what is expected to happen the day after and what is indeed happening, as for example for:

- c. Deviations in the load pattern (demand)
- d. Deviations in the generation of variable RES, namely wind and solar
- e. Unexpected unavailability of large power plants (equivalent to having unexpected outages)
- f. Unexpected reduction in the net transfer capacities (NTC) (equivalent to having unexpected loss of transmission lines)

With the above as variables, the random events generator builds a large number stylised cases, or experiments, each of which is assigned with a probability of occurrence. The assumed level of deviation of the variables and the probability of each experiment are based on expert judgement. Days of the year are classified to clusters according to their characteristics (season, whether it is working day or holiday), and each experiment regards a specific day cluster.

The simulations with the Unit Commitment simulator and the modelling of settlements for deviations between the Day-ahead market and the Intra-day market (with the Intra-Day and Balancing market simulator) are conducted for all experiments, and final results are reported after weighting the results for each experiment with the assigned probabilities.

L.15.k. Unit Commitment simulator (UC_Simul)

The Unit Commitment simulator mimics real-time operation, where all uncertainties regarding technical constraints as well as forecast deviations have been resolved. Note that we assume that all uncertainty is resolved in one step, i.e. we do not perform runs of the UC_Simul for different points in time between the DAM closure and the real-time (as if continuous IDM were operating).

In the UC_Simul, generators compete simultaneously for providing energy and reserves¹⁴. The model takes as inputs exogenously defined reserve requirements, the outcomes of the Random Event Generator on deviations to forecasted (in the dayahead simulation) demand, renewables generation, availability of power plants and NTC values, and the dispatch schedule and bidding according to the DAM simulator. The amount of capacity that is bound for reserve purposes according to the optimization with the UC model is not participating at all at the clearing of the intraday and balancing markets that follows. Therefore, in the modelling reserve refers to the capacities that participate in the reserve markets or procurement after the clearing of the intra-day and balancing markets.

The model runs for the pan-European electricity network, following the same modelling of power flows as in DAM_Simul. At this stage, network representation is more detailed in the UC_Simul than the DAM_Simul, in that for some countries it includes more than one node. In this way, in-country network limitations, which are of high importance not only for the flow of power within the country but also for the international flows, are taken into consideration.

The UC model uses the DAM solution as initial condition. The solution of the UC_Simul regarding dispatching of units differs from the solution of the DAM model due to:

a) The consideration of technical constraints of power plants in the UC_Simul. In particular, in the UC_Simul all technical constraints that generators encounter in real-time operation are represented from respective

 $^{^{14}}$ At this point it is important to clarify what is considered as reserve in the modelling. Demand for reserves is predetermined and exogenous.

- equations, namely the maximum hours of operation above technical minimum, ramping constraints, minimum up and down time constraints. Plant specific start-up and shut-down costs are also included.
- b) The consideration of demand for reserves, in other words, the simultaneous optimisation of offers for energy and reserves. UC_Simul includes equations that represent the technical limitations of each power plant for providing ancillary services.
- c) The deviations on load, renewables generation, availability of plants and NTC values introduced by the Random Events Simulator.

Bidding by generators for energy follows the same logic as in the DAM_Simul, i.e. generators bid strategically according to a scarcity bidding function. Bidding for reserves varies depending on user-defined options. The user may define administratively regulated offers for reserves, both in terms of quantities and in terms of payments for ancillary services (based on procurement and contracts), or opportunity cost bidding for reserves by generators, i.e. on the value that generators lose by binding their capacity for reserves instead of bidding this amount of capacity in the energy markets. The opportunity cost is calculated taking into account the hourly SMP price of the DAM solution. In particular, if we denote OC_n the opportunity cost of plant n, $GenDA_{n,h}$ the generation of plant n in hour h, $SMPDA_h$ the system marginal price of the DAM in hour h, VC_h the variable cost of plant n, $TotGenDA_n$ the total generation of power plant n in the DA market, then:

$$OC_n = \frac{\sum_h GenDA_{n,h} \cdot (SMPDA_h - VC_n)}{TotGenDA_n}$$

All hydro capacities (reservoirs) are assumed to bid in the UC_Simul. This is in contrast to the DAM simulation, where only the non-mandatory part of lakes is bidding, while the hydro generation that is assumed to be must-run production (due to excess water and other uses of water) is excluded from bidding. In this way, the simulation with the UC captures the role of hydro capacities for balancing purposes (thus capturing their role in the Intra-day and balancing markets) and their contribution to ancillary services.

Priority dispatching and demand response (if eligible to participate in the Intra-day and balancing markets in the user-defined options) are incorporated in the UC simulations the same way as they are incorporated in the DAM_Simul. The UC_Simul optimization of real-time unit commitment reduces deviations from the DAM solution as much as possible. For this reason, the model assumes penalty factors for the deviations from the DAM schedule (re-dispatching), which are taken into account in the objective function of the optimisation. Hence, re-dispatching costs occur for units which operate according to the UC at a different level compared to the DAM schedule. The deviations of the units' dispatching schedule between the UC model and the DAM model are financially settled in the simulations with the Intra-Day and Balancing market simulator.

L.15.l. Intra-Day and Balancing simulator (IDB_Simul)

The Intra-day and Balancing Simulator (IDB_Simul) simulates a stylised hourly market for the deviations that occur between the DAM_Simul solution and the UC_Simul solution. The deviations are the result of the assumed errors in the dayahead forecast on load, RES generation, availability of plants, etc. which are generated using the Random Events Generator. The simulator performs a single market clearing of the deviations, i.e. it does not simulate continuous intra-day markets. It runs simultaneously for all hours in every typical day, and determines an SMP price for deviations, the financial settlement of deviations and a revised schedule for operation of units as well as interconnectors.

Before running the IDM_Simul, for every hour, the nodes (countries) are categorized in regions based on a specific coupling criterion; adjacent nodes are coupled in a specific hour if and only if they share the same SMP for that hour.

Comparing the DAM and UC solutions, deviations in energy offers occur due to the consideration of technical constraints of plants in the UC model and due to other deviations in demand and renewables generation as adopted in the experiments with the Random Event Generator. The IDB_Simul, before settling financially these deviations, it further adjusts the unit commitment schedule of plants according to a set of rules, which determine which resources are eligible to bid in the IDM to meet the deviations. The bids are different for upward and for downward deviations of power supplied by the eligible resources.

For each coupled region and for each hour, all the dispatchable power plants that have altered their generation from the DAM solution to the UC solution opposite to the direction of demand deviation (sum of the demand deviations of the countries in the coupled region) are grouped separately. This group is further split into two independent subgroups, one for every direction of the demand deviation. If demand in the day-ahead simulation is lower than the one in UC and the generation of the unit is higher in the day-ahead simulation than the generation in UC, then this plant is not allowed to offer energy for upward deviations. If the reverse is true, then the power plant is not allowed to offer for downward deviations. The logic behind this, is that these plants are not load-following in the UC solution due to technical reasons, and thus should not be able to contribute in covering intra-day deviation. Hence, the deviations between DA and UC solutions in the generation volumes of the plants belonging to these two groups have to be met by the rest of the conventional plants.

It remains to define the supply quantities each power plant can provide to IDM. The majority of conventional power plants can participate in the IDM (including demand response), with the exception of capacities that have been scheduled to participate in the reserve and ancillary services market according to the UC solution, and the capacities that are not load following as described in the paragraph above. When deviations in demand are upward eligible power plants can potentially offer the entire remaining capacity above the level that has been scheduled in DAM, minus any amount qualified for upward reserve procurement. Equivalently, when deviations in demand are downward they can potentially offer the entire remaining capacity below the level that has been scheduled in DAM, minus their minimum generation level and any amount qualified for downward reserves. Hydro generators in particular, can offer energy only up to the maximum difference between DAM and UC solution, either upwards or downwards.

Units which were not dispatched in the DAM solution are allowed to start-up during the optimisation of IDB_Simul. Along the same lines, units which were dispatched in the DAM solution are allowed to shut-down. However, this only applies to flexible capacities (having ramping rates above a certain threshold value, as well as minimum up time lower than a threshold value, both defined by the user), while inflexible power plants are not allowed to either shut-down or start-up. None of the plants can offer energy which violates their ramping rates.

Resources that are ultimately eligible to participate in the IDM compete each other with their bidding offers. Energy offers for upward deviations are priced equal to the marginal cost of the unit plus a scarcity mark-up in case there is shortage on resources. Scarcity bidding methodology is the same as applied in the DAM_Simul. Energy offer prices for downward deviations are driven by variable and fixed operation and maintenance costs of each unit. Scarcity bidding applies here as well. Shut-down or start-up decisions incur additional costs, as they do in UC model.

Bidding prices and ultimately remuneration of resources depend on the assumed market liquidity, which varies across countries and across options. In countries and options that no IDM market is assumed, generators receive administratively set prices to cover for the deviations. In cases of illiquid markets, bidding is the same as the DAM bidding. In cases of liquid markets, bidding is defined using DAM bids as a basis, plus a mark-up reflecting scarcity in the market for deviations. Bids differ for upward and downward deviations. Energy offers for upward deviations are priced equal to the marginal cost of the unit plus a scarcity mark-up in case there is shortage on resources. Energy offer prices for downward deviations are based on the variable and fixed operation and maintenance costs of each unit, with scarcity mark-up applying as well.

Network modelling in the context of ID market follows the same approach as with the DAM_Simul. New power injections that occur during the optimization with the IDM_Simul take into account congestion of transmission lines according to the UC solution, in the sense that only residual capacity (beyond the schedule of the UC) of interconnectors is eligible to participate in the IDM.

L.15.m. Reserve and Ancillary Services market or procurement simulator (RAS_Simul)

In the simulation with the UC_Simul, binding of capacities for reserves has already been determined. This amount of capacities is assumed to not participate in the IDM. However, as the IDM determines an updated schedule of unit commitment compared to the UC solution, it is probable that some capacities that were offering energy according to the UC schedule offer less (or even shut-down) according to the IDM schedule. Therefore, it is probable that there are additional capacities available to participate in the reserve and ancillary services market compared to the UC solution. It is assumed that only gas turbines are eligible for this purpose, due to high ramping rates and short response times.

Thus, the RAS_Simul runs to re-settle financially the reserve and ancillary services market taking into account the updated unit commitment schedule from the IDM. The RAS_Simul uses the same demand for reserves as the UC model. Four types of reserves have been considered:

- 1. Frequency Containment Reserve (primary reserve)
- 2. Automatic Frequency Restoration Reserve (secondary reserve Automation Generation Control)
- 3. Manual Frequency Restoration Reserve (spinning tertiary reserve)
- 4. Replacement Reserve (non-spinning tertiary reserve)

The following market function cases can be defined by the model user:

- 1. Procurement based on TSO contracts with specific plants, at defined prices.
- 2. Plants bidding for the reserve obligations, but receiving remuneration based on administratively set prices
- 3. Competitive market for reserves with economic offers (bids) for prices and quantities.

The RAS_Simul applies the same bidding for reserves as the UC model. Eligible resources to participate in the market/procurement are differentiated according to user-defined options, and can be all units which have been opted to participate in the ID schedule, including demand response. In case participation of RES is allowed in the ID market, they are only eligible to bid for downward reserve.

Demand response is allowed to participate in the RAS market (depending on user-defined option) and is incorporated the same way as in the DAM Simul.

Resources available cross-border can also participate (differently constrained by policy option) in the reserve market, subject to limitation from availability of interconnection capacity, which is the capacity remaining after the schedule of the IDM. Resources not scheduled in the IDM can submit bids to market for reserve, but only for tertiary reserve.

The four reserve markets or procurements are inter-related because of technical restrictions of the plants, and therefore run simultaneously.

L.15.n. Mathematical Illustration of PRIMES-IEM model

DAY-AHEAD MARKET SIMULATOR (DAM SIMUL)

	DAY-AHEAD MARKET SII	TOLATOR (DAM	_ /
	Known Parameters and Functions		Unknown Variables
$d_{i,h}$	Inverse demand function	$Q_{i,h}$	Consumption of electricity
$b_{i,n,h}$	Price bidding function	$P_{i,h}$	System Marginal Price
$\overline{q}_{i,n,h}$	Power quantities in priority dispatch	$q_{i,n,h}$	Commitment schedule of power plants
$K_{i,n,h}$	Power plant capacities	$Up_{i,n,a,h}$	Supply of upward ancillary service
$M_{i,n,h}$	Technical minimum operation of a plant	$Dn_{i,n,a,h}$	Supply of downward ancillary service
$R_{i,n}$	Ramping capability of plant	$u_{i,n,h}$	Operating status of a plant (binary)
$Mup_{i,n,h}$	Minimum up time of a plant	$sd_{i,n,h}$	Shut down of a plant (binary)
$Mdn_{i,n,h}$	Minimum down time of a plant	$su_{i,n,h}$	Start-up of a plant (binary)
$fup_{i,n,a,h}$	Price bidding for upward ancillary services	$\sigma_{i,h}$	Inflows minus Outflows in a node of the network
$fdn_{i,n,a,h}$	Price bidding for downward ancillary services	$ heta_{i,h}$	Voltage phase angles at a node
net _{i k}	Network topology matrix	$f_{k,h}$	Flows over interconnectors
,,,,	-	·	(positive or negative)
$\omega_{k,kk}$	Matrix of line admittances	Sets	NlCtltl-C
T_k	Capacity of interconnectors	i or ii	Nodes of the network (one or many per country)
$NTC_{i,ii}$	Net Transfer Capacity between two nodes	h or hh	Time intervals (hours) in a year
		n	Power plants
		a	Reserve types
		k or kk	Interconnectors
	Equations for Day Ahead Market	Simulator (energy o	only market)
	$z_h = \sum_{i} \left(\int_0^{Q_{i,h}} d_{i,h}(y_{i,h}) dy_{i,h} - P_{i,h} \sum_{n} b_{i,n,h}^{-1}(y_{i,h}) dy_{i,h} \right) $	$P_{i,h}$)	Social Surplus to maximize
	$P_{ih} = d_{ih}(Q_{ih})$,	Inverse Demand Function
	$B_{i,n,h} = b_{i,n,h}(q_{i,n,h})$		Price bidding by plant as function of
	$D_{i,n,h} = D_{i,n,h}(q_{i,n,h})$		volume
	$q_{i,n,h} \leq K_{i,n,h}$		Capacity constraints of power
			plants
$\sigma_{i,h} = \sum_{i} \theta_{i,h} net_{i,k} \sum_{kk} \omega_{k,kk} net_{kk,i}$			Inflows minus Outflows in a node of the network
$f_{k,h} = -\sum_{i} \theta_{i,h} \sum_{k,k}^{k} \omega_{k,kk} net_{kk,i}$			Flows over interconnectors (positive or negative)
$\left f_{k,h}\right \leq T_k$			Physical capacity constraint for flows over interconnectors
$\left \sum_{k \subseteq net_{i,k}} \sum_{k \subseteq net_{i,k}} f_{k,h} \right \le NTC_{i,ii}$ $d_{i,h}^{-1}(P_{i,h}) - \sum_{i=1}^{n} \left(q_{i,n,h} + \overline{q}_{i,n,h} \right) = \sigma_{i,h}$			Restriction of bilateral flows due to Net Transfer Capacity
	$d_{i,h}^{-1}(P_{i,h}) - \sum_{n} \left(q_{i,n,h} + \overline{q}_{i,n,h}\right) = \sigma_{i,h}$		Balance of inflows and outflows in a node

Equations for Unit Commitment Simulator (or Day Ahead Market with co-optimization of reserves)

INTRA-DAY AND BALANCING MARKETS SIMULATOR (IDB_SIMUL)

Known Parameters and Functions		Unknown Variables	
$D_{i,h}^{up}$	Upward deviations	$q_{i,n,h}^{up}$	Upward balancing power output of power plants already opened
$D_{i,h}^{down}$	Downward deviations	$q_{i,n,h}^{down}$	Downward balancing power output of power plants
$b_{i,n,h}^{up}$	Price bidding function for upward offers	$q_{i,n,h}^{open}$	Upward balancing power output of power plants already opened
$b_{i,n,h}^{down}$	Price bidding function for downward offers	$pos_{i,n,h}$	Deviation from DAM variable (binary, 1 if plant committed in IDM and closed in DAM)
$ar{g}_{i,n,h}^{dam}$	Commitment schedule of power plants from DAM	$neg_{i,n,h}$	Deviation from DAM variable (binary, 1 if plant committed in DAM and closed in IDM)
$ar{g}^{uc}_{i,n,h}$	Commitment schedule of power plants from UC	$u_{i,n,h}^{id}$	Operating status of a plant (binary) taken into account DAM schedule
$\overline{u}_{i,n,h}$	Operating status of a plant (binary) from DAS and UC	$sd_{i,n,h}^{id}$	Shut down of a plant (binary)
$D_{i,h}^{dam}$	Demand from DAM	$su_{i,n,h}^{id}$	Start-up of a plant (binary)
$D^{uc}_{i,h}$	Demand from UC		
$ar{f}_{k,h}^{dam}$	Flows over interconnectors from DAM		
$ar{\sigma}_{k,h}^{dam}$	Inflows minus Outflows in a node of the network from DAM	Sets	
$C^{su}_{i,n,h}$	Bidding for starting up a power plant in IDM	int(n)	Intermittent RES power plants

$C^{su}_{i,n,h}$	Bidding for shutting down a	tn(n)	Power plants that are cannot offer up or down deviation due to technical constraints or due to
$C_{i,n,h}$	power plant in IDM	tn(n)	TSO instruction
	Equations for Intra Day Ah	ead Mar	ket Simulator
$z_h = \sum_{i} \sum_{n \notin (int)}$	$ \left(B_{i,n,h}^{up} q_{i,n,h}^{up} + B_{i,n,h}^{down} q_{i,n,h}^{down} + su_{i,n,h}^{id} C_{i,n,h}^{su} + sd_{i,n,h}^{id} C_{i,n,h}^{sd} \right) $		Cost of deviations to minimize
	$ \begin{aligned} & \overset{uc}{\sigma_{i,h}} - \sigma_{i,h}^{uc} - D_{i,h}^{dam} + \sigma_{i,h}^{dam} + \sum_{n \in (int \cup tn)} \bar{g}_{i,n,h}^{dam} \\ & - \sum_{n \in (int \cup tn)} \bar{g}_{i,n,h}^{uc} , 0) \end{aligned} $		Upward deviations
$D_{i,h}^{up} = \max(D_i)$	$\frac{dam}{di,h} - \sigma_{i,h}^{dam} - D_{i,h}^{uc} + \sigma_{i,h}^{uc} + \sum_{n \in (int \cup tn)} \bar{g}_{i,n,h}^{uc} - \sum_{n \in (int \cup tn)} \bar{g}_{i,n,h}^{dam}, 0)$		Downward deviations
	$B_{i,n,h}^{up} = b_{i,n,h}^{up} (q_{i,n,h}^{up})$		Price bidding by plant as function of volume for upward offers
	$B_{i,n,h}^{down} = b_{i,n,h}^{down} (q_{i,n,h}^{down})$		Price bidding by plant as function of volume for upward offers
,	$q_{i,n,h}^{up} + q_{i,n,h}^{up} \le K_{i,n,h} (1 - neg_{i,n,h})$		Capacity constraint for upwards offers of power plants
	$q_{i,n,h}^{down} \leq \bar{g}_{i,n,h} \left(1 - neg_{i,n,h} \right)$		Capacity constraint for downwards offers of power plants
	$q_{i,n,h}^{open} \leq K_{i,n,h} pos_{i,n,h}$		Capacity constraint for upwards offers of power plants Technical minimum constraint for upwards
	$q_{i,n,h}^{open} \geq M_{i,n,h} pos_{i,n,h}$		offers of power plants
	$\begin{aligned} & \left q_{i,n,h}^{up} - q_{i,n,h-1}^{up} \right \le R_{i,n} \\ & \left q_{i,n,h-1}^{open} \right \le pos_{i,n,h-1} R_{i,n} + su_{i,n,h}^{id} R_{i,n} \\ & \left q_{i,n,h}^{down} - q_{i,n,h-1}^{down} \right \le R_{i,n} \end{aligned}$		Ramping Constraint for upwards offers
$ q_{inh}^{open} $	$ q_{i,n,h-1}^{open} \le pos_{i,n,h-1}R_{i,n} + su_{i,n,h}^{id}R_{i,n}$		Ramping Constraint for upwards offers
1 - 1,11,11	$\left q_{inh}^{down} - q_{inh-1}^{down} \right \le R_{in}$		Ramping Constraint for downwards offers
u_{i}^{id}	$\vec{u}_{n,h} = \bar{u}_{i,n,h} + pos_{i,n,h} - neg_{i,n,h}$		Commitment Constraint
	$pos_{i,n,h} - pos_{i,n,h-1} \le su_{i,n,h}^{id}$		Start-up constraint in IDM
	$neg_{i,n,h} - neg_{i,n,h-1} \le sd_{i,n,h}^{id}$		Shut-down constraint in IDM
	$su_{i,n,h}^{id} + sd_{i,n,h}^{id} \le 1$		Shut or start constraint for IDM
	$pos_{i,n,h} + neg_{i,n,h} \le 1$		Shut or start deviation constraint
hh∈[(h	$\sum_{-Mdn_{i,n,h}-1\leq hh)\cap (hh\leq h)]}neg_{i,n,hh}\leq 1$		Minimum down time constraint
	$\sum_{h-Mup_{i,n,h}+1\leq hh)\cap(hh\leq h)} pos_{i,n,h} \leq 1$		Minimum up time constraint
$\sigma_{i,h} + \epsilon$	$\bar{\sigma}_{k,h}^{dam} = \sum_{i} \theta_{i,h} net_{i,k} \sum_{k,k} \omega_{k,kk} net_{kk,i}$		Inflows minus Outflows in a node of the network
$f_{k,h} + \bar{f}_{k,h}^{dam} = -\sum_{i}^{l} \theta_{i,h} \sum_{k,l}^{kk} \omega_{k,kk} net_{kk,i}$		Flows over interconnectors (positive or negative)	
	$\left f_{k,h} + \bar{f}_{k,h}^{dam} \right \le T_k$		Physical capacity constraint for flows over interconnectors
$\left \sum_{k \subseteq net_{i,k}} \sum_{k \subseteq net_{i,k}} f_{k,h} + \bar{f}_{k,h}^{dam} \right \le NTC_{i,ii}$			Restriction of bilateral flows due to Net Transfer Capacity
$D_{i,h}^{up} - D_{i,h}^{down}$	$-\sum_{n\notin (int\cup tn)} \left(q_{i,n,h}^{up} + q_{i,n,h}^{open} - q_{i,n,h}^{down}\right) = \sigma_{i,h}$		Balance of inflows and outflows in a node
RESE	ERVE AND ANCILLARY SERVICES M	IARKE	T SIMULATOR (RAS_SIMUL)

RESERVE AND ANCILLARY SERVICES MARKET SIMULATOR (RAS_SIMUL)

Kno	wn Parameters and Functions	Unknown Variables	
$ar{\mathcal{g}}^{id}_{i,n,h}$	Commitment schedule of power plants after IDM	$c_{i,h}$ Contribution of flows to reserve and ancillary service market	
$c^{up}_{i,h}$ $ar{f}^{id}_{k,h}$	Upper limit of contribution of flows to RAS Flows over interconnectors from DAM and IDM		

Equations for Reserve and Ancillary Services Simulator

Equations for Reserve and Ance
$$z_h = \sum_i \sum_a \sum_n \left(Bup_{i,n,a,h} Up_{i,n,a,h} + Bdn_{i,n,a,h} Dn_{i,n,a,h} \right)$$

$$Bup_{i,n,a,h} = fup_{i,n,a,h} \left(Up_{i,n,a,h} \right)$$

$$Bdn_{i,n,a,h} = fdn_{i,n,a,h} \left(Dn_{i,n,a,h} \right)$$

$$\bar{g}_{i,n,h}^{id} + \sum_a Up_{i,n,a,h} \le u_{i,n,h}^{id} K_{i,n,h}$$

$$\bar{g}_{i,n,h}^{id} + \sum_a Dn_{i,n,a,h} \ge u_{i,n,h}^{id} M_{i,n,h}$$

$$c_{i,h} \le c_{i,h}^{up}$$

$$\sum_n Up_{i,n,a,h} \ge Dup_{i,a,h} + c_{i,h} \bar{\sigma}_{k,h}^{id}$$

$$\sum_n Dn_{i,n,a,h} \ge Ddn_{i,a,h}$$

Cost of ancillary services to minimize

Bidding for upward ancillary services
Bidding for downward ancillary services
Upper bound of contribution to upward
ancillary service constraint for power plants
Upper bound of contribution to downward
ancillary service constraint for power plants
Upper bound of contribution to upward
ancillary service constraint for x-border flows

Balance for upward ancillary services

Balance for downward ancillary services

L.15.o. Methodology of the Modelling of Power Generation Investment under Uncertainty (optional)

The version of the power sector model of PRIMES which simulates oligopoly competition includes an option of valuing investment in power generation under uncertainty.

