To pdf - POLES

From IAMC-Documentation

Reference card - POLES

Contents

The reference card is a clearly defined description of model features. The numerous options have been organized into a limited amount of default and model specific (non default) options. In addition some features are described by a short clarifying text.

Legend:

☐ not implemented
☑ **implemented**
☑ **implemented (not default option)**

About

Name and version	POLES ADVANCE (other versions are in use in other applications)
Institution and users	JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles. main users: - European Commission, JRC - Universite de Grenoble UPMF, France - Enerdata
Documentation	POLES documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - POLES

Objective	POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates to as to deliver robust forecasts for both short and long-term horizons. It has quickly been used, in the late 90s, to assess energy-related CO2 mitigation policies. Over time other GHG emissions have been included (energy and industry non-CO2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.
Concept	Partial equilibrium
Solution method	Recursive simulation
Anticipation	Myopic
Temporal dimension	Base year:1990-2015 (data up to current time -1/-2), time steps:Yearly, horizon: 2050-2100

Note: Energy markets: yearly step
Power generation: 2-hour time steps
in representative days

Spatial dimension Number of regions:57

Note: Complete energy balances: 57 countries / regions covering the World, including detailed EU28, all OECD countries and main non-OECD countries Fossil fuel supply: 80 countries / regions

Policy implementation - Energy taxes per sector and fuel, carbon pricing - Feed-in tariffs, green certificates, low interest rates, investment subsidies - Fuel efficiency standards in vehicles and buildings, white certificates

Socio economic drivers

Model documentation: Socio-economic drivers - POLES

Exogenous drivers

- ☑ **Exogenous GDP**
- ☐ Total Factor Productivity
- ☐ Labour Productivity
- ☐ Capital Technical progress
- ☐ Energy Technical progress
- ☐ Materials Technical progress
- ☐ GDP per capita
- ☑ **Population**

Endogenous drivers

- ☑ **Value added**
- ☑ **Mobility needs**
- ☑ **Fossil fuel prices**
- ☑ **Buildings surfaces**

Development

- ☑ **GDP per capita**
- ☐ Income distribution in a region
- ☑ **Urbanisation rate**
- ☐ Education level
- ☐ Labour participation rate

Macro economy

Model documentation: Macro-economy - POLES

Economic sectors

- ☑ **Agriculture**
- ☑ **Industry**
- ☐ Energy
- ☐ Transport
- ☑ **Services**

Cost measures

- ☐ GDP loss
- ☐ Welfare loss
- ☐ Consumption loss
- ☑ **Area under MAC**
- ☑ **Energy system costs**

Note: Investments: supply-side only

Trade

- ☑ **Coal**
- ☑ **Oil**
- ☑ **Gas**
- ☐ Uranium
- ☐ Electricity
- ☑ **Bioenergy crops**

☐ Food crops	☐ Non-energy goods
☐ Capital	☑ **Liquid biofuels**
☑ **Emissions permits**	

Energy

Model documentation: Energy - POLES

Behaviour	Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.	
Resource use	☑ **Coal** ☑ **Oil** ☑ **Gas**	☑ **Uranium** ☑ **Biomass**
Electricity technologies	☑ **Coal** ☑ **Gas** ☑ **Oil** ☑ **Nuclear** ☑ **Biomass** ☑ **Wind**	☑ **Solar PV** ☑ **CCS** ☑ **Hydropower** ☑ **Geothermal** ☑ **Solar CSP** ☑ **Ocean**
Conversion technologies	☑ **CHP** ☐ Heat pumps ☑ **Hydrogen**	☐ Fuel to gas ☑ **Fuel to liquid**
Grid and infrastructure	☐ Electricity ☑ **Gas** ☐ Heat	☐ CO2 ☑ **H2**
Energy technology substitution	☐ Discrete technology choices ☐ Expansion and decline constraints	☐ System integration constraints
Energy service sectors	☑ **Transportation** ☑ **Industry**	☑ **Residential and commercial**

Land-use

Model documentation: Land-use - POLES; Non-climate sustainability dimension - POLES

Land-use	☑ **Cropland** ☑ **Forest** ☑ **Grassland**	☑ **Urban Areas** ☑ **Desert**

Other resources

Model documentation: Non-climate sustainability dimension - POLES

Other resources	☐ Water ☑ **Metals**	☐ Cement

Note: Steel tons

Emissions and climate

Model documentation: Emissions - POLES; Climate - POLES

Green house gasses	☑ **CO2** ☑ **CH4** ☑ **N2O** ☑ **HFCs**	☐ CFCs ☑ **SF6** ☑ **PFCs**
Pollutants	☐ NOx ☐ SOx ☐ BC	☐ OC ☐ Ozone
Climate indicators	☐ CO2e concentration (ppm) ☐ Radiative Forcing (W/m^2)	☐ Temperature change (°C) ☐ Climate damages $ or equivalent

Model Documentation - POLES

This documentation describes the POLES-ADVANCE version of the model, developed for the purposes of this project.

For the version of the model used in other JRC publications, see POLES (http://ec.europa.eu/jrc/en/poles) in the JRC website.

1) Model scope and methods - POLES

POLES (**Prospective Outlook on Long-term Energy Systems**) is a global recursive dynamic simulation model of the energy system and covers all anthropogenic greenhouse gases emissions.

It allows to simulate a wide range of energy policies, be they on the demand side or on the supply sector. It displays a high regional resolution and sectoral representation, and provide endogenous simulation of all steps of the energy system by vector and sector: final energy demand, transformation (including power generation), trade, primary supply, international and final user prices.

- The model describes full energy balances for multiple countries and regions covering the whole world, and primary supply for a different geographical disaggregation, as well as energy commodities trade and trade routes.
- It operates on a yearly time step and benefits from frequently updated databases, allowing it to capture the most recent developments of energy markets in various countries / regions.

- Additional modules allow covering GHG emissions from industrial sources; agriculture and land-use emissions are derived from linkages with specialized models.

Figure 1 below gives a schematic view of the POLES model. The red boxes are the main assumptions, calibration and scenario settings; the green box represents the energy balance resolution by country / region and the blue boxes represent the trade and key outputs (demand, supply, emissions).

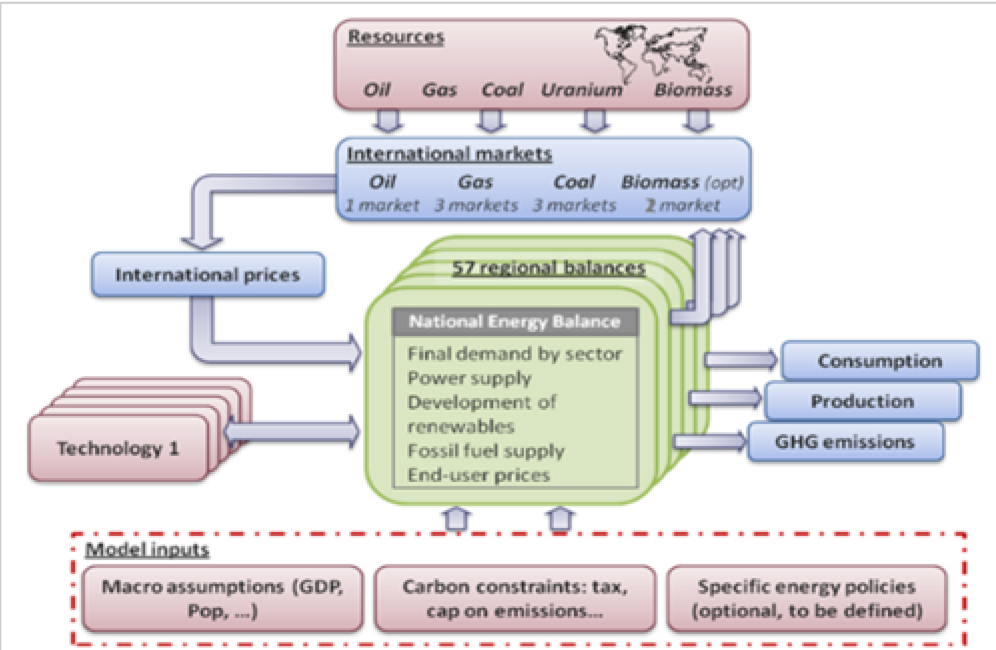

Figure 1: General scheme of POLES

Key input assumptions are population and growth of GDP per capita. The economic activity is then derived by the model at sectoral level, depending on economic growth and energy prices: economic sector value added, passengers and goods mobility, building stocks, etc..

