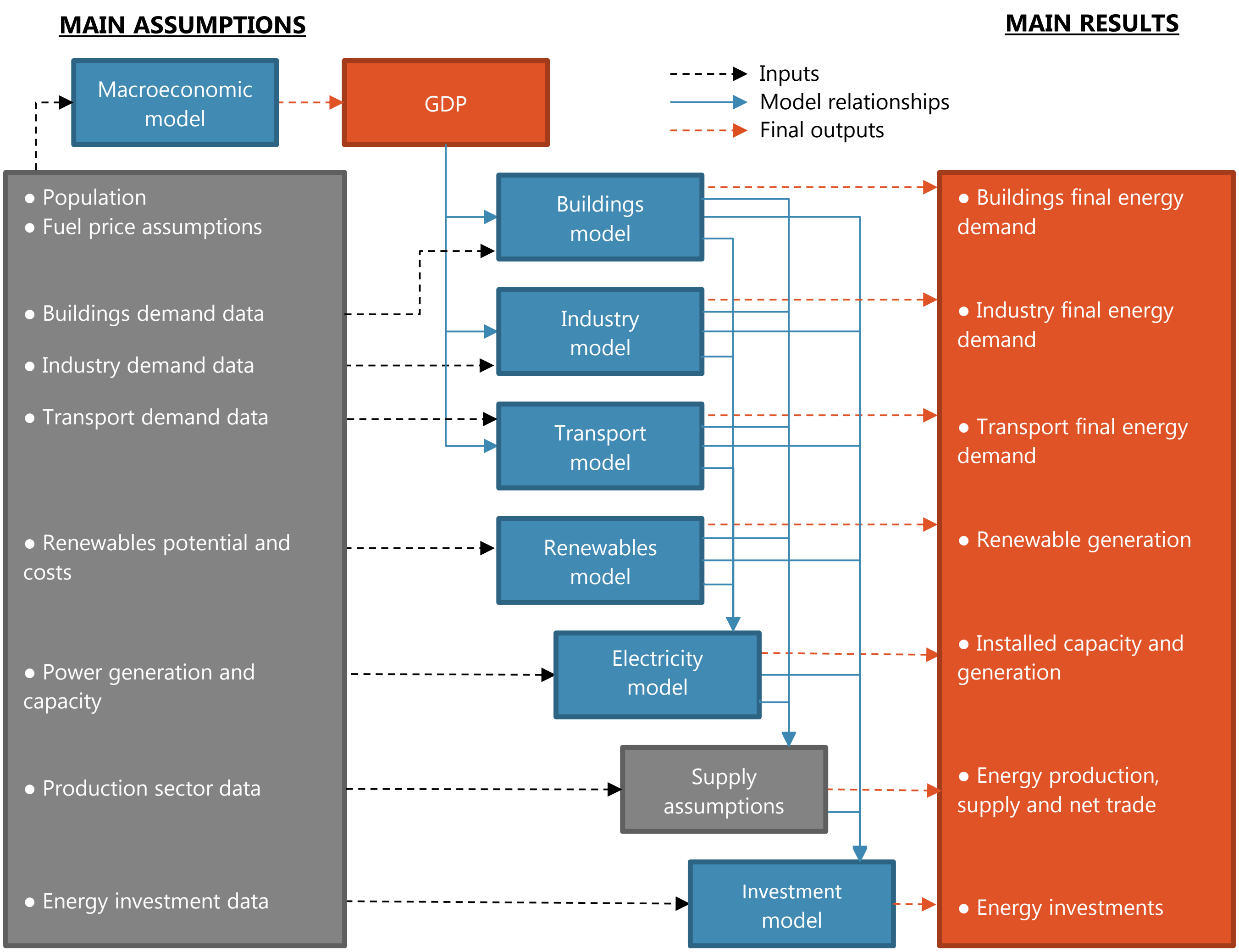
ANNEX I: MODELLING ASSUMPTIONS & METHODOLOGIES

1. INTRODUCTION

This report's projections stem from a series of models, which are applied to all 21 APEC economies. Regional and APEC-wide results are obtained by summing the results for relevant economies. There are seven sub-models in total: macroeconomic, industry, transport, buildings (including residential, commercial and agriculture), renewables, electricity, and investment (Figure 1). The projection period for all models (excluding the investment model) is 2013-2040 and 2015-2040 for the investment model.

