

**E<sup>3</sup>M Lab, Institute of Communication and  
Computer Systems**

# **The MENA-EDS Model**

**Middle East and North Africa  
Energy Demand and Supply Model**

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## 1. Introduction

MENA-EDS is a large-scale energy demand and supply model that simulates the formation of prices in energy markets, estimates the quantities demanded and supplied by the main energy system actors in an exhaustive manner, and incorporates energy related CO<sub>2</sub> emissions, environmentally oriented policy instruments and emission abatement technologies. The model is designed for medium-term and long-term projections and produces analytical quantitative results in the form of detailed energy balances for each country.

The model can be used to forecast energy trends and analyze the implications of different policy assumptions, covering the time horizon up to 2030 (the time horizon of the model can be extended to 2050). It is capable of supporting policy analysis in the following fields:

- Climate policy (CO<sub>2</sub> emissions reduction)
- Pricing policy (fuel taxation and/or subsidization)
- Promotion of new power generation technologies and renewable energy sources
- Energy efficiency on the demand side
- Promotion of alternative fuels

The model is written in the GAMS algebraic specification language, with Excel-based input and output interfaces. It is currently calibrated for the year 2010 and is capable of running for each consecutive year up to 2030. The model is currently being applied to the Southern Mediterranean countries and more specifically to the MED-10 region, that contains Turkey, North Africa (Algeria, Libya, Egypt, Morocco and Tunisia) and Middle East countries (Syria, Lebanon, Israel and Jordan).

## 2. Sectoral and technological coverage of the model

Final energy demand in the MENA-EDS model is simulated for three main sectors:

- The industrial sector (where 10 subsectors are included in the analysis depending on data availability). Data sets from international sources (e.g. Enerdata, IEA) and national statistical services are used and complemented with other general or sectoral information that can be obtained from other sources. Industrial production indices or value added data are used as main economic drivers. Projections of industrial value added (and of overall economic activity) are exogenous to the model and can be obtained from economic models to be run in parallel.
- The domestic/tertiary sector (where three main subsectors are included: households, services and agriculture). The model uses data such as agricultural production volume indices, total value added of services (usually taken from GEM-E3 projections),

average household income etc., depending on their availability. Combining such information with demographic and social forecasts from the United Nations<sup>1</sup> (including data such as population forecasts by age group, urbanisation rates), the final energy demand per sector can be projected.

- The transportation sector (that includes private passenger cars, road freight transport, passenger aviation and passenger and freight rail transport). Data on transport activity (usually measured in tn-km per year for freight transport or passenger-km for passenger transport) are derived from the IRF "World Road Statistics 2011"<sup>2</sup> and from the World Bank statistics.

The main sectors (and subsectors) for which final energy demand is projected together with the fuels used in each sector are presented in the following table:

<b>Sector</b>	<b>Subsector</b>	<b>Fuels</b>
<b>Industry</b>	Iron and Steel	Hard coal
	Non-Ferrous Metals	Lignite
	Chemicals	Diesel
	Building Materials	Fuel oil
	Paper and Pulp	Other liquids
	Food, Drink and Tobacco	Natural gas
	Textiles and Leather	Derived gases
	Construction	Steam
	Ore Extraction	Electricity
	Other industries	Biomass & Waste
<b>Tertiary-Domestic</b>	Services	Hard coal
	Residential	Lignite
	Agriculture	Diesel
		LPG
		Kerosene
		Other liquids
		Natural gas
		Derived gases
		Steam
		Electricity
<b>Passenger Transport</b>	Passenger Cars	Gasoline
		Diesel
		Bio-diesel
		Natural gas
		Electricity
		Hydrogen

<sup>1</sup> "World population prospects: the 2010 revision", United Nations, 2010

<sup>2</sup> "IRF-World Road Statistics 2011", International Road Federation, 2011

	Rail	Diesel
		Electricity
	Air	Kerosene
<b>Freight Transport</b>	Road Freight transport	Diesel
		Gasoline
		Bio-diesel
		Electricity
		Natural gas
		Hydrogen
	Rail	Diesel
		Electricity

*Table 1: Demand subsectors and fuels used in the MENA-EDS model.*

A very detailed representation of the power supply sector has been implemented in MENA-EDS model. The power generation technological options used in the model presented in Table 2: Power generation technologies used in the MENA-EDS model.

