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IFs ENERGY MODEL DOCUMENTATION

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1. Introduction

1.1 Overview

The International Futures system (IFs) represents energy and electricity through integrated dynamics that span multiple IFs models: energy, economy, environment, and infrastructure. It captures patterns of energy consumption and electricity use, the drivers behind them, and the production of energy from both fossil and non-fossil sources using different technologies. IFs also incorporates trade in energy, using both a pooled approach and a bilateral version. The model accounts for the environmental implications of fossil fuel use, while broader development and sustainability outcomes such as access to electricity and improved fuel use, are also represented.

Here we document the IFs energy model - a partial equilibrium model operating on physical energy, balancing consumption and production through a price variable that adjusts in response to supply-demand dynamics, with energy stocks serving as a buffer. Investment decisions are signalled by price and by cost, with cost shaped by resources, reserves, and technologies, and these dynamics in turn inform the treatment of the energy sector in the broader Economic Model. Ultimately, computations in the physical energy model feed into the Economic Model by replacing its sectoral calculations with the corresponding financial variables from the physical energy model.

Gross domestic product (GDP) from the Economic Model provides the basis for energy demand calculations. Energy demand elasticity represents the responsiveness of demand to prices, which evolve over the long run with changes in technology and resource availability. Thus, the physical constraints on the supply side are very important in determining the dynamics of the energy model.

IFs distinguishes nine energy production categories: oil, natural gas, coal, hydropower, nuclear, solar, wind, geothermal and other renewables. The other renewables category includes tidal, wave, biodiesel and biogas. For each category both conventional and unconventional sources are considered, but these have only been fully implemented for oil.[1] Currently, the model does not generate projections for consumption or trade by specific energy types. IFs rather computes aggregated regional or national energy demands and prices, on the assumption of high levels of long-term substitutability across energy types and a highly integrated market. The model also conducts energy trade only in a single, combined energy category. Finally, at the moment, there is no full reconciliation between the production of energy and electricity generation (see the IFs Infrastructure Model Documentation for a description of the electricity aspects of IFs).

1.2 Dominant Relations

Energy demand (ENDEM) is a function of GDP and the energy demand per unit of GDP (ENRGDP). Energy production (ENP) is a function of capital stock in each energy type,

[1] Conventional sources refer to oil extracted through standard drilling methods, while unconventional sources include those requiring advanced techniques such as shale oil extraction.

the capital/output ratio (QE) for that energy type, and a capacity utilization factor (CPUTF).

The following key dynamics are directly linked to the dominant relations:

DEMAND: Energy demand per unit of GDP depends on GDP per capita, energy prices, and an autonomous trend in energy efficiency. The first two of these are computed endogenously, the latter exogenously. The user can control the price elasticity of energy demand (***elasde***), speed at which energy price changes affect demand (***ehw***) and the autonomous trend in efficiency of energy use (***enrgdpgr***). The user can also use an energy demand multiplier (***endemm***) to directly modify energy demand.

PRODUCTION: For fossil fuels and hydro, there are upper bounds on production. For fossil fuels, these are based on reserve-to-production ratios, as well as user-specified upper bounds (***enpoilmax***, ***enpgasmax***, and ***enpcoalmax***). For hydro, the upper bound relates to hydropower potential. The model user can also control production using an energy production multiplier (***enpm***) to directly modify energy production by energy type. The user may also indirectly increase energy production through additional investment (***eninvm***), which will incorporate economic trade-offs. In contrast, a production multiplier (***enpm***) comes without any cost to increased production.

For renewable categories other than hydro, the model uses potential capacity (***resor***) in lieu of reserves or resources. This reflects availability or potential based on data or estimated from drivers such as land area. Unlike fossil fuels, where ***resor*** represents finite physical resources that directly constrain production, renewable potentials are effectively unlimited; instead of setting an upper bound, they influence capital costs and investment dynamics.

CAPITAL/OUTPUT RATIO: The capital/output ratio provides a measure of production cost, with declines reflecting efficiency gains and reduced capital intensity. User-controllable parameters (***etechadv*** and ***etechadvuncon***), applied to each fuel type, implement these cost declines due to technological improvements at the global level.

For fossil fuels, this is counteracted by a factor that increases the capital/output ratio as the amount of remaining resources decreases. The user can further modify the capital/output ratios with the multipliers (***qem*** and ***qeunconm***).

For renewable energy sources such as wind, solar, and geothermal, the capital/output ratio is equivalent to the levelized cost of electricity (LCOE) generation from these sources, though users can still modify capital output ratios with multipliers (***qem*** and ***qeunconm***). These energy sources are primarily used to generate electricity (except for geothermal, which can also provide direct heat).[2]

[2] LCOE is expressed as the cost per kilowatt-hour of electricity generated and is computed by dividing the total electricity produced over the lifetime of a plant by the sum of its capital costs, operations, and maintenance expenditures (IRENA, 2024). We will revisit the implications of variable renewable energy (VRE), including system integration costs and their effect on capital/output ratios in more detail later.

CAPITAL: Energy capital, by fuel type, is initialized based on the initial levels of production and capital/output ratios. Energy capital depreciates at a rate determined by the lifetime of energy capital (***lke***) and grows with investment. Total desired investment in energy capital is influenced by many factors, including existing capital, domestic and global energy demand, the production of other renewables, changes in the global capital/output ratio, world and domestic energy stocks, expected overall profits in the energy sector, and imports. Users can control the effect of expected profits (***eleniprof*** and ***eleniprof2***) and world energy stocks (***elenpr*** and ***elenpr2***). Desired investment by energy type increases with individual profit expectations, but also by limits related to reserve production factors (for fossil fuels and hydro), any exogenous restrictions on maximum production (for fossil fuels), ultimate potential (for hydro), and other, unspecified factors (nuclear). Users can influence the effect of profit expectations by fuel type (via ***elass***) as well as influence the desired investment by energy type (***eninvtm***), or in the aggregate (via ***eninvm***). The user can also specify an exogenous growth rate for energy investment by fuel type (***eprodr***). The Economic Model ultimately determines whether all of the investment needs can be met; in case of shortfalls, the investment in each type of energy is reduced proportionately.

RESOURCES/RESERVES/STOCKS: IFs separately represents ultimate resources and reserves, where the latter are the amount of energy resources available to be produced. Resources and reserves, both conventional and unconventional, are set in the pre-processor. The user can modify the default assumptions on ultimate resources, either directly (***resor***, ***resoruncon***) or via the use of multipliers (***resorm***, ***resorunconm***). Reserves decline with production and increase with discoveries. The rate of discovery depends on the ultimate resources remaining, the intensity of current production, world energy prices, and a base rate of discovery (***rdi***). The user can control the effect of world prices on discovery (***elasdi***), augment the base rate of discovery (***rdinr***), and use a multiplier to affect the rates of discovery (***rdm***). Finally, IFs keeps track of any production not used in the current year, i.e., stocks, and shortages.

ENERGY PRICES: Domestic energy prices are influenced by world stocks, domestic stocks, and the ratio of capital to production at the global level. The user can control the effect of domestic stocks on prices (***epra*** and ***eprafs***). Users can also include a “cartel premium” (***encartpp***) and a carbon tax (***carbtax***). More directly users can set domestic energy prices exogenously for just the first year (***enprixi***) or for multiple future years (***enprix***). The world energy price is calculated as a weighted sum of the domestic prices.

TRADE: The energy model also provides representation and model-user control over energy trade. The levels of imports (ENM) and exports (ENX), measured in physical terms (bboe), depend upon levels of production and demand, as well as past propensities to import and export energy. The user can set maximum limits on of energy imports (***enml***) and energy exports (***enxl***), as well as general limits on trade (***trademax***).

1.3 Structure and Agent System

Table 1: Model Structure and Agent System.

System/Subsystem	Energy
Organizing Structure	Partial market
Stocks	Capital, resources, reserves
Flows	Production, consumption, trade, discoveries, investment
Key Aggregate Relationships (Illustrative, not comprehensive)	Production function with exogenous technology change; Energy demand relative to GDP; Price determination
Key Agent-Class **Behavior Relationships** (Illustrative, not comprehensive)	Government taxes, subsidies

2. Flow Charts

This section presents several block diagrams that are central to the energy model: an energy system overview, energy production and energy consumption.

2.1 Energy Overview

The production growth process in energy is simpler than that in Agriculture or the full Economic Model. Because energy is a very capital-intensive sector, production depends only on capital stocks and changes in the capital-output ratio, which represents technological sophistication and other factors (such as decreasing resource bases) that affect production costs.

The key equilibrating variable is again inventories. It works via investment to control capital stock and therefore production, and via prices to control domestic consumption. Production and consumption, in turn, control trade.

Specifically, as inventories rise, investment falls, restraining capital stock and energy production, and thus holding down inventory growth. As inventories rise, prices fall, thereby increasing domestic consumption, which also holds down inventory growth.

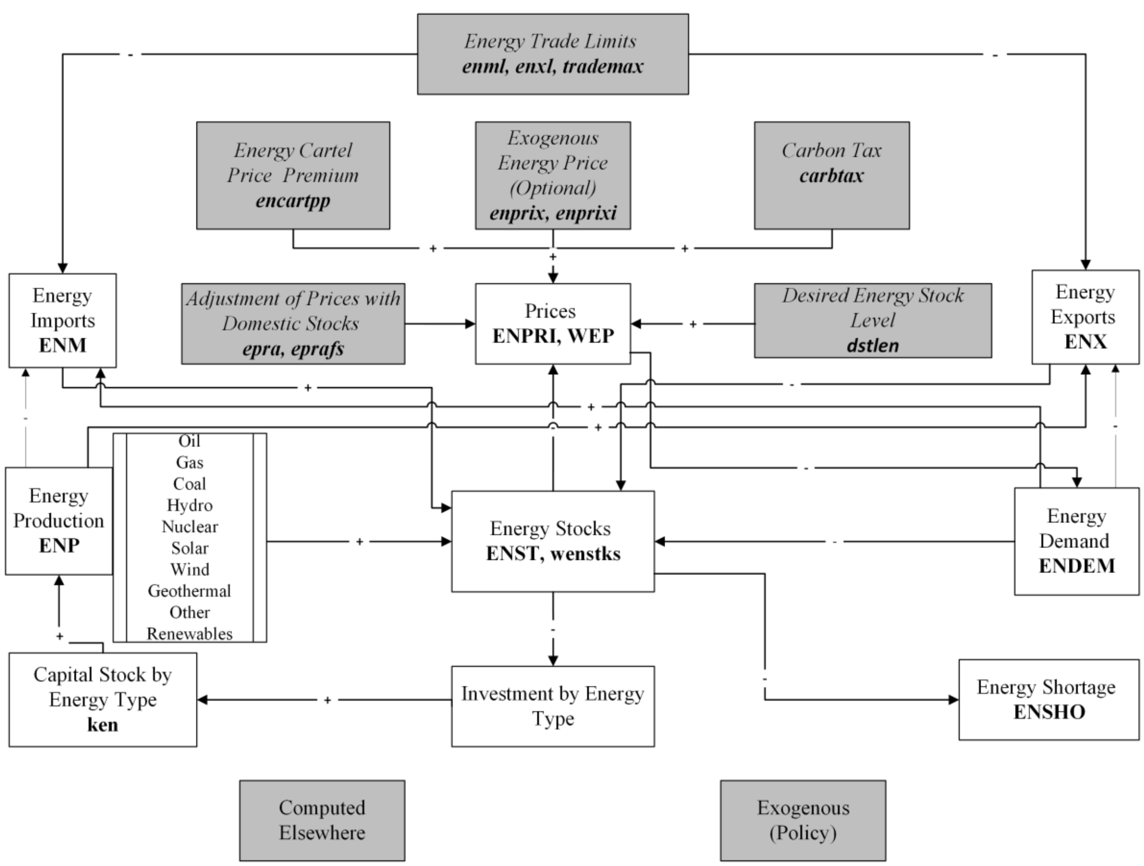

Figure 1: IFs Energy Model Overview.