Other critical assumptions are energy resources by type and localization.

The model has been used in cross-model comparison exercises and it has been tested in the framework of establishing diagnostic indicators to characterize model responses [1]. It has been used in several studies looking at transformation pathways of the energy system for the 21st century and the consequences in terms of emissions mitigation policies and technologies mix [2][3][4]. More recently, it has been used by the European Commission in its Global Energy and Climate Outlook (http://ec.europa.eu/jrc/geco).

1.1) Model concept, solver and details - POLES

POLES is a recursive dynamic simulation model. Variables are either calculated directly or are calculated based on the previous years' values, to which are applied the evolution of explanatory variables.

The economic decisions (investment and utilisation rate) are based on the current state of knowledge of parameters (costs of technologies, prices, ...) or with a myopic anticipation of future costs and constraints for the agent, also considering vintage, resource potentials and other inertia.

The model does not use foresight but rather myopic anticipation. Some foresight can be forced by using alternative runs as input files.

The model is developed on the Vensim (http://www.vensim.com/) software.

1.3) Temporal dimension - POLES

The model runs with a 1 year time step, usually from 1990 to 2050, the 1990-2015 period being almost entirely set by data and used for calibration. In the context of the ADVANCE project it has been run up to 2100.

1.4) Spatial dimension - POLES

Energy and emissions balances

The geographical representation is based on the importance of countries in energy consumption and GHG emissions. POLES describes full energy and emissions balances for 57 geographical units: 45 individual countries and 12 residual regions covering the World. Countries include all OECD (1990) countries and large non-OECD countries. All EU28 Member States and nearly all G20 countries are thus explicitly represented. The 45 individual countries are the following:

- EU28 Member States
- Norway
- Switzerland
- Iceland
- Turkey
- Russia
- Ukraine
- Canada
- USA
- Mexico
- Brazil
- Japan
- South Korea
- China
- India
- Indonesia
- Egypt
- South Africa

Additional individual countries are present in more recent versions of the model (Australia, New Zealand, Argentina, Chile, Iran, Saudi Arabia, Thailand, Malaysia, Vietnam).

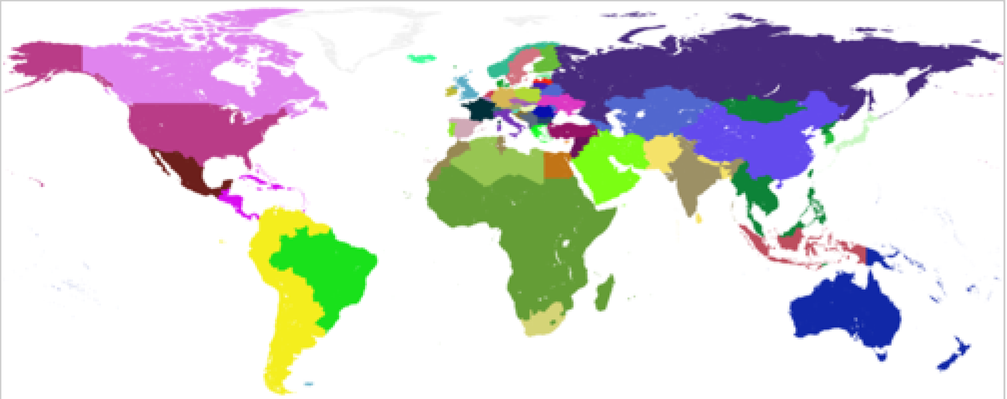

Figure 2: POLES - the World in 57 energy balances

Land use and renewable energies potentials (wind, solar, biomass) follow the geographical representation of the energy balances.

The international air and maritime bunkers are represented separately.

Energy demand at World level, and related emissions, is then the sum of all regions and bunkers.

Fossil fuels supply

The fossil fuels supply side is more detailed, with all important producing countries being represented allowing a very precise description of the supply side and a good understanding of the related issues at stake.

Oil and gas productions are described for 80 producers.

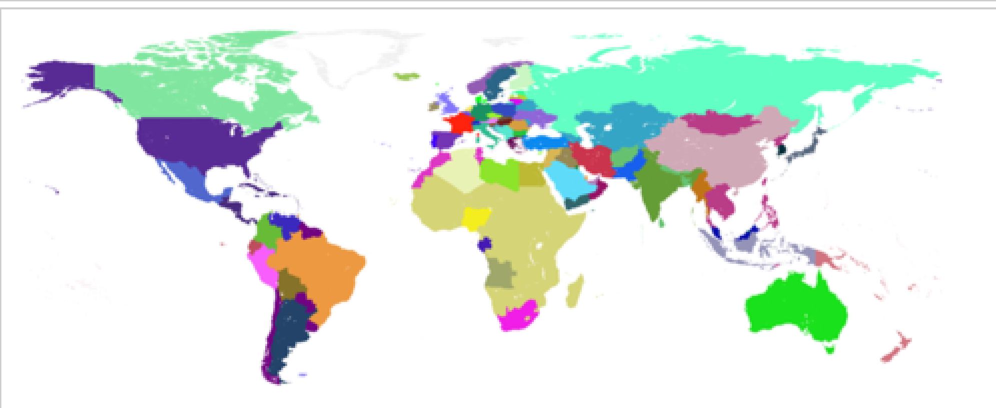

Figure 3: POLES - 80 oil and gas producers

Coal production distinguishes 74 producers, including an infra-national disaggregation for large producers (USA, China, Australia, India).

Trade

Producing regions and consuming regions are linked through energy markets.

- Oil producers supply a single world "pool" market

- Large gas producers export towards 14 regional consuming markets; small gas producers only supply domestic consumption
- Large coal producers export towards 15 regional consuming markets; small coal producers only supply domestic consumption
- Solid or liquid biofuels producers export towards a single world "pool" market
- A single world production of uranium is modelled

1.5) Policy - POLES

The POLES model is used to simulate:

- **GHG policies**
  - Country/region objective: Implementation of carbon (or CO2eq) pricing (iterative calibration)
  - Cumulated GHG/CO2 buget: Regional differentiation of constraint and carbon pricing permitting to reduce emissions within budget (iterative calibration)
  - Carbon leakage (limited)
- **Energy taxation policies**
  - GHG-related pricing policies (carbon pricing)
  - other environmental taxes (e.g. introduction of environmental damage tax on non-conventional fuels production)
  - fossil fuel subsidies (possibility to phase out)
  - introduction of renewable fuels subsidy
- **Support policies for specific technologies**
  - Electricity generation feed-in tariffs
  - Low interest loans or subsidies to capital cost in purchase of energy consuming equipment
  - Acceleration of the penetration emerging vehicle technologies
  - Modal shifts in passenger transport
- **Efficiency standards**
  - fuel efficiency standards in vehicles
  - penetration of low-energy consuming buildings
- **Openness to investment**
  - Reactivity to prices on exploration and production in oil and gas producing regions
  - Discount rates in investment
  - National preference in the sourcing of fossil fuels or national resource management in domestic fossil fuels production

Policies included are updated regularly to reflect the current state of affairs at country and sector level. See for example the list of policies (https://ec.europa.eu/jrc/sites/jrcsh/files/Table_GECO_Policies%20-%2020160601.xlsx) in the GECO (http://ec.europa.eu/jrc/geco) 2016 scenarios.