The simulation of oligopoly competition computes electricity market prices which define a stream of revenues for existing, or candidate for investment, plant. The revenues seen from the perspective of an investor or of a plant owner, support the decision about going forward with the investment or not. Similarly, it supports the decision for a plant owner about whether to maintain the plant in operation, or instead retiring the plant from the market. This "investment evaluation" process is simulated using the Investment Evaluation model.

The methodology followed to evaluate the value of power plants (existing or candidate for investment) considers uncertainty about the market in the future and heterogeneity of decision makers regarding the hurdle rates.

In order to account for uncertain market conditions, the approach introduces three random variables, namely ETS prices, gas prices and RES development. To introduce randomness around these factors we assume that each follows a Brownian motion which has been applied to the whole time series trajectory. Moreover, we take into consideration the interdependencies of the three random variables. The trajectory of the random variables in time is a random process which is the outcome of a 3-dimensional stochastic differential equation, having a pre-determined mean (using PRIMES projections for this purpose) and a covariance matrix defined so as to reflect the relationship between the three random variables.

ETS prices and gas prices are positively correlated, as a future of higher gas prices would imply a future where coal-based and other high-emitting generation is more competitive, and would therefore require higher ETS prices to achieve the EUCO emissions targets. ETS prices and RES development are negatively correlated, as the larger the development of RES the lower the required level of ETS prices for maintaining the EUCO emissions targets. Finally, gas prices and RES development are positively correlated as higher gas prices render RES more competitive.

With this basis, the model applies a Monte Carlo simulation technique to generate a large sample of scenarios, each being representative of a particular "event" of ETS

prices, gas prices and RES development. After reducing the number of random scenarios-events of our sample following a scenario reduction technique, the PRIMES Oligopoly model for each scenario-event computes the stream of revenues of each plant.

These streams of revenues are then used to calculate the plant specific present values (PVs) for each scenario-event. In particular, the PV is calculated as present value of revenues from the wholesale, balancing, ancillary services and CM markets, minus variable, fuel and O&M costs.

The approach, instead of considering specific rates of return for the PV calculations, assumes that plant owners are heterogeneous, and therefore considers a range of hurdle rates (desired rates of return) which are assumed to be normally distributed. The mean of the hurdle rates distribution is different for each Member State, reflecting the varying financing conditions in each. The user can vary both the mean value and the standard deviation of the probability distribution for the hurdle rates. The idea is that the distribution of hurdle rates depends on the competition context and the perceived certainty surrounding future revenues. This is assumed in order to reflect that under different market conditions the behaviour of plant owners would alter, and they would be willing to accept different rates of return (hurdle rates) for undertaking a project. In particular, when future revenues are considered to be more certain, investors are willing to accept lower rates of return (hurdle rates) to undertake a project, and vice versa. Similarly, in conditions of more intense competition investors tend to adopt lower hurdle rates, as otherwise they risk staying out of the market. These changes of the hurdle rates are purely behavioural, and very hard to quantify. However, this behaviour is key in the simulation and comparative analysis of the different options of this study and they need to be reflected to the extent possible. Following this logic, the investment evaluation process takes into account assumptions whether the revenues come solely from the wholesale market, which are uncertain as in a spot market, or also from capacity mechanisms or other similar forms of securities for the capital costs, which are more certain than in spot markets. Depending on the origin of revenues, the model applies for example lower hurdle rates and possibly lower standard deviation of the hurdle rates in the case of capacity mechanisms compared to the cases without.

The mathematical illustration follows. We may denote:

- s: a scenario-event, with probability of occurrence π_s
- ρ : the various types of decision makers, each applying a different hurdle rate, with frequency π_o
- *i*: a power plant

Then, the process described so far leads for every plant, old or new, to a collection of present values $PV_{\rho,s,i}$, each with probability $\pi_s \cdot \pi_\rho$.

The next step of the investment evaluation process is to compare this set of PVs with a benchmark, in order to assess how each project (plant) performs, and based on this assessment decide upon its viability. In other words, the evaluation needs to specify a probability that an investment is realized (or that an old project continues to operate) as a function of its performance. Two measurements need therefore to be defined: a) a measurement of the performance of each plant, and b) a probability function of deciding positively on investing on (or continue operation of) each plant, based on its performance.

New plants are considered to perform adequately if revenues minus costs are sufficiently high to counterbalance investment expenditures. In case the PV of revenues minus costs is negative, then definitely the investment should not be

realized, or in other words, the probability that the investment is realized should be zero. If the PV is positive, then the probability that the investment is realized should be getting higher with higher values of PV.

For old plants, the approach is different; an old plant is considered to perform well if revenues are sufficiently high to cover for fixed and O&M costs, i.e. when the PV is positive. A positive PV for old plants should imply that the probability that the plant retires prematurely is zero. But even if revenues do not suffice to cover for these costs (PV is negative), still the operation of the plant is of some worth to the decision maker due to its salvage value (i.e. the non-amortized investment cost, calculated specifically for each plant considering its remaining lifetime and investment cost), which is lost in case of premature retirement. Therefore, the probability that the plant retires should be increasing as the negative present value is increasing in absolute terms.

Following the above logic, we developed a "Performance ratio", denoted $Perf_{\rho,s,i}$. The Performance ratio is calculated differently for old and new plants. For new plants (denoted inew), the Performance ratio is the ratio of the present value of revenues over the cost of investment (I_{inew}):

$$Perf_{\rho,s,inew} = \frac{PV_{\rho,s,inew}}{I_{inew}}$$

For old plants (denoted iold), the Performance ratio takes an inverse form and is the ratio of minus the salvage value of the plant (S_{iold}) over the present value of revenues:

$$Perf_{\rho,s,iold} = \frac{-|S_{iold}|}{PV_{\rho,s,iold}}$$

Ultimately, the Performance ratio is used to derive a probability that a new investment project is undertaken or that an old project is continuing to operate. This probability function, referred to as probability of adequate performance and denoted $\pi_{\rho,s,i}$, has been specified:

• For new plants

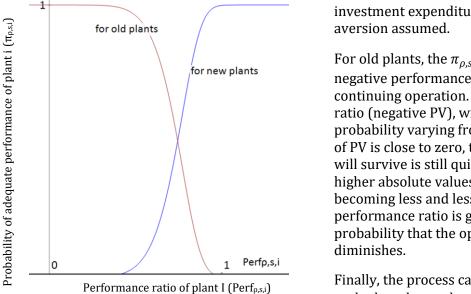
$$\begin{split} \pi_{\rho,s,inew} &= f(Perf_{\rho,s,inew}), \qquad for \, Perf_{\rho,s,inew} \geq 0 \\ \pi_{\rho,s,inew} &= 0, for \, Perf_{\rho,s,inew} < 0 \\ f(Perf_{\rho,s,inew}) &= 1 - \frac{\ln\left(1 + e^{-a(Perf_{\rho,s,inew})^a}\right)}{\ln(2)}, \qquad for \, Perf_{\rho,s,inew} \geq 0 \end{split}$$

For old plants

$$\begin{split} &\pi_{\rho,s,iold} = 1 - f(Perf_{\rho,s,iold}), \qquad for \, Perf_{\rho,s,iold} \geq 0 \\ &\pi_{\rho,s,iold} = 1, for \, Perf_{\rho,s,iold} < 0 \\ &f(Perf_{\rho,s,iold}) = \frac{\ln\left(1 + e^{-a\left(Perf_{\rho,s,iold}\right)^a}\right)}{\ln(2)}, \qquad for \, Perf_{\rho,s,iold} \geq 0 \end{split}$$

For new plants, the function is defined so as to ensure that a negative performance ratio (resulting from a negative PV) leads to zero probability of an investment being realized. For positive performance ratios, the probability takes a form that resembles

an S curve, and of course ranges between 0 and 1. For small values of the performance ratio, the probability is still very close to zero, as a decision maker would not be



i: power plant

ρ: type of investor

πρ,s,i

s: scenario event

willing to decide positively on an investment where the PV of revenues minus costs would be considerably lower than investment expenditure. This reflects the level of risk aversion assumed.

For old plants, the $\pi_{\rho,s,i}$ function ensures that those with negative performance ratio (i.e. positive PV) are definitely continuing operation. Plants with positive performance ratio (negative PV), will continue operation with probability varying from zero to one. If the absolute value of PV is close to zero, then the probability that the plant will survive is still quite large. However, as the PV takes higher absolute values (implying that revenues are becoming less and less compared to the costs) and the performance ratio is getting close to one, then the probability that the operation of the plant will continue diminishes.

Finally, the process calculates the probability of survival of each plant denoted as $ProbSurv_i$ by multiplying the probability of each scenario-event, times the frequency of the decision maker types, times the probability of adequate performance, and summing over the whole range of possibilities:

$$ProbSurv_i = \sum_{s} \sum_{\rho} \pi_{\rho, s, i} \pi_s \pi_{\rho}$$

This probability of survival is multiplied with the capacity of each plant in a scenario and yields with an updated capacity level. Next, these reduced capacities are used to run again the PRIMES Oligopoly model to compute power generation, revenues and total costs for consumers.

M. The PRIMES Gas Supply Model



Natural Gas is of great importance in the transition towards a clean and renewable energy system. Secure and affordable gas supply in the EU is of critical importance.

M.1. Scope of the model

The PRIMES energy system model includes a detailed gas supply module that provides projections for gas imports by country of origin, by transport mean (LNG, pipeline) and route as well as wholesale gas prices. The gas model studies the relationships between gas resources, gas infrastructure and the degree of competition in gas markets over the Eurasian and MENA area and evaluates their impacts on gas prices paid by gas consumers in the EU Member-States.

The gas model is a dynamic market competition model, which covers the entire Eurasian/MENA areas and the global LNG market. It presents in detail the gas infrastructure, present and future, as well as the different "agents" that participate in the market. The agents compete for access to gas infrastructure and for gas supply to customers, the latter being responsive to gas prices. The model considers the oligopolistic structure of the gas market, which includes market imperfections and can accommodate different assumptions about the degree of competition and the integration of the EU gas internal market.

The gas supply module uses as input the gas demand projections, available from the end-use sectors for demand (twelve industrial sectors, transport, residential, services and agriculture) and electricity generators of the PRIMES model. The model determines the equilibrium by finding the prices such that the quantity producers find best to supply matches the quantity consumers wish to use. Thus, the flow of gas over the entire gas network, the economic decisions of the agents and the market prices are endogenous and are computed dynamically. The module operates on an intertemporal basis from 2000 to 2030 and produces results by five year period.

M.2. Gas infrastructure

The gas module represents in detail the present and future gas infrastructure of each EU Member State, other European countries and the gas producing and consuming countries of the Eurasian/MENA area, including Russia, Ukraine, Belarus, the Caspian countries, Middle East, Persian Gulf and North African countries. The model also represents the supply possibilities of LNG worldwide and the global demand and trade of LNG. The infrastructure types include: gas pipelines (represented as a network), gas storage, LNG terminals, gas production and gas liquefaction.

The interregional flows of gas are simulated based on a gas transport network consisting of high-pressure gas pipelines and ship routes for LNG. A detailed representation of the physical natural gas pipeline system is used to represent the current and possible interregional transfers under engineering constraints, allowing the moving of gas from producers to end-users. Simultaneously with physical flows, the model projects the commercial transactions between suppliers and customers, which extend beyond neighbouring countries, involve transit routes and gas swaps to allow their implementation. Gas traders (arbitragers) are also included as well as gas transport system operators. Each country is assumed to have a single Transport System Operator (TSO), which manages flows coming into and out of the region. Each TSO represents a transhipment node in the gas supply module. Arcs, defined as routes carrying gas flowing between TSOs, connect the nodes. Each arc corresponds to an aggregation of the pipelines between neighbouring countries.

 $^{^{15}}$ In technical terms the model solves a Nash-Cournot oligopoly game with conjectural variations to find imperfect market equilibrium.

Arcs are also established from gas producers (fields) to transhipment nodes (TSOs) and to gas liquefaction plants. Only one gas producer and one LNG producer, if applicable, are considered by country, whereby the major gas (fields) and/or the liquefaction plants are represented for each country. In addition, the gasification plants (one by one) and the storage facilities (aggregated by country) are represented. The supply from each country is directly available to only one transhipment node. If the supply is made available to other countries (at an adjoining transhipment node), it needs first to pass through a transhipment node.

Detailed cost data (capital and variable operating) are associated with each type of gas infrastructure and so gas transportation costs, including LNG ship costs are calculated as a function of distances.

The final consumer gas prices are explicitly computed and reflect costs but also include market-related and depletion-related rents.

Gas supply and demand are balanced on a daily basis. A few typical days are represented per country. Variability of gas demand is determined bottom-up from the gas load profiles of various gas uses by sector as these are projected by the rest of the PRIMES model.

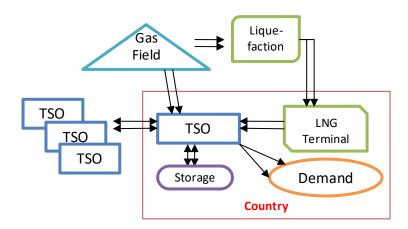
Among the supply sources gas storage is represented: storage inputs and outputs connected to each transhipment node to represent net storage withdrawals in the country as needed to manage gas balancing at peak times. During the off-peak period, net storage injections are calculated to establish gas storage balance over a year time period. The gasification plants are modelled also as storage facilities having more limited capacities than the underground storage facilities.

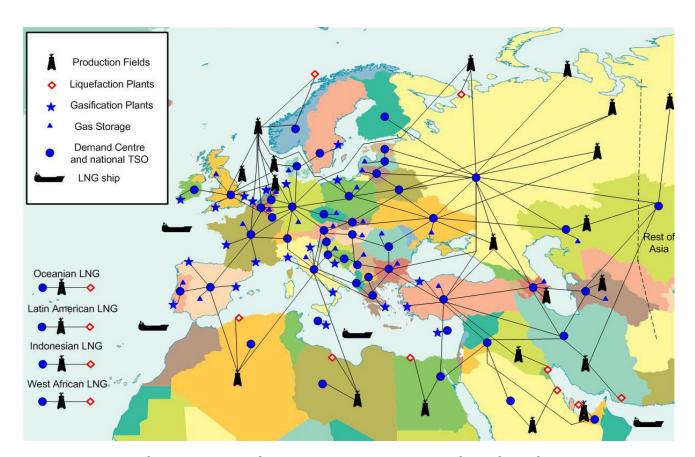
Third party access is assumed for gas infrastructures and regulated tariffs are applied, which are determined by the model by mimicking current practices based on regulated asset basis pricing methods. Exogenous parameters may be used to reflect different regulatory policies for pricing, access and use of gas infrastructure. Also long-term contracts are included as constraints between suppliers and customers. Duration and terms of existing (in the beginning of projections) long term contracts are exogenous. Upper and lower variability margins of flows over pipelines, reflecting physical and/or contractual limitations, are represented through exogenous parameters and constraints.

M.3. Modelling of competition

Gas producers and gas suppliers (traders) are considered as separate companies. A gas supplier and/or trader is assumed to have access to a limited number of gas production (or LNG) nodes and to a subset of gas demand nodes. This can vary by scenario to reflect different degrees of competition intensity and market integration in the EU. The traders are assumed to operate as financial brokers to profit from gas price differences between country-specific demand nodes. It is also assumed that each country-specific TSO operates a gas pool market (a hub) per country, which seeks to maximise consumer and producer surplus under imperfect competition among suppliers and price-elastic demand.

The **TSOs** operate as regulated monopolies and seek a regulated maximisation of profits from balancing demand and supply at each node. The TSOs perform a daily balancing of gas demand and supply, only in terms of "mass" of gas.

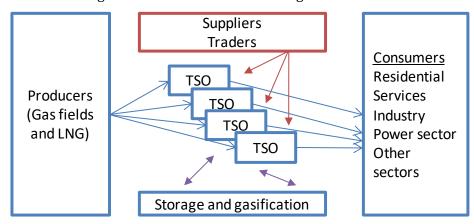




Pipeline capacities and investments are exogenous. Volume dependent curves are specified for computing tariffs for transportation between transhipment nodes (e.g. Member States and neighbouring – transit - countries). The tariff curves extend beyond current pipeline capacity levels and relate incremental capacity to corresponding estimated rates. The TSOs charge tariffs and apply mark-ups for transportation service.

Gas producers (fields) seek the maximization of rents from inter-temporal management of their exhaustible resources, selling to the pool managed by the TSO, while the **LNG producers**, gas storage and LNG storage operators maximize the profits from exploiting the storage facility. Gas production costs and potential rents are represented by cost-supply curves with increasing slope, constrained by resource potential. Use of gas facilities entails variable (nonlinear) and fixed costs.

Gas field reserve amounts are specified exogenously in the base year and based on the model extraction follows a net depletion profile while reserves includes increases in amounts due to exploration and recovery evolving in the future. Liquefaction, storage and LNG gasification capacities and investment are exogenous. The dates of commissioning of new infrastructures are exogenous.



The link between the TSOs and the gas consumers (residential sector, services sectors, agriculture sector, transport, industrial sectors and electric generators) correspond to gas flows, which implement the commercial gas flows between **gas suppliers**, **traders and customers**. Gas suppliers and traders seek to maximize profits by generating revenues from gas sales to consumers, while they incur costs by purchasing gas from pools that are managed by TSOs.

The demand functions of **gas consumers** are price elastic. Demand detailed by gas load segment and by sector is linked with the rest of PRIMES models.

The gas supply model determines oligopolistic market equilibrium over multiple period years (up to 2050) and calculates the market prices of gas and LNG by country, year and marginal system gas prices by load segment (typical days). The model projects physical gas flows over the entire Eurasian gas infrastructure system, calculates possible congestion for each gas facility (pipeline, LNG terminal, storage, etc.) and evaluates financial balances (costs versus revenues and rates of use) by gas infrastructure component. Thus, the model can support profitability analysis of new gas infrastructure (new pipelines, LNG terminals, etc.).

M.4. Model usage

The gas supply model has been used for specific gas sector policy analyses:

- Congestion and profitability of new gas transport routes
- Alternative scenarios about development of new gas suppliers
- Impact of gas shortages for certain upstream suppliers
- Changes in the global market for LNG and their impacts
- Impact of reduced gas demand in the EU owing to energy efficiency and RES
- Impact of growth of domestic gas demand within major gas suppliers outside Europe
- Impacts on the EU gas supply of growing gas demand in Asia

Summary of PRIMES Gas Supply Model

The Gas Supply model simulates an oligopoly market over multiple countries, involving many actors (consumers, TSOs, traders and upstream producers)

- Consumers are price takers with demand being elastic with prices
- TSOs manage gas hubs and minimize cost of gas supply
- Traders maximise profits, perform arbitraging operations and are price takers from upstream producers
- Upstream producers compete along a Nash-Cournot game (with conjectural variations)
- The number of competitors acting on each node change over time to reflect growing competition (long term trend towards a well-functioning market)

Operations and flows are constrained by a physical system involving pipelines, LNG terminals, gas storage facilities, liquefaction plants and gas producing wells. The market clearing for pipeline gas is on a Eurasian scale, while for LNG the coverage is global. Investment in gas infrastructure is exogenous. Characteristics of gas companies are also exogenous.

The model simulates two layers of flows: physical gas flows and commercial transactions

- A consumer on one node can be commercially supplied with gas produced at a node without direct link with the consumption node (e.g. if gas swaps implement the commercial transaction)
- Since the gas network constraints are binding, gas supply prices differ by node (country)
- Price determination reflects marginal costs, an endogenous mark-up and fixed costs that recover cost of infrastructure
- Upstream producers tariff gas according to a gas cost function inclusive of gas field exhaustion rents (Hoteling's rule)

The model simulates gas balancing on a daily basis, considering load characteristics of gas demand sectors and possibilities of storing gas and using LNG

N. Oil Products Supply Model and biofuel blending



The oil refining industry in the EU is likely to face declining demand for oil product and environmental constraints, including bio-fuel blending regulations.

The refinery sub-model of PRIMES is used to project domestic components of petroleum product prices, refining activities and refinery capacity expansion, including where appropriate technological change. Crude oil prices are exogenous to PRIMES.