<b>Plants</b>	<b>Technical – Economic Characteristics</b>	<b>Fuels</b>
Thermal Lignite	Capital Cost	Hard Coal
Thermal Hard Coal	Fixed O&M Cost	Lignite
Thermal Fuel Oil	Variable Cost	Fuel Oil
Thermal Natural Gas	Fuel cost	Diesel Oil
Thermal Biomass	Lifetime	Natural Gas
Gas Turbine Combine Cycle	Availability rate	Nuclear
Peak devices fuelled by diesel	Efficiency	Biomass & Waste
Peak devices fuelled by natural gas		Hydro
Supercritical Coal		Solar
Fluidised bed hard coal		Wind
Supercritical lignite		Geothermal
Fluidised bed lignite		
Integrated gasification lignite		
Integrated gasification hard coal		
Integrated gasification biomass		
Conventional Nuclear		
Nuclear-4th generation		
Large Hydro		
Small Hydro		
Wind on-shore		
Wind off-shore		
Solar Photovoltaic		
Concentrating Solar Power (CSP)		
Geothermal		

*Table 2: Power generation technologies used in the MENA-EDS model.*

### 3. Formation of fossil fuel prices for end users

Fuel prices per sector are determined on the basis of exogenous primary fuel prices (usually taken from the PROMETHEUS<sup>3</sup> world energy system model), taking also into account particular aspects of each country's national market, such as removal of subsidies, distribution costs, fuel taxation and gradual price reform. Fuel price data come mainly from Enerdata and the International Energy Agency.

Fuel prices for each of the model sectors/subsectors ( $p_{j,t}$ ) are forecast with the following equation:

$$p_{j,t} = rp_{j,t} + ap_j(pint_{l,t} - pint_{l,t-1}) + p_{j,t-1}$$

where

$j$  represents the specific fuel and  $t$  the time index

$rp_{j,t}$	is an exogenous residual adjustment
$pint_{l,t}$	is the international price of primary fuel $l$ that affects the price of the particular fuel (e.g. crude oil price if $j$ is a petroleum product such as gasoline, diesel, heavy fuel oil, LPG, kerosene etc., international gas price if $j$ is natural gas, international coal price if $j$ is imported hard coal or coke)
$ap_j$	is a parameter that links international fuel price with the price of a specific fuel in a specific sector and can be used to in order to represent price reform or other price policies

Average energy prices per sector ( $i$ ) are then determined as follows:

$$AP_{i,t} = \sum_j wap_{i,j,t} * p_{j,t}$$

where:

$wap_{i,j,t}$  are the weights of each fuel  $j$  in the total sectoral energy demand

These average prices affect the final energy demand of each sector through the price elasticities of demand equations (section 4).

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<sup>3</sup> PROMETHEUS is a stochastic world energy demand and supply model used by E3MLab-NTUA to regarding the evolution of the energy system and especially world price trajectories.

## 4. Demand side

MENA-EDS is a recursive dynamic model with annual resolution and has a predominantly triangular structure in order to limit contemporaneous simultaneity (simultaneity is modeled through lagged instances of endogenous variables). The MENA-EDS model takes as an exogenous input demographic, macroeconomic and sectoral activity projections, covering the major energy consuming sectors in industry, households, agriculture, the tertiary sector and transportation until 2030. These activity forecasts, together with consumer prices for fossil fuels are used to determine sectoral energy consumption. Long-term and short-term price effects are accounted for separately by using different elasticities, which (as well as activity elasticities) may change over time to account for real-world trends (e.g. restructuring) in each sector. The general equation below describes the main mechanism for determining the final energy demand in each sector  $C_{i,t}$ .

$$C_{i,t} = C_{i,t-1} * (1 + r_{C_{i,t}}) * \left( \frac{ACTV_{i,t}}{ACTV_{i,T-1}} \right)^\alpha * \left( \frac{AP_{i,t}}{AP_{i,t-1}} \right)^{\beta_1} * \left( \frac{AP_{i,t-1}}{AP_{i,t-2}} \right)^{\beta_2} * \prod_{k=1}^n \left( \frac{AP_{i,t-k}}{AP_{i,t-k-1}} \right)^{\varphi(k \setminus n) * \gamma}$$

where  $\varphi(k \setminus n)$  are the weights of the polynomial distributed lag used to estimate the long term price elasticity in each subsector,  $ACTV_{i,t}$  is the activity indicator for each sector (either GDP, sectoral value added, disposable income, tn-km or passenger-km),  $AP_{i,t}$  is the average energy price per subsector,  $\alpha$  represents the activity elasticity and  $\beta_1$ ,  $\beta_2$  and  $\gamma$  represent the price elasticities (short and long term).