The model has been used extensively to study climate mitigation scenarios:

- It has specifically been used to inform UNFCCC international negotiations, looking at global and regional climate mitigation scenarios and assessing the economic costs (and, in tandem with other models, the economic impacts) of the transition to a low-carbon economy: with relation to the Kyoto Protocol and beyond[5][6], in the negotiations around the COPs in Copenhagen and Doha[7][8][9] and more recently on the Paris Agreement[10][11].

- It has been used in several global climate policy modelling exercises[12][13][14][15][16], as well as studies on the national/regional level (Europe[17][18], Mexico[19], ...).

- Additionally, using MACCs from the model, it is possible to study regional emissions trading schemes and participation schemes in wider global regimes[20][21][22].
- It is being used by the European Commission in its Global Energy and Climate Outlook (http://ec.europa.eu/jrc/geco) publications.

2) Socio-economic drivers - POLES

The two main drivers, population and GDP, are exogenous.

2.1) Population - POLES

Population is an exogenous driver in POLES. The standard source used is the UN World Population Prospects[23] (latest), medium fertility scenario.

The model distinguishes only one population group.

2.2) Economic activity - POLES

GDP

GDP is exogenous and is derived from various international sources[24]. Latest work used GDP assumptions from:

- latest IMF forecasts [25] (for the short run)
- EU Ageing Report[26], OECD[27][28], MIT and CEPII forecasts (for the longer run)

Consistency with population is checked.

An on-going work will allow to connect POLES to the macro-econometric model MAGE (CEPII institute / JRC) through an energy factor in the production function that will link dynamically GDP, energy intensity and energy prices.

All other economic activities variables (value added, mobility, surfaces, ...) are endogenously calculated in POLES.

3) Macro-economy - POLES

The key marco-economic assumptions are derived from population and GDP.

Starting from historical data, which capture local specificities, sectoral economic activity variables are calculated:

- sectoral value added: depend on the level of development of the country/region, given by GDP per capita (industrialization phase followed by service-based economy);
- industrial physical production: depend on demand, which itself depends on the level of development;
- mobility (for passengers and for goods): depend on the cost of transport compared to income, and is declined in equipment rates and degree of utilisation of this equipment;
- buildings surfaces: depend on households size (occupancy per dwelling) and surface per dwelling, both depending on personal income.

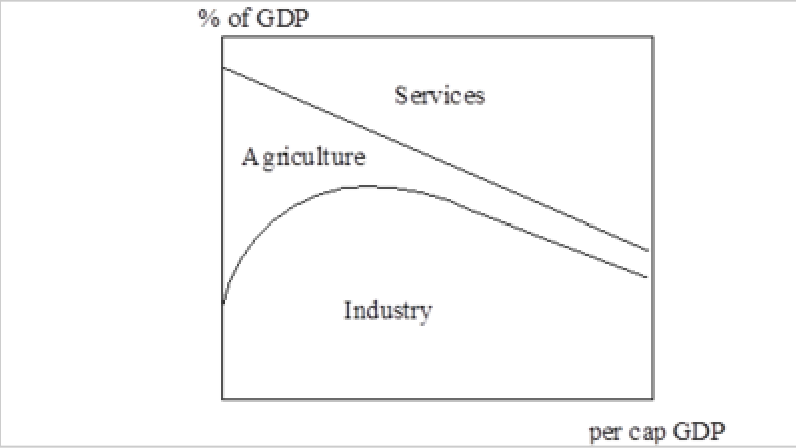

Figure 4: Share of value-added as a function of GDP per capita

3.1) Production system and representation of economic sectors - POLES

Sectoral disaggregation

All economic activity variables are endogenously derived from GDP per capita and energy prices. The energy demand in POLES is endogenously derived from sector-specific drivers: economic activity, end-user energy prices and policies, including time lagged effects. The modeling also considers vintage and fuel / technology substitution constraints.

The model differentiates the following sectors:

- Agriculture (economic activity: value added)
- Industry (value added and physical production), with 4 sub-sectors:
  - Steel, Chemistry, Non-metallic minerals and Other industry; energy uses and non-energy uses of fuels are differentiated.
- Services (value added): substitutable energy and captive electricity needs are differentiated
- Residential (surface, occupation rate): needs for space heating, water heating, space cooling, cooking, appliances and lighting are differentiated
- Transport (mobility), with 4 sub-sectors:
  - Road, Rail, Water, Air; additionally, international maritime bunkers and international air bunkers are differentiated.
  - The model differentiates passengers and goods transport, and various transport types: car, motorbikes, light duty vehicle, heavy duty vehicles.
  - Road vehicles are differentiated by engine (ICE, electric, hybrids, fuel cell) and fuel (oil products, biofuels, electricity, hydrogen, gas).
- In addition, own-energy uses and losses in transformation (power, synthetic fuels, ..) are explicitly considered.

Historical data on energy demand, activity variables and fuel prices are updated at least once a year from various sources. Energy demand and prices come mostly from: Eurostat, IEA, Enerdata. Energy demand data can be available up to year-1.

Behavioural change

Behavioral changes is captured in 2 ways in POLES:

- a change of the economic activity (applies to Residential and Transport): this change depends on income and energy prices through appropriate elasiticies;
- a change in the rate of use of energy consuming equipment: this change depend on energy prices through short-term elasticities.

4) Energy - POLES

POLES describes the world energy system, covering all energy carriers.

The model includes the following modules:

- Energy supply: production of fossil fuels and biomass and international trade
- Energy transformation: refining of fuels, production of synthetic fuels (e.g. liquid biofuels, hydrogen), power generation
- Final energy demand: industry, buildings, transport, agriculture

The technological description of the model varies according to the detail of the representation of each sector.

4.1) Energy resource endowments - POLES

The model distinguishes different geographical representations according to the resource considered.

Supply is linked to demand regions via trade:

- Oil: producers all export to single global market "pool"
- Gas: large producers export towards 14 importing regions; small producers only supply domestic demand
- Coal: large producers export towards 14 importing regions; small producers only supply domestic demand
- Solid biomass: producers supply domestic demand or export towards a global market depending on the relative cost of production
- Liquid biofuels: similar to solid biomass
- Uranium: single global supply cost curve
- Primary electricity (hydro, solar, wind): country-specific renewables potentials for power generation for domestic electricity demand

4.1.1) Fossil energy resources - POLES

The POLES model differentiates various types of fossil fuels:

- oil: conventional, tar, heavy and oil shale / onland & shallow, deepwater, artic;
- gas: conventional, shale gas / onland & shallow, deepwater and artic;
- coal: steam and coke.

The description below gives elements for oil, but they can be extended to gas and coal.