2.2 Energy Production Detail

Energy production is computed from the capital stock invested in energy and the capital-output ratios, adjusted by a capacity utilization factor and bounded by production limits specific to each energy type. Exogenous parameters allow users to modify both the drivers of production and the production volumes themselves. The capital-output ratios are affected by the amount of remaining resources as a share of the initial levels, technological progress, and user-controlled multipliers. The capacity utilization factor is influenced by domestic stocks and shortages.

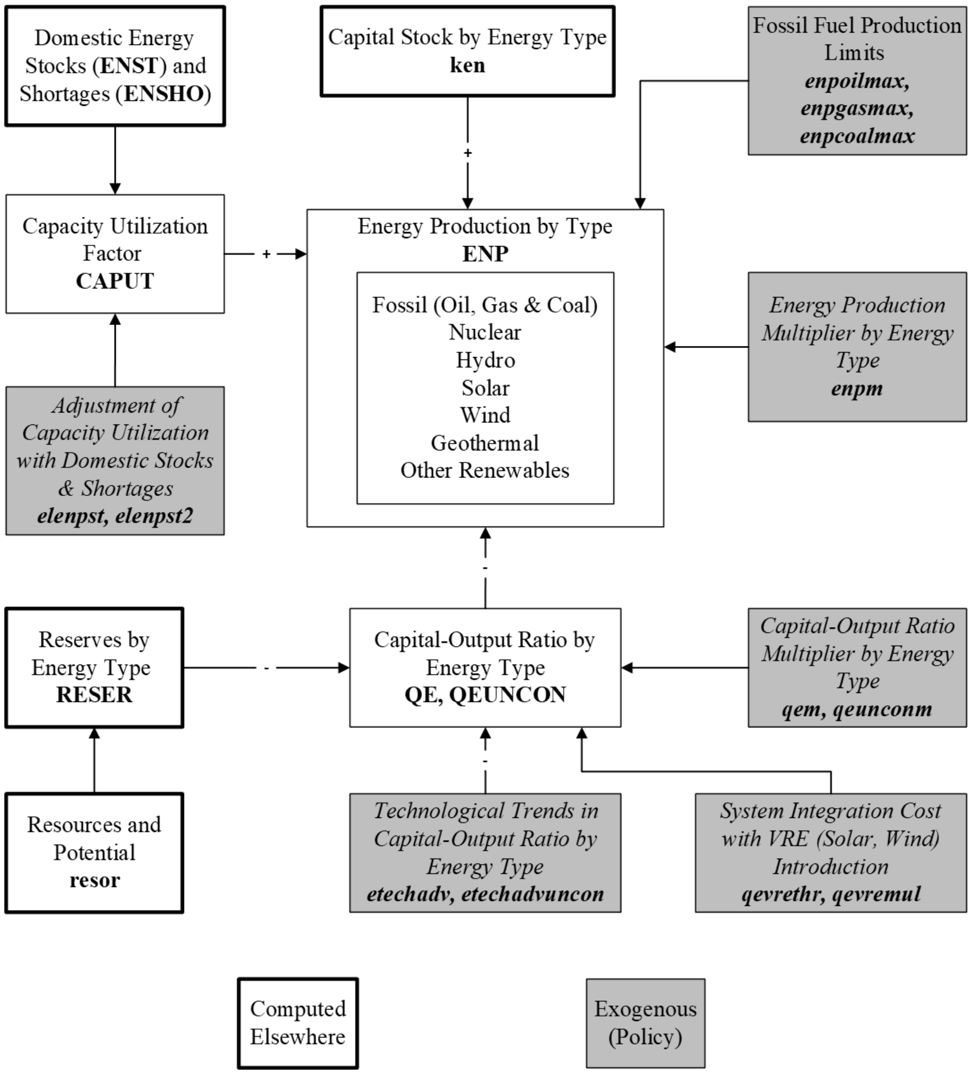

Figure 2: Energy Production in IFs

2.3 Energy Capital and Investment Detail

The capital stock by energy type decreases through depreciation and grows with new investment. Investment growth in the capital stock, though influenced by several factors, is driven primarily by energy profits and existing stocks. It can be adjusted through a user-defined scenario multiplier and is capped by production constraints linked to reserves availability for fossil fuels and resource potential for renewables. The user can use a direct multiplier on total energy investment, multipliers on energy investment by energy type to influence investment or specify a desired rate of growth in investment by energy type.

For renewable energy sources like wind, solar and geothermal, the capital-output rations are tied to the levelized cost of electricity (LCOE). In case of variable renewable energy (VRE) sources such as solar and wind, there comes an additional set of challenges associated with intermittency, dispatchability and storage. For renewables, the capital–output ratio corresponds to the LCOE with adjustments for system integration costs such as transmission, storage, and balancing in the case of variable renewables. Addressing these challenges requires additional expenditures on transmission, distribution, and balancing capacity. LCOE data published in the literature does not always incorporate such system integration costs, which can be substantial at higher penetration levels of VRE and also affect production costs (Hirth et al., 2015; Ueckerdt et al., 2013).

If these additional system costs are not considered, the model's forecasts for such renewable sources may overestimate the pace of cost reductions driven by technological learning and economies of scale, while at the same time underestimating the true investments required for large-scale deployment of wind and solar power.

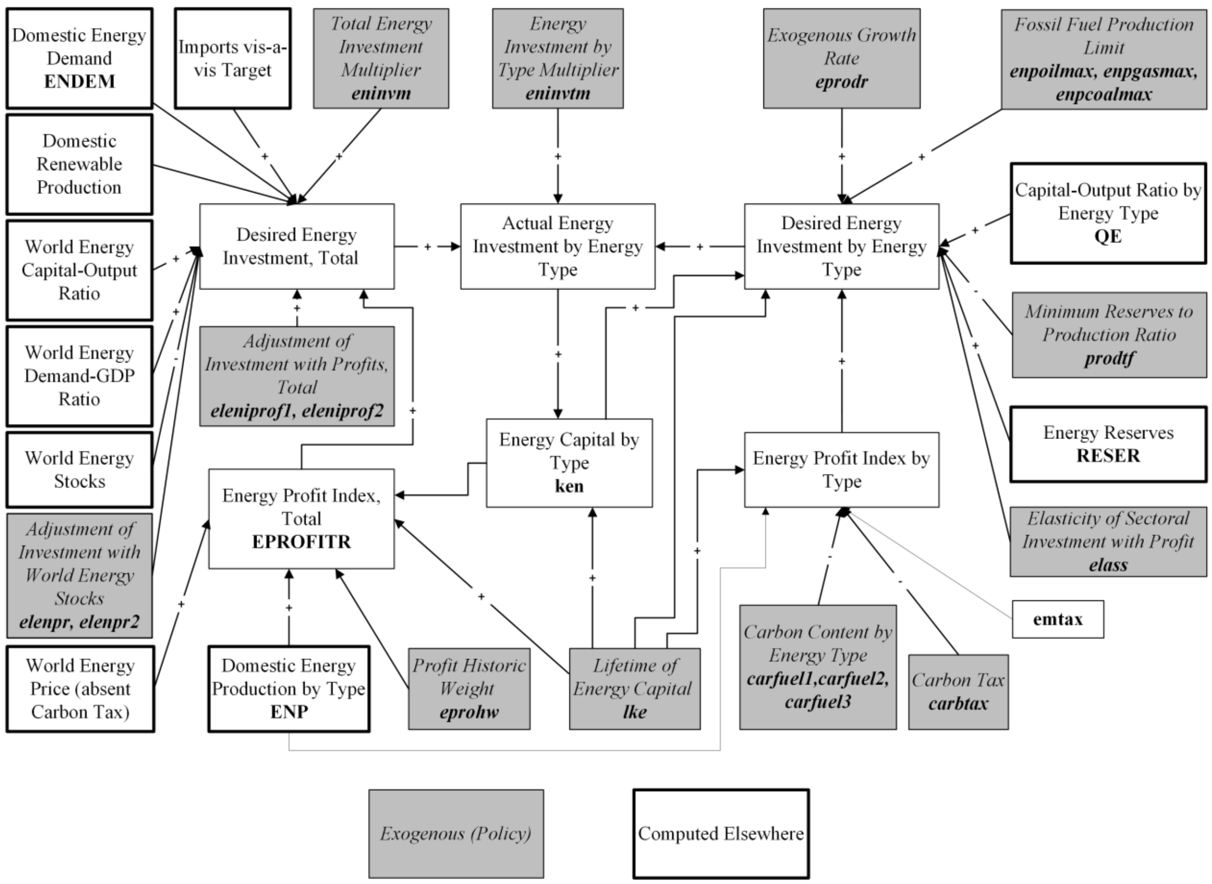

Figure 3: Energy Capital and Investment in IFs

2.4 Energy Demand Detail

Energy demand is estimated as a function of the energy demand per unit GDP (in PPP terms) and total GDP (in PPP terms), with adjustments related to energy prices and improvements in energy use efficiency. The energy demand per unit GDP depends on GDP per capita (in PPP Terms). The improvement in energy use efficiency is a combination of autonomous trend in efficiency of energy use (***enrgdpgr***) and an additional amount that accelerates the improvements for (non-exporting) countries that have efficiencies below the global average. The price effect takes into account both the domestic and global prices of energy, as well as any carbon tax (***carbtax***). The user can control the price elasticity of energy demand (***elasde***) and the historical weight used to smooth energy prices (***ehw***). Finally, the user can also use an energy demand multiplier (***endemm***) to directly modify energy demand.

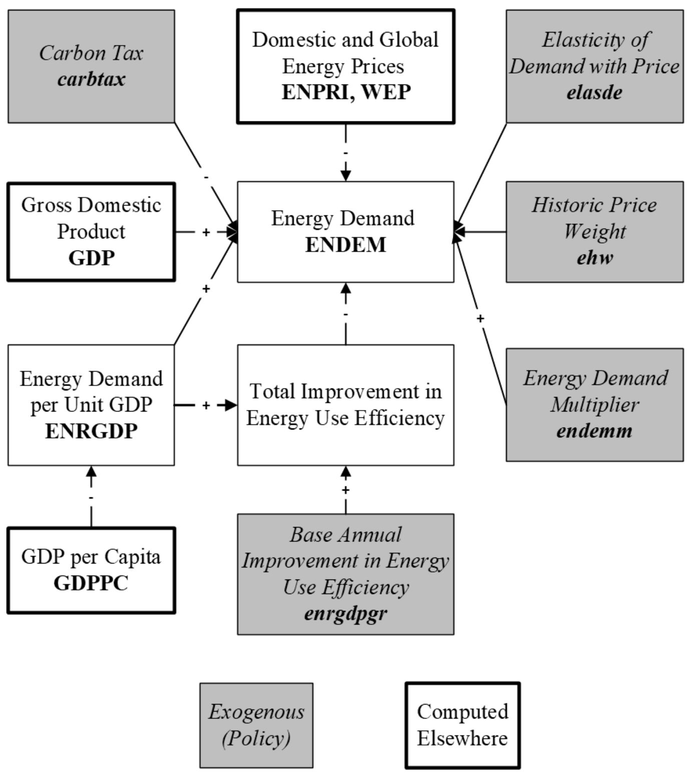

Figure 4: Energy Demand in IFs

2.5 Energy Resources and Reserves Detail

IFs distinguishes between ultimate resources and reserves, where the latter represent the amount of energy actually discovered and available for production. Ultimate resources are initially determined in the pre-processor, but the user can override these estimates using either absolute values (***resor***, ***resoruncon***) or multipliers (***resorm***, ***resorunconm***). There is also a parameter controlling the portion of unconventional oil that is economic to produce (***enresunce***). For non-renewable energy types, i.e., fossil fuels, reserves increase with discoveries and decrease with production. The rate of discovery includes a base rate (***rdi***) and an annual increment (***rdinr***). There are further adjustments related to the world energy price, the remaining resources, and the current rate of production. The user can control the effect of world prices on discovery (***elasdi***) and can also intervene with a discovery multiplier (***rdm***).