Figure 1 • Relationships between APERC's sub-models



The macroeconomic model's key assumptions for each economy includes data on:

- Historical and projected population;
- Historical and forecasted fuel prices (coal, oil, gas, gasoline, diesel and kerosene);
- Historical and projected domestic fossil fuel production (for coal, oil and gas);
- Historical and projected average energy sector own-use rates (for coal, oil and gas);
- Historical and projected percentage content of biofuel in road gasoline, road diesel, and rail diesel,
- Historical and projected fuel shares and efficiency rates for heat production (coal, oil ,as, new renewable energy, and nuclear);
- Historical vehicle stock and saturation level of vehicles;
- Economic potential and levelised cost of electricity (LCOE) for each renewable energy; and
- Historical and projected CO_2 factors for coal, oil and gas.

The final energy demand results come from the:

1. **Macroeconomic model:** projects the GDP for each economy expressed in 2012 USD PPP and provides macroeconomic data for other demand models;
2. **Transport model:** projects energy demand for domestic and international transport, by fuel type;
3. **Industry model:** projects demand in the industrial sector, for both energy and non-energy sectors, with breakdowns for each fuel type; non-energy refers to the fossil fuel used as a feedstock in the production of petrochemicals and other non-fuel products; and
4. **Building model:** projects demand in the buildings and agriculture sectors, including residential, commercial and agriculture, by fuel type.

The energy supply results come from the:

1. **Electricity model:** uses electricity demand in the transport, industry and buildings models to simulate electricity production from primary input fuels and optimises the capacity expansion for electricity generating capacity for fossil fuels;
2. **Renewable model:** simulates renewable generation (hydro, wind, solar, biomass, geothermal and others) and biofuel production (bioethanol and biodiesel) by modelling renewable energy potential, policies and targets to provide capacity, generation, and biofuels production potential; and
3. **Supply assumptions:** forecasts fossil fuel production.

The **investment model** calculates the investment necessary to realise the energy infrastructure required for each economy from 2015 to 2040. This model estimates investments in the upstream, downstream, electricity and energy transport sectors.

The data used in this outlook comes from a variety of sources:

1. **International organisations** such as the International Energy Agency (IEA), the United Nations Department of Economics and Social Affairs (UNDESA), the International Renewable Energy Agency (IRENA) and the Centre d'Études Prospectives et d'Informations Internationales (CEPII);
2. **Official government data**; and
3. **Associations and companies** such as the World Wind Energy Association and BP.

Some data is estimated due to unavailability, for example several inputs for Papua New Guinea.