Energy demand arises both from net increases in consumers' energy needs, the replacement of scrapped capacity and the existing surviving equipment. Regarding new energy demand, a compact but at the same time analytically rich specification encapsulates the dynamic process of technological substitution in all sectors taking into account the technical and economic characteristics (energy efficiency, availability, capital, fixed, variable and fuel costs) of the available technologies together with existing and potential policy instruments, such as taxes or subsidies, environmental legislation and any other national or international regulations.

The 'gap' between total final demand of each year and the demand arising from existing equipment is defined as:

$$GAP_t = C_{i,t} - \sum_j CREM_{i,jt}$$

and must be non-negative. The model takes into account lifetime of technologies in the different sectors in order to determine the demand arising from existing equipment  $CREM_{i,jt}$ . The 'gap' has to be filled by new equipment and several technologies (fuels) compete for this purpose.

An innovative aspect considered in the MENA-EDS model in order to determine the shares of different fuels/technologies in each sector is the size of each consumer (expressed e.g. as annual energy consumption of a type of consumer in industry, as annual utilisation rates of space or water heating boilers in households or as vehicle kilometres in road transport). Consumer size is important in the substitution process, as it provides the possibility for a more accurate coverage of technologies with different technical and economic data, and also allows considering potential economies of scale that can be achieved by different technologies. Thereby it can lead to a more appropriate economic representation of consumer choices in particular the relative importance of capital and fuel costs. To this aim, the size of different consumers is taken into account in the following way: Let  $x_0$  be the smallest consumer considered,  $x_n$  the largest consumer considered and  $x_m$  the median consumer. Let also:

$$V_r = \frac{n!}{(n-r)!r!} * \frac{\ln \left(\frac{x_m}{x_0}\right)^r}{\ln \left(\frac{x_n}{x_0}\right)^n} \ln \left(\frac{x_n}{x_m}\right)^{n-r} * x_0 * \left(\frac{x_n}{x_0}\right)^{\frac{r}{n}}, \text{ with } r = 0, \dots, n$$

It has to be noted that  $x_0$ ,  $x_n$  and  $x_m$  may be expressed in toe per year or in any other unit, depending on the most appropriate way to account for consumer size in each sector.

Let also:

$$SU_{i,r,t} = \sum_j w_{i,j,t} * [COST_{i,j,t} * x_0 * \left(\frac{x_n}{x_0}\right)^{\frac{r}{n}}]^{-\nu_i}$$

and

$$STT_i = \sum_{r=0}^n V_r$$

Then the technology shares in new equipment are calculated as follows:

$$SH_{i,j,t} = w_{i,j,t} * \frac{\sum_{r=0}^n [COST_{i,j,t} * x_0 * \left(\frac{x_n}{x_0}\right)^{\frac{r}{n}}]^{-\nu_i}}{STT_i} * \frac{V_r}{SU_{i,r,t}}$$

Regarding transportation, the share of which in total final energy demand is expected to rise considerably in the future, a more detailed approach is followed. The dynamics of the motor vehicle stock are simulated by considering the effect of economic developments on both the car ownership rates and the use of vehicles, without ignoring the impact of non-economic factors on the evolution of the vehicle stock, also allowing for potential saturation effects to appear in the market. Economic development (represented by an increase in GDP per capita) results in a growth in car ownership rates following S-shaped penetration curves simulating

take-off and saturation effects. The growth in incomes also results in a decline in the average lifetime of vehicles. Average consumption per vehicle is influenced by a variety of factors simulated in the model like vehicle utilization rates (km/year), driving conditions (urban versus country driving), the average size of vehicles and technological improvements leading to higher fuel efficiency.

In the MENA-EDS model, the competition between different car technologies is based on their cost per km, that includes annualized and discounted acquisition costs, fixed operating and maintenance costs and fuel cost (including taxes) and is modeled using the substitution mechanism described above. The passenger car technologies identified in the model include conventional ICE vehicles (using diesel, gasoline, natural gas or biodiesel as a fuel), conventional hybrid vehicles (using gasoline or diesel), plug-in hybrids (using gasoline or diesel), pure electric vehicles and fuel cell vehicles (using hydrogen).

Activity in the other transport modes (measured in tn-km or passenger-km per annum) is calculated in the model taking into account GDP effects, utilization rates and the evolution of fuel prices. Forecasts of the evolution of these utilization rates are derived from analyses of past trends and independent exogenous forecasts. Technology substitution in the "gap" takes place leading to the gradual adoption of more cost-effective vehicle technologies and the higher penetration of environmentally friendly options in the case of climate change mitigation scenario.

## 5. Electricity generation

Recognising the key role of the power generation sector in energy and climate policy, a very detailed representation of this sector has been implemented in the MENA-EDS model.