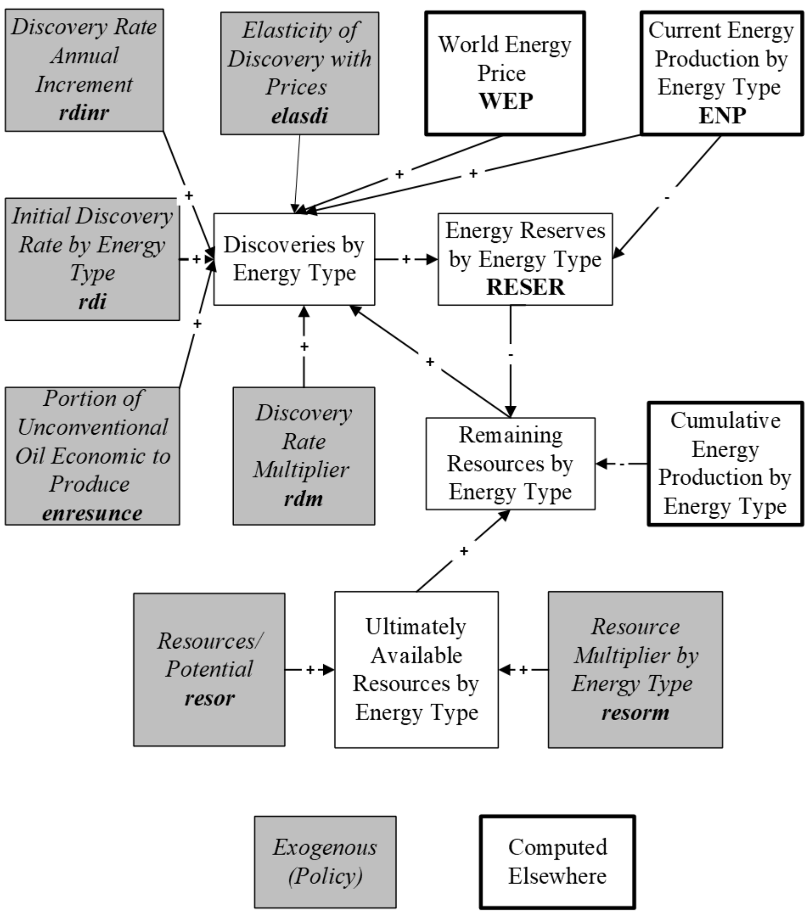

Figure 5: Energy Resources and Reserves in IFs

3. Equations

This section will present and discuss the equations that are central to the functioning of the energy model: supply, demand, trade, stocks, price, investment, economic linkages, capital, natural resources and energy indicators. Here we follow the order of calculations in all years but the first, noting specific calculations that are made in the first year or pre-processor as necessary. A table has been added as an appendix to this document, linking the variables to the historical data series used to initialize them.

3.1 Energy Demand

The key energy demand variable in IFs, ENDEM, tracks total primary energy demand. For the most part, IFs does not represent the transformation of this primary energy into final energy forms, or end-user energy demand. The one exception relates to electricity use, which is described in the documentation of the Infrastructure Model.

In the first year, total primary energy demand is calculated as an apparent demand based on a balancing equation that equates energy demand with supply, defined as production plus net trade, and a balancing energy stock. While the supply side is obtained from historical data, the initial value for the stock is estimated from an aggregate stock base, obtained by adding demand and supply, on which a desired stock level (***dstlen***, 10% by default) is applied and then augmented by the expected growth in production following standard practice in storage planning.

$$ENST_{r,t=1} = \left(\textstyle\sum_e ENP_{r,e,t=1} + ENDEMEst_r\right) * dstlen$$ [3]

$$ENDEM_{r,t=1} = \sum_e ENP_{r,e,t=1} + ENM_{r,t=1} - ENX_{r,t=1} - ENST_{r,t=1} * AVEPR_{r,t=1}$$

Where,

- *ENP*, *ENM*, *ENX*, *ENST*, and *AVEPR* are energy production, energy imports, energy exports, estimated energy stocks, and an average of the expected growth in production across all energy types (e) for a country, or region (r) in the first year (t) of the projection horizon. The calculations of the initial values of these variables are described later in the Equations section under the appropriate headings.

Note that this calculation does not directly use the historical data on total primary energy demand and there can be a significant difference between the initialized value of ENDEM and the actual historical data for the base year. This information is used by the variable ENDEMSH, which is described in the Infrastructure documentation.

In future years, the calculation of total primary energy demand begins with an estimate of the predicted amount of energy demand per unit of GDP (in PPP terms),

[3] Since energy demand is not yet computed for the first year, an estimate (ENDEMEst) is obtained from the energy balance equation, with the stock term based solely on the supply side.

compendemperunit, as a function of GDP per capita (in PPP terms).[4] This function is show in the figure below [5]:

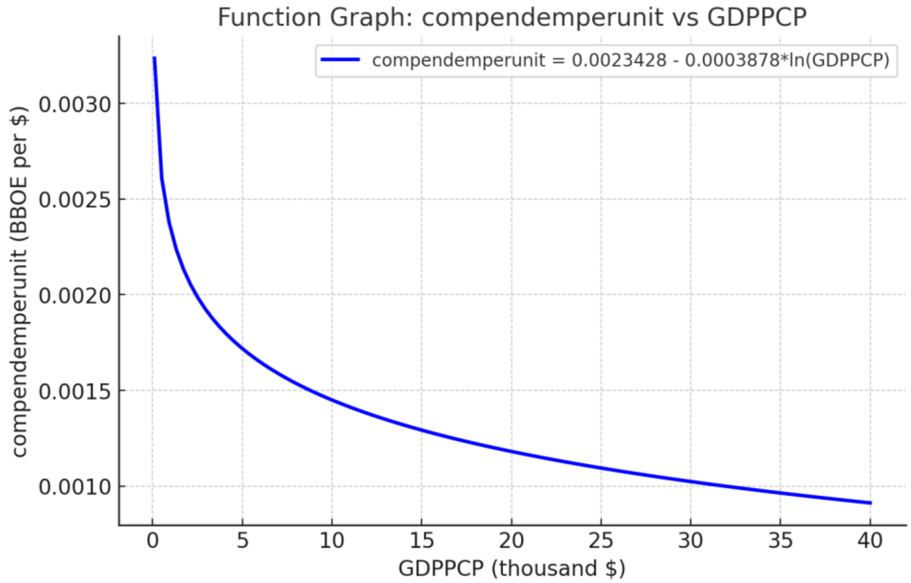

Figure 6: Relationship between compendemperunit and GDP per capita

A small amount, 0.0005 barrels of oil equivalent (boe), is added to this computed value to account for the fact that the demand data used to estimate the function above is less than apparent demand globally.

The initial data for countries is unlikely to fall exactly on this function. To reconcile this fact, IFs calculates values for both predicted energy demand per unit GDP in the first year, compendemperuniti, and empirical demand per unit GDP (in PPP terms) in the first year, actendemperuniti.[6] Over a time period of 75 years, controlled by the parameter ***enconv***, IFs gradually adjusts the difference between these two values so that the estimate of energy demand per unit GDP (in PPP terms) eventually does fall on the function.

IFs then calculates an initial estimate of total energy demand, endemba, by multiplying this adjusted value of energy demand per unit GDP (in PPP terms), endemperunit, by GDP (in PPP terms).[7]

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[4] Here, IFs uses GDP from the previous time cycle, with an estimate of growth, to calculate GDPPCP, because the recursive structure of IFs computes current GDP later. The current value of population, POP, has already been computed at this stage.

[5] The exact equation is compendemperunit = 0.0023428 -0.0003878*ln(GDPPCP).

[6] There is also an adjustment to the empirical demand that occurs during the initialization. Due to data inconsistencies and/or the exclusion of non-traded energy sources such as traditional biomass from production data, energy demand initialized using the balance method described above can turn out to be very low for some countries. The initialization code adjusts the base-year ENDEM for such cases to ensure that energy demand per unit of GDP at PPP is not less than a fifth of the value computed using the energy intensity function.

[7] IFs uses GDP from the previous time cycle here, because the recursive structure of IFs computes current GDP later.

$$\mathrm{endemba_r} = GDPP_{r,} * \mathrm{endemperunit_r}$$

IFs then considers the effect of price on total primary energy demand. IFs keeps track of the global energy price as both an index (WEP, base year = 100) and as an actual dollar value (WEPBYEAR, $ per BBOE). It also tracks a country level energy price index (ENPRI, base year =100).[8] Finally, it can also consider a tax on carbon, expressed by the variable CarTaxEnPriAdd, which has the units $ per BBOE.

The calculation of the effect of prices on total energy begins with the calculation of a variable called renpri. renpri is a moving average country-level price index that starts at the level of the country level price index in the base year, ENPRII, and then tracks changes in world energy prices and country-level carbon taxes.[9] The historical weight is controlled by the parameter ***ehw***, so that:

$$\mathrm{renpri}_{r,t} = \boldsymbol{ehw} * \mathrm{renpri}_{r,t-1} + (1 - \boldsymbol{ehw}) * \left(WEP_{t-1} + \mathrm{CarTaxEnPriAdd}_{r,t-1} * \frac{WEP_{t=1}}{WEPBYEAR_{t=1}}\right)$$

where

- *renpri* is the moving average country level price index
- ***ehw*** is the weight given to the historical value of renpri
- *WEP* is the global energy price index
- *WEPBYEAR* is the global energy price in $ per BBOE
- *CarTaxEnPriAdd* is the country level carbon tax in $ per BBOE of total energy and is calculated as the exogenous value of the carbon tax in $ per ton of carbon, ***carbtax***, times a production weighted average of the carbon contents of oil, gas, and coal, ***carfuel**$_e$* ***, where e is 1-3***:

$$\mathrm{CarTaxEnPriAdd_r} = \frac{\sum_e \left(ENP_{r,e} * \boldsymbol{carfuel_e}\right)}{\sum_e ENP_{r,e}} * \boldsymbol{carbtax_r}$$

The parameter specifying the price elasticity of energy demand, ***elasde***, is adjusted based on the relationship between renpri and and ENPRII to yield a new parameter, elasadjusted.

$$\mathrm{elasadjusted_r} = \boldsymbol{elasde_r} * \frac{ENPRII_r}{\mathrm{renpri}_r}$$

[8] The model also has a variable representing the price index in each economic sector, one of which is energy. This value is stored in the variable PRI, which uses an index value of 1 in the base year. ENPRI and PRI (energy) track each other, with former having a value 100 times that of the latter due to the different initial index values.

[9] Because energy prices and carbon taxes are computed later in the model sequence, the previous year's values are used here.

This, in effect, decreases the price elasticity of energy demand as prices increase.

This adjusted elasticity is then used to calculate the impact on energy demand, elasterm[10] as

$$\mathrm{elasterm_r} = 1 + \frac{\mathrm{renpri}_r + ENPRII_r}{ENPRII_r} * \mathrm{elasadjusted}_{\boldsymbol{r}}$$

The user can also introduce a further adjustment to total primary energy demand with a multiplier, ***endemm***, yielding:

$$ENDEM_r = \mathrm{endemba}_r * \mathrm{elasterm}_r * \boldsymbol{endemm_r}$$

IFs makes a final adjustment to total primary energy demand related to changes in energy efficiency of the economy unrelated to prices.[11] All countries receive an annual boost in energy efficiency related to technology given by the parameter ***enrgdpr***. In addition, if a country is not a major energy exporter and its economy is less energy efficient than the global average, measured as ENDEM divided by GDP (in PPP terms)[12], it gets an additional boost to its energy efficiency. This effect is cumulative, so ENDEM is adjusted as follows:

$$ENDEM_r = ENDEM_r * \left(1 + \frac{\mathrm{EnRGDPGRCalc_r}}{100}\right)^{iy}$$

where

- *EnRGDPGRCalc* is the annual average boost in energy efficiency, combining both the general technology-driven boost and the additional “catch-up” boost for less efficient economies
- *iy* is the number of years since the base year plus 1

Finally, IFs makes an initial estimate of energy use per unit GDP in market exchange rate (MER) terms in a separate variable, ENRGDP. This calculation uses an estimated GDP in MER, derived from the previous year’s MER-based GDP and its growth rate. The value is later corrected once the final computation of GDP in MER becomes available in the model sequence.