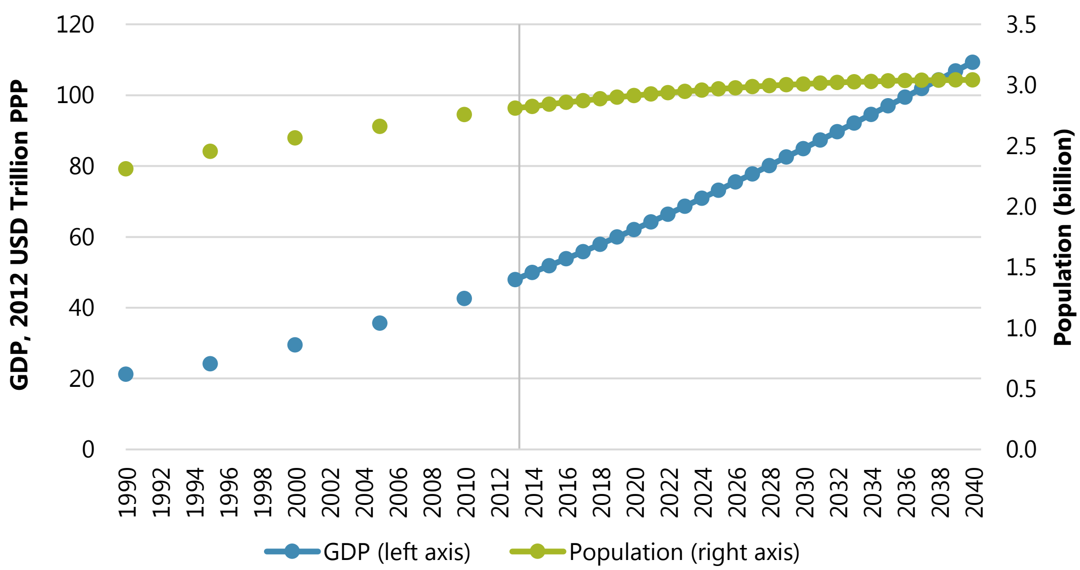
KEY MACROECONOMIC ASSUMPTIONS

The key macroeconomic assumptions include GDP, population and energy prices. These assumptions are widely used in energy supply and demand models. The population projections are from UNDESA, CEPII and individual economies' projections. The GDP projections are from APERC analysis based on the Cobb-Douglass function. The energy price projections are from the Institute of Energy Economics, Japan (IEEJ).

GDP AND POPULATION

GDP and population data shape the kind of energy services consumers are able to afford. Owing to fast-growing developing economies and relatively stable-growing developed economies. APEC-wide real GDP in 2040 will be above USD 109 trillion, about 2.3 times real GDP in 2013, with an average annual growth rate of 3.1%. APEC's population is forecast to increase by 8% (0.3% AAGR) from 2013 to 2040, exceeding 3 billion in 2040.

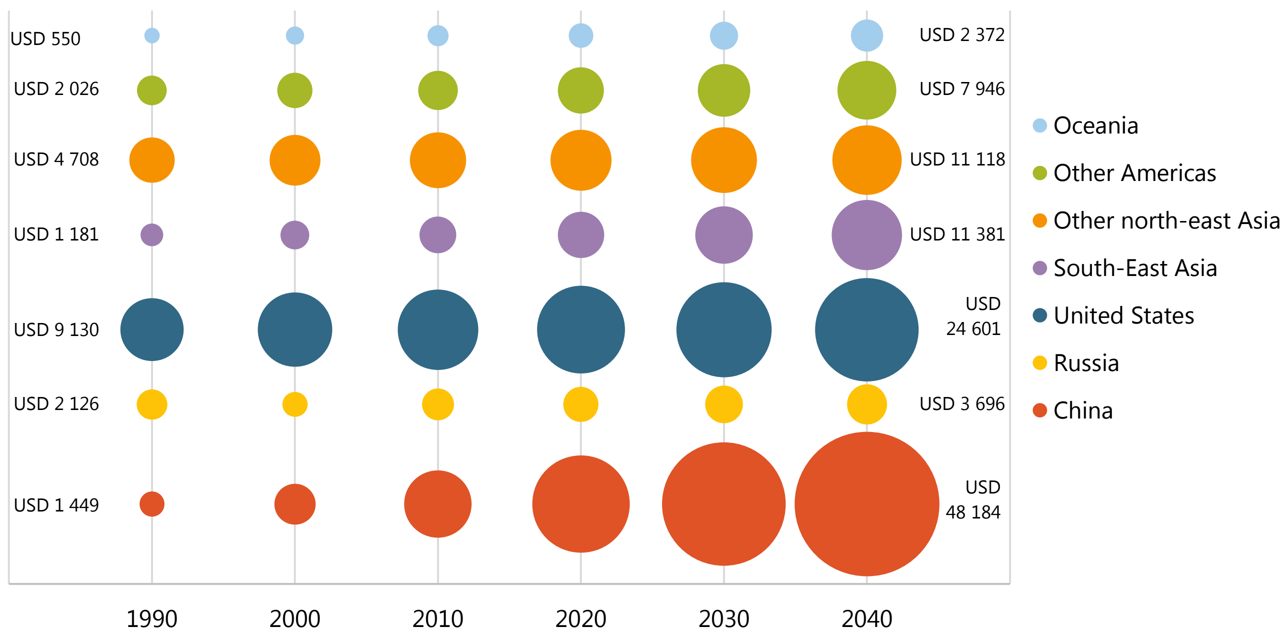
Figure 2 • APEC GDP and population assumptions