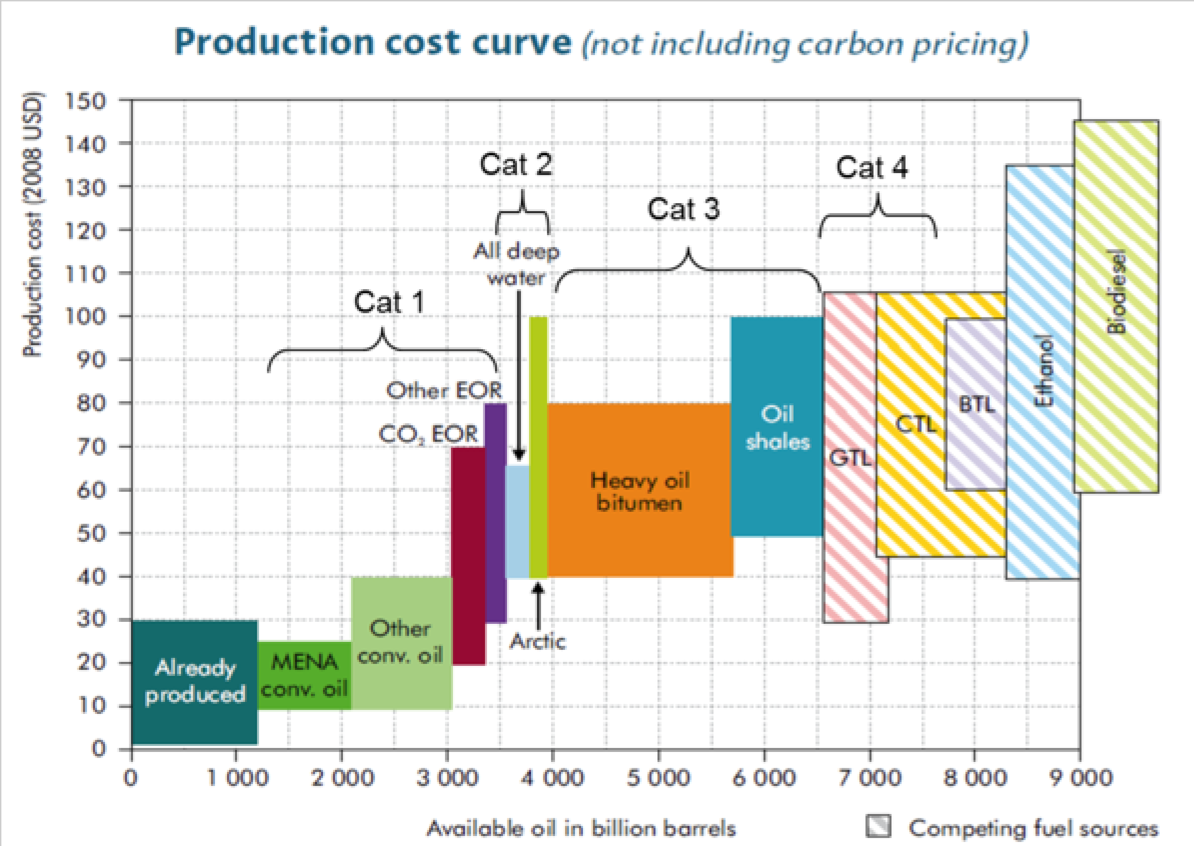

Figure 5: Static aggregated oil production cost curve

While this figure gives an aggregated static cost curve, the model actually uses *dynamic* cost curve per resource type integrating the cost of energy needs for production for each production country/ region. Consequently POLES fossil fuel cost curves thus evolve over time, by region and with the scenario settings (for instance: a CO2 pricing will affect the production cost of tar sands).

The supply module transforms resources into reserves through discovery effort (exploration and drilling) that depends on remaining resources, the (dynamic) production cost curve and international fuel prices, through elasticities that capture openness to investment and resource management strategies.

Reserves are then turn into production depending on remaining reserves, the (dynamic) production cost curve and international fuels prices.

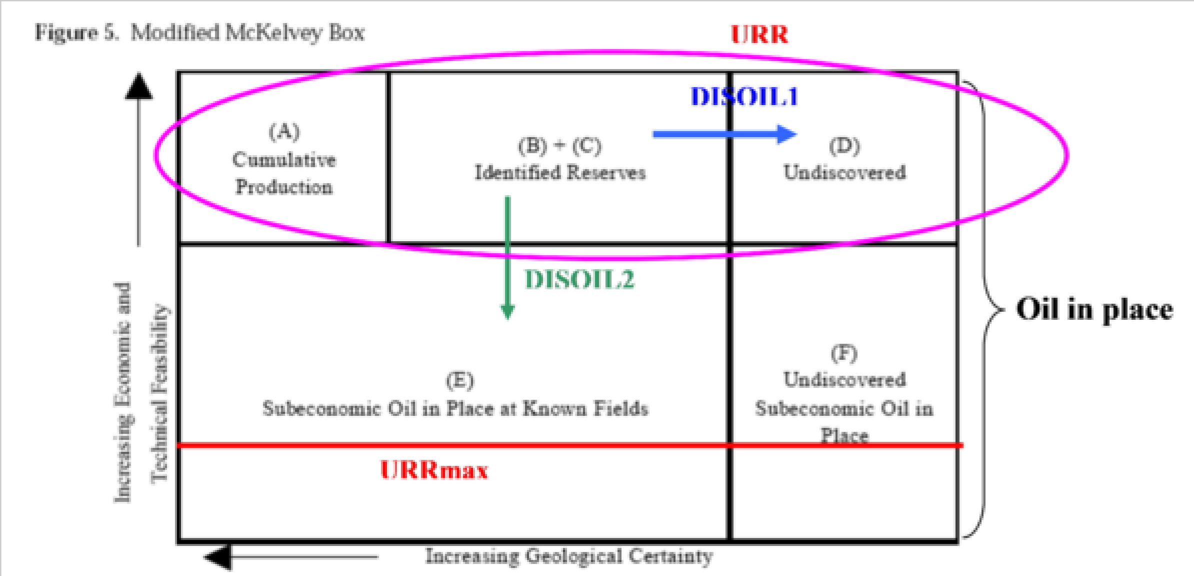

Figure 6: Reserves discovery process in POLES (URR: ultimate Recoverable Resources, DISOIL: Discovery of oil)

The model has been used in several studies of the role of fossil fuel resources and in low-carbon transition pathways[29][30], particularly in the aspects of energy security[31][32][33].

Sources of information include: BGR[34], USGS[35], IEA[36], Enerdata[37], WEC[38], MIT, industry estimates

4.1.2) Uranium and other fissile resources - POLES

Uranium resources used in LWRs are represented at World level only (sources: IAEA / NEA Red Book, CEA estimates, ..). An Uranium price is derived from a global supply cost curve. LWR capacity development is also constrained by the amount of remaining resources. Fast breeders development is contrained by the production of waste from LWR.

Sources of information include: IAEA/NEA Red Book[39], estimates from CNRS/CEA/LPSC, ..

4.1.3) Bioenergy - POLES

Primary biomass resources for energy uses are classified in 3 categories for all countries/regions:

- energy crops (in agricultural area, grassland)
- short rotation crops (cellulosic)
- forest residues (cellulosic)

Energy crops are dedicated to 1st generation biofuels, the 2 other categories are used in all other energy uses (a further split of biomass feedstocks has been implemented for Europe using information from the model GREEN-X (http://www.green-x.at/)). POLES uses by default a simplified modeling of land use to estimate the potential of these resources: land available, yields (evolve over time, based on historical evolution), share of harvest/land that can be allocated to energy uses.