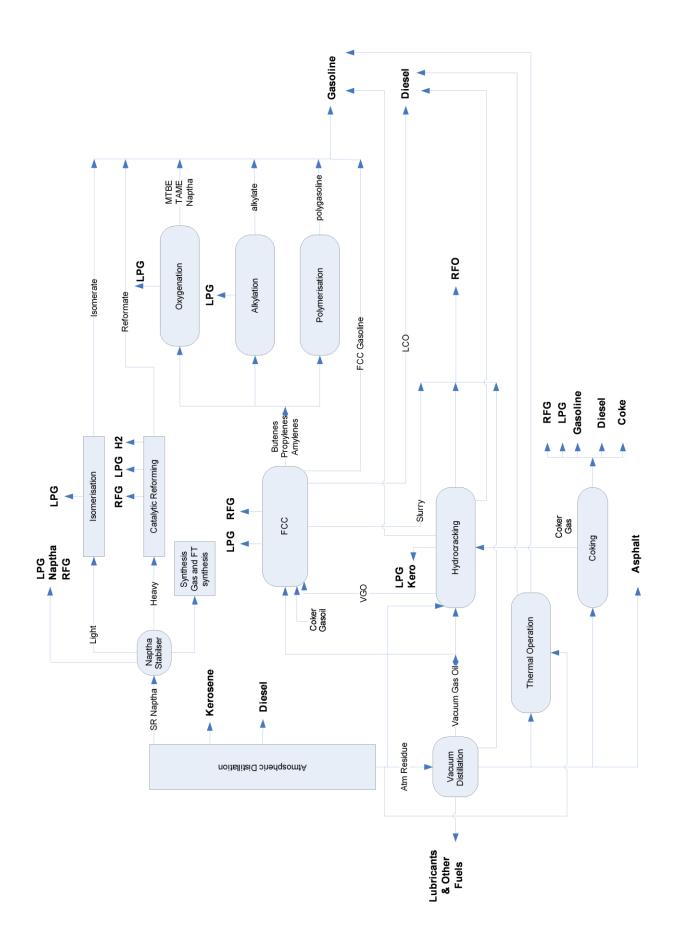
The petroleum supply market in the EU is modelled as one stylised refinery by country involving distillation and cracking processing facilities which differ by country and are projected to the future through endogenous investment. The generic processing units are atmospheric distillation, vacuum distillation, coking, catalytic cracking, hydrocracking, and visbreaking. Net imports of petroleum products by European country are projected according to time trends and relative prices using a simple reduced-form import-export graph representation.

The model projects changes in the structure of refinery activities (building and composition of processing units and energy consumption) to produce an intertemporal least cost product mix that satisfies the demand projected by the rest of PRIMES energy demand and supply modes. The activities are constrained by specific technical constraints, which simulate operation of refining over a stylised graph, which includes intermediate streams as flows between processing units. Capacity is allowed to expand, under technical limitations. Investment schedules are developed endogenously. The regulatory framework concerning product quality and types are incorporated as simple additive factors that increase cost of production.

End-use petroleum product prices are formed as function of crude oil cost recovery (which are exogenous) marginal costs of refining, plus transportation costs, distribution costs and taxes. Marginal costs are allocated to product types based on results of the refining optimisation.

An add-on modelling in petroleum supply model projects blending of oil products with biofuels, for gasoline, diesel, kerosene and fuel oil. The modelling of blending follows the perspective of product suppliers who are constrained by policy to reduce average emission factors of the blended products or to meet blending regulations. In doing so they define blending percentages to meet regulations, to respect technical constraints concerning combustion of the blended product and to minimise cost of blended products. The suppliers are price takers of biofuel components as these are determined in the biomass supply model of PRIMES. For cost minimisation the suppliers take into account carbon prices/values as price signals of emission reduction policies. Because of the blending, prices of blending products and their average emission factors are determined and are then used as inputs by other PRIMES sub-models.

The following figure illustrates the structure of the stylised refinery modelled in PRIMES for each country.



O. Rest of Energy Branch related to fossil fuels

Primary production of fossil fuels

The PRIMES model database includes data on domestic potential fossil fuel resources by country, covering crude oil, shale oil, natural gas, and solid fuels (coal and lignite). The reserve data have the form of cost-quantity curves with increasing slopes. Extraction activity by country and by fuel type is projected using reduced-form equations. Drivers are demand for fuels (projected in the rest of the PRIMES model), international prices of fossil fuels (used to evaluate profitability of domestic extraction by comparing international prices to domestic costs based on the cost-quantity curves), policy-driven parameters which promote domestic production of fossil fuels by setting lower limits on production schedule or by subsidizing domestic costs. The fossil fuel extraction model solves inter-temporarily. Projection of natural gas extraction is coordinated with projections by the more detailed gas supply model.

Solid Fuel Conversion Plants The model calculates in a simple way inputs and outputs of plants that convert solid energy forms. The following are included: briquetting of coal and lignite; coke production from coal; coke-oven-gas production; blast furnace gas production. Output from such plants depends on demand calculated by the rest of the PRIMES model. Energy consumption, losses and emissions are projected using reduced form equations, which take into account efficiency improvement possibilities and environmental policies, including carbon prices.

The coke and derived gas activities are related to the existence and operation of blast furnaces in a country.

Other conversion processes

The model includes representation of processes, which convert fossil fuels such as coal liquefaction, oil gasification, production of gas works, and recovery of oil feedstock. Inputs and outputs are based on simple technical descriptions of the processes. Activity depends on demand and on time trends, which are specific by country. Gas works is a declining activity. The rest of the processes depend on domestic primary production of fossil fuels. Energy consumption, losses and emissions are calculated.

Losses of oil and gas transportation

Losses of oil pipelines, as well as of gas transportation and gas infrastructure are calculated using fixed loss ratios. The calculation is integrated in the gas supply submodel and distinguishes between different types of gas infrastructures.

Non Energy
Consumption

The model treats petrochemical consumption of fuels for energy and non-energy purposes (raw material) within the sub-model treating the chemicals sector and its sub-sector. Other fuels used for non-energy purposes (e.g. asphalt) are linked to activity of the construction sector.

Energy
Consumption
by Energy
Branch

The PRIMES model computes in detail energy consumption by fuel type and electricity that are used by sectors producing or converting fossil fuels. Fuels are used by motor drives and engines. Steam and electricity are used in specific energy uses. The list of sub-sector of the energy branch is the following: Coal, Lignite extraction; Gas, Oil extraction; Briquetting; Coke production; Gas works; Pipelines and compressors; LNG terminals; Nuclear fuel and waste; Refineries; Energy in other Transport uses (port cranes and airport vehicles).

P.Projection of Energy Balances

Projection of Eurostat balances PRIMES produces Excel reports containing projected energy balances by country following the detailed format and statistical conventions of Eurostat. The projection figures come from the various PRIMES sub-models and are fully balanced, in the sense that they respect all balancing conditions of Eurostat methods, including balancing at: gross inland consumption and supply, demand and supply at final energy consumption, balance of transfer between products, consistency between inputs, outputs, losses and energy consumption of each energy transformation activity, etc. All figures are measured in ton of oil equivalent. Reporting of projected emissions is also detailed as the energy balances.

Treatment of on-site industrial CHP

The projected energy balances have two distinct forms depending on the treatment of fuels uses to produce steam by on-site industrial CHP units (the CHP plants which do not sell steam to other users):

- a) as in Eurostat methods, i.e. by including these fuels in industrial energy consumption and by not showing the steam produced by the corresponding on-site industrial CHP;
- b) as in PRIMES, i.e. by including these fuels in transformation input tables (for power/steam generation), by including the corresponding steam in transformation output tables (for power/steam generation) and by showing the steam amounts in final consumption of industry (by sector).

The data on on-site industrial CHP are produced during PRIMES model calibration using data from Eurostat CHP surveys and other sources of information by industry sector. The calibration model takes cares to produce consistent splits of CHP between on site and distributed steam activities by sector, to match the more aggregated statistical figures of Eurostat. Projection of on-site CHP, distinctly from CHP with steam distribution, is produced by the PRIMES power/steam model, using assumptions regarding the evolution of steam selling market as part of the overall industrial steam consumption.

Calculations consistent with CHP Directive For this purpose, the fuels, which are inputs to CHP plants, split between a part corresponding to an equivalent electricity-only plant and another part corresponding to steam output by the CHP plant. The calculation uses a formula, which is similar to that used by the guidelines implementing the CHP Directive using distinct parameters by type of CHP technology. The fuel to steam ratios as produced by this calculation are usually higher than one, because steam is a by-product of efficient CHP technologies and the additional fuel amount needed to produce steam on top of fuels used for the equivalent electricity-only plant is much lower than fuel amounts used by boilers to produce the same amount of steam.

This calculation method allows PRIMES to compute in projections the ratio indicating the share of electricity and steam produced by CHP by including only the part of CHP, which complies with the efficiency criteria for CHP, which are prescribed in the CHP Directive. Thereby, the model can also evaluate energy and cost impacts of imposing policy-driven targets concerning the share of efficient CHP in the future.

Energy Forms in PRIMES Energy Balances		
Solids		
	hard coal	
	patent fuels	
	coke	
	tar, pitch, benzol	
	lignite	
	other solids	
Crude oil		
Feedstock to refineries		
Liquids		
	refinery gas	
	liquefied petroleum gas	
	gasoline	
	kerosene	
	naphtha	
	diesel oil	
	fuel oil	
	other liquids	
Gas		
	natural gas	
	coke-oven gas	
	blast furnace gas	
	gasworks gas	
Biomass-waste		
	Ethanol	
	Bio-gasoline	
	Bio-diesel	
	Bio-kerosene	
	Bio-heavy	
	Bio-gas	
	Solid biomass	
	Solid waste	
	Gas waste	
	Liquid biomass	
Nuclear		
Hydro		
Wind		
Solar		
Tidal and other renewables		
Geothermal heat		
Methanol		
Hydrogen		
Steam/Heat distributed		
Electricity		

Primary ener	gy
	Primary production
	Recovery from coal liquefaction plants
	Recovery from gas to liquids plants
	Recovery of gas from blending of various methane
	Net imports
	Stock changes (+ or -)
	Bunkers
Gross inland	consumption
Total transfo	rmation input
	Transformation input in thermal power stations
	Transformation input in nuclear power stations
	Transformation input in district heating plants
	Transformation input for production of hydrogen and biofuels
	Transformation input in patent fuel and briquetting plants
	Transformation input in coke-oven plants
	Transformation input in blast furnace plants
	Transformation input in gas works
	Transformation input in refineries
	Transformation input in hydrogen production
	Transformation input in methanol production
	Transformation input in ethanol production
	Transformation input in charcoal production
	Transformation input in for blended natural gas
	Transformation input in coal liquefaction plants
	Transformation input in gas-to-liquids (GTL) plants
Total transfo	rmation output
	Transformation output from thermal power stations
	Transformation output of nuclear power stations
	Transformation output from district heating plants
	Transformation output of hydrogen and biofuels
	Transformation output of patent fuel and briquetting plants
	Transformation output from coke oven plants
	Transformation output from blast furnace plants
	Transformation output from gasworks
	Transformation output from refineries
	Transformation output from hydrogen production
	Transformation output from methanol production
	Transformation output from ethanol production
	F 777777

I Oral Concilm	otion of the energy branch
Total collsulli	Energy branch consumption - own consumption and pumping in power generation
	Energy branch consumption - own consumption and pumping in power generation Energy branch consumption - refineries
	Energy branch consumption - remeries Energy branch consumption - other sectors
	Consumption in Charcoal production plants (Energy)
	Consumption in Gas-to-liquids (GTL) plants (Energy)
	Consumption in Gasification plants for biogas
	Consumption in gas system (storage, LNG, etc. except pipeline gas)
	Consumption in Coal Liquefaction Plants
	Consumption in Oil and gas extraction
	Energy Sector Consumption Coke-Oven & Gas-Works Plants
	Energy Sector Consumption Mines & Patent Fuel/Briquetting plants
	Consumption in Nuclear industry
	Pumped storage power stations balance (derived aggregate)
	Own Use in Electricity, CHP and Heat Plants
Distribution lo	•
	inal consumption
Non-energy co	•
ivon energy ex	Final non energy consumption
	Final non energy consumption in petrochemicals
	Final non energy consumption in other sectors
Final energy o	onsumption in industry
-	Final energy consumption in iron and steel
	Final energy consumption in non-ferrous metal industry
	Final energy consumption in chemical industry
	Final energy consumption in glass, pottery and building materials industry
	Final energy consumption in paper and printing industry
	Final energy consumption in food, drink & tobacco industry
	Final energy consumption in textile, leather & clothing industry
	Final energy consumption in engineering and other metal industry
	Final energy consumption in other industries
Final energy o	onsumption in transport
	Final energy consumption in railways
	Final energy consumption in road transport
	Final energy consumption in air transport
	Final energy consumption in inland navigation
	Final energy consumption in Pipeline transport
	Final energy consumption in other transport (port cranes, airport vehicles, etc.)
Final energy o	onsumption in households, services. etc.
- 35 -	Final energy consumption in households
	Final energy consumption in services
	riliai ellergy collsulliption in services

Q. The PRIMES Biomass model



The PRIMES Biomass model is a modelling tool aimed at contributing to the energy system projections for the EU Member-States and the impact assessment of policies promoting renewable energy sources and addressing climate change mitigation. The detailed numerical model simulates the economics of supply of biomass and waste for energy purposes through a network of processes, current and future, which are represented at a certain level of engineering detail for which a very detailed database of biomass and waste processing technologies and primary resources has been developed.

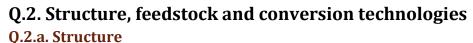
The model transforms biomass feedstock –therefore primary energy- into bio-energy commodities –secondary or final form- which undergo further transformation in the energy system, e.g. as input into power plants, heating boilers or as fuels for transportation.

The model calculates the inputs in terms of primary feedstock of biomass and waste to satisfy a given demand for bio-energy commodities; the model further estimates the land use and the imports necessary and provides quantification of the amount of production capacity required. Furthermore, all the costs resulting from the production of bio-energy commodities and the resulting prices of the commodities are quantified.

The model covers all EU27 Member States individually and covers the entire period from 2000 to 2050 in five-year periods. It is calibrated to Eurostat statistics wherever possible for the years 2000 to 2010. Data from Eurostat is complemented by other statistical sources to fill in the database necessary for the model to function.

The model can operate as a standalone model if the demand for bio-energy commodities is given exogenously, but is more often used together with the PRIMES Energy System Model as a closed loop system.

The PRIMES Biomass model is developed and maintained at E3modelling. The model databases were improved over the years and were recently harmonised with other European models within the Biomass Futures project. The current model version has been thoroughly updated in autumn 2011 where the technology and process database was updated. The historical data are updated to the latest available 2010 statistics.



The general structure of the model can be described in the following way:

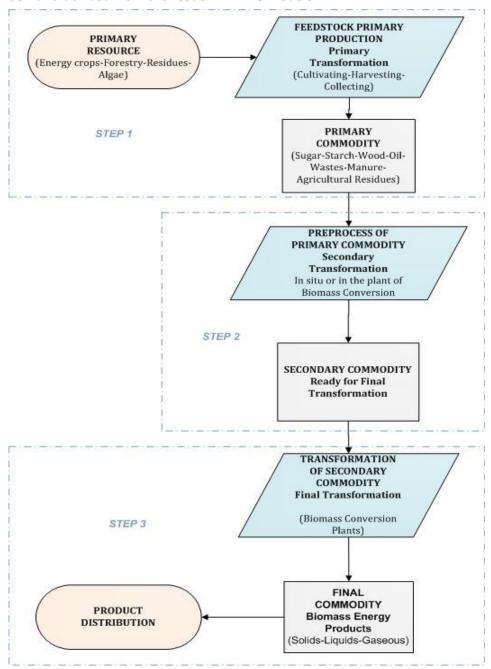
Step 1: A primary biomass commodity (e.g., sugar, starch etc) is produced/derived from the primary resource (e.g. energy crops) through a primary transformation stage (e.g. cultivation).

Step 2: The primary commodity is then, passed through a pre-processing stage (e.g. drying) that produces a secondary/intermediate commodity.



PRIMES has devoted much focus on biomass supply because technology transformation in this sector and supply potential are important for sustainability goals.

Step 3: The secondary commodity is the input to the transformation process from which the final energy product (e.g. biofuel) is derived. Logistics are taken into account as part of the different processes. Final bio-energy supply exactly matches demand derived from the rest of PRIMES models.



Q.2.b. Feedstock

The primary production of biomass has been classified into the following categories: energy crops, agricultural, forestry and industrial waste and aquatic biomass (i.e. algae). Depending on the type of the plants that are cultivated, energy crops are further distinguished into starch, sugar, oil and lignocellulosic crops. This classification is dictated by the differentiation of the methods that each plant category may be processed with and the final products that derive from them. Starch crops include resources such as maize, wheat, barley etc., sugar crops refer mainly to sugar beet and sweet sorghum and oil crops consist of rapeseed, sunflower seed, olive kernel etc. Regarding lignocellulosic crops there is a distinction between wood crops, such as poplar, willow etc., and herbaceous lignocellulosic crops like miscanthus, switch grass, reed etc.

Forestry is split into wood platform, i.e. organised and controlled cutting of whole trees for energy use, and wood residues, i.e. the collecting of forestry residues only.

As mentioned above several types of wastes have been identified as potential sources for energy supply. These include industrial solid waste, pulp industry waste (black liquor), used oils and fats, municipal waste, sewage sludge, landfill gas, manure and animal wastes. The table below summarises all the types of primary biomass/waste effectively used in the model.

Energy Crops	Forestry	Wastes and	Aquatic Biomass	
		Residues		
Starch Crops	Wood Platform	Agricultural Residues	Algae Biomass	
Sugar Crops	Forest Residues	Wood Waste		
Oil Crops		Waste Industrial Solid		
Lignocellulosic Crops		Black Liquor		
		Used oils and fats		
Herbaceous Crops		Municipal Waste		
 Wood Crops 		Sewage Sludge		
		Landfill Gas		
		Manure		
		Animal Waste		

Q.2.c. Biomass Conversion

The PRIMES Biomass model includes numerous production pathways for the production of biofuels for transportation, both for road and non-road, as well as pathways producing bio-energy commodities as inputs into electricity and heat generation sectors. The end products available in the model include bio-energy commodities such as biofuels for road transportation, biogas, small scale solids (mainly pellets) and large scale solids, which mainly are for use in the power generation and industry. Transportation biofuels include diesel and gasoline from biomass (both conventional and advanced biofuels), bio-kerosene for aviation, bio-heavy for navigation, as well as bio-gas. For gasoline and diesel the model differentiates between conventional and advanced biofuels, which are considered to be fully fungible with conventional fuels and can therefore be used in existing engines. For gaseous bio-energy commodities, the model differentiates between bio-methane, which is biogas upgraded to pipeline quality and biogas.

Some of the bio-energy production technologies, such as fermentation of sugars for ethanol production or transesterification of vegetable oil for the production of biodiesel, are technologically and economically mature processes and are already well established in Europe for the production of biofuels. Other technologies, such as pyrolysis of wood, offer significant benefits, regarding mainly the utilisation of cheaper and abundant feedstock, require further research and development to become economically competitive. This process is fully endogenous in the PRIMES biomass model.

An extensive literature review was conducted in order to identify those biomass-to-bio-energy commodities conversion technologies that bear significant potential for future penetration in the biofuel market. The choice of the technologies that are finally selected to be included in the PRIMES biomass model was made based on the current status of technical and economic development, research efforts and possibilities for future improvements, type of feedstock and type and characteristics of final products. The technologies that are incorporated in the model are based on the different conversion chains which constitute pathways of primary biomass transformation to ready-to-use bio-energy commodities.

FEEDSTOCK	PRODUCTION PATHWAY	END PRODUCT	
Starch crops, Sugar crops	Fermentation	Ethanol	
Woody Biomass	Enzymatic Hydrolysis and Fermentation	Cellulosic Ethanol	
	Enzymatic Hydrolysis and Fermentation		
Woody Biomass	HTU process, deoxygenation and upgrading		
Woody Biolilass	Pyrolysis, deoxygenation and upgrading	Ethanol	
	Pyrolysis, Gasification, FT and upgrading	(advanced)	
Woody Biomass, Black Liquor	Gasification, FT and upgrading		
Aquatic Biomass	Transesterification, Hydrogenation and Upgrading		
Oil crops	Transesterification	Biodiesel	
Starch crops, Sugar crops	Enzymatic Hydrolysis and deoxygenation	Diodiesei	
Oil crops	Hydrotreatment and deoxygenation		
Woody biomass, Black Liquor	Gasification and FT		
Aquatic Biomass	Transesterification and Hydrogenation	Biodiesel	
	HTU process and deoxygenation	(advanced)	
Woody biomass	Pyrolysis and deoxygenation		
	Pyrolysis, Gasification and FT		
	Gasification and FT		
Woody biomaga	HTU process and deoxygenation		
Woody biomass	Pyrolysis and deoxygenation	Bio-kerosene	
	Pyrolysis, Gasification and FT		
Aquatic Biomass	Transesterification and Hydrogenation		
Woody biomass	Gasification and methanol Synthesis	Bio-methanol	
Woody biomass	Gasification and DME Synthesis	Bio-DME	
Woody biomass, Black Liquor	Gasification		
Organic Wastes, Starch	Anaerobic Digestion	Piogas / Pio mothana	
Woody biomass	Enzymatic Hydrolysis	Biogas/ Bio-methane	
Woody Diolliass	Catalytic Hydrothermal Gasification		
Woody biomass	Hydrothermal Upgrading (HTU process)		
Woody Diolliass	Pyrolysis	Bio Heavy Fuel Oil	
Black Liquor	Catalytic Upgrading of black liquor		
Landfill, Sewage Sludge	Landfill and sewage sludge	Waste Gas	
Organic Wastes	Anaerobic Digestion	waste uds	
Industrial Waste, Municipal Waste (solid)	RDF	Waste Solid	
Woody biomass		Small Scale Solid	
Woody biomass		Large Scale Solid	

Sugars & Starch Fermentation

Q.2.d. Technologies for Bioethanol production

Bioethanol is used in spark ignition vehicle engines either blended with gasoline or in pure form if the engines are properly modified. At present bioethanol is mainly produced from sugar crops via fermentation. Currently in Europe sugar beet and sweet sorghum are mainly used as feedstock. Starch crops are also being used as feedstock. In that case an additional pre-process stage is needed to hydrolyse starch into simpler sugars before fermentation that implies a cost difference between sugar & starch fermentation processes. Thus, in PRIMES Biomass Model Sugar Fermentation & Starch Fermentation are treated as separate technologies.

Lignocellulosic Fermentation Bioethanol can also be produced using as feedstock lignocellulosic crops through the biochemical conversion of the cellulose and hemicelluloses components of biomass feedstock into fermentable sugars. Cellulosic ethanol has the potential to perform better in terms of energy balance, greenhouse gas (GHG) emissions and land-use requirements than starch-based biofuels. Unlike production of bio-ethanol from sugar

and starch crops, this process is still under development however, a lot of research is taking place both in Europe and in the USA implying significant potential.

Q.2.e. Technologies for Biodiesel production

Transesterification

Biodiesel is merely produced from vegetable oils by catalytic transesterification with methanol. Biodiesel produced in this way has similar properties with fossil diesel and may be used in conventional engines blended up to a proportion with fossil diesel or in modified engines in higher proportions. Vegetable oils may be produced from several biomass sources, such as rapeseed, soya been, sunflower, olive kernel etc. In Europe the most common feedstock for the production of vegetable oil as feedstock for further conversion into biodiesel is rapeseed. Other vegetable and animal fats as well as used oils may also be used as feedstock to the transesterification process. Transesterification is a well-established technology and is largely deployed in Europe. Additionally, research has been performed to examine algae oil production from microalgae cultivation that could be used as feedstock for the production of biodiesel via transesterification offering various potential advantages when compared with traditional oil crops.