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[10] elasterm is not allowed to fall below 0.2

[11] This is generally referred to as autonomous energy efficiency improvement, or aeei.

[12] An estimate of this year’s GDPP based on the previous year’s GDPP and a growth rate is used here due to the order of calculations.

3.2 Energy Supply

The computation of energy production (ENP) is considerably easier than that of gross sectoral production in the Economic Model or of agricultural production in the agricultural model. Only capital is considered important as a factor of production (not labor, land, or even weather). Energy production is initially estimated by dividing the quotient of capital stock (ken) invested in each energy category and the appropriate capital-to-output ratio (QE). A multiplier, ***enpm***, can be used to increase or decrease production. This yields:

$$ENP1_{r,e} = \frac{ken_{r.e}}{QE_{r,e}} * \boldsymbol{enpm_{r,e}}$$

The dynamics of the capital-to-output ratios, QE, are discussed in section 3.8.

Known reserves, or potential capacity (RESER) and exogenously specified maximums pose constraints on production of certain energy types. The energy types affected are oil, gas, coal, and hydro. Production of oil, gas, and coal can be constrained either by the availability of known reserves (RESER) or by an absolute cap exogenously specified by the model user. The impact of reserves (or, potential, in the case of Hydro) is felt via a limit on the fraction of reserves that can be extracted for production in any year. Specifically, the reserve-to-production ratio may not fall below the value of ***prodtf***, which is initially set in the pre-processor, but can be overridden by the user. In addition, as the actual reserve-to-production ratio approaches this limit, its rate of decrease is limited. The exogenously specified maximums apply only to oil, gas, and coal, and are given by the parameters ***enpoilmax***, ***enpgasmax***, and ***enpcoalmax***. This yields a second estimate for energy production, given as:

$$ENP2_{r,e} = MIN\left(\frac{RESER_{r,e}}{MAX\left(\boldsymbol{prodtf}_{r,e}, sResProdR_{r,e} - 1\right)}, enpmax_{r,e}\right)$$

where

- *e* only applies to oil, gas, coal, and hydro
- *enpmax* takes on the value ***enpoilmax***, ***enpgasmax***, and ***enpcoalmax***, depending upon the fuel.
- *sResProdR* is the reserve-to-production ratio from the previous year; this limit only takes effect when *sResProdR* falls below 30 and remains above ***prodtf***

IFs then selects the minimum of ENP1 and ENP2 as the estimate of energy production ENP. The dynamics of energy reserves are discussed in section 3.8.2.

Two final adjustments are made to energy production. The first accounts for capacity utilization, *ENPCAPUT*, and the second only comes into play when a restriction is placed on energy exports. Since these are not calculated until the calculation of energy stocks and shortages, they are described in the appropriate places in sections 3.4. and 3.5.

3.3 Energy Trade

The energy model in IFs keeps track of trade in energy in physical quantities; the trade in energy in monetary terms is handled in the Economic Model. As opposed to the agricultural model, where trade in crops, meat, and fish are treated separately, the energy model considers trade in energy in the aggregate. Furthermore, it only considers production from oil, gas, coal, and hydro as being available for export. Finally, as with other aspects of trade, IFs uses a pooled trade model in the standard version of the model, with a representation of bilateral trade available in the dyadic version of the model.

The initial estimates of a country's energy imports and exports are determined using its propensity to import and propensity to export, applied to trade bases derived from moving averages of energy production and demand. Using moving averages smooths short-term fluctuations and better reflects long-term patterns in energy trade behavior.

The moving average of energy production, identified as smoothentot, is calculated simply as a moving average of production of energy from oil, gas, coal, and hydro. In the first year of the model:

$$smoothentot_{r,t=1} = EnTot_{r,t=1} = \sum_{e} ENP_{r,e,t=1}$$

where

- e is oil, gas, coal, and hydro

In future years,

$$smoothentot_{r,t} = 0.9 * smoothentot_{r,t-1} + 0.1 * \sum_{e} ENP_{r,e,t}$$

where

- e is oil, gas, coal, and hydro

The moving average of energy demand, identified as smoothpendem has a few more nuances, particularly after the first year. In the first year, IFs calculates:

$$smoothpendem_{r,t=1} = ENDEM_{r,t=1}$$

In future years, rather than using the value of ENDEM calculated earlier, the model uses a slightly different measure of energy demand, referred to as pendem. pendem differs from ENDEM in two main ways:

1. Rather than using the moving average country-level price index, renpri, to calculate the effect of prices on energy demand, it uses only current values:

$$\text{PEnPri}_{r,t} = WEP_{t-1} + \text{CarTaxEnPriAdd}_{r,t-1} * \frac{WEP_{t=1}}{WEPBYEAR_{t=1}}$$ [13]

2. It does not include the additional catch-up boost in energy efficiency beyond ***enrgdpr*** in calculating the autonomous changes in energy efficiency

Thus, in future years, we have

$$smoothpendem_{r,t} = 0.8 * smoothpendem_{r,t-1} + 0.2 * pendem_{r,t}$$

A country's propensities to import and export energy are given by the variables MKAVE and XKAVE. These are moving averages of the ratios of imports to an import base related to energy demand and exports to an export base related to energy production and demand, respectively. MKAVE is initialized to the ratio of energy imports to energy demand in the first year. A maximum value, MKAVMax is also set at this time to the maximum of 1.5 times this initial value or the value of the parameter ***trademax***. XKAVE is initialized to the ratio of energy exports to the sum of energy production from oil, gas, coal and hydro and energy demand from all energy types in the first year. Its maximum value, XKAVMAX is set to the maximum of this initial value and the parameter ***trademax***. MKAVE and XKAVE are updated once the computations of exports and imports are finalized; this update process is described at the end of this section.

The initial estimates of energy exports, ENX, and energy imports, ENM, are calculated as:

$$ENX_r = MIN(XKAVE_r, XKAVMAX_r) * exportbase_r$$

$$ENM_r = MIN(MKAVE_r * pendem_r, MKAVMAX_r * smoothpendem_r)$$

where

$$exportbase_r = smoothentot_r + smoothpendem_r$$

At this point, IFs makes some adjustments to energy imports and exports depending upon whether a country is considered in energy surplus or deficit. Where a country sits in this regard involves considering domestic and global stocks in addition to current production and demand.

Domestic energy stocks are computed as the sum of stocks carried over from the previous year, while also considering any shortages, ENSHO, the calculation of which is described later in this document

$$stocks_{r,t} = ENST_{r,t-1} - ENSHO_{r,t-1}$$

[13] The previous year's values of WEP and CarTaxEnPriAdd are used as the current year's values are not calculated until later in the model sequence.

A stock base is also calculated as the sum of energy demand and production, using moving averages for both.

$$StBase_r = smoothentot_r + smoothpendem_r$$

The ratio of stocks to StBase can be defined as domesticstockratio. A moving average of a trade base, smoothtradebase, is also calculated for each country, using the sum of its energy exports and imports, adjusted for the size of its energy demand:

$$smoothtradebase_{r,t} = MAX\left(ENDEM_r, 0.9 * smoothtradebase_{r,t-1} + 0.1 * 2 * (ENX_r + ENM_r)\right)$$

Where

$$smoothtradebase_{r,t=1} = MAX\left(ENDEM_{r,t=1}, 2 * \left(ENX_{r,t=1} + ENM_{r,t=1}\right)\right)$$

Global energy stocks, GlobalStocks, and the global stock base, GlobalStBase, are the sum of the domestic stocks and stock bases across countries, and the value of the globalstockratio is defined as GlobalStocks divided by GlobalStBase.

For each country, the level of deficit or surplus, endefsurp, is calculated as:

$$endefsurp_r = (globalstockratio - domesticstockratio_r) * StBase_r$$

This implies that if a countries stock ratio is less (greater) than the global average, it is considered in deficit (surplus).

If a country is in deficit, i.e., endefsurp > 0, IFs will act to reduce its exports and increase its imports. The recomputed value of exports is:

$$ENX_r = MAX\left(0.5 * ENX_r, ENX_r * \left(1 - \frac{endefsurp_r}{smoothtradebase_r}\right)\right)$$

In words, the decrease in energy exports is determined by the ratio of the level of deficit to the smoothed trade base, but can be no greater than 50 percent.

The recomputed value of imports is:

$$ENM_r = ENM_r * \left(1 + \frac{endefsurp_r}{smoothtradebase_r}\right)$$

with a maximum level given as:

$$ENMMax_r = ENM_r + \left(\frac{pendem_r * MKAVMAX_r - ENM_r}{5}\right)$$

Similarly, if a country is in surplus, i.e., endefsurp < 0, IFs will act to increase exports and reduce imports. The amount of increase in exports is controlled, in part, by the exchange rate for the country, EXRATE, specifically its difference from a target level of 1 and its change from the previous year. As with other adjustment factors of this type, the ADJSTR function is used, yielding a factor named mul.[14] This factor is bounded between 0.95 and 1.05 and is applied to ENX before recomputing it, as shown in the next equation, where endefsurp is a negative number:

$$ENX_r = ENX_r * \left(1 - \frac{endefsurp_r}{smoothtradebase_r}\right)$$

Here, a maximum export level is given as:

$$ENXMax_r = ENX_r + \left(\frac{exportbase_r * XKAVMAX_r - ENX_r}{5}\right)$$

> *where* this maximum value is computed prior to the adjustments to ENX noted above.

The recomputed value of imports is:

$$ENM_r = MAX\left(0.5 * ENM_r, ENM_r * \left(1 + \frac{endefsurp_r}{smoothtradebase_r}\right)\right)$$

In words, the decrease in energy imports is determined by the ratio of the level of surplus to the smoothed trade base, but can be no greater than 50 percent.

Because of the frequent use and importance of government trade restrictions in energy trade, model users may want to establish absolute export (***enxl***) or import (***enml***) limits, which can further constrain energy exports and imports. An export constraint may also affect the production of oil and gas as described in the next section.

As it is unlikely that the sums of these values of ENX and ENM across all countries will be equal, which is necessary for trade to balance. IFs includes an adjustment process to reconcile the difference. IFs computes actual world energy trade (WET) as the average of the global sums of exports and imports.

$$WET = \frac{\sum_r ENX_r + \sum_r ENM_r}{2}$$

[14] ADJSTR is an algorithmic implementation of the PID controller that drives the system towards equilibrium.

and recomputes energy exports and imports, as:

$$ENX_r = WET * \frac{ENX_r}{\sum_r ENX_r}$$

$$ENM_r = WET * \frac{ENM_r}{\sum_r ENM_r}$$

This maintains each country's share of total global energy exports and imports.

IFs can now update the moving average export (XKAVE) and import (MKAVE) propensities for the next time step. This requires historic weights for exports (***xhw***) and imports (***mhw***), yielding the equations:

$$XKAVE_{r,t+1} = XKAVE_r * \boldsymbol{xhw} + (1 - \boldsymbol{xhw}) * \frac{ENX_r}{exportbase_r}$$

$$MKAVE_{r,t+1} = MKAVE_r * \boldsymbol{mhw} + (1 - \boldsymbol{mhw}) * \frac{ENM_r}{smoothpendem_r}$$

A further adjustment is made related to the import propensity, MKAVE, related to the difference between this propensity and a target level, ImportTarget, and the change in this difference since the previous year. This target starts at the level of MKAVE in the first year and gradually declines to 0 over a 150 year period. As in many other situations in IFs, this process makes use of the ADJUSTR function to determine the adjustment factor applied on the import level to move it gradually towards in its path to target. The value of mulmlev is not allowed to exceed 1, so its effect can only be to reduce the value of MKAVE.