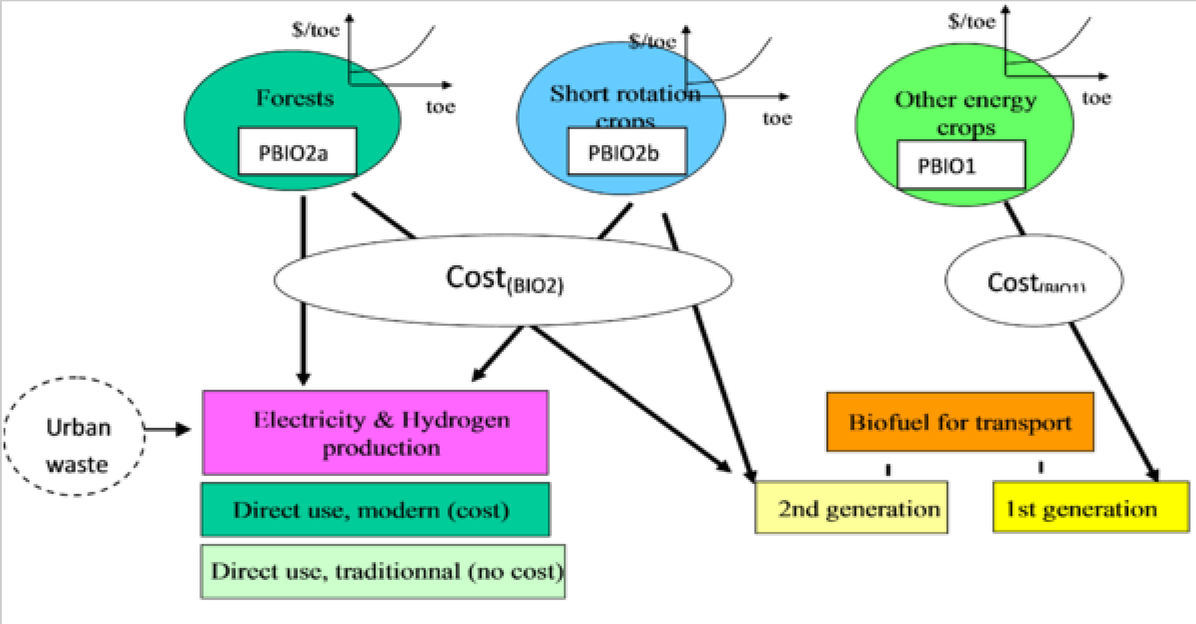

Figure 7: Biomass resource use in POLES

POLES also uses in a standard way exogenous estimates of potentials: for instance a soft linkage with the model GLOBIOM (http://www.globiom.org/)/G4M has been implemented that goves potential estimates and cost curves for all World regions (with the model GREEN-X at EU level). Biomass supply cost curves are attached to the various biomass types and come from GREEN-X, GLOBIOM and other sources.

The conversion into liquid biofuels distinguishes first generation (agricultural energy crops) and second generation (cellulosic).

The model has been used in several studies to examine the future use of biomass as an energy source[40], bio-energy trade[41][42] and the role of biomass in emissions mitigation[43][13].

Information sources include: FAO[44].

4.1.4) Non-biomass renewables - POLES

Hydro resources

Hydro resources are defined for all countries / regions. They constraint the development of hydro power (which depends on identified projects and average power production costs).

Sources of information include: WEC[38], IEA[36].

Solar resources

Solar resources are defined as the maximum amount of solar energy that can harvested for the energy system. Solar energy in urban areas depends on the rooftop surface, solar energy in non-urban areas depends on land-use and distance to consuming centres. The resource is then used in the energy system depending on the economic conditions, considering network constraints. The model uses mostly inside calculation considering solar irradiation, land use, population density and urban areas.

Source: Pietzcker et al[45]

Wind resources

The model distinguishes between total resource and technical potential that is considered as harvestable, depending on distance to consuming centres and depths (for offshore resource). Total resources come from NREL estimates, technical potential can be internally calculated or also derived from NREL estimates. This potential is then used in the energy system depending on the economic conditions, considering network constraints.

Source: NREL[46]

The system integration of renewables in the model has been tested in several studies[47][48].

4.2) Energy conversion - POLES

The model distinguishes the following energy conversion processes:

- Electricity production: detailed representation of power generation capacities and production
- Heat production: coverage of distributed means (cogeneration, solar), no coverage of centralized means
- Gaseous fuels: gas (natural gas and methane recovery), hydrogen
- Liquid fuels: crude oil refineries; liquid fuels production from coal, gas and solid biomass
- Solid fuels: coal (and coke), biomass

4.2.1) Electricity - POLES

The electricity system consists of 3 main parts:

Demand load curve

The model considers 2 typical days (winter and summer), each split into 12 time arrays of 2 hours each. The demand load curve is derived from the sum of sectoral electricity demand load curves (end uses), net trade and losses.

In the POLES-ADVANCE version these two days are the base of 27 days each, which are the combinations of low, medium and high situations for demand, wind production and solar production. This way, extreme situations are taken into account in the operation and planning of the power system.

Operation (production and storage)

The model considers first the non-dispatchable energy sources (hydro, wind, solar). The residual load is met by dispatchable generators based on their variable costs (efficiency and fuel cost, including additional taxes or financial support schemes). A proxy for the power price is computed based on the marginal producer's cost. Storage technologies and demand response (which shift a part of the load to another time slice of a given day) are used if the within-day spread of two-hourly prices compensates their efficiency losses. The number of full load hours of each production and storage technology is the weighted aggregation of these 54 days. Some over production can appear when the non-dispatchable productions (also taking into account a minimum power output for must-run technologies) exceed demand. When possible it is stored; otherwise it is curtailed and the load factors of wind and solar are decreased accordingly.

Capacity planning

The planning of new capacities needs to address expected future electricity needs (based on a rolling ten-year extrapolation) while considering the upcoming decommissioning of existing plants (with vintage) and the special contribution of wind and solar (non-dispatchable).

The 648 time-slices per year (54*12) are organised in seven blocks with expected capacity factors of 8760 hours, 8030 hours, 6570 hours, 5110 hours, 3650 hours, 2190 hours and 730 hours. The associated number of full load hours define different total production costs for each of these blocks. This defines the theoretical technology market shares together with coefficients that are calibrated to replicate historical technology mix. Non-dispatchable wind and solare are first determined, in competition with all technologies. However, they don't produce constantly on all seven blocks. Once their capacity is decided (limited by a maximum potential), the remaining need per investment block is updated with the actual production of wind and solar (which is deduced from the current participation of wind of solar in each block).

The dispatchable technologies are then planned based on the remaining capacity needs for each investment block, the theoretical market shares and the resource constraints for some technologies.

Table 1: Electricity production technologies in POLES

Fuel	Technologies
Nuclear	Conventional nuclear design
	New nuclear design ("Generation IV")
Coal	Pulverized fluidized coal
	Pulverized fluidized coal with CCS
	Integrated coal gasification with combined cycles
	Integrated coal gasification with combined cycles with CCS
	Conventional coal thermal turbine
	Conventional lignite thermal turbine
Gas	Conventional gas thermal turbine
	Gas turbine
	Gas combined cycles
	Gas combined cycles with CCS
	CHP (decentralized)
	Gas fuel cell (decentralized)
Oil	Conventional oil thermal turbine
	Oil combined cycles
Biomass	Conventional biomass thermal turbine
	Biomass gasification
	Biomass gasification with CCS
Hydro	Run-of-river
	Reservoir (lake)
	Small hydro (<10 MW)
Wind	Onshore
	Offshore
Solar	Utility PV
	Distributed PV (decentralized)
	Solar thermal power
	Solar thermal power with storage
Ocean	Tidal & wave ocean
Geothermal	Geothermal power
Other	Hydrogen fuel cell (decentralized)
Storage	Pumped hydro
	Compressed air
	Batteries (lithium ion)
Demand-side solutions	Vehicle-to-grid
	Load shifting

In addition to the technologies mentioned in the figure above, one POLES version includes further detail of biomass technologies in the EU, based on work with the GREEN-X model.

Electricity prices

Total production cost is the sum of fixed cost (investment, discount rate, fixed O&M) and variable cost (fuel cost, efficiency, variable O&M), including further taxes or financial support schemes. Investment costs evolve with learning functions (exogenous, endogenous 1 factor, endogenous 2 factors). Efficiency is exogenous. Fuel costs are derived from endogenous fuel prices and assumptions on taxation policies.

Finally the POLES model calculates electricity prices from system production cost for base load (used to set the price for industry) and peak load (used to set the price for residential-services-transport).

Information sources include: Enerdata, Eurostat, IEA[49], ENTSO-E, ETDB, WEC[38], EC-JRC[50].

The model has been used to study the power system costs of mitigation policies under various configurations[51][52]. The sysytem integration of variable renewables in the model has been tested in several studies[48][47].

4.2.2) Heat - POLES

Steam can be produced by heat and power cogeneration (CHP) plants and steam-only plants, the inputs of which are accounted for within the "own use" of the energy sector. The production of steam is not simulated explicitly. The model checks that the evolution of steam demand is consistent with the evolution of the "own use" of the energy sector and with the availability of CHP compatible power plants.

Other heat-related demand is satisfied by boilers and heaters using other energy vectors (oil, gas, coal, biomass, electricity, solar heat).