Fischer Tropsch Synthesis

The production of diesel from coal via the Fischer-Tropsch process is a technology with long history. Historically the approach has focused on the conversion of coal-to-liquid fuels and chemicals. Recently the utilisation of biomass derived syngas is proposed for the production of Fischer-Tropsch biodiesel. The thermo-chemical route involves the production of a synthesis gas, which is cleaned, before passed through the Fischer-Tropsch process, to create a range of liquid fuels, but primarily synthetic diesel. The production of Fischer-Tropsch diesel requires thorough cleaning and conditioning of the biomass derived syngas, which currently bears a lot of technical difficulties and challenges and deteriorates the economics of the technology. However, the combination of the multiple feedstock gasification with the synthesis of Fischer-Tropsch diesel is an attractive alternative for the production of a fossil diesel substitute.

Pyrolysis

Pyrolysis oil is produced by a thermo-chemical conversion process called flash pyrolysis. In order to be used as transport fuel, pyrolysis oil has to be hydrodeoxygenated using catalysts and stabilised to reach specific quality requirements. Since it is not mixable with fossil diesel, the resulting fuel may only be used directly in modified diesel engines. Pyrolysis oil can also be used for co-firing in power and steam generating units, or may be gasified for the production of syngas. The technology has not reached to a maturity status yet and there are significant difficulties that have to be overcome. However, since almost any type of biomass can be used in flash pyrolysis, including lignocellulosic biomass, the technology is attractive and bears significant potential for future deployment.

Hydro Thermal Upgrade

Another substitute of fossil diesel is proposed by converting almost all types of biomass into liquid biofuel via a process called hydro-thermal upgrading (HTU). During HTU process, the biomass is decomposed in water to produce a crude oil-like liquid called 'bio-crude'. The resulting 'bio-crude' is further upgraded through hydrogenation with catalysts to achieve fossil diesel quality and may be blended in any proportion with conventional fossil diesel. The technological status of the HTU process has not reached maturity yet. Furthermore, it is a highly energy intensive process which further reduces its economic performance. Nevertheless, the utilization of a wide variety of feedstock ranks HTU as a candidate technology for future production of biodiesel.

Q.2.f. Technologies for bio-kerosene production

Bio-kerosene is alternative for jet fuel having similar properties to petroleum-derived kerosene. Currently bio-kerosene production is under research and only test flights have been performed. The airline industry aims not only at replacing fossil with

renewable fuels but also to improve fuel efficiency standards and reduce the volume of greenhouse gas emissions. PRIMES includes fungible bio-kerosene production in the period mainly after 2030.

Q.2.g. Technologies for biogas and bio-methane production

A series of biological processes in which microorganisms break down biodegradable material (biomass); in the absence of oxygen, anaerobic bacteria ferment biomass into biogas. Biogas can be produced this way from almost any organic matter such as agricultural residues, animal waste and manure. In the PRIMES Biomass Model, Anaerobic Digestion is used to produce biogas from every raw material mentioned above. Biogas is a mixture of CO_2 and CH_4 . Methane represents approximately a 60% in the total mixture. In order to increase CH_4 proportion in the mixture, biogas passes through an upgrading process where CO_2 is absorbed or scrubbed and finally leaves 98% of bio-methane that can be directly injected into the natural gas grid.

Biogas can also be produced via gasification. This route has a big potential as a wider range of feedstock like wood can be used. Biomass is gasified at high temperature, producing bio-syngas. The bio-syngas enters a gas cleaning section and then passes through a methanation unit where CO and H2 are converted into bio-methane and CO2. After CO2 removal, the gas is ready for injection into the natural gas grid.

Waste gas consists of Sewage Sludge Gas and Landfill Gas that can be produced via anaerobic digestion technology using Waste Sewage Sludge and Waste Landfill Gas as feedstock. Anaerobic digestion for the production of waste gas is currently widely used in Europe. Due to the impurity and the lower methane content of waste gas compared to that of the biogas (bio-methane) described above, waste gas cannot be injected into the natural gas grid and its main applications are to produce electricity and heating at small scale.

Q.2.h. Technologies for bio-heavy production

Bio-heavy includes 'bio-crude' and 'pyrolysis oil' produced via Pyrolysis and Hydrothermal Upgrade. It is mainly produced to be further altered into biodiesel through transesterification, but could also be used for heat generation or as transport fuel in bunkers.

Q.2.i. Technologies for Small & Large Scale production of solids

Small & Large Scale Solid (woody) consists of wood logs and pellets for small and large-scale combustion for power and heating generation, produced from pelletizing and logging processes of wood biomass.

Waste solid consists of Mass burn waste (MBW) and Refused derived fuel (RDF). Mass burn refers to the incineration of unsorted municipal waste in a Municipal Waste Combustor (MWC) or other incinerators designated to burn only waste from municipalities. RDF is a solid fuel for direct combustion and covers a wide range of waste materials processed to fulfil guideline, regulatory or industry specifications mainly to achieve a high calorific value. Waste derived fuels include residues from MBSW recycling, industrial waste, industrial hazardous waste, biomass waste, etc. RDF can be produced from municipal solid waste through a number of different processes that in general consist of separation and sorting, size reduction (by shredding, chipping and milling), drying and finally transforming the combustible waste into cylindrical solid fuel.

Q.2.j. Technologies for bio-hydrogen production

Bio-hydrogen is a promising future energy source due to its very high-energy content and the fact that it produces almost no emissions when burnt. It could perform either as direct fuel in engines that would burn pure hydrogen or as electric power source for electric motor vehicles (through a fuel cell). Bio-hydrogen can be produced from

Anaerobic Digestion

Gasification

Waste Gas production

Solid woody biomass

Waste Solid production

bio-syngas, a mixture of H_2 and CO formed from biomass derived char, oil or gas. In PRIMES Biomass model, bio-syngas is derived through biomass gasification, to achieve higher ratios of H_2 /CO, an important factor that affects its performance as fuel source. The resulting mixture passes then through a solvent separation system to absorb CO and release bio-hydrogen.

Q.3. Biomass Model Methodology

The PRIMES Biomass model is an economic supply model that computes the optimal use of resources and investment in biomass transformation processes, to meet a given demand for final biomass energy products under least cost conditions. The PRIMES Biomass model solves a non-linear optimisation model. Concatenated with the rest of the PRIMES suite, establishing a closed loop, the PRIMES Biomass model uses a Mixed Complementarity Problem (MCP) algorithm to determine the equilibrium of demand and supply, and the prices of bio-energy commodities. The time horizon of the model is 2050. The model provides dynamic projections to the future from 2015 until 2050 in 5-year time periods with years 2000 to 2010 being calibration years.

The **PRIMES biomass model** solves for cost minimisation from the perspective of a biomass supply planner, who fully anticipates demand, fuel prices, biomass costs and technology improvement potentials if deployed in large scale. The optimisation is constrained by:

- a) the graph of possible conversions and transformations of feedstock to final bio-energy commodities,
- b) demand for bio-energy commodities,
- c) availability of land and feedstock,
- d) cost-supply curves denoting import possibilities and
- e) policy regulations including sustainability and fuel quality criteria.

The model determines:

- a) the optimal use of biomass/waste resources,
- b) the investments in technologies for biomass conversion to bio-energy commodities,
- c) the use of land,
- d) the imports from outside the EU and the intra-EU trade of feedstock and bio-energy commodities,
- e) the costs and the consumer prices of the final bio-energy products as well as
- f) the greenhouse gas (GHG) emissions resulting from the bio-energy commodities life-cycle.

The decision on investment for the secondary and final transformation processes is endogenous using technology vintages and dynamics of technology development. Furthermore, **endogenous learning-by-doing for all technologies** has been included, to simulate technological change and decrease of costs of technologies as related to the cumulative experience gained in the process of commodities production. Improvements in each technology are described by one learning-by-doing curve for each technology, uniform for all Member States of the EU; therefore learning-by-doing effects spill over to the whole EU.

0.3.a. Inputs

Overview of input data

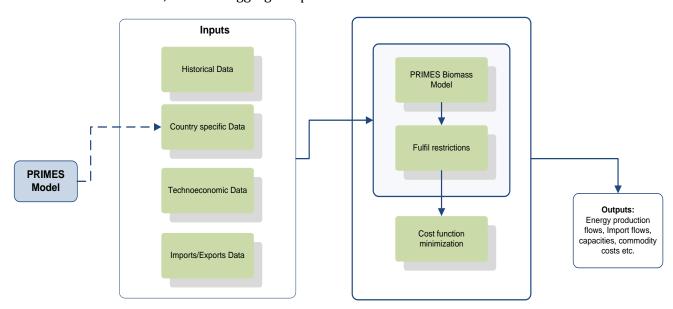
The model input data are country specific data. They include data on:

- agricultural land use productivities and availability,
- costs and commodity prices (prices of electricity, gas and other liquid fuels come from the rest of the PRIMES model),
- technical-economic features of biomass conversion processes including learning by doing potential
- biomass and waste resources potential and the cost supply curves,
- import and bilateral trade possibilities.

For the feedstock prices, the model uses cost-supply curves (with increasing slopes) which are specific by country and depend on land availability, productivity trends and the use of fertilizers (counted in the external effects). Exogenous assumptions and estimates are used about land availability and yield improvement possibilities for the various energy crops. The yields are assumed to increase over time due to technology developments and depending on deployment of specific agricultural policies, which vary by scenario.

Q.3.b. Endogenous trade

Endogenous trade of feedstock and bio-energy commodities The model fully formulates trade of both primary biomass and end bio-energy commodities within the EU and with regions outside the EU. Tradable feedstock considered are pure vegetable oil, which is mainly imported palm oil, and solid biomass. The bio-energy products assumed tradable are solid biomass, conventional and next generation biodiesel, bioethanol, bio-gasoline (meaning cellulosic bioethanol) and bio-kerosene. The trade takes place both between EU Member States with endogenous transportation costs depending on transportation possibilities and with other countries outside the EU. The regions outside the EU carrying biomass trading with the EU are modelled in aggregate categories including North America, CIS and the rest of the world. The trade that takes place between Europe and the rest of the world includes as main providers for wood CIS and North America, while for sugarcane bio-ethanol Brazil. Imported oil is for the most part palm oil mainly from Indonesia and Malaysia. Import possibilities from outside the EU are described through cost-supply curves, which change over time and in the context of different scenarios depending on assumptions about biomass use for energy purposes in the rest of the world. Trade within the EU depends on transportation costs, which are determined, based on aggregate spatial information.



Q.3.c. Mathematical specification of the model

The biomass supply model of PRIMES solves a problem of minimizing total long-term supply costs of meeting a given demand for bio-energy commodities, which is derived from the rest of PRIMES model. The minimization is subject to equilibrium constraints, which represent the cost structure of various feedstock supplying possibilities, as well as the cost functions of technology suppliers. Policy-related restrictions are represented as overall constraints, such as for example the sustainability criteria. It is assumed that a variety of biomass producers and transformers acting in all EU Member-States compete with each other in production and in biomass commodity trading among the Member-States. Thus, the optimization solves for all the Member-States simultaneously as well as for the entire time horizon

assuming perfect anticipation by all market actors. The model also determines bioenergy commodity prices because of maximizing social surplus by Member-State subject to recovering all types of fixed and variable costs of biomass supply.

At a first glance the biomass supply optimization resembles a least cost transport problem consisting of finding the least cost way of meeting demand for bio-energy commodities (denoted by i) through feedstock resources (denoted by s) which are stepwise transformed into final commodities in a variety of processes (denoted by j). The technically feasible conversion and transformation pathways are considered to belong to the mapping h(s,j,i). Both demand and supply are located at the EU Member-States (denoted by n), which are linked together through a transportation network used for trading bio-energy commodities among the Member-States. In addition, the Member-States are connected to non-EU regions for importing biomass feedstock and/or ready-made bio-energy commodities.

Feedstock can be produced in the EU from crops, residues (agriculture, forestry), and wastes. Owners of resources used to produce feedstock (such as land, residue, or waste collectors) are assumed to have different cost structures and to compete with each other. Thus, supply of feedstock is assumed to derive from cost-supply curves, denoted by $f_s(F_s)$, which depend on quantities produced annually (F_s) and exhibit decreasing returns to scale. The cost supply curves are also specified by Member-State (n) and over time (t).

Exporters from outside the EU addressing the Member-State markets are assumed to price feedstock or bio-energy commodities according to their own cost-supply structure, which is subject to resource limitations. Thus, import prices increase with imported quantities (s or i) following an ascending cost-supply function: $m_{k,(s \text{ or } i)}(M_{k,(s \text{ or } i)})$ where M denotes imported quantities and k denotes the various non-EU importing origins.

The processes (j) transforming feedstock into bio-energy commodities have processing capacities $(K_{j,t})$ which are formed by accumulating investment $(I_{j,t})$. The technology characteristics (unit costs, efficiency, and input/output ratios) are specific to the year of investment, but for new installations they evolve over time depending on technology supply which follows learning-by-doing curves, denoted by $\ell_j(\sum_n \sum_t I_{j,n,t})$ exhibiting decreasing costs and increasing performance as a function of total installed capacity in the EU.

Production in time t from a processing unit j built in time τ (i.e. $G_{j,\tau,t}$) is constrained by available capacity ($K_{j,\tau}$). In addition, the rate of use of capacities cannot decrease below a certain level, otherwise, the capacity is not at all used. As the optimization assumes perfect foresight, obviously only capacities with sufficiently high rates of use will be built. Thus, the model simulates competition between various processing technologies.

Both the decreasing costs due to the learning curves and the capacity usage constraints violate standard convexity requirements and so the optimization is formulated as a mixed-integer programming problem.

The main unknown variables are: $F_{s,n,t}$ the domestic production of feedstock, $G_{i,j,n,\tau,t}$ the production of processes, $M_{k,s,n,t}$ and $M_{k,i,n,t}$ the imports of feedstock and readymade bio-energy commodities from non EU countries, $K_{j,n,\tau}$ and $I_{j,n,\tau}$ the capacity and investment in processes (of vintage τ) and $X_{i,n,n,t}$ the exchanges of bio-energy commodities between the EU Member-States (nn being an alias of n).

Market equilibrium is formulated by Member-State and for each bio-energy commodity, requiring that total supply from domestic production and imports (both

outside the EU and from other EU countries) meets exactly given demand in each period. Market equilibrium is thus ensured through the following condition:

$$\sum_{j}\sum_{\tau\leq t}G_{i,j,n,\tau,t}+\sum_{k}M_{k,i,n,t}+\sum_{nn}(X_{i,nn,n,t}-X_{i,n,nn,t})=d_{i,n,t}\ \forall n,\forall t$$
(1)

where $d_{i,t}$ is the demand for bio-energy commodities, given from the core PRIMES model.

Production by transformation processes uses inputs and outputs related to each other through a production possibility function, denoted by $g_{s,j,i}$ which determines demand for feedstock $(G_{s,j,i,n,\tau,t}^{(f)})$ and fuel (and electricity) consumption $(G_{s,j,i,n,\tau,t}^{(e)})$:

$$G_{s,j,i,n,\tau,t}^{(f)} = g_{s,j,i}(G_{i,j,n,\tau,t}) \qquad (\forall s, \forall j, \forall i) \in h(s,j,i) \text{ and } \forall n, \forall t, \forall \tau \leq t$$
 (2)

$$G_{s,i,i,n,\tau,t}^{(e)} = g_{s,j,i}(G_{i,j,n,\tau,t}) \qquad (\forall s, \forall j, \forall i) \in h(s,j,i) \text{ and } \forall n, \forall t, \forall \tau \le t$$
 (3)

Capacities of processing are determined by investment accumulation, as follows (initial conditions concerning old existing capacities are not shown):

$$G_{i,j,n,\tau,t} \le K_{j,n,\tau,t} \ \forall i, \forall j, \forall n, \forall t, \forall \tau \le t$$
(4)

$$G_{i,i,n,\tau,t} \ge u_{i,n,\tau} K_{i,n,\tau,t} \text{ or } G_{i,i,n,\tau,t} = 0 \quad \forall i, \forall j, \forall n, \forall t, \forall \tau \le t$$
 (5)

$$K_{j,n,\tau,t} = I_{j,n,\tau} - D_{j,n,\tau,t} \quad \forall j, \forall n, \forall t, \forall \tau \le t$$
(6)

where $u_{j,n,\tau}$ is the minimum rate of use of capacities and $D_{j,n,\tau,t}$ denotes the decommissioned capacities, which depend on technical lifetime. The time index τ , which must be lower or equal than current projection time t, denotes the technology vintage for processing units and so production as well as technology characteristics are specific to a vintage.

Total demand for feedstock by type has to be met by domestic production and by imports from non-EU countries:

$$\sum_{k} M_{k,s,n,t} + F_{s,n,t} = \sum_{(j,i)\in h(s,j,i)} \sum_{\forall \tau \leq t} G_{s,j,i,n,\tau,t}^{(f)} \quad \forall s, \forall n, \forall t$$
(7)

The part of domestic feedstock originating from crops is associated with land use $(L_{s,n,t})$ through a production function $(y_{s,n})$ which exogenously assumes yield growth trends, specifically by crop type and by country. Similarly, other feedstock types, such as residues or waste, are using primary resources, which are also denoted by, $L_{s,n,t}$ and their use depends on productivity trends captured through the function $y_{s,n}$. Total domestic resources by type of feedstock give upper bounds $\overline{L}_{s,n,t}$, which represent technical potentials.

$$L_{s,n,t} = y_{s,n}(F_{s,n,t}) \quad \forall s, \forall n, \forall t$$
(8)

$$L_{s,n,t} \le \bar{L}_{s,n,t} \quad \forall s, \forall n, \forall t \tag{9}$$

Emissions of greenhouse gases are related to energy consumption in the transformation processes, which include collection and transportation of feedstock, and to emissions related to domestic production of crops. Emissions by type of bio-

energy commodities across the chain of production will have to be lower than a threshold (a sustainability criterion):

$$\sum_{\substack{(s,j)\in h(s,j,i)\\ \leq xe_{i,n,t}\cdot d_{i,n,t}}} \sum_{\forall \tau \leq t} em^{(e)} \cdot G_{s,j,i,n,\tau,t}^{(e)} + \sum_{\substack{(s,j)\in h(s,j,i)\\ \forall i,\forall n,\forall t}} em^{(f)} \cdot a_{s,j,i} \cdot \sum_{\forall \tau \leq t} G_{s,j,i,n,\tau,t}^{(f)}$$

$$(10)$$

where em are greenhouse gas emission factors, xe is the specific emission threshold (the sustainability criterion) and $a_{s,j,i}$ denote the share of feedstock of type s used to produce bio-energy commodity i through a process of type j.

It is assumed that the actors optimizing total biomass supply anticipate the economics of feedstock supply, as well as the cost functions of imports and the learning curves of technology supply. Thus, they take into account the gradients of the corresponding cost-supply curves in their optimization. In this sense, the optimization corresponds to a problem of mathematical programming with equilibrium constraints.

Total biomass supply system cost include in addition the annuity payments for capital investment in transformation processes, the variable and energy costs, the fixed operation and maintenance costs and the transportation costs which depend on distances between the Member-States. The annuity payments depend on a weighted average cost of capital $(\rho_{j,n})$ which may differ by country and by type of process. The aggregation of total costs over time use present values discounted using a social discount rate (δ) .

Total intertemporal biomass supply system cost is then defined as follows:

$$Cost = \sum_{t=1}^{T} e^{-\delta \cdot t} \sum_{n} \left(\sum_{s} \left(\sum_{f} f_{s}(F_{s,n,t}) + \sum_{k} m_{k,s}(M_{k,s,n,t}) \right) + \sum_{s} \sum_{t \leq t} n_{j,n}(\rho_{j,n}) \cdot \ell_{j} \left(\sum_{nn} \sum_{t \in I} I_{j,nn,tt} \right) \cdot I_{j,n,\tau} + \sum_{j} \sum_{i} \sum_{\tau \leq t} v_{i,j,n}(G_{i,j,n,\tau,t}) + \sum_{k} m_{k,i}(M_{k,i,n,t}) \right)$$

$$+ \sum_{i} \left(\sum_{nn} r_{i,n,t}(X_{i,nn,n,t}) + \sum_{k} m_{k,i}(M_{k,i,n,t}) \right)$$

$$(11)$$

where f_s , $m_{k,s}$, ℓ_j , $v_{i,j,n}$, $r_{i,n,t}$, $m_{k,i}$ denote respectively the feedstock cost-supply function, the imported feedstock cost-supply function, the technology learning-by-doing function, the variable cost function for processes, the transportation cost function for intra-EU trade and the cost-supply function for imported bio-energy commodities from outside the EU. Annuity payment factors for capital investment are represented by $n_{i,n}(\rho_{i,n})$.

The optimization problem consists in minimizing total cost given by (11), subject to the constraints that are described by (1) to (10) and to non-negativity constraints for the unknown variables. The anticipation of the equilibrium conditions by the cost-minimizing agent is incorporated directly in the objective function through the cost-supply curves and so it is not needed to solve the model using an MPEC¹⁶ algorithm.

¹⁶ Mathematical programming with equilibrium constraints (MPEC) is the study of constrained optimization problems where the constraints include variational inequalities or complementarities. The lower level optimization problems represent decision by suppliers (of feedstock, imports and technology) for which it is assumed that they have analytical solutions in the form of cost-supply functions.

The dual variable of (1) is the long-term marginal cost of demand for bio-energy commodities and the dual variable of (7) is the long-term marginal value of feedstock supply.

To determine the prices of bio-energy commodity by type and by country, the model formulates a Ramsey-Boiteux pricing methodology. This rule takes the perspective of a multiproduct monopolist, which sets the prices to maximize social surplus subject to a constraint on profits for which total costs include fixed and sunk costs. Such a rule often applies to regulated utilities, which develop new infrastructures, and is consistent with regulators aim at maximizing welfare together with ensuring effective investment. For long term planning, as it is the purpose of the model, the Ramsey-Boiteux pricing is appropriate for an emerging industry, such as biomass production for energy purposes. The price-setting outcome is also compatible with well-functioning markets, which will have to be competitive while providing assurance about fixed cost recovery.