Finally, XKAVE and MKAVE are checked to make sure that they do not exceed their maximum values, XKAVMAX and MKAVMAX, respectively.

3.4 Domestic Energy Stocks

IFs sets a target for energy stocks in each country as a fraction of a domestic stock base, StBase, which was defined earlier as the sum of a moving average of energy demand, smoothpendem, and a moving average of the production of oil, gas, coal, and hydro, smoothentot. This fraction is defined by the parameter ***dstlen***.

Stocks are initialized in the first year as ***dstlen*** multiplied by the initial domestic stock base, which is the sum of production of all energy types and an estimated value of apparent energy demand (ENDEMEst).

$$ENST_{r,t=1} = \boldsymbol{dstlen} * \left(\sum_e ENP_{r,e,t=1} + ENDEMEst_{r,t=1}\right)$$

where

- *e* includes all energy types

- *ENDEMEst* is calculated as:

$$ENDEMEst_{r,t=1} = (1 - \boldsymbol{dstlen} * AVEPR_r) * \left(\sum\nolimits_e ENP_{r,e,t=1} + ENM_{r,t=1} - ENX_{r,t=1}\right)$$

where

- *e* includes all energy types
- *AVEPR* is a weighted average energy production growth rate across energy types

In future years, IFs begins by summing the moving average energy demand, smoothpendem, across all countries, storing this value as WENDEM and the same for moving average energy production from oil, gas, coal, and hydro, smoothentot, which it stores as WorldEnp. It also sums the moving average energy demand just for countries that have low propensity for exports, XKAVE < 0.2, and stores this value as WEnDemIm.

At this point, IFs adjusts energy production by multiplying by a capacity utilization factor, ENPCAPUT, which is assumed to be the same for all energy types in a country.

$$ENP_{r,e,t} = ENP_{r,e,t} * ENPCAPUT_{r,t-1}$$ [15]

The value of ENPCAPUT is initialized to 1 in the first year. How it changes in time is described in the next section after the description of the calculation of the domestic price index.

An initial estimate of energy stocks, ENST, is then calculated as the previous year's stocks augmented by production and imports and reduced by use and exports

$$ENST_r = ENST_{r,t-1} + \sum\nolimits_e ENP_{r,e} + ENM_r - ENDEM_r - ENX_r$$

If after this calculation, there are excess stocks, i.e., ENST > ***dstlen*** * StBase, and there is an export constraint, given by ***enxl***, adjustments are made to the production of oil and gas, and, in turn, to energy stocks.[16] The total reduction in oil and gas production is given as the amount of excess stocks, with a maximum reduction being the total amount of oil and gas production. This total amount of reduced production is then shared proportionately between oil and gas. The total reduction is also removed from ENST.

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[15] This is the first of the two adjustments to energy production noted at the end of section 3.2.

[16] This is the second of the two adjustments to energy production noted at the end of section 3.2.

Later, after the determination of prices, ENST is modified to: 1) ensure that they are not less than zero and 2) to account for any global shortfalls. These modifications are described in the next section.

3.5 Energy Prices and Final Adjustments to Domestic Energy Stocks and Capacity Utilization

IFs keeps track of separate domestic, ENPRI, and world, WEP, energy price indices, that apply to all types of primary energy in IFs energy model. These are initialized to a value of 100 in the first year. It also tracks the world energy price in terms of dollars per BBOE, WEPBYEAR, which is initialized as a global parameter.

A number of steps, involving several variables, are needed for the calculation of energy prices. These include a world stock base, wstbase, world energy stocks, wenstks, world energy production by energy type, WENP, world energy capital, WorldKen, and a global capital output ratio, wkenenpr. These are calculated as follows:

$$wstkbase = \sum_{r} StBase_r$$

$$wenstks = \sum_{r} \left(ENST_r - ENSHO_{r,t-1}\right)$$

$$WENP_e = \sum_{r} ENP_{r,e}$$

$$WorldKen = \sum_{r} \sum_{e} \left(ken_e * \frac{ENCAPUT_r}{MAX(5, \boldsymbol{lke_e})}\right)$$

$$wkenenpr = \frac{WorldKen}{WorldEnp}$$

where

- *ENSHO* is domestic energy shortage (described below)
- *ken* is capital stock for each energy type
- ***lke*** is the average lifetime of capital for each energy type

In cases when at least one country has an exogenous restriction on the production of oil, i.e., enpm(oil) < 1 for at least one country, a few additional variables are calculated:

$$GlobalShortFall = \sum_{e} Max\left(0, \sum_{r} ENP_{r,e,t-1} - 1.05 * \sum_{r} ENP_{r,e,t}\right)$$

$$WorldEnProd = \sum_{e} WENP_e$$

$$ShortFallSub = GlobalShortFall * MIN\left(10, \frac{WorldEnProd}{WENP(oil)}\right)$$

Otherwise, these three variables all take on a value of 0.

These values are used to calculate an adjustment factor driven by global energy stocks that affect domestic energy prices. The effect in the current year, wmul, is calculated using the ADJSTR function, which looks at the difference between world energy stocks, wenstks and the desired level, given by ***dstlen*** * wstbase, and the change in world energy stocks from the previous year. The presence of an exogenous restriction on the production of oil has two effects on the calculation of wmul. First, the value of ShortFallSub affects the two differences that feed into the ADJSTR function. Second, the elasticities applied in the ADJSTR function are tripled.

The adjustment factor calculated in the current year is not applied directly to the calculation of domestic energy prices. Rather, a cumulative value, cumwmul, is calculated as:

$$cumwmul_t = cumwmul_{t-1} * (1 + (wmul - 1) * \boldsymbol{eprohw})$$

Other factors affect the domestic energy price index – domestic energy stocks, possible cartel price premiums, ***encartpp***, the first-year value of the world energy price index, IWEP, changes in the global capita output ratio from the first year, whether the user has set a global energy price override. ***enprixi,*** and whether there is any restriction on oil production.

The domestic energy stocks affect a country-specific "markup" factor, MarkUpEn. This starts at a value of 1 and changes as a function of the value of a multiplier, mul, which is calculated using the ADJSTR function. Here the differences are those between domestic energy stocks and desired stocks, given as ***dstlen*** * StBase, and the changes in energy stocks from the previous year. Shortages from the previous year are also taken into account. The user can also control the elasticities used in the ADJSTR function with the parameters ***epra*** and ***eprafs***. This markup evolves over time as

$$MarkUpEn_{r,t} = MarkUpEn_{r,t-1} * mul$$

The domestic energy price index, ENPRI, is first calculated as:

$$ENPRI_r = \boldsymbol{X} * mul_r * cumwmul + \boldsymbol{encartpp}$$

where

- ***X*** = ***enprixi,*** exogenously set equilibrium price for the base year, in dollars, when this parameter is set to a value greater than 1, and IWEP, initial world energy price (WEP) set as an index starting at 100, otherwise

It is then recomputed with bounds to prevent wild price fluctuations:

$$ENPRI_{r,t} = MIN\left(ENPRI_{r,t}, ENPRI_{r,t-1} + \boldsymbol{encartpp_t} - \boldsymbol{encartpp_{t-1}} + \boldsymbol{X}\right)$$

where

- ***X*** is 100 to accommodate larger rise when there is a restriction on oil production in at least one country and 20 otherwise

Furthermore, ENPRI is not allowed to fall by more than 10 points in a given year.

It is possible for the user to override this price calculation altogether. Any positive value of the exogenous country-specific energy price specification (***enprix***) will do so.

It is only now that a country's energy stocks and shortages are finalized for the current year. If ENST is less than 0, then a shortage is recorded as ENSHO = -ENST and ENST is set to 0. In addition, for countries that have a low propensity for exports, XKAVE < 0.2, a share of any global shortfall is added to their shortage, with the share determined by the country's share of moving average energy demand among those countries, with WEnDemIm representing the sum of smoothed demand for them.

$$ENSHO_r = ENSHO_r + \ GlobalShortFall * \frac{smoothpendem_r}{WEnDemIm}$$

The energy shortage enters the Economic Model in the calculation of gross sectoral production.

The same deviations in domestic stock from its target level and in its rate of change since the previous year, accounting for past shortages are used to adjust the value of energy capacity utilization (ENPCAPUT), introduced earlier. The ADJSTR function generates a multiplier (Mul) that signals how capacity utilization should respond to these level and rate differences, with response elasticities defined by ***elenpst*** and ***elenpst2***. In addition, the resulting capacity utilization is smoothed over time to ensure gradual adjustment.

$$ENPCAPUT_{r,t} = 0.5 * ENPCAPUT_{r,t-1} + 0.5 * Mul$$

This value is further assumed to converge to a value of 1 over a period of 100 years and is bound to always have a value between 0.2 and 2, with values exceeding one indicating a need for additional investment.

This still leaves the need to calculate the world energy price. IFs actually tracks a world price including carbon taxes, WEP, and a world price ignoring carbon taxes, WEPNoTax. *Carbon taxes are ignored* in cases where the energy price is set exogenously using ***enprix***.

In both cases, the world energy price is a weighted average of domestic energy prices:

$$WEP = \frac{TENPRI}{TENP}$$

$$WEPNoTax = \frac{TENPRINOTAX}{TENP}$$

where

$$TENP = \sum_r \sum_e ENP_{r,e}$$

$$TENPRINoTax = \sum_r \sum_e (ENPRI_r * ENP_{r,e})$$

$$TENPRI = \sum_r \sum_e \left(\left(ENPRI_r + CarTaxEnPriAdd_r * \frac{WEP_{t=1}}{WEPBYEAR_{t=1}} \right) * ENP_{r,e} \right)$$

where

- *WEP* and *WEPBYEAR* are world energy prices per boe, with the former expressed as an index value and the latter in dollars (WEP includes the carbon tax). The above equation uses initial values (t = 1).
- The term with CarTaxEnPriAdd is ignored in countries with exogenous energy prices in a given year.
- *CarTaxEnPriAdd* is the country-level carbon tax, expressed in dollars per BBOE, applied to the total carbon-emitting energy produced within the country. Its computation is shown earlier.

Finally, the value of WEPBYEAR is computed as:

$$WEPBYEAR_t = WEPBYEAR_{t=1} * \frac{WEP_t}{WEP_{t=1}}$$

3.6 Energy Investment

Energy investment is modelled with relative complexity in IFs, as adjustments in investment constitute the primary mechanism through which the energy market reaches equilibrium in the long run. It is also different and perhaps slightly more complex in IFs than investment in agriculture. Whereas the latter involves computing a single investment need for agricultural capital, and subsequently dividing it between land and capital, in energy a separate demand or need is calculated for each energy type, based on profit levels specific to each energy type.

We begin by calculating a total energy investment need (TINEED) to take to the Economic Model and place into the competition for investment among sectors. This investment need is a function of energy demand, adjusted for shifts in energy intensity, capital intensity, and energy stock at the global level, and country-specific profitability and the investment-demand ratio. The equation below presents this initial calculation of TINEED.

$$TINEED_r = ENDEM_r * mulendem * \frac{wkenenpr_t}{wkenenpr_{t=1}} * mulkenenpr * mulwst * mulstocks^{0.5} * mulrprof_r * mulrenew_r * sendeminvr_r$$

where

- *Mulendem* represents annual change in global energy intensity computed as the ratio of global energy demand per unit GDP in the current year to that in the previous year

$$mulendem = \frac{WENDEM_t / WGDP_t}{WENDEM_{t-1} / WGDP_{t-1}}$$

- *wkenenpr* represents global capital intensity and is computed as the ratio of global energy capital to global energy production

$$wkenenpr = \frac{WorldKen}{WorldEnp}$$

- *mulkenenpr* is the ratio of wkenenpr in the current year to that in the previous year

$$mulkenenpr = \frac{wkenenpr_t}{wkenenpr_{t-1}}$$

- *mulwst* and *mulstocks* are factors related to global energy stocks. mulwst is calculated using the ADJSTR function, where: the first order difference is that between global energy stocks, wenstks, and desired global energy stocks, DesStocks = ***dstlen*** * wstbase; the second order difference is between the level of world energy stocks in the current year and those in the past year; and the elasticities are given by the parameters ***elenpr*** and ***elenpr2***. mulstocks is also related to global energy stocks, but is more directly related to the desired level of global energy stocks:

$$mulstocks = \frac{DesStocks}{MAX\left(0.5 * DesStocks, MIN(4 * DesStocks, wenstks)\right)}$$

Note that mulstocks will always take on a value between ¼ and 4.