4.2.3) Gaseous fuels - POLES

Gas

Natural gas domestic production and imports directly supply gas for consumption. Additional gas production can come from:

- Urban waste methane recovery:
- Underground coal methane recovery
- Gas production fugitive emissions recovery
- Coke oven gas is captured in the final energy demand of the iron and steel sector

All three are determined by the effect of carbon pricing on the relevant emissions source.

Hydrogen

The model uses a complete module to represent hydrogen production (14), transport and use in various sectors: transport (fuel cells or thermal use), but also in stationary uses in industry and buildings (fuel cells or blending with natural gas). Water electrolysis from grid is coupled with the electricity load curve (hydrogen is produced preferentially during base load).

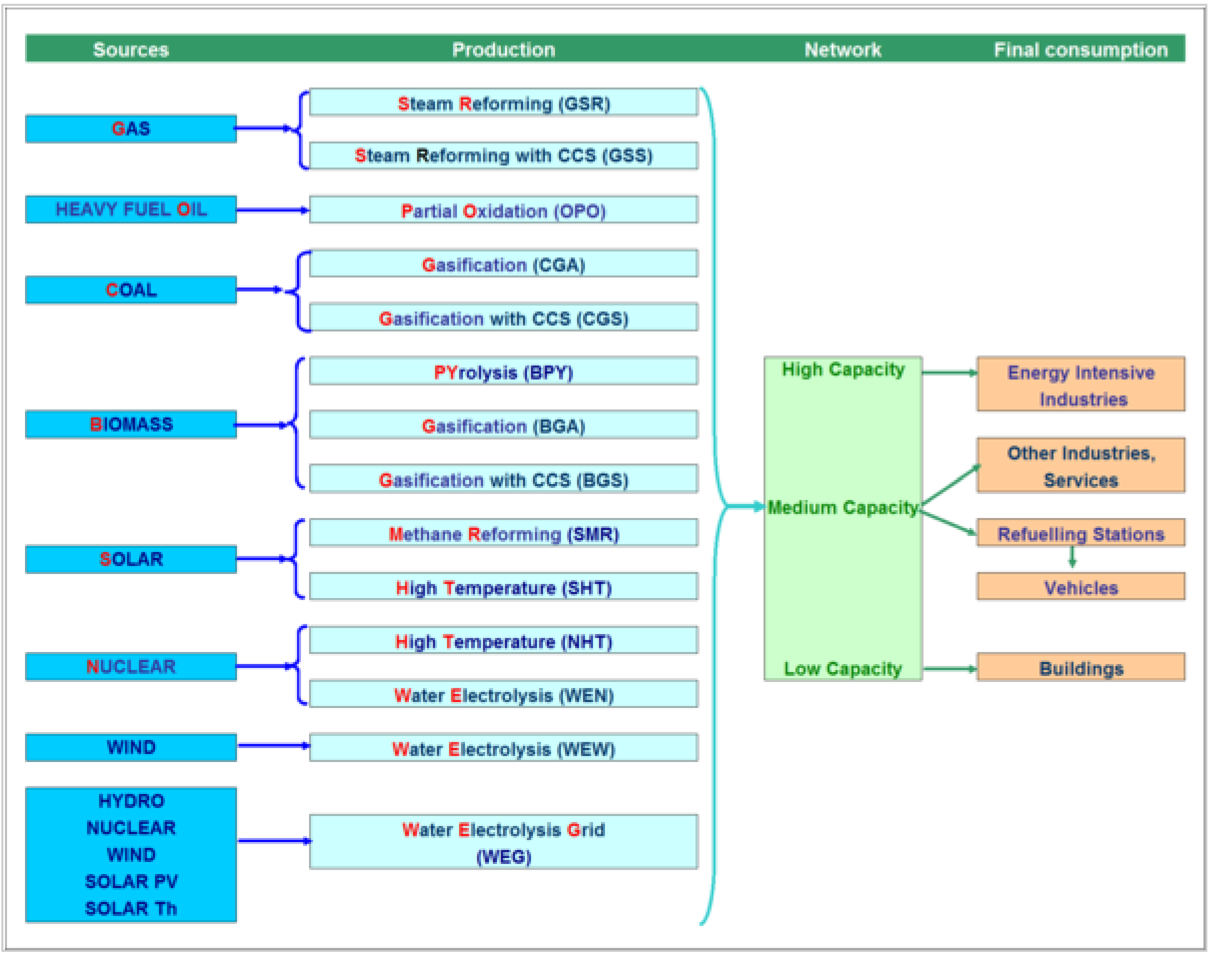

Figure 8: The hydrogen module in POLES

Hydrogen in the energy system in particular has been the subject of studies with the model[3].

4.2.4) Liquid fuels - POLES

Oil products

Crude oil production is transformed into oil products (one energy carrier represented in the model) with a refineries efficiency.

Biomass to Liquids

The POLES model differentiates 4 biomass-to-liquids production technologies, each described by cost, efficiency estimates and use of feedstock type:

- 1st generation bioethanol and biodiesel;
- 2nd generation bioethanol and biodiesel.

The use of the different liquid biofuels is restricted by blending constraints (with oil products) in the various sectors.

Information sources include: IEA, OECD, DEFRA, DFT, JEC

Coal to Liquids

The Coal-to-liquid production (Fischer Tropsch) is described by one generic technology (cost and efficiency) to which a CCS module can be added.

The development of CTL depends on the distance between production cost and the oil price.

Information sources include IEA, EIA.

Gas to Liquids

Similarly to CTL production, the gas-to-liquids production is described by one generic technology (cost and efficiency) to which a CCS module can be added.

The development of GTL depends on the distance between production cost and the oil price.

Information sources include IEA, EIA.

4.2.5) Solid fuels - POLES

Coal

Coal primary supply (imported or domestically produced) is directly fed to consumption.

Sectors consume steam/thermal coal or coking coal (iron and steel sector). The coking coal transformation is captured in final energy demand.

Biomass

Biomass primary supply (imported or domestically produced; in energy units) is directly fed to consumption.

Solid biomass can be used to produce liquid biofuels or electricity in energy transformation; or in direct combustion in final demand.

4.2.6) Grid, pipelines and other infrastructure - POLES

Own use of the energy sector

Fossil fuel extraction

POLES describes explicitely the direct energy use, and the corresponding emissions, of the following fuels: - tar sands - extra heavy oil - oil shale

All other energy use related to fossil fuel extraction is captured in one single factor, expressed by fuel as a % of the energy production and kepy constant over time at the last historical value.

Refineries

The energy use in the refining sector is captured through a coefficient, expressed as a % of the demand for oil product, kept constant over time at the last historical vakue

Others

Other own-energy uses are captured through a coefficient, expressed by fuel as a % of primary energy demand, kept constant over time at the last historical value.

Losses in Transport & Distribution

Grids and pipelines are not modelled explicitly. Pipelines are captured through transport costs as compared to other trade routes.

Losses in T&D are expressed by fuel as a % of final energy use, and by default kept constant at the last historical value.

They can be adjusted depending on the scenario (for instance to capture a decrease in electricity losses, ..).

4.3) Energy end-use - POLES

Energy end-use is distinguished in demand for:

- industrial sectors;
- buildings (residential and services);
- transport (road, rail, water, air);
- agriculture.

Information sources include: Enerdata, Eurostat, IEA, IISI, World Bank. Sector-specific information is frawn from: IISI, EIA, Odyssee, IRF, UIC, UNCTAD.

4.3.1) Transport - POLES

Several modes are distinguished in the model (road, rail, water, air), for both passenger and goods transport.

Mobility depends on income and prices, with all steps (activity variables and unit consumptions) using specific equations and parameters. In particular, in the case of cars, the model uses the notion of "budgetary coefficient" that constraints the mobility (dynamic elasticities) through a maximum share of yearly income that can be dedicated to energy purchases.

Passenger mobility is the sum of individual modes, which are indirectly interdependant (though opposite behaviors to prices) and capped by saturation effects (max number of vehicles per capita, ..). Goods mobility is calculated at national level and then split across modes, apart from Maritime bunkers which is calculated only at Global level.