It is assumed that the bio-energy commodities address different markets where they compete against other forms of energy and that demand for these commodities depend on prices. The numerical values of the price elasticities are known using the core PRIMES model, which among others calculates the demand for the bio-energy commodities. Assume that the implicit demand functions are denoted by $d_{i,n,t}(p_{i,n,t})$ where $p_{i,n,t}$ are the prices of the bio-energy commodities. Let us denote by $\pi_{i,n,t}(d_{i,n,t})$ the inverse demand functions. Cost of supply of bio-energy commodities is known by solving the optimization problem mentioned above, which defines an implicit cost function denoted by $C_{n,t}(d_{i,n,t}, \forall i)$ as depending on the entire bundle of bio-energy commodity demand by country. Consequently, total revenue $R_{n,t}$ by country, profit $\Pi_{n,t}$ and social surplus $W_{n,t}$ can be calculated as follows:

$$R_{n,t} = \sum_{i} \pi_{i,n,t}(d_{i,n,t}) \cdot d_{i,n,t} \quad \forall n, \forall t$$
(12)

$$\Pi_{n,t} = R_{n,t} - C_{n,t} (d_{i,n,t}, \forall i) - \Phi_{n,t} \quad \forall n, \forall t$$
(13)

$$W_{n,t} = \sum_{i} \left(\int_{0}^{d_{i,n,t}} \pi_{i,n,t}(z) \cdot dz \right) - C_{n,t} \left(d_{i,n,t}, \forall i \right) - \Phi_{n,t} \quad \forall n, \forall t$$
 (14)

Price determination derives from maximizing social surplus $W_{n,t}$ calculated by (14), subject to profit, calculated by (13), being equal to a fixed value $\overline{\Pi}_{n,t}$ which is typically set equal to zero or to an exogenously defined level. Solving this problem leads to price setting through:

$$p_{i,n,t} = \pi_{i,n,t} (d_{i,n,t}^*) \quad \forall n, \forall t$$
 (15)

where $d_{i,n,t}^*$ results from social surplus maximization under the profit constraint. The parameter $\Phi_{n,t}$ may be used to represent a variety of fixed or sunk costs that are needed to develop the emerging bio-energy market, as well as opportunity costs for example in relation to prices of energy commodities competing with bio-energy ones.

Q.4. Representation of policies and measures

The PRIMES Biomass model is designed to take into account legislation that concerns the use of biomass in energy sector and thus constitutes a tool for the evaluation of the way policies affect the biomass supply system. Additional to current legislation the model is able to simulate other policy contexts, therefore the impacts of different policies, beyond current legislation, and measures can be simulated.

The EU
Climate &
Energy
package
Emissions
constraints

The achievement of the EU 20-20-20 targets is implemented in the PRIMES energy system model and the demand delivered to the PRIMES Biomass model therefore includes these targets. Currently, the model takes into account the RES Directive (Directive 2009/28/EC), the Fuel Quality Directive (Directive 2009/30/EC) and the Biofuels Directive (Directive 2003/30/EC).

Restrictions per bio-energy commodity express that the greenhouse gas emissions (GHG) as percentage of emissions avoided for each biomass commodity have to lie above a certain percentage threshold, determined by current legislation. The threshold imposed by the RES and the Fuel Quality directives is used, but constraints that are more stringent can apply depending on the scenario.

Carbon emissions are calculated for each final bio-energy commodity as a sum of emissions in all stages of the chain of commodity production and transformations. The emissions are computed by multiplying the quantities of energy forms (oil products, gas, and electricity) used in the production and transformation of biomass commodities by specific emissions factors. These factors are obtained from the results of the rest of PRIMES model.

Emissions resulting from indirect land use change (ILUC) can be included in the calculation of the overall emissions, despite the fact that ILUC emissions are not taken into account in current legislation methodologies.

Sustainability criteria

Additional to the GHG mitigation criterion, other sustainability related restrictions can be effectively applied in the PRIMES Biomass model. The criteria currently used in the model are the ones set out by the RES and the Fuel Quality directive and are related to high biodiversity land and to land with high carbon stock. According to legislation, the raw materials used as biomass feedstock cannot be obtained from high biodiversity areas, such as undisturbed forests, high biodiversity grasslands and nature protection areas, unless the production of that raw material is obtained harmlessly. Furthermore, land with high carbon stock cannot be converted to biomass feedstock cultivation area, thus areas such as wetlands, continuously forested areas and peat lands are excluded from the land that can be used for the production of energy crops. These criteria set restrictions to the total acreage of land dedicated to energy crops used in the model, as the energy crops production can only take place in a sustainable manner.

Other sustainability constraints, beyond the ones set out by the RES Directive and the Fuel Quality Directive or enhancement thereof can also be incorporated in the PRIMES Biomass model, such as constraints concerning sustainable use of fertilizers and the quality of water and air. Extensions of the sustainability criteria to imported fuels can also be incorporated in different ways e.g. by assuming higher prices or reducing the quantities available for imports.

Other policies

The model can further implement other policies and measures. In different scenario contexts, policies towards climate change mitigation can be simulated, such as policies facilitating the use of Renewable Energy Sources and the application of carbon values to the ETS and non-ETS sectors. Furthermore, measures such as subsidies can be effectively incorporated in the model, as well as sensitivity analysis on the effect of various parameters, such as conventional fuel prices, on the biomass supply system.

Q.5. Database of PRIMES biomass model

The construction of the biomass database was one of the most demanding and time consuming tasks in the model development process. Extensive literature research has been carried out in order to establish a reliable technical and economic database for each stage of biomass conversion chain. The current model database has been thoroughly updated in autumn 2011, when the technology and process data were

updated. The historical data are updated to the latest available 2010 statistics. The model databases were recently harmonised with other European models within the context of the Biomass Futures project, while extensive use was also made of data developed from previous projects, such as VIEWLS, REFUEL, BIOPOL and JRC.

The database of the PRIMES Biomass model has several components, which can broadly be classified as: the historical statistical data; techno-economic data related to technological parameters for the processes; country specific data relating to agricultural/land use parameters as well as cost data; and import/export data referring to the trade of commodities outside the EU.

Historical data

The PRIMES biomass model uses historical data from 2000 to 2010 for calibration and is able to represent the historical biomass situation in the EU. Where data is available the model is, like all PRIMES family models, fully calibrated to Eurostat; as not all data for biomass is available in Eurostat the model uses also further information sources, such as FAOstat and Enerdata. The effort of collecting, analysing and filtering the most reliable data available for the past years, demands a long time endeavour. This process was fully concluded in autumn 2011.

Technicaleconomic data

The techno-economic data specifies the characteristics of the technologies and are updated to reflect the latest technology developments; the projections for the development of technologies to the future were also updated to the latest available data and literature available.

The data underlying the final values used within the PRIMES Biomass model are taken from a large variety of sources including ECN and OEKO; expert judgement, external consultation with experts, in particular when technology data was not found in literature or when it was not possible to determine the robustness of a data source.

HISTORICAL DATA	DESCRIPTION	SOURCE
Bio-energy production	Amounts of final bio-energy commodities produced	Key source for the data concerning bio- energy production for historical years is Eurostat
	Production technologies used	The information concerning the production technologies used derive from several sources, such as Aebiom and EurObserver
Land data	Includes the cultivated land per crop for the production of biofuels for historical years.	Aebiom and other sources
Technical data for historical years	All techno-economical information needed for historical years, including costs per processes (capital, fixed and variable costs), heat rate of processes followed, fuel consumption	The techno-economical information used mainly came from ECN and OEKO and were complemented by studies of NTUA and the Agricultural University of Athens
Energy crop production cost	This data set includes all the essential information for the computation of the production cost of energy crops for historical years per crop type and country (land yield, land renting cost, labour cost, cost of equipment, cost and uptake of fertilizers and nutrients, fuel prices)	The data concerning the production crop of the energy crops was derived from various sources such as USDA, FAO and FAOSTAT and several others were consulted such as the International Fertilizer Agency
Imports data	Information regarding the trading activity that took place internally in the European Union and among European Union and the rest of the world.	Data from various sources were used including the NREAPs
Fuel prices	Fuel prices for fossil fuels used during the production process	PRIMES model: based on Eurostat and Enerdata

TECHNICAL-ECONOMIC DATA	DESCRIPTION	SOURCE
Cost per process	Here capital, fixed and variable costs are represented per process, from historical and current years to future estimations of technological maturity.	For the collection of the technical- economic data many sources and reports
Heat rate	Model heat rate is used to indicate the efficiency of each process.	were consulted. External consultation with experts from the Chemical
Technical Lifetime	Technical lifetime for every transformation process.	Engineering Department of NTUA and the Agricultural University of Athens took place.
Amortisation	The period to amortise a process investment.	The data that form the PRIMES Biomass
Utilisation	Utilization rate of a production facility.	model database are harmonised with other European models.
Technical availability	Estimates about the availability of a technology at a commercially mature level	outer European models.
Fuel consumption	Amount of energy consumed per technological process.	

In PRIMES Biomass model, numerous conversion pathways are combined to shape the biomass to energy conversion route, producing a variety of bio-energy products. A schematic overview of the biomass conversion technologies effectively used in the model is presented in Annex.

Data was researched for each component of the process in order to have updated data for technologies, which currently do not exist, or for which data are not available, e.g. data concerning the processes for the conversion of aquatic biomass to final bioenergy commodities.

Countryspecific data This data refers mainly to agricultural and land use parameters and data referring to costs, including cost supply curves for feedstock as well as commodity prices (electricity, gas, other liquid fuels). The data mentioned in this section refers to country specific data about future developments; past years are covered in the section on historical/statistical data.

Several sources were used to construct the primary biomass potential databases. The available energy crops production is determined endogenously by the model using exogenous assumptions pertaining land availability and land productivity yields. The yields are crop specific and are assumed to increase overtime due to technology improvements in agriculture and additional agricultural policies. The model uses curves to simulate different types of land with different land productivity and fertiliser needs.

Concerning primary biomass potentials, several sources were used to form the model databases. Information on energy crops were mainly derived from EEA studies and EUWood data and estimates was used to determine forestry potential. The municipal waste and landfill potential is based on values derived from GAINS and own analysis.

The analysis was based on the population growth estimations for each Member State and used data derived from Eurostat waste statistics. Expert judgements were used in order to disaggregate the waste potential derived from Eurostat into the four categories used in waste management. Thus, the amount of waste land filled, composted, incinerated and recycled was determined and therefore the waste potentials that can be effectively used for energy purposes were specified. Regarding black liquor, studies were used to determine current potential, whereas potential projections to future years followed paper and pulp industry growth rates.

EU27 MEMBER STATE DATA	DESCRIPTION	SOURCE
Potentials	Potentials for all biomass types of feedstock resources identified, are available, within the PRIMES biomass model in great detail.	A number of sources were used for the construction of the potentials database, such as EUwood, EEA, Alterra etc.
Demand on biofuels and other bioenergy products	PRIMES biomass model is linked with PRIMES core model as it is determined to compute all the outputs to meet a given demand of bioenergy products projected by PRIMES model. The demand is provided by country and by fuel. External sources which give biofuel demand can be used	The most frequently used data source is the PRIMES Energy System Model. Depending on the scenario other external sources can be used, e.g. the National Renewable Action Plans (NREAPs) submitted by the EU Member States
Energy fuel prices	Another input for PRIMES biomass model, are the fuel prices of electricity, diesel oil and natural gas calculated by PRIMES core model, that are being consumed through the various biomass transformation processes, to produce final bioenergy products from primary biomass feedstock.	PRIMES: the costs for the fuels depend on the scenario context in which the scenario is run
Cost supply curves	Estimated economic supply curves for all biomass supply categories in which the initial biomass primary resources have been analysed.	
Land data	Land availability for dedicated energy crops cultivation for every European Member State.	
Energy crops yield	Possible yields for different kinds of energy crops (sugar, starch, oil, wood lignocellulosic and herbaceous lignocellulosic crops) differentiated per European country taking into consideration climate and currently dominant types of crops.	The data concerning energy crops was derived from various sources such as EEA, USDA, FAOSTAT, EUWood, as well as from previous projects such as VIEWLS and REFUEL
Energy crops production cost	Detailed information on land renting cost, land yield, labour cost, cultivation cost, price and crop absorption factor of fertilizers and nutrients and fuel prices for agriculture (given by PRIMES core model), that are available per energy crop type and European country, result in calculating the overall energy crop production cost.	
GHG Emissions	To compute the total CO ₂ emissions and emission savings resulted from the extensive use of biomass derived energy, emission factors from PRIMES core energy model for electricity, diesel oil and natural gas are included within the inputs of PRIMES Biomass model. For electricity the values are country specific based on the mix of fuels in power generation and they change over the years based on the scenario projection. Moreover percentages that simulate the abatement of CO ₂ emissions that needs to be accomplished according to the EU Renewable Energy Directive are included.	PRIMES Energy System model IPCC methodology for the calculation of N ₂ O emissions IFPRI, OEKO for ILUC emissions

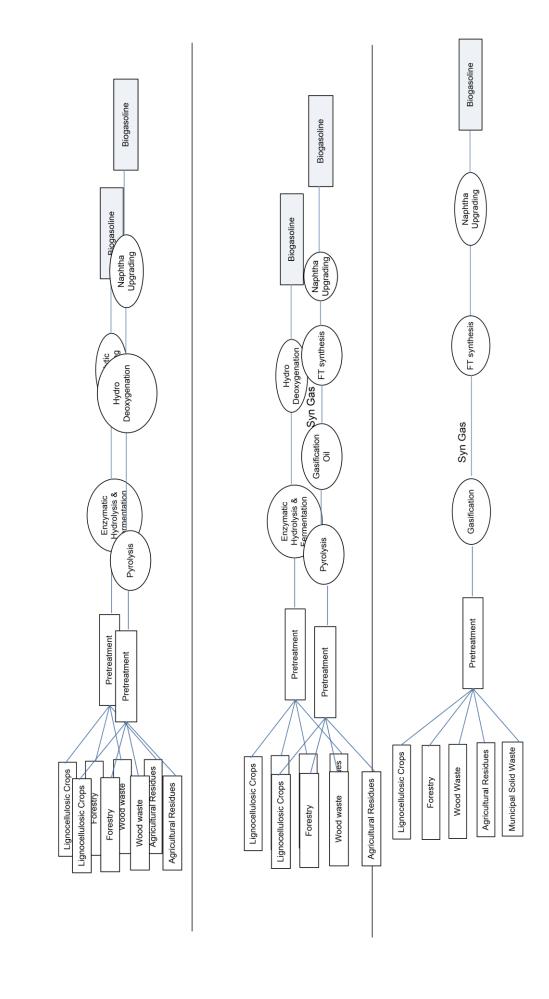
Trade & Import data

The Primes Biomass model allows trade of biomass feedstock and end bio-energy commodities between Member States, as well as between the EU and the rest of the world. Information concerning the trading activity of Europe, both internal and international, is covered. Historical data sets are collected from the year 2000 to 2010, in order to comply with statistics. The necessary data for the construction of this part of the database were derived from several sources.

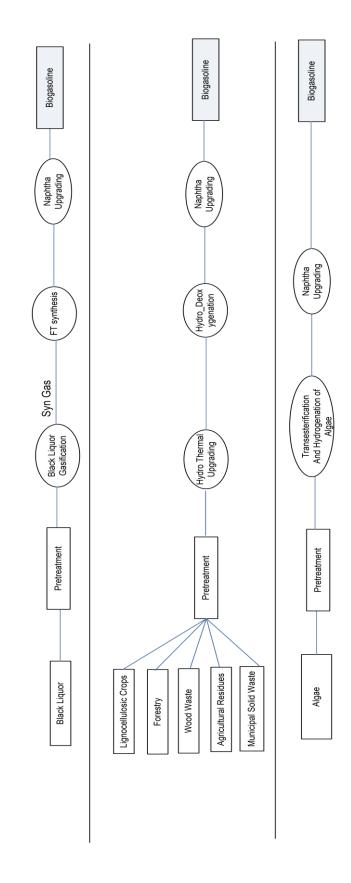
TRADE & IMPORT DATA	DESCRIPTION	UPDATES THROUGH BIOMASS FUTURES PROJECT	
Potentials	Potentials for all products (biomass feedstock or end energy products) imported internationally are available in detail.	Data from various sources were used to form this part of the database, such as IEA, Enerdata,	
Imports exports supply curves	Estimated economic supply curves for all international imports and exports activities.		
Distances and trade connections	Trade matrix simulating distances and trade connections between member states and rest of the world.	Eurostat, NREAPs, the U.S. DOE, FERN and FAOSTAT	
Transport	Costs and means used for transportation regarding internal European trade and international imports		

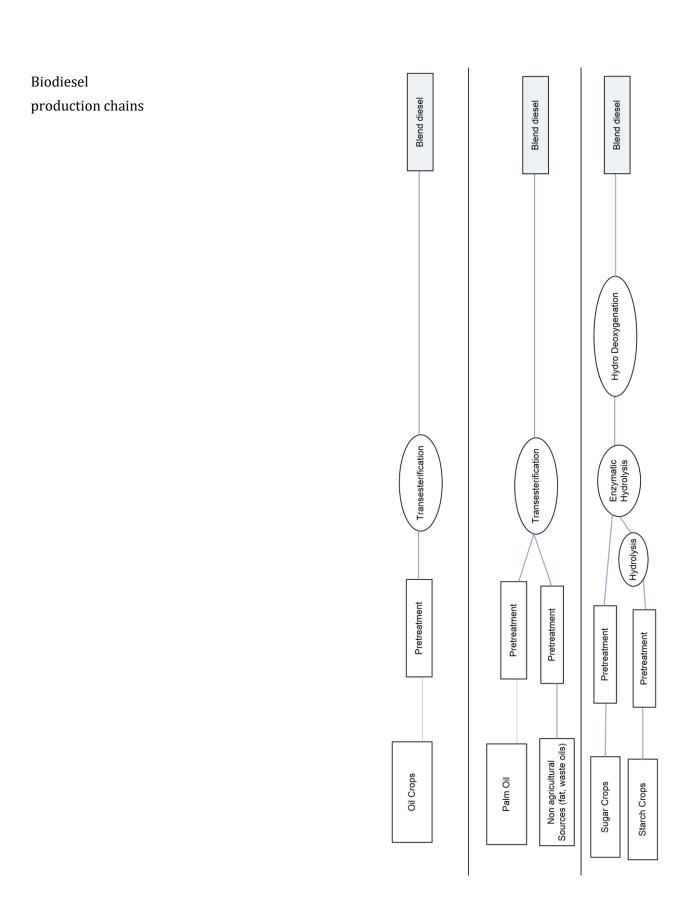
Q.6. Biomass Conversion Chains **Bioethanol Production Chains** Bio ethanol Bio ethanol Pretreatment Pretreatment Agricultural Residues Lignocellulosic Crops Starch Crops