- *mulrprof* is a function of changes in the expected level of profits in the energy sector as a whole in a country, EPROFITR. Energy profits are calculated as the ratio of returns, EnReturn, to costs, ProdCosts. EPROFITR is actually a moving average of these profits relative to those in the base year, with a historical weighting factor controlled by the parameter ***eprohw***. In full, we have:

$$EnReturn_r = WEPNoTax * \sum_e ENP_{r,e}$$

$$ProdCost_r = \sum_e \frac{ken_{e,r}}{MAX(5, \boldsymbol{lke_e})}$$

$$EnReturn_r = \frac{EnReturn_r}{ProdCost_r}$$

$$EPROFITR_{r,t} = \boldsymbol{eprohw} * EPROFITR_{r,t-1} + (1 - \boldsymbol{eprohw}) * \frac{EnReturn_{r,t}}{EnReturn_{r,t=1}}$$

We can now calculate mulrprof using the ADJSTR function. The first order difference is between the current value of EPROFITR and a target value of 1; the second order difference is the change in the value of EPROFITR from the previous year; the elasticities applied to these differences are given by the parameters ***eleniprof*** and ***eleniprof2***.

- *Mulrenew* represents the reduction in investment needs that occurs as renewables such as solar and wind, with relatively lower and declining costs expand. It is computed as a function of the share of non-hydro renewables in the energy mix in a country. It is assigned a value of 1 unless the production of energy from renewables exceeds 70% of total energy demand. If so, we have:

$$mulrenew_r = MAX\left(0.5{,}1 - \left(\frac{ENP_{r,renew}}{ENDEM_r} - 0.7\right) * 1\right)$$

Given these conditions, mulrenew can take on values between 0.5 and 1, with smaller values associated with larger amounts of renewable production.

- *sendeminvr* is a moving average of the ratio of investment need to energy demand in a country, with an accounting for changes in the global capital production ratio since the first year and is updated as[17]:

$$sendeminvr_{r,t+1} = 0.95 * sendeminvr_{r,t} + 0.05 * \frac{TINEED_{r,t}}{ENDEM_{r,t}} * \frac{wkenenpr_{t=1}}{wkenenpr_t}$$

[17] Note the careful use of the time subscripts. sendeminvr is not updated until after the computation of the initial value of TINEED, so the initial calculation of TINEED needs to use the previous year's value of sendeminvr. Furthermore, the updating of sendeminvr occurs after TINEED has been adjusted to reflect any inventory reductions, but before the investment multiplier, ***eninvm***, is applied.

After this initial calculation, two further adjustments are made to TINEED. The first is a reduction related to a possible reduction of inventory, invreduc, carried over from the previous year. The calculation of invreduc is described later in this section, where we look at reductions in investment in specific energy types due to resource constraints or other factors. The effect on TINEED is given as:

$$TINEED_r = TINEED_r - MIN\left(0.7 * invreduc_{r,t-1}, 0.6 * TINEED_r\right)$$

Thus, the reduction in TINEED can be no more than 60 percent.

Finally, the user can adjust TINEED with the use of the multiplier ***eninvm***.

Before this total investment need, TINEED, is passed to the Economic Model, there is a chance that it may need to be further reduced. This depends on the calculation of a bound, TINeedBound. TINeedBound arises from a bottom-up calculation of the investment needs for each energy type individually, ineed. These depend upon the profits for each energy type and any possible bounds on production related to reserves and other factors.

As with the estimate of total profits to energy, the returns by energy type depend upon production and costs[18].

$$EnReturnS_{r,e} = \frac{ENP_{r,e}}{EnCost_{r,e}}$$

For the non-fossil fuel energy types – hydro, nuclear, solar, wind, geothermal, and other renewable – EnCost is based solely on capital depreciation

$$EnCost_{r,e} = \frac{ken_{r,e}}{\boldsymbol{lke}_e}$$

where
e = hydro, nuclear, solar, wind, geothermal, and other renewables

For the fossil fuel energy types – oil, gas, and coal – we must also consider any possible carbon taxes. EnCost is calculated as

$$EnCost_{r,e} = \frac{ken_{r,e}}{\boldsymbol{lke}_e} + ENP_{r,e} * \boldsymbol{carfuel}_e * \boldsymbol{carbtax}_r$$
$$+MAX\left(-0.5 * \frac{ken_{r,e}}{\boldsymbol{lke}_e}, ENP_{r,e} * (\boldsymbol{carfuel}_e - AvgCarFuel) * emtax_r\right)$$

where
- *e* = oil, coal, gas

[18] Energy prices are not considered here because we are interested in relative profits, which are not affected by prices since all energy types are assumed to sell at the same price.

- ***carfuel*** is the carbon content of the fuel in tons per BBOE
- *AvgCarFuel* is the unweighted arithmetic average of the carbon content of oil, gas, and coal
- ***carbtax*** is an exogenously specified country-specific carbon tax in $ per BBOE
- *emtax* is twice the number of years since the first year and reflects carbon cost adjustments - higher for more polluting fuels and lower for cleaner ones.

The change in eprofitrs from the first year is then calculated as:

$$eprofitrs_{r,e} = \frac{EnReturnS_{r,e,t}}{EnReturnS_{r,e,t=1}}$$

An average return, avgreturn, is calculated as the weighted sum of the individual returns:

$$avgreturn_r = \frac{\sum_e \left(ENP_{r,e} * EnReturnS_{r,e}\right)}{smoothentot_r}$$

Investment need by energy type, ineed, grows in proportion to capital and as a function of relative profits.

$$ineed_{r,e,t} = ineed_{r,e,t=1} * \frac{ken_{r,e,t-1}}{ken_{r,e,t=1}} * eprofitrs_{r,e}^{\boldsymbol{elass}_{r,e}}$$

where

- ***elass*** are country and energy-specific user controlled parameters

At this point, ineed is checked to make sure that it does not fall by more than 20% or increase by more than 40% in any single year.

Also, if the user has set an exogenous target for production growth, i.e., ***eprodr*** > 0, all of the above is overridden and ineed is calculated as:

$$ineed_{r,e} = \frac{ken_{r,e} * (1 + \boldsymbol{enprodr}_e)}{\boldsymbol{lke}_e}$$

These investment needs are checked to make sure that they do not exceed what the known reserve base can support. This applies only to oil, gas, coal, and hydro. An initial estimate of the maximum level of investment is given by:

$$maxinv_{r,e} = \left(\frac{RESER_{r,e}}{\boldsymbol{prodtf}_{r,e}} - \frac{ken_{r,e}}{QE_{r,e}} + \frac{ENP_{r,e}}{\boldsymbol{lke}_e}\right) * QE_{r,e}$$

where

- *e* = oil, gas, coal, or hydro

The first term in parentheses, when multiplied by QE, indicates the amount of capital that would be necessary in order to yield the maximum level of production given the lower bound of the reserve production ratio, ***prodtf***. The second term is simply the current level of capital and the third term indicates the level of depreciation of existing capital. This implies that countries will not make investments beyond those that would give it the maximum possible level of production for a given energy type.

At the same time, IFs assumes there is a minimum level of investment, which is basically 30% of the capital depreciated during the current year:

$$mininv_{r,e} = 0.3 * \frac{ENP_{r,e}}{\boldsymbol{lke}_e} * QE_{r,e}$$

where

- e = oil, gas, coal, or hydro

In cases where the current production of oil, gas, or coal already equals or exceeds the exogenously specified maximum for a country – ***enpoilmax***, ***enpgasmax***, or ***enpcoalmax*** – maxinv is set equal to mininv. This again avoids useless investment.

A further constraint is placed on the maximum investment level in capital for hydro production. This is done by simply replacing RESER/***prodtf*** in the calculation of maxinv with the value ENDEM * EnpHydroDemRI * 2, where EnpHydroDemRI is the ratio of energy produced by hydro in the base year to total energy demand in that year. In other words, the growth in energy production from hydro in the current year from the first year cannot exceed twice the growth in total energy demand over that period, even if reserves are available, and capital investments are restricted accordingly.

$$maxHydroProd_{r,t} = 2 * \frac{ENDEM_{r,t}}{ENDEM_{r,t=1}} * ENP_{r,Hydro,t=1}$$

The constraints placed on investment in nuclear energy differ somewhat from these other fuels. IFs does not have an explicit measure of reserves for nuclear. Rather, it is assumed that the growth in capital in nuclear energy cannot exceed 1 percent of existing capital plus whatever is required to account for depreciation:

$$maxinv_{r,e} = \left(0.01 * \frac{ken_{r,e}}{QE_{r,e}} + \frac{ENP_{r,e}}{\boldsymbol{lke}_e}\right) * QE_{r,e}$$

where

- e = nuclear

Also, the minimum level of investment for nuclear energy is assumed to be 50 percent of the capital depreciated in the current year, rather than 30 percent as with oil, gas, coal, and hydro.

There is no limit to the investments in capital for the other renewable categories.

Given these restrictions, the investment needs for oil, gas, coal, hydro, and nuclear are updated so that mininv <= ineed <= maxinv. Any reductions from the previous estimates of ineed are summed across energy types to yield the value of invreduc, which will affect the estimate of TINEED in the following year as described earlier.

The final estimates of ineed for each energy type are summed to yield TINeedBound. If TINEED is greater than TINEEDBOUND, then TINEED is recalculated as the average of the two:

$$TINEED_r = 0.5 * (TINEED_r + TINeedBound_r)$$

This value of TINEED is passed to the Economic Model as IDS_{energy},

$$IDS_{r,s=energy} = sidsf_r * TINEED_r$$

where

- *sidsf* is an adjustment coefficient that reconciles differences between the initialized values of energy investment in the physical energy model and those in the Economic Model. These differences may arise from data discrepancies or differences in monetary units. Computed in the first year of the model run, sidsf gradually converges to a value of 1 after a number of years specified by the parameter ***enconv***.

In the Economic Model, the desired investment in energy must compete with other sectors for investment (see more about linkages between the Energy and Economic Models in section 3.7). Once these sectoral investments are determined, a new value for investments in the energy sector, $IDS_{s=energy}$, is passed back to the Energy model. The adjustment coefficient is then applied to yield:

$$inen_r = \frac{IDS_{r,s=energy}}{sidsf_r}$$

In the meantime, the desired investment for each energy type can be modified with a country and energy-type specific parameter ***eninvtm***, and a new value of TINEED is calculated as the sum of these new levels of desired investment. The amount of the available investment, inen, going to each energy type is then calculated as:

$$ineed_{r,e} = inen_r * \frac{ineed_{r,e} * \boldsymbol{eninvtm_{r,e}}}{TINEED_r}$$

i.e., all energy types receive the same proportional increase or decrease in investment.

Part of these investments offsets capital depreciation, while the remaining share (KEN_shr) increases the capital stock.

$$KEN\_Shr_{r,e} = ineed_{r,e} - \frac{ken_{r,e}}{\boldsymbol{lke}_e}$$

The new level of capital is determined as:

$$ken_{r,e,t+1} = \left(ken_{r,e,t} + KEN\_Shr_{r,e}\right) * (1 - CIVDM_r)$$

where

- *CIVDM* is an exogenous factor reflecting civilian damage from war

Note that there is no guarantee that KEN_Shr is positive, so it is theoretically possible for ken to fall below 0; IFs checks to make sure that this does not happen.