The competition across vehicle types (6 types of vehicles in cars and trucks: conventional ICE, electric, plugin hybrid, H2 fuel cell, H2 thermal, gas) uses a multinominal logit function that depends on the total cost for the user, considering fixed cost (investment, life-time, user discount rate) and variable cost (consumption per km, fuel price), and is constrained by infrastructure developments for refueling stations.

Fuel price (that affects mobility, consumption per unit and competition across technologies) includes end-user energy taxation policies, which include carbon prices.

Finally, biodiesel and bioethanol are differentiated, both capped by blending constraints depending on the oil products (gasoline, diesel, kerosene, heavy fuel).

The table below gives a general overview of the transport module in POLES.

Table 2: The transport module in POLES

Mobility	Mode	Vehicles/scope	Fuel used	Engines	Activity	Link to income	Link to fuel prices
Passengers	Road	Cars	Liquids (oil products, biofuels), electricity, gas, hydrogen	ICE, hybrid, electric, CNG, hydrogen fuel cell, hydrogen thermal	vehicles; mileage; occupation	"+"	"-"
		Motorbikes	Liquids	ICE	vehicles; mileage	"+"	"-"
		Buses	Liquids, electricity, gas, hydrogen	ICE, hybrid, electric, CNG, hydrogen fuel cell, hydrogen thermal	passenger-kilometers	"+"	"+"
	Rail		Oil products, electricity, coal		passenger-kilometers	"+"	
	Air	National	Liquids		passenger-kilometers	"+"	"-"
		International	Liquids		passenger-kilometers	"+"	"-"
Goods	Road	Heavy trucks	Liquids, electricity, gas, hydrogen	ICE, hybrid, electric, CNG, hydrogen fuel cell, hydrogen thermal	ton-kilometres; mileage; load	"+"	"-"
		Light trucks	Liquids, electricity, gas, hydrogen	ICE, hybrid, electric, CNG, hydrogen fuel cell, hydrogen thermal	vehicles; mileage; load	"+"	"-"
	Rail		Liquids, electricity, coal		ton-kilometres	"+"	
	Waterways		Oil products			"+"	
	Maritime	International	Liquids		ton-kilometres	"+"	"-"

Transport energy use and associated emissions in the context of climate mitigation strategies have been studied in the model in several publications[53][54].

4.3.2) Residential and commercial sectors - POLES

Residential

In POLES the energy demand in the residential building sector depends on the building stock and the fuel prices. The building stock is based on the evolution of surface needs, which depend on number of persons per household and on the surface per dwelling, both dependent on income per capita. The module simulates the need for new surface, considering lifetime of existing buildings. In addition it calculates an amount of renovated buildings in the existing stock.

Energy demand is grouped into several energy services. For each service, a useful energy need is calculated; it is then converted into final energy demand with competition between fuels. The competition across fuels (logit) is based on total cost for the user (fixed cost, fuel utilization efficiency), it is constrained by the lifetime of the existing equipment, and is calibrated on historical data of energy demand and prices. The following services are modelled:

- Space heating: depend on surfaces, energy prices and HDD (heating degree-days). Final energy demand is split into three sub-categories representing the diffusion of 3 building types of different levels of insulation (applying to new and renovated surfaces).
- Water heating: depend on surfaces, energy prices and HDD.
- Cooking: depend on surfaces and energy prices.
- Space cooling: final demand of electricity directly calculated, based on diffusion of air conditioning equipment (depends on income, CDD) and efficiency of use (depends on income, CDD (cooling degree-days), electricity prices and insulation).
- Appliances: final demand of electricity directly calculated, depends on income and electricity prices.
- Lighting: depend on surfaces, electricity prices.

Additionally, the contribution of solar heating (in space and water heating) and of decentralized means of electricity production (heat and power cogeneration, decentralized PV or fuel cells) are taken into account: competition with other energy fuels or with grid electricity (based on relative cost for the consumer, including possible support schemes for some technologies). Coal and traditional biomass are phased out based on their low efficiency.

Fuels considered are: electricity, oil, gas, coal, modern biomass, traditional biomass, hydrogen, steam.

Electricity can be produced locally (with cogeneration, decentralized PV or fuel cells) and then competes with network electricity.

Services

For the Services sector, the building stock is represented by sectoral value added. Similar to surfaces in the Residential sector, new surfaces and renovation of the existing stock is represented by shares of value added.

Energy demand is grouped into:

- Substitutable energy demand (heating, cooking, hot water): total theoretical energy demand depends on sectoral value added and average energy prices. The sectoral value added is split into 3 levels of energy efficiency to capture the diffusion of insulation technology that substitutes for final energy consumption (applying to new and renovated surfaces). Diffusion drivers are GDP per capita, energy cost for the user (investment, fuel price, subsidies) and investment in insulation. The competition across fuels (logit) is based on total cost for the user, and is constrained by the lifetime of the existing equipment; it is calibrated on historical data of energy demand and prices.
- Captive electricity: depends on total sectoral value added and electricity prices.

Solar heat, decentralized electricity production, coal and traditional biomass are represented in a similar way to Residential.

The impacts of climate change on energy use and comfort in the residential sector have been studied with the model in several publications[55][50].

4.3.3) Industrial sector - POLES

The industry is represented in POLES through different sectors and processes.

The general modeling describes energy needs per sector / process dependent on an activity variable and energy prices. Total demand of energy depends on the activity variable and energy prices.

The activity variable is sectoral value added, or for the steel industry physical production of tons of steel. The latter depend on national demand and a global market, on which countries compete based on existing production capacities, the dynamics of the local market and the energy cost. The role of electrical steel increases with the amount of steel being recycled, blast furnace being the difference between total production needs and the contribution of electrical arc furnaces.

Competition across fuels / boilers (multinomial logit) takes place between oil, gas, coal, biomass and purchased steam based on costs for the user, considering the lifetime of existing equipment. The competition calibrated on historical data on prices and market shares.

Electricity needs, that also depend on the activity variable and electricity prices, can affect the need for other fuels through increased efficiency of the industrial processes.

The different industral sectors and processes are shown in the figure below.

Table 3: The industrial sectors in POLES

Sector	Process	Activity variable	Fuel, energy use	Fuel, non-energy use
Steel	Blast furnace	tons	Electricity, oil, gas, coal, biomass	coke
	Electrical	tons	Electricity	
Non-metallic minerals		value added	Electricity, oil, gas, coal, biomass, hydrogen, steam	
Chemistry		value added	Electricity, oil, gas, coal, biomass, hydrogen, steam	oil, gas, coal, biomass
Other industry		value added	Electricity, oil, gas, coal, biomass, hydrogen, steam	

Note that the steel industry equations describe physical production, which depends on national demand and a global market, on which countries compete based on existing production capacities, the dynamics of the local market and the energy cost. The role of electrical steel increases with the amount of steel being recycled, blast furnace being the difference between total production needs and the contribution of electrical arc furnaces.

4.3.4) Other end-use - POLES

Agriculture

Energy use of the agriculture, fisheries and forestry sector is captured with the value added of agriculture and income per capita.

4.4) Energy demand - POLES

Energy demand from the various end-uses (industry, buildings, transport, agriculture) is aggregated into totals that have to be supplied by the energy transformation module.

The following energy vectors are modelled:

- oil
- gas
- coal
- biofuels (solid: traditional, modern; transport: liquid biofuels: transport)
- electricity
- marketed heat
- hydrogen

Total demand of energy depends on the relevant activity variable (surfaces, mobility needs, value added) and sectoral energy prices. Competition across fuels takes place based on costs for the user (also considering the lifetime of existing equipment); it is calibrated on historical data on prices and market shares. Additional trends are used to model non-cost drivers (autonomous technological trends or non-price policies such as efficiency standards).