Bio-gasoline production chains Advanced Biogasoline production chains

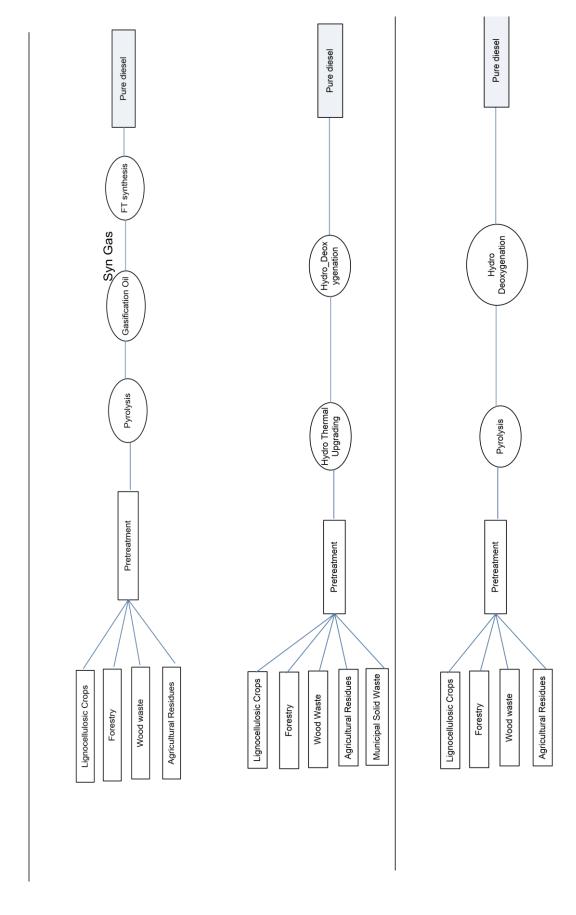


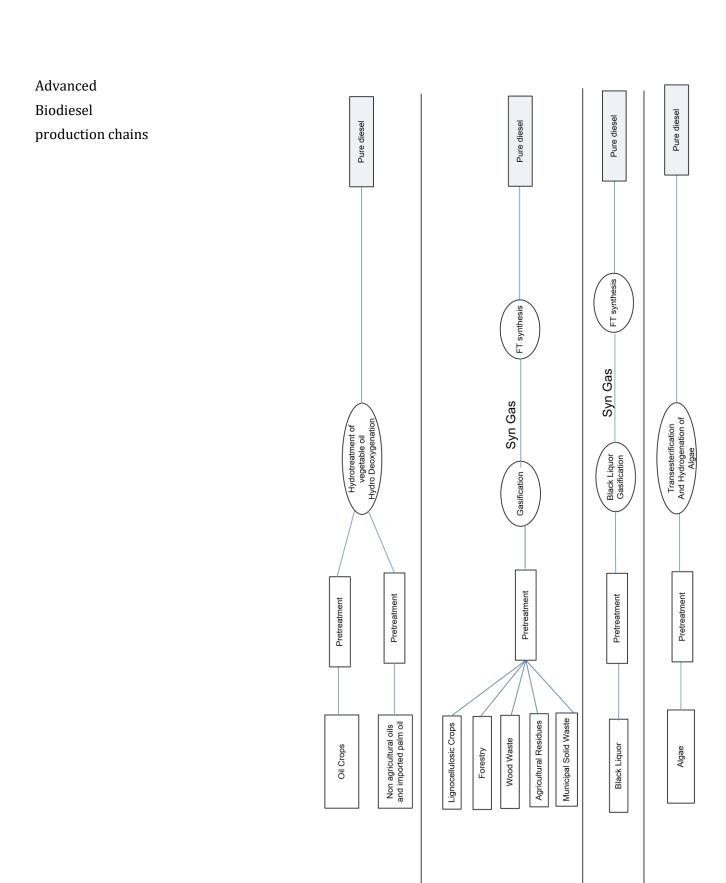
Advanced biogasoline production chains



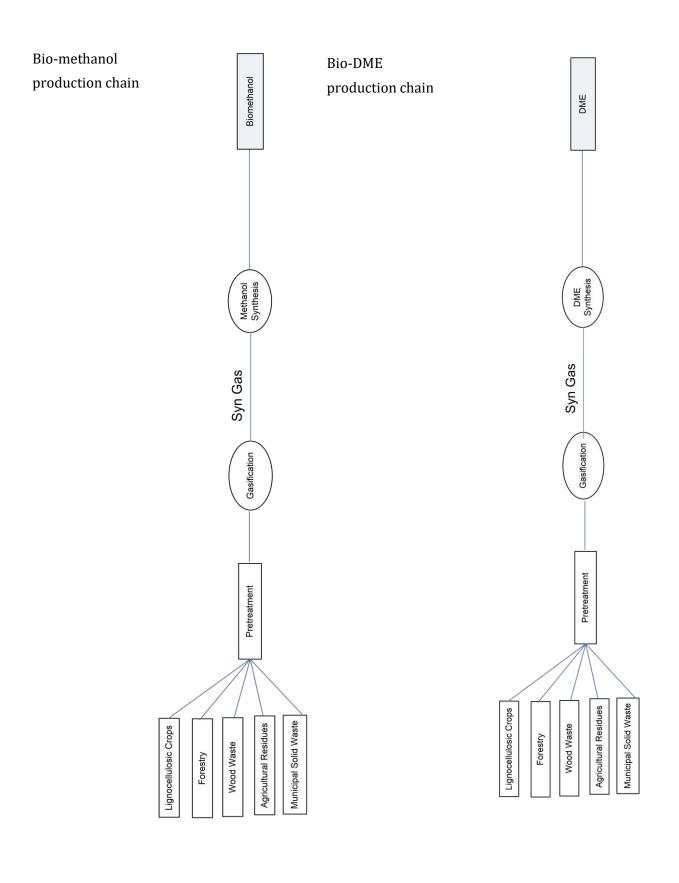


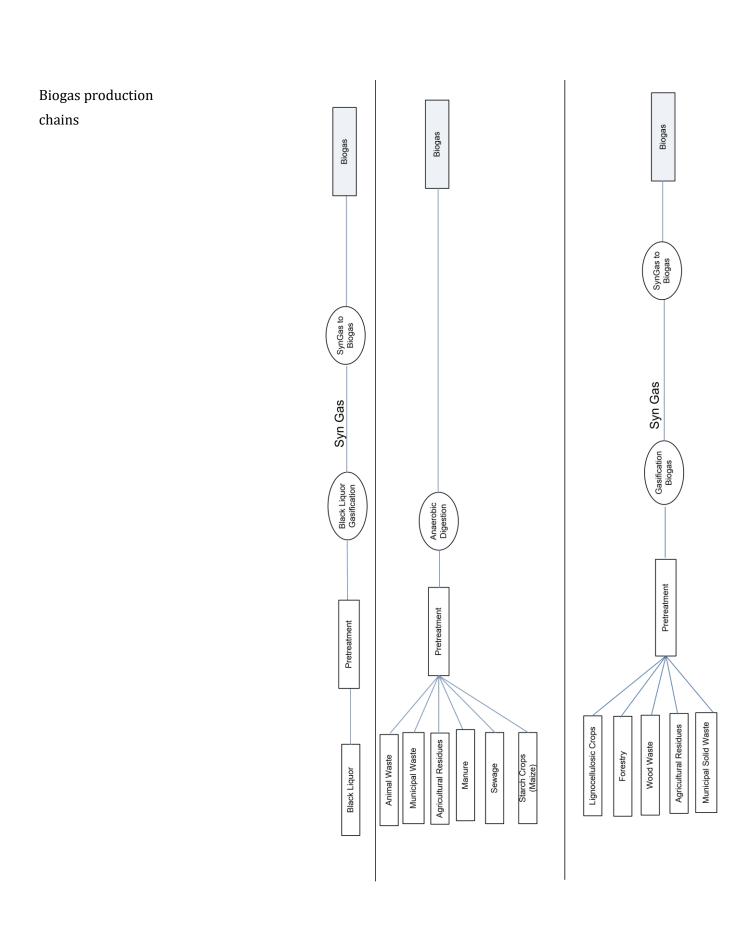
Advanced Biodiesel production chains

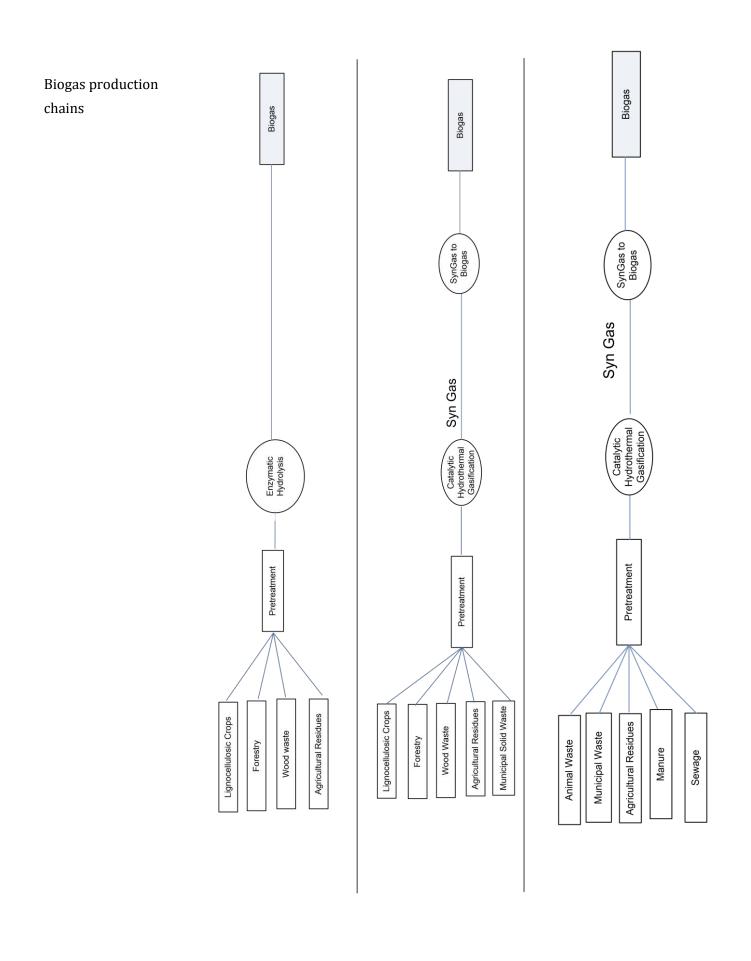




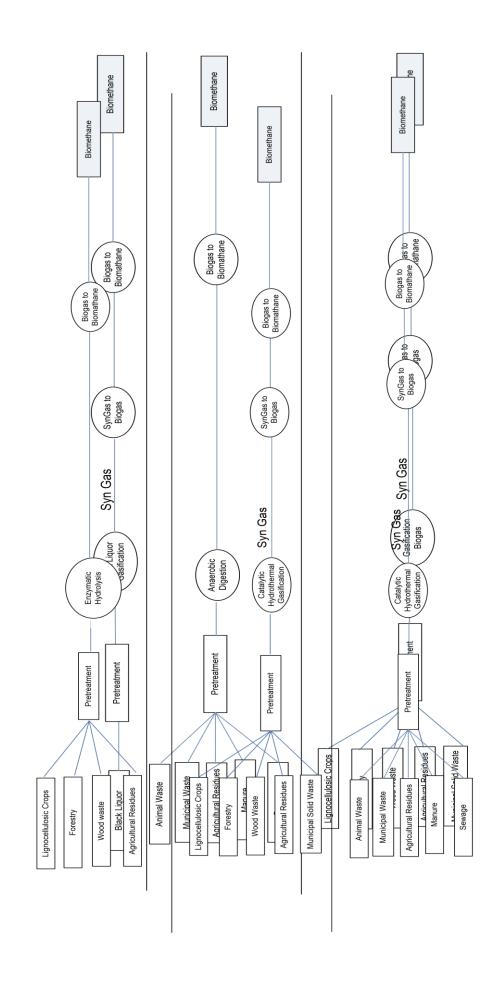
Bio-kerosene Kerosene production chains Bio-kerosene Kerosene production chains Kerosene Kerosene FT synthesis Hydro Deoxygenation Hydro_Deox ygenation FT synthesis Syn Gas Syn Gas Gasification Transesterification
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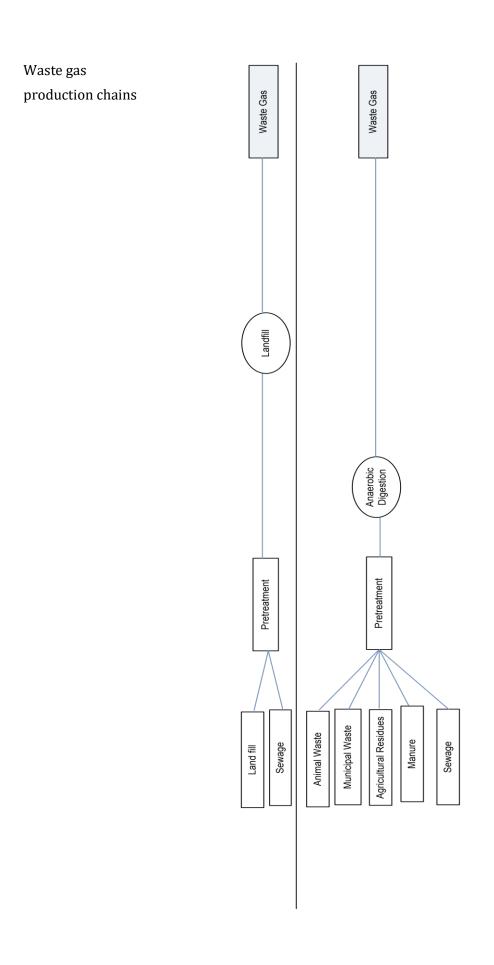


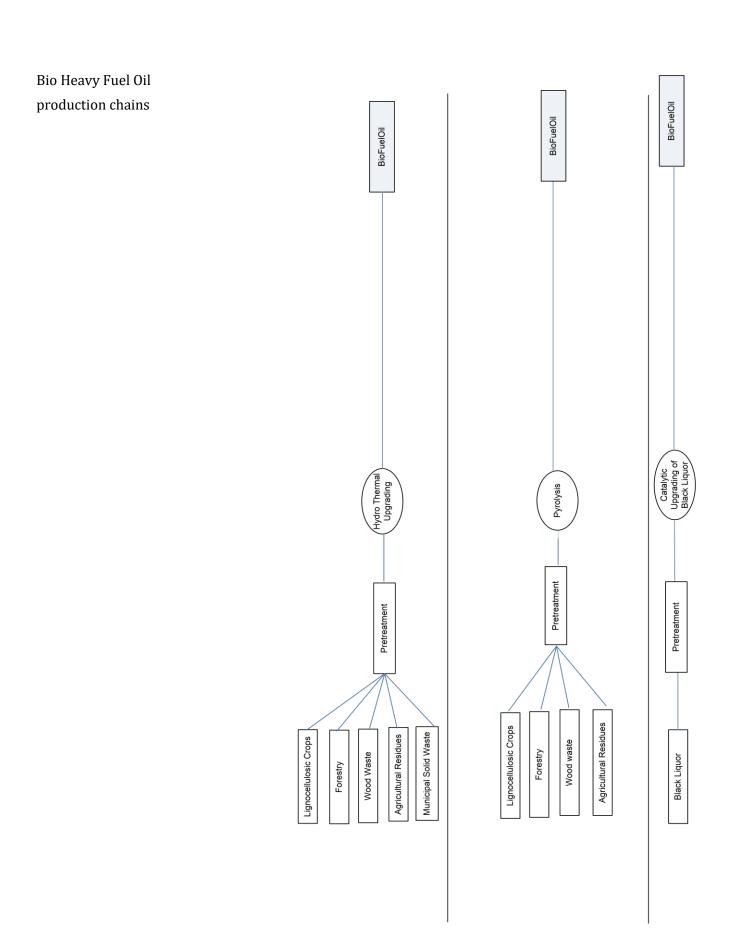




Bio-methane production chains Bio-methane production chains



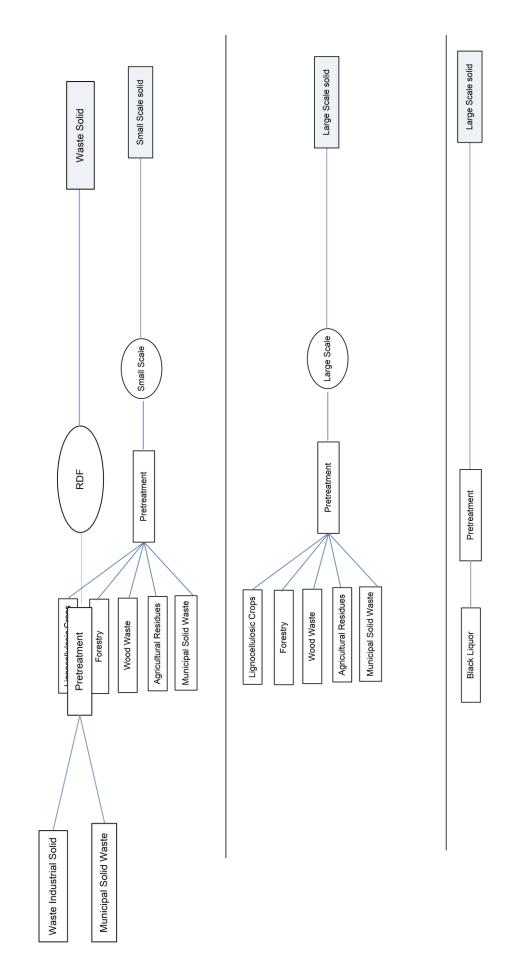


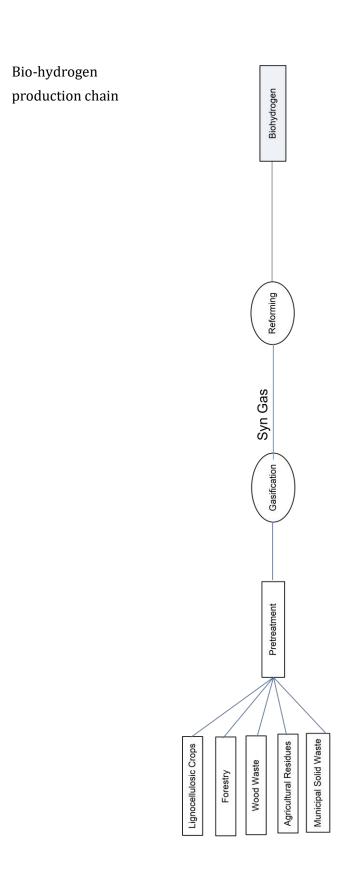


Solid Biomass

production chains
Waste Solid

production chain





R.PRIMES New Fuels Model

A novel PRIMES model extension has been developed which aims at capturing the market penetrations and future role of synthetic fuels, hydrogen, electricity, heat, steam, chemical storage, carbon dioxide as a feedstock source, as well as the synergies and competition between them. It will have a horizon up to 2070, similarly to the updated main PRIMES model. The model represents the process flow with engineering and economic details. It simulates hourly operation of a system with electricity, hydrogen, gas, heat, steam and synthetic fuels in a synchronised way to be able to analyse storage and finally the benefits deriving from sectoral integration.

The novel PRIMES model extension includes an aggregated representation of the electricity, gas, heat and biomass models of PRIMES integrated into the process flow modelling. It includes an aggregated way fuel choice in the demand sectors, but demand for useful energy is exogenous coming from PRIMES.

It includes alternative pathways for the production of numerous low or zero-carbon energy carriers, such as hydrogen, synthetic methane and synthetic liquid hydrocarbons produced via Power to X (PtX) routes. At the same time, it includes conventional energy carriers such as fossil hydrocarbons, biofuels, electricity, steam, heat, etc. Given the large penetration of variable renewables in the future EU power mix, the need for electricity storage will become more and more prominent. The new module of PRIMES is operating at an hourly resolution and it can capture effectively the operation of large-scale power storage systems. For example, the module determines the hours of the day with excess renewables generation in order to produce energy carriers (e.g. hydrogen) that can be used for the production of electricity later when renewable generation is limited (storage). However, at the same time, the new module is also able to decide whether economics favour the production of synthetic hydrocarbons (using e.g. hydrogen as feedstock) instead of providing storage services. In this way, it captures competition for carriers that can serve different purposes (storage vs. feedstock) for different customers (power generator vs. synthetic fuel factories).

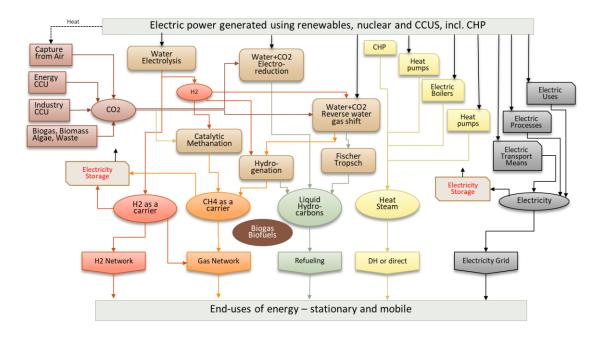


Figure 6: A process flow diagram of the new PRIMES sub-model

All the aforementioned factors must be considered simultaneously, and along with the operation of the rest of energy system (e.g. demand for synthetic kerosene, availability of biofuels, etc.). Therefore, the new module includes aggregate representations of the electricity, gas, heat and biomass models of PRIMES, integrated into the process flow modelling, thus it includes, in an aggregated manner, endogenous fuel choices in the demand sectors. Demand for useful energy is exogenous coming from PRIMES. The remaining models of the PRIMES suite modules are then calibrated so as to reproduce the fuel mixes as calculated by the new model. E.g. PRIMES-TREMOVE respects the share of synthetic gasoline vs. bio-gasoline (and petroleum-based gasoline) used by cars, as this is calculated by the new model extension.

The module is pan-European and solves all countries of Europe simultaneously in order to capture trade of the carriers, location of new factories and infrastructure (power grids, gas, H₂ network and distributed heat). It optimizes the investments and operation of the system under perfect foresight assumptions. It includes several nonlinear mechanisms:

- Cost-potential non-linear curves for exhaustion of resources (increasing slope)
- Non-linear learning curves (technology) and economies of scale (factory), both with decreasing slopes
- Uncertainties and heterogeneity implying hidden-perceived costs which non-linearly depend on enabling conditions (such as a carbon price).

In a nutshell, the new model covers the following energy forms:

• Electricity: It can be produced via numerous sources, either fossil or carbon-free. Electricity can be stored in a plethora of ways, either

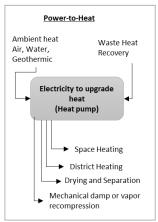
- directly in batteries, or via the conversion to intermediate energy forms (pumped storage, chemical storage as hydrogen, methane etc.).
- Heat and steam: Produced via heat pumps, boilers, CHPs units, for distributed or on-site consumption.
- Carbon dioxide: Carbon dioxide serves an important role; it acts as the main feedstock source for the production of synthetic hydrocarbons. It can be captured from air or via applying CCU technologies to energy and industrial applications. Only the former though guarantees that the synthetic fuels produced will be carbon neutral (or even providing negative emissions, in case they are combusted in biomass fuelled power plants equipped with CCS technology-BECCS).
- Hydrogen: Carbon-free hydrogen is assumed to be produced via electrolysis running on renewable electricity. It can serve as an energy carrier (either combusted or used in fuel cells in stationary or mobile applications), as feedstock for the production of synthetic fuels, or as a means of storage for balancing the generation of variable renewables. Hydrogen can be transferred via dedicated pipelines (that require investments in infrastructure) or blended in the natural gas stream up to a certain share (15%) due to technical limitations.
- Biofuels (liquid and gaseous) They are produced using feedstock of biomass origin. The model distinguishes fungible from non-fungible biofuels. The former can fully substitute petroleum products, the latter are blended up to certain shares with fossil based gasoline and diesel because of technical limitations. Upgraded biogas (bio-methane) can be blended to the natural gas stream.
- Synthetic methane Synthetic CH₄ is an output of a process such as methanation, which utilises hydrogen and carbon dioxide as inputs. The process is energy-intensive, requiring large amounts of electricity. This carrier is usually referred to as "clean gas", since its net carbon intensity is lower than the one of natural gas, and the pathways to produce it as Power-2-Gas (P2G, PtG). Depending on the origin of CO₂ synthetic methane can be considered even as carbon free, if the CO₂ is captured from ambient air.
- Synthetic liquid hydrocarbons Usually referred to as Power-2-Liquids (P2L, PtL); such fuels can fully substitute petroleum based products in mobile applications with no radical changes in ICE powertrains. The conventional powertrains continue to run on fuels with characteristics similar to the ones of conventional oil products. Such vehicles exhibit no range limitations and therefore synthetic fuels could be more easily adapted by transport consumers. The competition with the "electrification of the transport system" can hence be assessed by the enhanced PRIMES model characteristics. However, PtL fuels would probably find more room for development in transport modes, where decarbonisation options are limited (aviation, long distances road freight transportation), where they have to compete only with advanced biofuels (with limited domestic resources) and/or technologies that are currently at low TRL levels (e.g. electric aircrafts). Synthetic hydrocarbons are produced in the model with two main

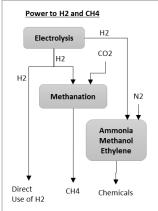
pathways whose intermediate products are either syngas (blend of CO and H2), or alcohols (methanol).

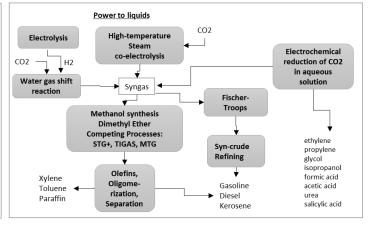
- Electricity Storage Although technically, not an energy form, power storage is an important element of the new module. Storage can be served either via batteries or via the intermediate step of producing hydrogen and/or synthetic methane for later use. The operation of the module at an hourly resolution allows capturing the appropriate time segments for power injection to storage, and extraction from storage at a later time interval.
- Fossil fuels serving as conventional energy carriers. Their use results in GHG emissions.

The graphic below illustrates the linkage of the new fuels model with the chemicals (fertilizers and petrochemicals) structure, to possibly replacing naphtha and natural gas reforming by RES-generated liquid fuels. This would be a way of storing carbon dioxide into materials. In this way, the PRIMES model handles the relationship between the industrial energy model and the industrial processing model regarding the possibility of reusing captured carbon dioxide.

The power model also handles several options of carbon dioxide capturing: a) CCS and CCU from fossil fuel plants, b) From biomass plants equipped with carbon dioxide capturing, c) from the ambient air, d) From the industrial sector capturing for reuse. The model ensures a balance between carbon dioxide capturing, reuse and storage in materials or in geological caverns. The optimisation is cost-based and takes into account nonlinear cost-supply (potential) curves of geological storage, that represent social acceptance as hidden cost factors.







S. Greenhouse Gas Emissions and Policies

CO2 emissions

from energy and

with GAINS all

GHG emissions..

industrial processes and in coordinated use

S.1. Emissions

 CO_2 emissions from energy are computed by multiplying quantities of fossil fuel combusted (measures in energy terms) by emission factors, which are specific to fuels. Abatement of energy-related CO_2 emissions is an endogenous result of the model and depends on fuel mix, technology and process mix within the energy system. The model projects a configuration of the energy system to the future and computes energy-related CO_2 emissions. The model does not include any explicit marginal abatement cost curve (MAC) for energy-related CO_2 emissions. Abatement and its relation with costs result from energy system simulation. MACs can be quantified using the results of the model for a variety of imposed abatement levels.