The final investment value for each energy type is saved in the variable ENINVTM after reconversion with the adjustment coefficient discussed earlier.

$$ENINVT_{r,e} = ineed_{r,e} * \; sidsf_r$$

3.7 Economic Linkages

The Economic Model and the two physical models have many variables in common. As in the Agricultural Model, IFs generally uses the values in the physical model to override those in the Economic Model. To do so, it computes coefficients in the first year that serve to adjust the physical values subsequently. The adjustment coefficients serve double duty - they translate from physical terms to constant monetary ones, and they adjust for discrepancies in initial empirical values between the two models.

Section 3.6 already described how desired investment, TINEED, is passed to the Economic Model using the adjustment coefficient sidsf. The adjustment coefficient, ZSR is used to convert production, ZS, in the energy sector (s=2):

$$ZS_{r,s=2} = ZSR_r * WEPBYear_{r,t=1} * \sum^{e} ENP_{r,e}$$

Where

$$ZSRI_r = \frac{ZS_{r,s=2,t=1}}{WEPBYear_{r,t=1} * \sum^{e} ENP_{r,e,t=1}}$$

ZSR is a convergence of ZSRI to a value of 1 in 30 years and WEPBYear converts the energy units, which are in BBOE to dollars.

The adjustment coefficient SCSF is used to convert consumption:

$$CS_{r,s=2} = SCSF_r * ENDEM_r * 0.6$$

Where

$$SCSF_r = \frac{CS_{r,s=2,t=1}}{ENDEM_{r,t=1} * 0.6}$$

Note that this assumes that 60 percent of total primary energy goes towards final consumption. SCSF remains constant over time.

For stocks, imports, and exports, global energy price, WEPBYear serves as the adjustment coefficient

$$ST_{r,s=2} = WEPBYear_{r,t=1} * ENST_r$$

$$XS_{r,s=2} = WEPBYear_{r,t=1} \quad * ENX_r$$

$$MS_{r,s=2} = WEPBYear_{r,t=1} * ENM_r$$

Finally, the indexed price (with a base of 1) in the energy sector of the economic submodel (PRI) is simply the ratio of current to initial regional energy price (ENPRI) time the value of PRI in the first year.

$$PRI_{r,s=2} = PRI_{r,s=2,t=1} * \frac{ENPRI_r}{ENPRI_{r,t=1}}$$

3.8 Resources and Reserves: Capital-to-Output Ratios and Discoveries

3.8.1 Capital-to-Output Ratios

Resource base is important in selected energy categories of IFs: conventional oil, natural gas, coal, hydroelectric power, and unconventional oil. Unconventional fossil fuels, extracted through non-traditional methods, are accounted for outside the standard energy categories in separate variables that adjust related resources and reserves. Resources are not important in the nuclear category, which represents an undefined mixture of burner, breeder and fusion power.

Resource costs, as represented by the capital required to exploit them, increase as resource availability in the resource-constrained categories decreases. The capital-to-output ratio captures the increased cost. Kalymon (1975) took a similar approach. More specifically, the capital-to-output ratio (QE) increases in inverse proportion to the remaining resource base (as the base is cut in half, costs double**;** as it is cut to one fourth, costs quadruple). The model multiplies the initial capital output ratio by the initial resource base (RESOR) times a multiplier (RESORM) by which a model user can exogenously increase or decrease model assumptions. It then divides that product by initial resources minus cumulative production to date (CUMPR).

Total available resources by energy type, ResorTot, are calculated as:

$$ResorTot_{r,e} = \boldsymbol{resorm}_{r,e} * \boldsymbol{resor}_{r,e} + \boldsymbol{resorunconm}_{r,e} * \boldsymbol{resorunconm}_{r,e}$$

where

- ***resor*** and ***resoruncon*** are exogenously assumed levels of the ultimate amount of conventional and unconventional forms of each energy type. There is no assumption about conventional resources for nuclear and *only oil and gas include unconventional resources*
- ***resorm*** and ***resorunconm*** are multipliers that can be used to change the amount of assumed ultimate resources by energy type

All energy types begin with basic capital-to-output ratios, BQE and BQEUC. These are initially set equal to the same values of QE and QEUNCON, which are derived in the pre-processor, and then evolved according to exogenous assumptions about technological advance for each energy type:

$$BQE_{r,e,t} = BQE_{r,e,t-1} * \left(1 - \boldsymbol{etechadv}_{e,t}\right)$$ [19]

$$BQEUNCON_{r,e,t} = BQEUNCON_{r,e,t-1} * \left(1 - \boldsymbol{etechadvuncon}_{e,t}\right)$$

Recall that technological improvements result in declining amounts of capital required for each unit of energy produced.

The initial translation of this basic capital-to-output ratio to the value actually used to determine energy production varies by energy type.

This is most straightforward for nuclear and unconventional energy, which do not take into account remaining resources:

$$QE_{r,e,t+1} = BQE_{r,e,t} * \boldsymbol{qem}_{r,e}$$

where

- *e* is nuclear
- ***qem*** is an exogenous multiplier

$$QEUC_{r,e,t+1} = BQEUC_{r,e,t} * \boldsymbol{qeunconm}_{r,e}$$

where

- *e* is oil or gas
- ***qeunconm*** is an exogenous multiplier

For hydro and other renewable categories, the model is based on production potential rather than depletable resource stock. QE depends upon the ratio of total potential capacity to the portion that remains untapped (resor_rem) and increases as production shifts from easily accessible resources to those that are progressively harder to develop. resor_rem is calculated as the gap between potential and current production, derived by subtracting the first-year production level from the current level, smoothed with a moving average. In other words, it is not cumulative production that is important, but rather the portion of resources used annually.

[19] There used to be an additional impact of ICT broadband that would further reduce the BQE for other renewables, but that is currently not active in the model.

$$QE_{r,e,t+1} = BQE_{r,e,t} * \frac{ResorTot_{r,e}}{resor\_rem_{r,e}} * \boldsymbol{qem_{r,e}}$$

where

$$resor\_rem_{r,e} = ResorTot_{r,e} - ENPGR_{r,e}$$

$$ENPGR_{r,e} = SmoothENP_{r,e} - ENP_{r,e,t=1}$$

$$SmoothENP_{r,e,t} = 0.8 * SmoothENP_{r,e,t-1} + 0.2 * ENP_{r,e}$$

- *e* = hydro, solar, wind, geothermal, or other renewables

As explained earlier in this document, QE for renewables represents the levelized cost of electricity generation (LCOE) using these technologies. In addition to the two primary drivers of LCOE—technological advancement and resource potential—IFs also models a system integration cost for variable renewable energy (VRE) sources, namely solar and wind. This is implemented through a multiplier, mulvre, which activates when the share of VRE in total energy use exceeds a specified threshold, ***qevrethr***. The threshold is a user-adjustable, country-specific parameter with a default value of 50 percent. Another country-specific user parameter, ***qevremul***, determines the magnitude of mulvre, once the threshold is crossed. The cost impact is capped at 50 percent.

$$QE_{r,e} = QE_{r,e} * mulvre_{r,e}$$

$$mulvre_{r,e} = MIN\left(1.5, 1 + Max(0, \left(vreshare - \boldsymbol{qevrethr_{r,e}}\right)) * \boldsymbol{qevremul_{r,e}}\right)$$

Where,

- *e* = solar and wind, and

$$vreshare = MAX(1, \frac{ENP_{r,e=solar} + ENP_{r,e=wind}}{ENDEM_r})$$

For oil, gas, and coal, the logic is similar, but the definition of remaining resources take into account cumulative production over time, which is subtracted from total available resources, making sure the remaining resources do not fall below 10% of the total resource base :

$$resor\_rem_{r,e} = MAX\left(ResorTot_{r,e} - CUMPR_{r,e}, MaxFac_{r,e}\right)$$

$$CUMPR_{r,e,t} = CUMPR_{r,e,t-1} + ENP_{r,e}$$

$$MaxFac_{r,e} = 0.1 * ResorTot_{r,e}$$

Furthermore, the capital-to-output ratio is calculated as a moving average

$$CompQE_{r,e} = BQE_{r,e} * \left(\frac{ResorTot_{r,e}}{resor\_rem_{r,e}}\right)^{0.4}$$

$$QE_{r,e,t+1} = \left(0.8 * QE_{r,e,t} + 0.2 * CompQE_{r,e}\right) * \boldsymbol{qem_{r,e}}$$

where

- *e* is oil, gas, or coal

3.8.2 Discoveries

Energy reserves decrease with production and increase with discoveries, the latter of which are limited by remaining resources and other factors. This only applies to oil, gas, and coal.

$$RESER_{r,e,t+1} = RESER_{r,e,t} + rd_{r,e,t} - ENP_{r,e,t}$$

The rate of discovery, rd, is initially computed as a function of a number of factors related to global energy prices, remaining resources, global and domestic production, and several exogenous assumptions

$$rd_{r,e} = rdi\_aug_e * wepterm * reterm_{r,e} * \boldsymbol{rdm_{r,e}}$$

where

- *e* = oil, gas, coal
- ***rdm*** is a country and energy-specific exogenous multiplier
- *rdi_aug* is an energy-specific factor driven entirely by exogenous assumptions about initial rates of discovery, ***rdi***, and annual increments, ***rdinr***:

$$rdi\_aug_e = \boldsymbol{rdi}_e + \boldsymbol{rdinr}_{r,e} * (t - firstyear)$$

- *wepterm* is a global factor driven by the growth in world energy prices from the first year and an exogenously defined elasticity, ***elasdi***

$$wepterm = 1 + \frac{WEP_t - WEP_{t=1}}{WEP_{t=1}} * \boldsymbol{elasdi}$$

- *reterm* is a country and energy-specific factor representing an average of a country's remaining resources as a share of original resources and its share of current global production

$$reterm_{r,e} = 0.5 * \left(\frac{ResorTot_{r,e} - CUMPR_{r,e} - RESER_{r,e}}{\sum_e\left(ResorTot_{r,e,t=1} - RESER_{r,e,t=1}\right)} + \frac{ENP_{r,e}}{WENP_e}\right)$$

A further assumption is that the rate of discovery cannot exceed 4 percent of the remaining resources in a country, where remaining resources are specified as:

$$resor\_rem_{r,e} = ResorTot_{r,e} - CUMPR_{r,e} - RESER_{r,e}$$

where

- e = oil, gas, coal
- For oil the amount of unconventional oil in ResorTot is also affected by the parameter ***enresunce***[20]

3.9 Energy Indicators

Among useful energy or energy-related indicators is the ratio (ENRGDP) of energy demand (ENDEM) to gross domestic product (GDP).

$$ENRGDP_r = \frac{ENDEM_r}{GDP_r}$$

Global energy production by energy type (WENP) is the sum of regional productions (ENP).

$$WENP_e = \sum^{R} ENP_{r,e}$$

Global energy production is the basis for examining the build-up of carbon dioxide and Climate Change, as described in the documentation of the Environmental model.

The ratio of oil and gas production globally to total energy production (OILGPR) helps trace the transition to other fuels.

$$OILGPR = \frac{WENP_{e=1} + WENP_{e=2}}{\sum^{E} WENP_e}$$

Global energy reserves (WRESER) and global resources (WRESOR) are sums by energy type across regions, the latter taking into account any resource multiplier (RESORM) that a user specifies to modify basic model resource estimates.

$$WRESER_e = \sum^{R} RESER_{r,e}$$

$$WRESOR_e = \sum^{R} (RESOR_{r,e} * RESORM_e)$$

[20] This only affects Canada, which has a value of ***enresunce*** = 0.3. Why this is not included in the QE calculations is unclear.