Generation requirements in each country are determined by the electricity demand in the different sectors (industrial sectors, households, services, agriculture, transport), which is calculated in the energy demand module, own-consumption of power plants, electricity trade between countries and transmission and distribution losses (see the equation below).

$$PROD_t = \sum_i C_{elc,i,t} + CEN_t + LOS_t - NIMP_{elc,t}$$

where  $C_{elc,i,t}$  is the electricity demand arising from the different sectors  $i$ ,  $CEN_t$  is the electricity consumption of the energy branch,  $LOS_t$  represents the losses during the transmission and distribution of electricity and  $NIMP_{elc,t}$  are the net imports of electricity.

The sectoral origin of the electricity demand is used to construct the annual load duration curve, by taking into account that energy intensive sectors demand is mainly base load, while

pronounced peaks characterize demand in services and households. After calculating base and peak load ( $B_t$  and  $M_t$  respectively), the annual load duration curve can be constructed by estimating the parameter  $\lambda_t$  implicitly from the following equation:

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

The electricity required to satisfy generation needs is produced from a wide variety of generation technologies (for a detailed specification of the technologies see Table 2: Power generation technologies used in the MENA-EDS model.

). The power plants are characterized by the type of fuel they use (if any), their efficiency in generating electricity, their availability rates (capacity factors), their investment costs and their fixed and variable operating and maintenance costs. The MENA-EDS model uses the technical and economic data for power generation technologies from the PRIMES model taking into account regional specificities, such as the higher capacity factors for Concentrated Solar Power (CSP) and photovoltaics.

The main categories of power generation options are:

- Gas-fired technologies, using steam turbine, gas turbine or combined cycle
- Coal-fired technologies, which include thermal, fluidized bed, supercritical and integrated gasification technologies using hard coal or lignite as a fuel
- Oil-fired technologies, including thermal fuel oil and peak devices fuelled by diesel
- Nuclear technologies, conventional and fourth generation
- Biomass-fired technologies, including thermal and integrated gasification
- A wide variety of renewable technologies, including hydroelectricity (large or small scale), wind (onshore and offshore), solar (CSP, photovoltaic) and geothermal.

The expansion of total power capacity depends on the evolution of electricity requirements:

$$TOTCAP_t = (1 + r_t) * TOTCAP_{t-1} * \frac{PROD_t}{PROD_{t-1}}$$

with  $r_t$  an exogenous residual adjustment that adjusts the above relationship to a country's particularities.

The 'gap' ( $GAP_t$ ) that has to be filled by new capacity depends on the required total capacity (as calculated above) and the retirement of plants that reach the end of their lifetime. The model also takes into account already decided investments in specific power plants which are known today ( $DINV_{j,t}$ ) and the already decided plans for decommissioning of old and inefficient power plants ( $DECOMP_{j,t}$ ):

$$GAP_t = TOTCAP_t - TOTCAP_{t-1} + \sum_j (DECOMP_{j,t} - DINV_{j,t}) + \sum_j (CAP_{j,t-1} * SCR_{j,t})$$

where  $CAP_{j,t}$  is the capacity and  $SCR_{j,t}$  is the scrapping rate of technology  $j$ .  $SCR_{j,t}$  includes normal scrapping, due to plants reaching the end of their lifetimes, and premature scrapping, due to changes in variable and fuel costs which render the continuation of plant's operation economically unsustainable. The inclusion of the latter form of scrapping is important in order to enable the modelling of rapid technical transformation, as the renewal of equipment stock accelerates. The general algebraic formulation for the premature scrapping rate is:

$$PRESOCR_{j,t} = 1 - \frac{VC_{j,t}^{-\gamma}}{h_{j,t} * \sum_{i \neq j} (C_{i,t}^{-\gamma}) + VC_{j,t}^{-\gamma}}$$

where  $PRESOCR_{j,t}$  is the pre-mature replacement rate of technology  $j$ ,  $VC_{j,t}$  represents the variable (including fuel) cost of technology  $j$  and  $C_{i,t}$  is the total production cost of technology  $i$  (index  $i$  represents all competing technologies in a sector including technology  $j$ ). Factor  $h_{j,t}$  is used for scaling purposes and  $\gamma$  is a factor that represents conditions which influence investment decisions, for example acceptability of new technologies in the sector.