When in a scenario CO_2 pricing, taxation or quantity limitations apply, the model acts from emissions to the energy system simulating a feedback effect. A quantity limitation on emissions may be treated at the level of each sector or for a country's energy system or for the EU as a whole. In such cases, the model also considers the shadow value of the carbon constraint, which is termed carbon value and influences demand and supply decisions of agents.

A carbon value differs from carbon taxes as it does not entail direct payments, although may inducing higher indirect costs. When policy instruments involving CO_2 emission allowances apply, the quantity of available emission allowances are represented as a carbon constraint and the shadow value, which is computed by the model, acts as a carbon value. When in addition allowances are purchased on auctions, then direct payments are induced and the model considers them in the simulation of agents' choices.

 ${\rm CO_2}$ from process emissions are computed through simple relationships which involve physical production of the relevant industrial commodities (e.g. cement). Simple techniques that may reduce such emissions are represented through marginal abatement cost curves. Higher emission reductions are represented by assuming Carbon Capture and Storage techniques, which apply on the processing of industrial commodities. The representation includes capital and variable costs of CCS, as well as electricity consumption associated with capture, which adds up to total demand for electricity.

Emissions of non CO2 Greenhouse Gases are included in the PRIMES report based on calculations using marginal abatement cost curves and projections quantified by the GAINS model of IIASA.

When in a scenario GHG emission constraints apply, the PRIMES model computes allocation of reduction efforts to the various emission components (energy CO_2 , process CO_2 and the various non CO_2 GHGs) by considering equalisation of carbon values (i.e. equal marginal abatement costs). Sector specific emission reduction constraints can also be treated.

S.2. Emission Reduction

The approach for modelling EU policies concerning greenhouse-gas-emission reduction includes the following:

 $^{^{17}}$ Emission factors by fuel are in accordance to 2007/589/EC. In specific cases where the country specific emissions diverge substantially from the emission factors of 2007/589/EC, country specific emission factors are used.

- The model can analyse various emission constraints: per sector, per country or EU-wide
- The sectors are grouped in ETS and non ETS, with different representations of mechanisms

For ETS

- An EU-wide emission constraint is applied reflecting total volume of allowances (per year) and assumptions about permissible international credits (e.g. CDM)
- Grandfathering (free allowances) can be represented through exogenous quotas per sector and per country; carbon prices are, entirely or partially (reflecting degree of market competition), treated as opportunity costs and price signals, but actual payments only correspond to excess emissions by sector
- Auctioning of allowances is represented by modelling carbon prices inducing true payments by sector
- Carbon prices are determined iteratively (until ETS volume of allowances is exactly met) and apply on all ETS sectors and countries in a uniform way
- Inter-temporal aspects, such as arbitraging over time within the ETS, are considered in the modelling by introducing cumulative allowances as a constraint and excluding borrowing from the future (the model running is however iterative, as inter-temporal optimisation was not technically possible because of computer limitations)

For non ETS

- The model can handle non ETS emission reduction targets either on a country level or EU-wide assuming possible exchanges between MS
- Carbon values (i.e. shadow prices associated with the volume constraint) serve to convey price signals to non-ETS sectors without entailing direct payments (only indirect costs)
- Carbon prices and carbon values act on top of any other policy measure (of specific character, for example standards, specific taxes, subsidies, RES policies and obligations, etc.), thus ETS carbon prices determined endogenously depend on the extend of other policies and measures assumed for a scenario

LULUCF emissions

 Included through linkage with models GLOBIOM and CAPRI, which take inputs from PRIMES biomass model

PRIMES does not model the international market for carbon credits (e.g. CDM). Usually the scenarios assume that the EU is a price-taker of the marginal CDM price and that there is an upper bound on the volume of carbon credits to be taken from CDM. Thus, if the assumed CDM price is lower than the estimated EU ETS carbon price, carbon credits from CDM are taken up to the upper bound. Using PRIMES in linked form with Prometheus model or other global model (e.g. GEM-E3, POLES), it is possible to simulate global ETS and carbon markets with different groupings (bubbles).

S.3. ETS Market Simulation

From a modelling perspective it is complex to optimise dynamically in order to achieve emission targets which are defined in cumulative terms. This is the case of the EU ETS regulation: EU ETS allowances are to be decreased by a fixed amount every year calculated by applying 1.74% on base year ETS emissions and allowances not

ETS Market Simulation used to justify emissions can be banked for future use but borrowing from allowances to be issued in the future is not permitted.

Cumulative emission constraints (carbon budget) are also included as an emission constraint in decarbonisation scenarios handled using PRIMES. In such cases, the modelling is complex because of dynamic arbitration due to the cumulative character of the carbon budget, which must be met. A usual policy request is also to include emission reduction targets for specific years (i.e. 2020, 2030 and 2050) or for one period (i.e. 2030) together with a cumulative carbon budget for the entire projection period.

Mathematically, determining ETS carbon prices as a function of time under constraints about cumulative emissions and end-horizon emissions is a typical optimal control problem, which resembles to optimal control problems applied in economics of depletable resources. Take the example of oil extraction: in the analogy, carbon prices are the oil prices, cumulative emissions are the oil reserves and the annual abatement cost curve is the annual oil production cost curve. The result of this problem is that if marginal costs of production (emission abatement) remain unchanged over time then the rate of exhaustion of reserves (the annual emissions) must be such that the resulting annual price of oil (carbon price) is exactly equal to the discount rate used to calculate the present value of revenues and costs (auction payments). This is called a Hoteling rule for price determination.

From a computational perspective, it is impossible to solve the entire PRIMES model as an optimal control problem because this would imply full inter-temporal balancing of all demand and supply optimisations simultaneously with the inter-temporal clearing of the ETS market. The computer time would be very large.

Instead, PRIMES follows an iterative process. The demand and supply sub-models apply inter-temporal foresight at various degrees (shorter in demand, longer in supply) and so by anticipated ETS carbon prices influence agents' decisions. Based on expert judgment the model starts using a first approximation of time path of ETS carbon prices. Then the loops of the PRIMES model run to find market equilibrium until the end of the projection horizon. The resulting cumulative emissions and point emissions (e.g. in 2020, 2030 and 2050) compare to targets. Depending on deviation from targets, the time path of ETS carbon prices re-adjusts. The adjustment depends on surplus of allowances. High surplus implies that holders of allowances tend to sell as they anticipate waiting long time before obtaining the Hotelling-based return. Depending on assumptions about their foresight horizon, they may behave more or less risk-averse, which influences the timing of selling when high surpluses persist. Agents who use allowances to justify emissions are also risk averse in situations of high surpluses because of perception of high regulatory uncertainty when the market is destabilised by high surpluses. Therefore, these agents tend to be reluctant in banking allowances in periods of low prices, when high surpluses persist. In summary, the ETS trajectory adjustment depends on surpluses.

Version 6 includes representation of the Market Stability Reserve (MSR) regulations and the retirement of allowances in early stages. The MSR aims at reducing and maintaining EUA surplus within boundaries: Emission distribution will reduce if surplus >833MtCO2; Emission distribution will increase if surplus <400MtCO2. The model's logic on MSR is that the structural reform of the EU ETS reduces the risk of holding banked allowances by those being long and provides an incentive to those being short (such as power generators) to buy allowances at periods of low prices. As the system is automatic the stability of the ETS system will be granted under all circumstances (e.g. economic crisis or growth, strong change in international fuel prices, changes in policies), providing for regulatory security and higher

predictability. Therefore, the structural reform will help smoothing the trajectory of carbon prices.

If carbon values apply to non-ETS sectors and if they are equal to ETS carbon prices, then carbon values also change in each iteration. It is reminded that each iteration involves full running of PRIMES over the entire period, therefore the iterative process is time consuming and includes human time spent to decide on the re-adjustment of carbon price trajectory in each iteration.

T.Prices of Energy Commodities

T.1. Introduction

PRIMES takes as input projection of prices of imported fossil fuels in Europe. Usually they are based on projections by world energy models such as Prometheus (E3-Modelling), POLES (Grenoble or JRC) and IEA's WEO. The international fossil fuel price projections apply uniformly on all EU MS, but border prices are further differentiated by country taking into account transport costs and systematic differences of country prices from average EU import prices due to market reasons. Such differences are calculated using observed time series of prices on which an econometric function is possibly estimated serving to extrapolate the differences to the future. It is taken care to avoid extrapolating price differences, which are due to market distortions that may have occurred in the past.

The prices of domestically produced fossil fuel prices are based on costs of extraction plus subsidies. The subsidies are either direct (known based on collected information) or indirect, when for example prices of domestic fossil fuels are defines equal to imported fossil fuel prices although domestic extraction cost is higher. Data are generally missing to estimate the subsidy component in detail, so in many cases PRIMES uses imported prices as estimates of prices of domestically extracted fossils. Nonetheless, PRIMES has devoted much effort to estimate cost of extraction for coal and lignite, by collecting data from national sources. In particular for lignite, PRIMES include differentiated extraction costs by country, based on collected information.

Based on the above, PRIMES calculates fossil fuel prices at primary energy level as weighted sum of prices at imports and costs or prices of domestic extraction. The model projects fossil fuel prices in the domestic markets by sector of consumption, to take into account price differentiation by sector. Pre-tax fossil fuel prices by sector are calculated by adding three components, as follows. After-tax prices add excise taxes and VAT rates as exogenous parameters.

- a) cost corresponding to the primary energy price of the fuel,
- b) cost of fuel processing (e.g. refinery, briquetting, coking, etc.) which is specific to each fossil fuel type,
- c) cost of transportation and distribution which is specific to the customer (sector) type.

The latter component is supposed to reflect not only transportation and distribution costs but also costs due to diseconomies of scale for small-scale customers (e.g. delivery of briquettes to residential sector). The same component includes cost of refueling at service stations for conventional transport sector fuels.

For natural gas, power generation is supplied by high pressure network, industry by high pressure or medium pressure pipelines and residential and services customers by low-pressure pipelines. The regulated tariffs of transport and distribution are different for each type of pipeline, hence by sector. Similarly the requirements for gas balancing are different by sector, thus prices of gas differ by sector, also because of weighting pipeline and LNG gas or services from storage. Gas balancing costs are estimated using shares of LNG and gas storage in gas supply. The regulated tariffs are calculated and projected by the model, based on costs of regulated asset basis and on a levelized costing method using a regulated discount rate. The tariff computation is compared and validated with information collected for past years.

The prices of bio-energy commodities are projected using the PRIMES biomass model which includes a pricing model. Similarly, electricity and distributed steam/heat

prices are calculated using the PRIMES power/steam model, which includes a pricing model. The unit costs of refinery products are computed using the refinery module.

T.2. Mathematical illustration of price calculation

The methodology described below applies to crude oil, refinery products, natural gas, coal, lignite, coke and biomass or waste products.

The prices of imported fossil fuels (w_j) are exogenous, namely for crude oil, natural gas and coal. The unit costs of domestically produced fossil fuels are also exogenous (d_i) .

The price p_{ji} of a commodity j paid by a consumption sector i considers as separate components the price of energy m_{ji} and the tariffs paid for transport and distribution φ_{ji} . Additive taxes or subsidies (τ_{ji}) or multiplicative taxes (σ_{ji}) , where applicable, are exogenous.

The general formulas for computing the price are as follows:

$$p_{ji} = (m_{ji} + \tau_{ji}) \cdot \sigma_{ji} + \varphi_{ji}$$

$$m_{ji} = \alpha_{ji} + \beta_{ji} \cdot [\lambda_{ji} \cdot w_j + (1 - \lambda_{ji}) \cdot d_j]$$

$$or \quad \Delta \ln m_{ji} = \alpha_{ji} + \beta_{ji} \cdot \Delta \ln[\lambda_{ji} \cdot w_j + (1 - \lambda_{ji}) \cdot d_j]$$

$$\varphi_{ji} = \theta_{ji} \cdot \frac{RAB_j + \sum_t C_{j,t} (1 + \rho_j)^{-t}}{\sum_t D_{j,t} (1 + \rho_j)^{-t}}$$

In the above, λ_{ji} represents the main driver of prices and usually, but not necessarily, it takes values 0 (domestic costs prevail) or 1 (import prices prevail). It is possible, that import prices are drivers of a commodity price, although the commodity is domestically produced; in this case opportunity costs drive pricing. The additive factor α_{ji} results from two components, $\alpha_{ji} = \gamma_j + \delta_{ji}$, where γ_j measures supply costs to a country which apply in addition to import prices (or extraction cost) to reflect transport costs, special contracting conditions, etc., and δ_{ji} is an additive component of the pricing conditions for sector i, as for example volume discounts, supply costs, etc. The multiplicative factor β_{ji} represents the degree of correlation of commodity prices with import prices or domestic costs.

When information exists allowing decomposition of imports of commodity j by origin, the equation for m_{ji} includes w_j also decomposed by origin. For example, consider natural gas imports decomposed in pipeline gas and LNG. Different price components form w_j and the weight of LNG can be differentiated by sector i to represent differentiated use of balancing gas in relation to the demand profile of the sector.

The tariffs of transport and distribution apply only for network-based carriers. Their computation uses the regulated asset basis, RAB_j , which is estimated based on network length and characteristics, the anticipated investment and maintenance or operation expenditures in the future, $C_{j,t}$, the anticipated demand, $D_{j,t}$, and the regulated discount rate ρ_j .

The parameters in the formulas above are computed in the calibration stage of the modelling, so as to reproduce base-year prices. The parameters α_{ji} and β_{ji} are computed for refinery products by the detailed refinery sector module of PRIMES, only if the model running has included the refinery module, otherwise the computation uses calibrated coefficients. The detailed biomass supply model of PRIMES computes the domestic component of the prices of biomass or waste. For the

supply of heat by district heating networks, the model computes distribution costs as shown above and uses estimation of average cost of heat production, as the domestic cost component d_j , resulting from the power and heat model of PRIMES. The unit domestic cost d_j includes any environment-related cost or tax item that possibly applies on domestic production.

U. PRIMES reporting on Energy System Costs

PRIMES reports on costs and prices by sector in detail.

For policy evaluation, PRIMES reports on costs from the perspective of final energy consumers, namely industry, households, services and transportation. Such costs per sector are decomposed in:

- Annuity payments for capital based on the sector's discount rate (alternatively annualised cash payments for investment)
- Annuity payments for direct energy efficiency investments (or annualised cash payments for investment)
- Variable costs for operation and maintenance
- Fuel, electricity and distributed steam/heat purchasing costs (which reflect all costs incurring by energy suppliers, including taxes, ETS, etc.)
- Direct tax payments
- Disutility costs (income compensating variation of utility applicable for residential, services and transport of individuals)

Adding these costs for all demand sectors the model computes the Total Energy System Costs, which can be seen as payment by the rest of the economy in order to get the required energy services. Obviously the total energy system costs does not refer only to the purchasing of energy commodities but also to all kinds of expenditures incurring to consumers for energy purposes, since equipment purchasing costs and energy efficiency enabling expenditures are included. Total energy system costs are also reported as % of GDP to indicate the cost of energy services for the economy.

Auction (ETS) revenues may be excluded from total energy system cost when assuming that the recycling of public revenues in the economy is performed without transaction costs. The reported total energy system cost excluding auction payments as % of GDP is thus a better measurement of energy cost impacts from a macroeconomic perspective.

Tax revenues from energy are reported separately include revenues from excise taxes, VAT rates and ETS auctions.

Cash payment for investment is also reported by sector and by type of investment, separately including investment in infrastructure.

The expenditures in energy-related equipment, such as for appliances and vehicles, are calculated based on total purchasing costs, which of course does not correspond only to the energy-related component of the equipment. To isolate energy-related costs, PRIMES calculates an indicator of incremental capital costs specifically for transport equipment: incremental unit capital costs (per vehicle) in a future year relative to base year values are assumed to occur for energy and emission reduction purposes and so the increment is used to calculate capital costs entering Total Energy System Costs.

V.Methodology on Discount Rates

V.1. Overview of discount rates within a modelling approach

The PRIMES model explicitly considers the time dimension and performs dynamic projections. The model projects decisions in which they explicitly consider the time dimension of money flows as perceived by actors. Following microeconomic theory, they actors have preferences about the time dimension of revenues and costs, in the sense that they have to discount an amount defined at future time to make it equivalent to an amount available at present time. The time preference has nothing to do with inflation and is subjective.

The PRIMES model mimics decentralised decisions of the actors so that each actor can apply his individual discount factor, in contrast with other models, which formulate central planning optimisation and assume that the central planner applies a uniform discount factor on behalf of all actors.

The central planning approach can be characterised as normative, whereas the descriptive approaches, as PRIMES follows, use market-based discount factors differing by agent. PRIMES follows a descriptive approach because it aims at assessing policy impacts as close as possible to reality in order to avoid under- or overestimation of the costs and difficulties of transformation towards meeting targets. Central planning models may have different aims, as for example to evaluate what should be the "optimum" system if the world was ideal. They project technology diffusion in the context of an idealised world, which can be misleading for policy making aiming at promoting technology diffusion.

Capital-budgeting decisions enter the PRIMES model in all sectors, both in demand and supply of energy. The simulation mimics the appraisal undertaken by a decision-maker of whether purchasing of equipment or investing in energy savings or infrastructure is worth the funding. The decision involves comparison among alternative options, e.g. technologies, which have different proportions of upfront costs and variable operating expenditures (including fuel costs). As the cost structure, in terms of CAPEX and OPEX, differ across the various options, the decision maker has to do arbitration over time. Therefore, the decision maker's time preferences, in other words the discount factor, influences his choices. The time preference is inherently subjective and the decision maker appraises whether the upfront spending is worth the funding, compared to other options of using the funds, while taking into account uncertainty surrounding the investment options and the scarcity of funding.

Therefore, the value of the discount factor depends on many factors, such as the interest rates prevailing in capital markets, the degree of access to such markets for fund raising, and mostly by the value that the actor associates to own funding resources, such as equity capital or savings of individuals.

Therefore, private discount factors reflect opportunity costs of raising funds by the actor on a private basis. Obviously, the opportunity costs of raising funds differ by sector and by type of actor, being very different by income class. They also vary with

¹⁸ In economics, time preference is the relative valuation placed on a good at an earlier date compared with its valuation at a later date. In mathematical terms, the decision maker uses a discount factor, say d (a rate measured as a percentage), so as to be indifferent when has to choose between a present amount F and a future amount $F \cdot (1+d)^{-t}$ available with certainty time t.

the degree of risk associated to the decision options. In contrast, social discount rates¹⁹ reflect opportunity costs of raising funds by the state or the society.

Private discount factors depend on policies when for example actors use high discount rates due to market distortions and non-market barriers. There are many examples of policies influencing discount rates in sectors such as energy efficiency, renewables and even nuclear or CCS investment. The state may apply support schemes to mitigate risks and reduce the individual discount rates, such as feed-intariffs (FIT), contracts for differences (CfD), power purchase agreements (PPA), sovereign guarantees on investment, reduced taxation, subsidies on interest rates, and generally innovative financing mechanisms. Policies may also transfer risk hedging from individuals to institutions, the latter being able to manage risk collectively and thus more efficiently; examples are the energy service companies (ESCO), the policies obliging utilities to save energy at the premises of their customers, the loans by development banks, etc. All these policies show in PRIMES as reductions of individual discount factors.

V.2. Capital budgeting decisions in PRIMES

An investment choice always involve upfront costs and variable-operating expenditures or revenues which take place over time (e.g. annually). The decision draws on a comparison of different investment options.

The PRIMES model uses different capital budgeting methods in the various submodels. Examples are as follows:

- In the standard version of the power sector model, the choice of options for power capacity expansion uses equivalent annuity costs (EAC). This is part of intertemporal minimization of costs, which guide investment choices within stylised generator portfolios. In the model version, which represents market imperfections, the calculation evaluates expected Net Present Value of investment (NPV), which include risk aversion factors, for each capacity expansion option. The actor either invests and chooses an option or decides not to invest at all.
- In the sub-model, which calculates, investment based on feed-in tariffs or on contracts for differences (CfDs) the model uses a method based on Internal Rate of Return (IRR) calculation by type of investment project from which it derives the probability of investment implementation. Instead of assuming a single threshold value for acceptable IRR, the model uses a frequency distribution of threshold values depending on the IRRs in order to capture heterogeneity of actors and different investment circumstances.
- In the sub-models, which calculate tariffs for using infrastructure subject to regulation as a natural monopoly (power grids, gas network, recharging infrastructure for vehicles, etc.), PRIMES follows the NPV method and uses the regulated rate of return as discount factor.
- In the sub-models, which include investment options for energy savings (e.g. insulation of buildings, control systems in industry, etc.) PRIMES calculates equivalent annuity costs of the energy saving investment and compares annual capital costs to economised annual expenditures due to lower energy consumption. The model calculates a payback period, which combines with frequency distribution of threshold values reflecting heterogeneity of consumers and installations, to determine likelihood of investment.

¹⁹ If social discount rates are used in simulations of private investment decisions, the modeller implicitly assumes that the economy has no funding scarcity and perfect capital markets allow unlimited liquidity.

In the demand sub-models, which include technology choice by type of equipment or vehicle, the formulations calculate equivalent annuity costs for each option and formulate a frequency distribution of technology choices based on relative EACs to reflect heterogeneity of consumers.

V.3. Methodology for defining values of discount rates

The model follows different approaches by sector.

V.3.a. Decisions by firms generally follow the approach of the weighted average cost of capital (WACC) to define discount rates.

The WACC expresses the unit cost of capital for a firm depending on the source of funding, with each type of source using a different interest/discount rate. The main distinction is between equity capital (E) and borrowed capital (D). The former is valued at a subjective discount rate r_e and the latter at a market-based lending rate r_d . A simple WACC formula is as follows:

$$WACC = \frac{E}{E+D}r_e + \frac{D}{E+D}r_d$$

To determine the discount rate on equity the model follows the methodology of the capital asset pricing method (CAPM) which is:

$$R_e = R_f + \beta \cdot (R_m - R_f) \iff \beta = \frac{R_e - R_f}{R_m - R_f}$$

 R_f is the risk-free interest rate. R_m is the benchmark or specific market rate of return on capital (expressing the usual practice of the sector). β is a subjective ratio expressing risk premium of equity relative to risk free options over the usual risk premium of the sector expressed by the difference of the market specific rate and the risk-free rate. Obviously $\beta>1$ indicates a risk averse behaviour, which implies high WACC values compared to risk prone behaviours using $\beta<1$. Technology- or project-specific risk premium values correspond to using a value of β higher than one.

An alternative formulation for estimating the unit capital cost of equity (COE) is to decompose R_e as follows:

$$COE = R_e = R_f + ERP + SP + IRP + CSRP$$

In the above R_f is the risk-free rate, ERP the equity risk premium, SP the size risk premium, IRP the industry risk premium and CSRP the company-specific risk premium.