4.5) Technological change in energy - POLES

Technological change in the various sectors takes place through competition in the new capacity planning ("gap", multinominal logit), which depends on expected utilisation costs of the competing technologies (myopic anticipation, no perfect foresights). Technological change is constrained by the vintage of existing capital stock ("unscrapped consumption") and resource availability. In addition to upgrading possibility, accelerated retirement can be considered in some specific cases (e.g. some coal plants in the power generation sector).

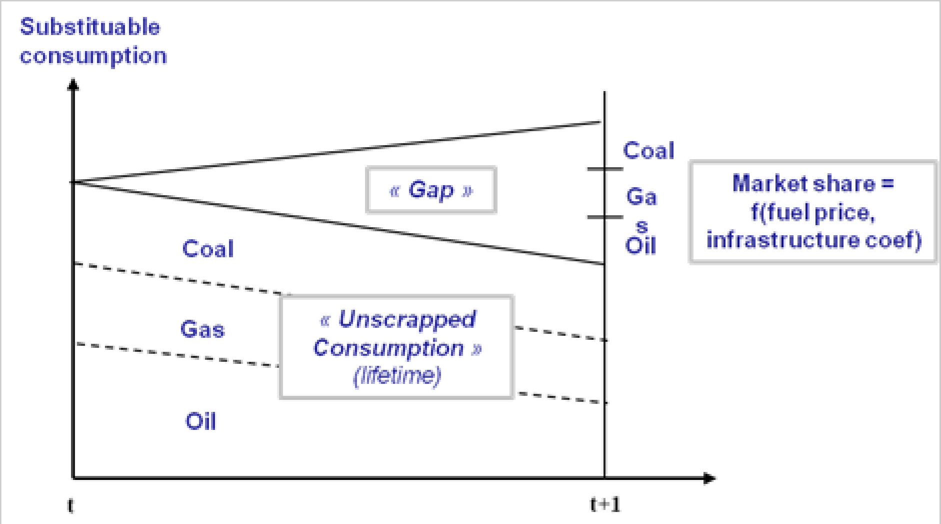

Figure 9: Schematic of the energy needs and depreciation procedure in POLES

Costs usually consider fixed costs (investment, lifetime, O&M, discount rate) and variable costs (fuel price, efficiency, O&M).

Investment costs can be exogenously set or endogenously simulated through learning curves (1 or 2-factors learning curves) depending on the sector.

It must be noted that the competition also considers, in addition to the cost component, a "reality parameter" that is calibrated (directly in the model or with external procedures) to replicate the historical situation given used cost estimates. This parameter is essential to compensate for imperfect cost estimates or to capture drivers of economic decisions that are poorly or not at all represented in the model (national industrial policy choices, etc..). The model also includes the possibility to test "network effect" for new technologies (accelerated adoption beyond some market share threshold).

Future scenarios with technological change have been studied with the model in several reports[2][3][56][57].

5) Land-use - POLES

Land surfaces are disaggregated in the following categories:

- The surfaces dedicated to Agricultural activities (crops, meadows, pastures). They evolve with an annual trend using population and agricultural productivity (exogenous); the growth decreases when land use is close to saturation).
- The surface of forests evolves to account for the expansion of the agriculture surface.
- Urban areas evolve with an annual trend using urban population and GDP growth.
- Inland water and desert areas evolve with exogenous trends.
- Finally grassland surface (grasslands, shrublands, savannas, natural vegetation mosaic) is the difference between the total country / region area and all other surfaces.

Energy biomass is produced from the following surfaces:

- 1st generation biofuels: agricultural area, grassland
- other uses: forest area (for forest residues), grassland (for short rotation crops)

Yields evolve over time, based on historical evolution.

GHG emissions from agriculture and land-use are derived from a soft linkage with the GLOBIOM (http://www.globiom.org/) model.

See Bioenergy - POLES

Information sources include: FAO.

6) Emissions - POLES

All Kyoto defined greenhouse gases are included POLES: CO_2, CH_4, N_2O, SF_6, HFCs, PFCs. Note that HFCs and PFCs are respectively gathered into one category, the corresponding global warming potentials (GWP) being the average ratio between historical inventories expressed in CO_2e and in grams, the ratio are then kept constant.

The model directly covers all emissions from the energy sector and the industry sector. Other emissions (agriculture, land use) come from a soft linkage with the GLOBIOM/G4M model.

GHG policies affect these emissions: energy CO_2 is derived from the changes in the energy sector induced by the policy, other emissions are affected by specific marginal abatement cost curves (MACCs).

Information sources include: UNFCCC GHG inventories[58], IPCC Assessment Reports, EDGAR database[10], IEA[36], EIA, FAO[44].

The model has been used extensively to study climate mitigation scenarios[5][8][11][16]. See the Policy page for more examples.

6.3) Carbon dioxide removal (CDR) options - POLES

The following carbon dioxide removal options are modelled:

- CCS in power generation: with coal, gas, biomass
- CCS in synthetic liquid fuels production: from coal, gas, solid biomass
- CCS in hydrogen production: with coal, gas, biomass
- CCS in industry: with combustion of coal, biomass
- Net sinks in LULUCF: from lookup curves linking carbon price, biomass production cost and biomass demand (share of biomass potential used)

7) Climate - POLES

The model produces annual greenhouse gases emissions (and, in certain model versions, air pollutants and short-lived climate species).

The climate effects are calculated thanks to the MAGICC diagnostics toolbox using model outputs.

Most studies with the model are on climate mitigation. However, the impacts of climate change on energy use and comfort in the residential sector have also been studied with the model[55][50].

8) Non-climate sustainability dimension - POLES

Metals

Demand for tons of steel is represented in order to inform the iron and steel industry sector. This provides a better activity indicator instead of value added and allows for the study of changes in the geographical allocation of steel-making due to energy price changes and carbon leakage. See Industrial sector - POLES.

Water

In certain versions of the POLES model, water use associated to the production of electricity is modelled. A water use is associated per technology and provides projections of water needs based on installed capacities per technology.

Additionally, the model has been used for studying the side-effects of the energy system and associated emissions in terms of air pollution[14] and health[59].

9) Appendices - POLES

9.2) Data - POLES

Synthetic view of POLES data sources:

Macro-economic drivers

Population

- UN (2015, medium fertility)

GDP

- World Bank (2015), EC (2015), IMF (2016), OECD (2013, see also Dellink et al. 2014)

Value added

- World Bank (2015); projection endogenous

Mobility, vehicles, households, tons of steel

- Sectoral databases; projections endogenous

Energy resources

Oil, gas, coal

- BGR (2014), USGS (2013), WEC (2013), sectoral databases

Uranium

- OECD (2014)

Biomass

- EU: Green-X model1
- Non-EU: GLOBIOM model

Hydro

- Enerdata (2015)

Wind, solar

- NREL (2013), Pietzcker (2014)

Energy balances

Reserves, production

- BP (2015), Enerdata (2015), IEA (2015); projections endogenous

Demand by sector and fuel, transformation (including. power), losses

- Enerdata (2015), IEA (2015); projections endogenous

Energy prices

International energy prices, prices to consumer

- EIA (2016), Enerdata (2015), IEA (2015); projections endogenous

GHG emissions

Energy CO2

- Derived from energy balances; endogenous

Other GHG Annex 1

- UNFCCC (2015); projections endogenous, and derived from data from GLOBIOM

Other GHG Non-Annex 1 (excl. LULUCF)

- EDGAR[10]; projections endogenous, and derived from data from GLOBIOM

LULUCF Non-Annex 1

- FAO (2015); projections endogenous, and derived from data from GLOBIOM

Technology costs

The model's learning curves based on literature, including but not only: EC JRC (2014), IEA Technology Roadmaps, WEC (2013), TECHPOL database (developed in several European research projects: SAPIENT, SAPIENTIA, CASCADE MINTS - see for instance: [1] (http://cordis.europa.eu/result/rcn/47819_en.html))

10) References - POLES

EDGAR [10] testing OECD/NEA 2014 [39] testing

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