Competition between technologies occurs in terms of market shares within the gap. The allocation of new investments is modeled as a quasi cost-minimizing function and is determined by the long term marginal costs (that include the annualized capital costs, the fixed and variable operation and maintenance costs and fuel costs) of the competing options. The shares in the gap for the year  $t$  are calculated as follows:

$$share_{j,t} = \frac{w_{j,t} * C_{j,t}^{-\gamma}}{\sum_j w_{j,t} * C_{j,t}^{-\gamma}}$$

The above equation determines the market share in gap of technology  $j$  ( $share_{j,t}$ ) based on its long term marginal cost  $C_{j,t}$ . In this specification, the weights  $w_{j,t}$  can be interpreted as reflecting the relative economic and technical “maturity” of each technology while the parameters  $\gamma$  represent the sensitivity of the share in gap with respect to the total cost of each technology.

In the MENA-EDS model, the annual load duration curve, together with operating costs and the installed capacities of the different technologies, are used in determining capacity utilization for each time segment and hence fuel inputs in the power generating sector. Firstly, the year is divided into nine hour segments, which are symbolized by the index  $u$ ,  $u = 0-8$ . The total required electricity production is then approximated by the following formula:

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

The following intermediate variable is used in order to rank the various competing technologies according to their variable (including fuel) cost in each time segment:

$$sh_{j,t} = \frac{k_{j,t} * VC_{j,t}^{-\gamma}}{\sum_j k_{j,t} * VC_{j,t}^{-\gamma}}$$

where  $VC_{j,t}$  represents the variable operating and maintenance costs and the fuel costs, i.e. the short term marginal cost of each power generation technology, which is the main determinant for plant dispatching in each hour segment.

The extent to which the various power plant types will be used in each hour segment  $u$  ( $u = 0-8$ ) is determined from the following relationship:

$$\sum_j CAP_{j,t} * e^{-\frac{\alpha_{u,t}}{sh_{j,t}}} = (M_t - B_t)e^{-\lambda_t*(0.25+u)} + B_t$$

which, for each time segment  $u$ , is solved implicitly for  $\alpha_{u,t}$ . The latter must not be negative, since this would mean that there is not sufficient capacity to cover the demand in that hour segment.

Thus the amount of electricity produced using technology  $j$  is:

$$x_{j,t} = \frac{PROD_t * CAP_{j,t}}{TOTPROD_t} * \sum_{u=0}^8 e^{-\frac{\alpha_{u,t}}{sh_{j,t}}}$$

The price of electricity is determined as a function of long term and short term average marginal cost and is differentiated between different types of consumers (industrial sectors, services and households), reflecting the differential costs of supplying the different sectors. These differences mostly arise from the fact that different technologies supply different segments of the load duration curve but also from economies of scale in distribution to the different types of consumer.

The power generation sector as modeled in the MENA-EDS model is designed to simulate a reaction to a carbon tax, which typically generates a shadow cost. In consequence the investment choices for new power plants are strongly affected, favoring carbon-free (RES and nuclear) and CCS technologies. Through the price formation mechanism outlined above, CO<sub>2</sub> abatement costs are passed on to the consuming sectors to the extent that supplying them is associated with increased generation costs. As a result of the increase in electricity prices, electricity demand (and production) from the different model sectors will decline.

Hence, there is a reduction in CO<sub>2</sub> emissions due to a price driven decline in power generation.

## **6. Primary Fuel Production**

In order to determine hydrocarbon production, the model considers the resource base (reserves and undiscovered resources) in the different countries. Undiscovered resources are derived from geological studies (USGS<sup>4</sup>, BGR<sup>5</sup>) that take into account promising areas and the extent to which they have already been explored. Undiscovered resources become reserves through an equation linking gross additions to reserves to the size of undiscovered resources and a long term price effect (the prices used are those pertaining in international trade). Net additions to reserves are calculated through a motion equation by subtracting production in any given year. Production of oil is determined by reserves and a long term price effect. For natural gas both local and export demand are also considered (especially in view of pipeline exports). Demand also plays a role in the determination of solid fuel production.

The extent to which demand or even other factors (reserves, prices) influence production is subject to additional exogenous assumptions that reflect sector and country particularities. These include existing plans and prospects for export infrastructure.

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<sup>4</sup> "World petroleum assessment 2000", USGS, 2000

<sup>5</sup> "Reserves, Resources and availability of energy resources", annual report BGR, 2010

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"IRF-World Road Statistics 2011", International Road Federation, 2011

**Additional sources and websites:**

German Aerospace Center (DLR) DESERTEC Project:

(<http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10200/>)

Enerdata energy reports and database: (<http://www.enerdata.net/>)

IEA database: <http://www.iea.org/>

Paving the Way for the Mediterranean Solar Plan project :(<http://www.pavingtheway-msp.eu/>)