Surveys of equity risk premium indicate that the values used in practice differ by country and over time reflecting country-specific and economic context-specific risks. The valuation of country-specific or condition-specific equity risk premium is relatively independent of the financial situation of the banking system concerning the lending interest rates or the liquidity of funding by banks. Even under perfect bank liquidity and low lending interest rates, equity risk premium can be high reflecting country-specific uncertainties.

The literature has extensively published survey results of WACC rates (or the ERP rates) used as common business practice in various sectors. The surveys show that capital intensive sectors generally use lower WACC (or ERP) rates than labour-intensive sectors; also WACC rates are higher in small scale projects compared to large scale ones and the WACC rates can be significantly high in technologically emerging sectors or applications. The WACC rates are lower for firms holding dominant positions in markets. They are lower also when they are state-owned or supported by the state, compared to firms operating in fierce competition conditions. New entrant firm in a market with a dominant incumbent firm usually applies a higher WACC than the incumbent, and this is part of the cost of new entry.

Based on these considerations, the PRIMES model applies (or can apply) slightly different WACC rates by business sector, by type of technology (mature versus emerging) and by scale level (e.g. industrial or decentralised versus utility scale).

V.3.b. Decisions by individuals using a subjective discount rate to annualize investment (upfront) costs following the equivalent annuity cost method.

A vast literature collected as part of PRIMES modelling research has published numerous statistical surveys, which estimate the subjective discount rate that individuals implicitly use when making a choice between equipment varieties having different upfront costs and different variable operating costs.

A pioneering research²⁰, back in the '70s, has used a large sample of data based on surveys of purchasing of air-conditioning systems by individuals; the sample included a variety of air conditioning types with different purchasing costs and different energy efficiency rates. Using the sample, the author econometrically estimated the median value of the discount rate that implicitly individuals use to make their choices. He founds a median value between 24 and 26% for the discount rate and points out to the fact that this value substantially exceeds values used in engineering calculations to determine the so-called life-cycle costs for evaluating the trade-off between energy efficiency and higher initial capital costs.

The low rates used in engineering calculations suffer from two shortcomings: from a positive standpoint, they are too low to forecast accurately consumer behaviour and thus can be misleading for policymaking purposes, while from a normative standpoint they are too low to suggest how individuals should make their choice of equipment. The lower bound of the individual discount rate (within the confidence interval based on the sample population) is equal to 15%, which is also much higher than values used in engineering calculations. The author compares the estimated values to the interest rate of 18% applied on credit cards at that time and finds logical that individuals value cash scarcity (opportunity costs of raising funding from a private perspective) at a rate above the rate prevailing in the credit market. The state policy may see the difference between the individual and the social discount rates as a non-

²⁰ Probably the first paper of this kind was the one by Jerry A. Hausman, Professor at MIT, USA Boston, paper published as "Individual discount rates and the purchase and utilization of energy-using durables", The Bell Journal of Economics (Vol. 10, No 1, spring issue), 1979.

price market barrier, a sort of market imperfection. Therefore, policies based on efficiency standards are effective for inciting energy-efficient choice of appliances in circumstances with strong barriers compared to price-based policies, precisely to offset barriers causing high individual discount rates.

The econometric analysis has also verified that the implicit discount rate has a negative strong correlation with income and is as low as 3.6% for high-income classes.

Economic theory suggests that discount rates should decrease as income rises, even with perfect capital markets, since the marginal income tax rate rises with income and the gains from using efficient appliances are untaxed. A histogram of individual discount rates depending on income level can be seen in the graph below. The median value of the discount rates is 24% and the income elasticity is -1.5, which indicate a remarkably high increase of the discount rate for low-income percentiles.

The findings mentioned above are common to numerous studies and publications surveying purchasing behaviours for a large variety of equipment types. To illustrate these findings, many authors proposed terms such as "energy efficiency gap" or "energy efficiency paradox" to describe the implications of using high individual discount rates rather than engineering-oriented or social ones.

Kenneth Train²¹, as well as Sanstad, Blumstein and Stoft²² summarised the findings of many surveys of the '80s and '90s of consumer behaviour for a large number of equipment. All surveys confirmed the strong inverse correlation of individual discount rates and income. The estimations confirmed the large variation of individual discount rates mainly as inverse function of income per household:

- 14% 56% for heating equipment
- 5%-90% for cooling equipment
- 5%-30% for automobiles
- 4%-88% for insulation of houses
- 15%-45% for double glazing and other similar measures in buildings
- 15%-62% for cooking and water heating equipment
- 4%-51% for boilers (difference with heating equipment, see first bullet)
- 35%-100% for refrigerators and
- 20%-40% for small black appliances.

The surveys²³ also revealed that beside income, which is the main explanatory factor of variance of discount rates, the range depends on the age of the persons and the ownership of the property.

A similar approach uses the concept of hurdle rates, which express the minimum rate of return on a project or investment required by the decision maker to compensate for risk associated to future gains. Several econometric studies based on surveys provided evidence that hurdle rates effectively used by individuals and small firms to make investment decisions on energy efficiency are set at levels much above interest rates considered by large firms for equity capital in the context of capital asset pricing methods.

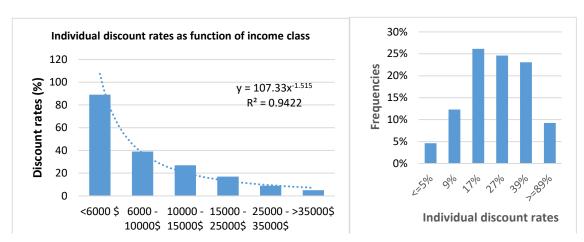
²¹ "Discount rates in consumers' energy-related decisions: a review of the literature", Energy, Vol. 10, No 12, pp. 1243-1253, 1985

 $^{^{22}}$ "How high are option values in energy-efficiency investment?" Energy Policy, Vol. 23, Mo 9, pp. 739-743, 1995

²³ The following references include data from surveys and econometric estimations of individual discount rates: 7, 8, 11, 13, 18, 20, 21, 23, 26, 31, 37, 38, 39, 44, 55 (See references section)

Modern behavioural economics propose models which deviate from classical microeconomics (e.g. bounded rationality $model^{24}$, loss aversion $model^{25}$) which are asserted to explain the persistence of high hurdle rates (equivalently discount rates) in choices for energy-efficiency investments, with initial investments being given asymmetrically greater weight than future savings.

Illustration of dependence of individual discount rates on income



But, despite the different explanatory approaches there is no doubt in the literature about the persistence of high hurdle and discount rates at levels much above engineering and social rates, as well as the strong inverse correlation of the rates with income. Until today, there has been no statistical survey finding low hurdle or discount rates for individuals making selection of energy efficient investment or equipment purchasing despite the campaigns and strong policies favouring energy efficient choices.

This advocates in favour of maintaining high values of discount and hurdle rates for individuals consistently in the modelling. It is equally important to recognise that neglecting heterogeneity of consumers (for example when modelling only a representative consumer by sector) is a serious shortcoming of the modelling. This call upon introducing frequency distributions by income class, or by size and other characteristics and vary the discount rates across classes.

Based on the empirical findings about high discount rates, the literature proposed many explanations. Overall, it is common that energy-efficient technologies entail longer payback periods and greater risks and uncertainties than conventional technologies. According to the reviewed literature, specific causes may include:

- lack of information about cost and benefits of efficiency improvements;
- lack of knowledge about how to use available information;
- uncertainties about the technical performance of investments;

²⁴ Bounded rationality is the idea in decision-making, rationality of individuals is limited by the information they have, the cognitive limitations of their minds and the finite time they have to make a decision. According to this theory, the decision maker is a satisfier, seeking a satisfactory solution rather than the optimal one. Nested decision making models, in which the first level nests refer to seemingly non-economic choices (e.g. colour, convenience, and modernity) imply biased selection of lower level nests, which involve economic considerations and thus the selection can deviate from economic optimality.

²⁵ In economics and decision theory, loss aversion refers to people's tendency to strongly prefer avoiding losses to acquiring gains. Most studies suggest that losses are twice as powerful, psychologically, as gains. This point of view can be represented also by classical microeconomic theory by assuming strong risk aversion.

- lack of sufficient capital to purchase more expensive but efficient products (or capital market imperfections);
- income level and consequently savings resources;
- high transaction costs for obtaining reliable information;
- risk averse attitudes associated with possible financial failure of the investment, etc.

Ownership status is a relevant socio-economic explanation of high implicit discount rates.

The literature argues that the relationship between low income and high implicit discount rates derive partly from poor access of low-income households to capital markets and low liquid capital availability than higher-income households. As a result, even when adequate information on investment returns are certain, lower-income households are reluctant to invest in efficient technologies unless complementary economic instruments are in place. All these explanations imply that appropriately targeted policies have to be in place to reduce the individual discount rates and to make energy efficiency investment more attractive to consumers.

The above-mentioned concepts, both about the discount rates and the policies that can lower their values, reflect onto PRIMES model design. The NEMS model in the US DOE/EIA follows a quite similar approach, as recommended by Sanstad and McMahon²⁶.

V.3.c. Discount factors used to evaluate tariffs of using infrastructure regulated as a natural monopoly.

The model²⁷ uses discount rates based on surveys of actually applied regulated rates of return by state and regulatory agencies in various countries and for different types of infrastructure. The surveys indicate that the regulated rates of return on assets of natural monopolies are set significantly above social discount rates and use the WACC method. The main difference from private practices is that the state agencies or regulators do not accept high-risk premium factors on equity capital, in contrast to private practices. This is justified on the basis that the natural monopoly business has by definition lower risks compared to business subject to competition.

V.3.d. Business sectors

To determine discount rate values reflecting reality one has to start from a risk-free (or low risk) discount rate. Business surveys indicate that equity risk premium (which adds on top of risk free discount rate) is significantly above risk-free rates. The capitalization structure consisting of borrowed funds at lending interest rate and equity capital valued at equity risk premium. Practice suggests that companies add risk premium factors that are specific to a country and/or specific to a sector and/or specific to a project. Country-specific risk premium are relevant for the short-term

$$P = \frac{RAB + \sum_{t=1}^{T} \frac{C_t}{(1+d \pm r)^t}}{\sum_{t=1}^{T} \frac{D_t}{(1+d \pm r)^t}}$$

RAB is the regulated asset basis (roughly the cumulative cost of investment). C_t are the annual operating variable and fixed costs. D_t denotes the expected future use of the infrastructure (measured as a volume indicator). T is the time horizon. d is the regulated discount rate expressing the allowed rate of return on capital and r expresses either a discount on return on capital (if it is deduced) targeted by the regulator or a bonus (when it is added) used as an incentive for technology or coverage improvement.

 ^{26 &}quot;Aspects of Consumers' and Firms' Energy Decision-Making: A Review and Recommendations for the National Energy Modelling System (NEMS)", Lawrence Berkeley National Laboratory, April, 2008
 27 The tariffs of using infrastructure are calculated using the following formula:

and not for long-term projections. Technology-specific risk premium depend on the degree of technology or market maturity. Sector-specific risk premium differentiates depending on degree of competition. Therefore, it is lowest for investment by regulated natural monopolies (e.g., for grids and other infrastructure).

V.3.e. Households

The discount rates used for investment decisions by households in version 6 of the PRIMES model differentiate by household category based on distributions of household types. The aim is to capture heterogeneity of behaviours for individual investment choices by lower or higher income households as well as differentiation according to type of equipment. Based on the literature, the private discount rates used by households strongly differentiate by income class. Statistical observations have confirmed that the discount rates differ by type of energy investment. Surveys have found lower implicit discount rate values for choice of cars than for housing equipment. Surveys have also identified that for heating systems and for thermal integrity expenditures specifically for new-built houses (i.e. choices undertaken when building the house), the individual discount rates are lower than in similar choices when renovating existing houses. The reason is that it is more uncertain to undertake refurbishment investment than incorporating efficient technologies in new houses taking also into account that the efficiency choices for new houses will last longer than for existing houses.

For this reason, the model applies lower discount rates (than the default values by income class) for new buildings concerning thermal integrity and heating systems. Targeted policies may reduce individual discount rates and such policies can be part of scenario designs. Policies such as the energy labelling and certain measures included in Energy Efficiency Directive and the promotion of energy service companies are examples of such policies.

Version 6 of PRIMES takes into consideration the above-mentioned differentiations of discount rates by sector. Optionally the model user can modify the discount values by scenario.

V.4. Use of discount factors for energy system costs reporting V.4.a. Overview

Once having ran the model for a scenario, which means after simulating behaviours and market clearing, which are using the discount rates shown in the previous section, the PRIMES model calculates total energy system costs for reporting purposes.

In an energy system, there are demanders and suppliers of energy. To assess the cost impacts from a macroeconomic perspective, the crucial element is the amount that end use sectors (households and firms, in services and industry, transport and agriculture) are required to pay in order to get the energy services they need. Energy services reflect the purpose of using energy, for example, for supporting heating, cooling, entertainment, mobility and transportation, industrial production, i.e., uses that enable utility and activity for final energy consumers. Energy services delivery is due to energy commodities purchased by end-consumers and self-production of energy. Both depend on energy efficiency at the consumption level.

The end-users undergo investment for purchasing equipment (e.g. boilers, vehicles, etc.), for insulating buildings and for installing energy saving systems.

From an accounting perspective, the investment expenditures of end-users of energy are capital expenditures (CAPEX). Part of investment expenditure for equipment purchasing correspond to energy purposes. For example, the additional cost of a highly efficient vehicle (on top of cost of a conventional vehicle) incurs for energy

purposes. Only such additional investment costs enter the accounts of energy-related investment of end-users.

In addition, the final energy consumers incur annual variable and fixed costs which include the purchasing of energy commodities from energy supplying and trading sectors, the maintenance costs of equipment and other annual costs (e.g. assurance costs, vehicle taxes, etc.). These annual costs are operating expenditures (OPEX).

Energy supply and trading sectors fully recover their total costs (CAPEX and OPEX) from revenues paid by end-consumers. Therefore the total energy system cost only includes the CAPEX and OPEX incurred by end-consumers, with their OPEX already incorporating the CAPEX and OPEX costs incurred by the supply and trading sectors. The PRIMES model determines the prices of supply and trading sectors in a manner that fully recovers total supply costs using the WACC that represents the real unit cost of capital experienced by a firm operating in energy supply sectors.

The PRIMES report aggregates CAPEX and OPEX of end-consumers to show a single total cost figure with annual periodicity. To do this, also the CAPEX figures related to investments by final energy demand consumers need to be annual following the equivalent annuity cost method, which involves use of a discount factor over the lifespan of the investment. The annualised equivalent cost expresses the cost incurred for the end-consumer for owning an asset until the end of its lifetime. As such it expresses the gradual accumulation of resources to be able to replace the asset as the present value of the annuity payments for capital is by definition equal to the investment (upfront) expenditure (see formulas of equivalent annuity cost method in Annex I).

The choice of discount rate for the CAPEX cost reporting by final energy demand consumers can reflect different perspectives, but should reflect in any case the perspective of the private investor faced with real world investment constraints

In the past, the PRIMES model has used for this cost reporting the opportunity costs of raising funds as perceived by the end-consumers when making the investment choices, using the default discount rates by end-consumer for investment decisions in all scenarios even if in a scenario policy assumptions led to reduced discount rates for the investment decision. The reason of this choice was to maintain comparability of total costs across scenarios. This approach has the drawback that perceived high discount rates is the result of market failures (such as lack of information, split incentives) which are accounted for as a cost.

An alternative approach could be to base the cost reporting of the CAPEX by final energy demand consumers on true payments for capital costs. This implies that the CAPEX has to be annualised using lending rates for the part of capital borrowed from banks and equity rates for the rest. It has the drawback that it does not reflect the fact that there are also opportunity costs associated with higher debt rates (i.e. risk averseness as well as reduced incentives to make other investments). In addition, detailed information would need to be collected to identify the borrowing rates faced by different end-users. Furthermore, equity rates are subjective and therefore assumptions are necessary regarding their values. Finally, a dilemma similar to that of the approach using discount rates that take into account opportunity costs arises. Policies may enable reduction of equity discount rates and if this differs by scenario, comparability of costs is lost across scenarios.

Summary of cost concepts used to calculate total energy system costs

	Final energy consumers	Energy supply sectors	Total energy system costs
CAPEX	Investment expenditures for purchasing equipment, vehicles and appliances and for thermal integrity and other energy saving purposes in the premises of the consumers	Investment expenditures for power generation plants, power grids, gas networks, refineries, primary fuel extraction, etc.	CAPEX incurred directly for final energy consumers
OPEX	Purchasing of fuels, distributed heat and electricity, as well as other annual expenditures for operation and maintenance	Purchasing of fuels and annual operating and maintenance expenditures	OPEX incurred directly for final energy consumers
Profits or deficits of financial balance	Not applicable	Applicable to energy supply sectors ad network operators depending on scenario assumptions about market distortions	included indirectly in costs for purchasing energy commodities by end consumers
Taxes, subsidies and auction revenues	Applicable for both CAPEX and OPEX	Applicable for both CAPEX and OPEX	Energy tax revenues included. Revenues from auctioning ETS allowances not included, assuming perfect recycling in the economy.

In conclusion, comparability across the scenarios is of key importance and implies that the discount rates used in the cost accounting must not vary between scenarios. Considering the draw-backs of both approaches listed above it is proposed to account the costs associated with CAPEX for final energy demand consumers using a lower rate that is more in line with the WACC used for the supply and industry sector. This would mean that high perceived discount rates, which may be the result of market failures (such as lack of information, split incentives), would no longer be accounted for as a cost, and from a cost accounting perspective would treat demand side sector and supply side sectors in a similar manner.

V.4.b. Present Value Calculation Method

Assume that there are two options to compare, namely i and j which require upfront costs I_i , I_j (assumed with a negative sign) and imply variable-operating costs and/or revenues $v_{i,t}$, $v_{j,t}$ where t denotes time, which are negative when they are net costs and positive when they are net revenues.

Net Present Value (NPV) is the difference between the present value of cash inflows and cash outflows, where future values are discounted using a discount factor *d*:

$$NPV_h = \sum_t \frac{v_{h,t}}{(1+d)^t} + I_h \quad with \ h = i, j$$

The choice uses the rule that an option is preferable if NPV is positive, otherwise it is rejected. In case of alternatives, the option with the highest NPV is preferable. In case all cash flows are negative, (costs) then the option with less negative NPV is preferable.

The *payback period method* determines how long it will take to pay back the initial investment using the sum of expected future revenues. Future revenues may be savings on future costs that would otherwise occur. This method does not calculate present values and thus does not use a discount factor. The numerator uses investment expenditures expressed as a positive amount. The denominator can include positive and/or negative cash flows (net revenues/savings or net costs, respectively):

$$PBP = \frac{|I_h|}{\sum_t v_{h,t}} \quad with \ h = i, j$$

If PBP is negative, the project is rejected. To accept a project, it is necessary that it lead to a PBP, which stands below a threshold that the decision-maker defines as the maximum reasonably acceptable payback period. The choice of a threshold value is of the same nature as the choice of the value of a (subjective) discount factor and is also different by type of actor or project, it involves risk and is conceived relatively to lowrisk (or free-risk) alternatives. If more than one option achieve PBPs below the threshold value, the option with the lowest PBP (shorter payback period) is preferable.

The *Internal Rate of Return* (IRR) method, which in principle is similar to the NPV method, calculates which discount factor would make a stream of cash flows to have a NPV equal to zero. The IRR represents how much of a return an investor can expect to realize from a particular project. The IRR is calculated implicitly by solving the following problem:

Calculate d_h so that:

$$NPV_h = \sum_t \frac{v_{h,t}}{(1+d_h)^t} + I_h = 0 \quad \text{with } h = i,j$$

The calculation implies that different IRRs d_h will be obtained for different options, such as i and j. The IRR method is not applicable to cases having only negative cash flows (costs). Deciding whether to pursue the investment requires assuming a threshold value for IRR to retain any project with IRR above the threshold value and in case of multiple options retain the one with highest IRR above the threshold value. The choice of the threshold value is subjective, involves risk consideration and has a relative meaning with reference to low risk or free-risk options.

The *equivalent annuity cost method* expresses the NPV as an annualized cash flow by dividing it by the present value of the annuity factor. The annuity factor involves assumption of a discount factor (d), which as before is subjective, involves risk considerations and is relative to low or free-risk options. This method is appropriate when assessing only the costs of specific investment options that have constant or slightly changing annual variable and operating costs over time. In this form, it is known as the equivalent annuity cost (EAC) method and represents the cost per year of owning and operating an asset over its entire lifespan. For example, if the annual variable operating cost $v_{h,t}$ is the same over time and L_h is the economic lifetime of the project h, then the annual total cost of the asset is:

$$EAC_h = I_h \cdot \frac{d}{1 - (1 + d)^{-L_h}} + v_{h,t}$$
 with $h = i, j$

In this formula, I_h and $v_{h,t}$ are assumed to be positive and to represent costs. The EAC method applies when asset selection performs from a cost minimisation perspective. The EAC method does not say whether it is worth investing, as this requires consideration of revenues from the asset. It is easy to verify that the present value of the equivalent annuity costs are exactly equal to initial investment.

Although the above-mentioned capital-budgeting methods seem different to each other, in essence, they are quite similar and all involve, explicitly or implicitly, consideration of a discount factor or a threshold value, which are subjective, involve risk and are relative to risk-free options.

V.4.c. Mathematical illustration of cost reporting in PRIMES

Assume that t denotes time and tt represents the time of implementing a new investment. Obviously $tt \leq t$. Based on model projections for a scenario, the cost reporting routine knows $CAPEX_{i,tt}$ representing investment expenditure implemented in tt by an end-consumer, with i spanning all such investment cases. The end-consumers also incur variable and fixed annual operating and maintenance costs represented by $OPEX_{i,t}$. The CAPEX are annualised as $AnnCAPEX_{i,t}$ following the equivalent annuity cost method, using a discount factor d_i specific to i with lifetime L_i , as follows:

$$AnnCAPEX_{i,t} = \sum_{tt \le t} CAPEX_{i,tt} \cdot \frac{d_i}{1 - (1 + d_i)^{-L_i}} \cdot (1 \text{ if } tt + L_i \le t, \text{ or } 0 \text{ otherwise})$$

Total annual energy system costs $AnnTC_t$ is:

$$AnnTC_{t} = \sum_{i} (AnnCAPEX_{i,t} + OPEX_{i,t})$$

Total cumulative energy system cost CumTC derives as present value of total annual energy system costs using a social discount rate equal to δ :

$$CumTC = \sum_{t} AnnTC_{t} \cdot (1 + \delta)^{-t}$$

Notice that δ is different from the private discount rates d_i used to annualise CAPEX. Therefore CumTC evaluated for different scenarios ranks the scenarios from a social, public policy perspective.