4. References

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Annex 1: Data Tables read in Pre-Processor

Series Name	Definition	Years	Source
SeriesEnConHydroBP	Hydro-electricity consumption	1965-2022	BP's Statistical Review of World Energy
SeriesEnConNucBP	Nuclear-electricity consumption	1965-2022	BP's Statistical Review of World Energy
SeriesEnConTotalWDI	Total Energy Consumption - WDI	1959-2017	WDI 2017 Pull
SeriesEnElecAccess%National	Access to electric energy National (% of population)	1990-2023	World Development Indicators (WDI), World Bank
SeriesEnElecAccess%Rural	Access to electricity in Rural areas (% of population)	1990-2023	World Development Indicators (WDI), World Bank
SeriesEnElecAccess%Urban	Access to electricity in Urban areas (% of population)	1990-2023	World Development Indicators (WDI), World Bank
SeriesEnElecConsPerCap	Electricity consumption per capita	1960-2023	World Development Indicators (WDI), World Bank
SeriesEnElecShrEnDem	Electricity consumption as a percentage of total energy consumption	1960-2014	WDI 2014 May BATCH PULL
SeriesEnElecTotalCapacityEIA	Total electricity installed capacity	1980-2023	US Energy Information Administration (EIA)
SeriesEnExportsCoalIEA	Energy Exports, Coal and coal products	1960-2023	IEA World Energy Balances
SeriesEnExportsNatGasIEA	Energy Exports, Natural Gas	1960-2023	IEA World Energy Balances
SeriesEnExportsOilIEA	Energy Exports, Crude, NGL and feedstocks	1960-2023	IEA World Energy Balances
SeriesEnExportsOilProductsIEA	Energy Exports, Oil products	1960-2023	IEA World Energy Balances
SeriesEnExportsPeatIEA	Energy Exports, Peat and peat products	1975-2023	IEA World Energy Balances
SeriesEnExportsTotalIEA	Energy Exports, Total	1960-2023	IEA World Energy Balances

SeriesEnImportsCoalIEA	Energy Imports, Coal and coal products	1960-2023	IEA World Energy Balances
SeriesEnImportsNatGasIEA	Energy Imports, Natural Gas	1960-2023	IEA World Energy Balances
SeriesEnImportsOilIEA	Energy Imports, Crude, NGL and feedstocks	1960-2023	IEA World Energy Balances
SeriesEnImportsOilProductsIEA	Energy Imports, Oil products	1960-2023	IEA World Energy Balances
SeriesEnImportsPeatIEA	Energy Imports, Peat and peat products	1972-2023	IEA World Energy Balances
SeriesEnImportsTotalIEA	Energy Imports, Total	1960-2023	IEA World Energy Balances
SeriesEnPotentialGeothermalSustainable	Available sustainable heat potential, excl. water stress and economic constraint	2015	From hot rock to useful energy: A global estimate of enhanced geothermal systems potential
SeriesEnPotentialSolarLandConstraints	Practical potential, long-term	2018	World Bank
SeriesEnPotentialWind	Wind energy potential (onshore + offshore)	2006	PNAS
SeriesEnProdBiodieselIEA	Production, Biodiesels	1990-2023	IEA World Energy Balances
SeriesEnProdBiogasIEA	Production, Biogases	1970-2023	IEA World Energy Balances
SeriesEnProdCoal	Coal production	1960-1995	WRI CD 98
SeriesEnProdCoalBP	Coal production	1981-2022	BP‘s Statistical Review of World Energy
SeriesEnProdCoalIEA	Production, Coal and coal products	1960-2023	IEA World Energy Balances
SeriesEnProdElec	Energy Produced in Electricity in KJ	1960-2015	WDI 2014 May BATCH PULL
SeriesEnProdGas	Natural gas production	1960-1997, 2000-2005	WRI CD 00-01
SeriesEnProdGasBP	Gas (natural) production	1970-2022	BP‘s Statistical Review of World Energy
SeriesEnProdGeothermIEA	Production, Geothermal	1960-2023	IEA World Energy Balances
SeriesEnProdOil	Oil production	1960-1995, 2000-2005	WRI CD 98
SeriesEnProdOilBP	Oil production	1965-2022	BP‘s Statistical Review of World Energy

SeriesEnProdOilIEA	Production, Crude, NGL and feedstocks	1960-2023	IEA World Energy Balances
SeriesEnReserCBMBGR	Coalbed methane reserves	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserCoalBP	Coal reserves	2007-2014	BP’s Statistical Review of World Energy 2013
SeriesEnReserGas	Energy reserves, gas	1960, 1967-2012	WEC; Oil and Gas Journal; 1960 estimated
SeriesEnReserGasBGR	Natural gas reserves	2009-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserGasBP	Gas (natural) reserves	1980-2020	BP‘s Statistical Review of World Energy
SeriesEnReserHeavyOilBGR	Heavy Oil Reserves	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserHyd	Energy reserves, hydro	1960, 1999	WRI Annual
SeriesEnReserOil	Energy reserve, oil, in billion barrels	1952-2012	WEC; Oil and Gas Journal; 1960 estimated

SeriesEnReserOilBGR	Crude oil reserves	2009-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserOilBP	Oil reserves	1980-2020	BP‘s Statistical Review of World Energy
SeriesEnReserOilSandsBGR	Oil Sands Reserves	2010-2018, 2020-2022	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserShaleGasBGR	Shale Gas Reserves	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnReserShaleOilBGR	Shale Oil Reserves	2011-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorCBMBGR	Coalbed methane Resources	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für

			Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorCoalBGRBBOE	Coal resources	2010-2015	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorGasBGR	Natural gas resources	2009-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorHeavyOilBGR	Heavy Oil Resources	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorOilBGR	Crude oil resources	2009-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"

SeriesEnResorOilSandsBGR	Oil sands resources	2010-2018, 2020-2022	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorShaleGasBGR	Shale Gas Resources	2010-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorShaleOilBGR	Shale Oil resources	2011-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"
SeriesEnResorTightGasBGR	Tight Gas Resources	2011-2018, 2020-2023	BGR; "Reserves, Resources and Availability of Energy Resources"Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover; Annual Report. Reserves, Resources and Availability of Energy Resources"

Annex 2: Key Variables in Energy Model

Name	Unit	Dimensionality	Description	Where Initialized[1]
ENX	bboe[2]	1	Energy exports	PP, then reset FY
ENM	bboe	1	Energy imports	PP, then reset FY
ENPOILMAX	bboe	1	Maximum oil production	PP, read from table CountryParameters in file IFs.mdb.
ENPGASMAX	bboe	1	Maximum natural gas production	PP, read from table CountryParameters in file IFs.mdb.
ENPCOALMAX	bboe	1	Maximum coal production	PP, read from table CountryParameters in file IFs.mdb.
ENP	bboe	9	Energy production by type (Oil, Gas, Coal, Hydro, Nuclear, Solar, Wind, Geothermal and Other Renewables)	PP
ENPRR	ratio	9	Energy production growth rate by type	PP
RESER	bboe	4[3]	Known and exploitable energy resources by energy type	PP
resor	bboe	9	Total available resources/potential by energy type	PP
ENST	bboe	1	Total available energy stock	FY
ENSHO	bboe	1	Energy shortage	FY
ENDEM	bboe	1	Energy demand or total energy required across various sectors, representing overall consumption needs accounting for trade	FY
QE	$/barrel	9	Amount of capital required per unit of energy production by type	PP
QEUNCON	$/barrel	3	Capital required per unit of energy production for unconventional energy sources	
[1] *PP indicates pre-processor; FY indicates first year of model.*				
[2] *Billion barrels of oil equivalent*				
[3] *Includes oil, gas, coal and hydro. Remaining renewables' show no value as we consider the theoretical potential in the variable resor.*				

Annex 3: Key User-controllable Parameters in Energy Model

Name	Unit	Dimensionality	Description	Default Value
carbtax	$/ton	country, year	Carbon tax	0
carfuel1	Tons/BOE	year	Carbon content of oil	0.117
carfuel2	Tons/BOE	year	Carbon content of gas	0.086
carfuel3	Tons/BOE	year	Carbon content of coal	0.115
dstlen	Ratio	year	Desired energy stock level as portion of stock base	0.1
ehw	Ratio	year	Energy historical weight factor for impact of price on demand	0.95
elasde	None	year, country	Elasticity of energy demand to price changes	-0.35
elasdi	None	year	Elasticity of energy discoveries to price	0.2
elass	None	year, country, energy type	Elasticity of energy supply to profit, actually elasticity of investment by energy type to profit	0.2
elendemict	None	year	Elasticity of energy demand to ICT index	-0.001
eleniprof	None	year	Elasticity of energy investment to profit level	0.05
eleniprof2	None	year	Elasticity of energy investment to change in profit level	0.1
elenpr	None	year	Elasticity of energy investment to inventory level	-0.4
elenpr2	None	year	Elasticity of energy investment to change in inventory level	-0.8
elenpst	None	year	Elasticity of energy production to world inventory level	-0.4
elenpst2	None	year	Elasticity of energy production to change in world inventories	-0.8
encartpp	$/bbl	year	Energy cartel price premium	0
enconv	Years	year	Energy demand convergence time to predicted values	90
endemm	Multiplier Base 1	year, country	Energy demand multiplier	1
eninvm	Multiplier Base 1	year, country	Total energy investment multiplier	1
eninvtm	Multiplier Base 1	year, country, energy	Energy investment by energy type multiplier (shifts	1

		type	within total)	
enml	BBOE	year, country	Energy imports limit	0
enon	<= 0.5 on, > 0.5 off	year	Energy-economy link	1
enpm	Multiplier Base 1	year, country, energy type	Energy production multiplier	1
enprix	Index base 100	year, country	Energy price override	100 for 2022; 110 for 2023
enresunce	Fraction	year, country	Energy resources unconventional, portion economic to produce	0 (0.3 for Canada)
enrgdpgr	Percent	year	Energy demand to GDP ratio, annual technology-based change	-1.34 for 2022
enxl	BBOE	year, country	Energy exports limit	0
epra	None	year	Energy price responsiveness to stock/inventory levels vs. desired level	-0.3
eprafs	None	year	Energy price responsiveness to changes in stock/inventory levels	-0.6
eprodr	Rate	year, country, energy type	Energy production growth rate (exogenous); actually desired capital growth rate by energy type	0 (for each energy type)
eprohw	None	year	Energy, historical weight for profits in investment	0.3
etechadv	Rate	year, energy type	Energy production technology, annual decrease in cost	0.005, 0.008, 0.004, 0.001, 0.004, 0.011, 0.009, 0.004, 0.004
etechadvuncon	Rate	year, energy type	Unconventional energy production technology, annual decrease in cost	0.005 (for each energy type)
hwf	Fraction	year	Historical weight factor for expected economic growth	0.8
lke	Years	year, energy type	Lifetime of energy capital	10, 10, 15, 40, 20, 20, 20, 20, 20

prodtf	Ratio	year, country, energy type	Minimum reserve ratio	14.1, 16.7, 21.3, 2, 0, 0, 0, 0, 0 (varies by country)
qem	Multiplier Base 1	year, country, energy type	Capital costs-to-output ratio multiplier	1
qeunconm	Multiplier Base 1	year, country, energy type	Capital costs-to-output ratio for unconventional sources multiplier	1
qevrethr	Ratio	year, country	Variable renewable share at which system integration impacts solar and wind costs	0.5
qevremul	Multiplier Base 1	year, country	Variable renewable energy cost multiplier	1
rdi	BBOE	year, energy type	Rate of discovery for fossil fuels and hydro, initial	40, 40, 20, 10, 0, 0, 0, 0, 0
rdinr	BBOE	year, energy type	Rate of discovery of fossil fuels and hydro, basic annual increment	0.5, 1, 1, 2, 0, 0, 0, 0, 0
rdm	Multiplier Base 1	year, country, energy type	Rate of discovery of energy, multiplier	1
resorm	Multiplier Base 1	year, country, energy type	Resources of energy, multiplier	1
resorunconm	Multiplier Base 1	year, country, energy type	Resources of unconventional energy, multiplier	1
squeez	Switch	year	Switch that squeezes economic production when there are energy shortages	0
trademax	Ratio	year	Trade, maximum as portion of tradable production base	1.3