Sources: UNDESA (2015), World Bank (2015a, 2015b), CEPII (2012) and APERC analysis.

APERC's model shows that developing economies will maintain relatively high GDP growth rates due to their low labour costs and increased transfer of technologies from developed economies. The projections show that by 2040, the gap between developing and developed economies narrows. In terms of GDP in USD 2012 PPP, China becomes the largest economy by 2020, while the GDP of South-East Asia would be comparable to other north-east Asia by 2040 (Figure 3).

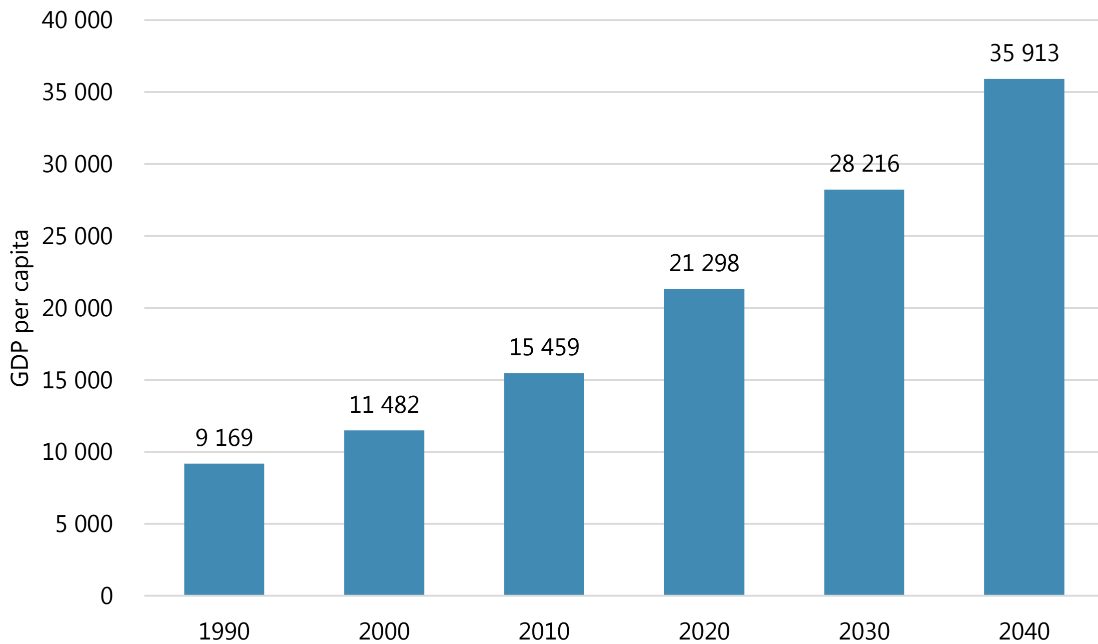
Figure 3 • GDP by regional grouping, 1990-2040, 2012 USD billion PPP



Sources: UNDESA (2015), World Bank (2015a, 2015b), CEPII (2012) and APERC analysis.

Average GDP per capita in the APEC region rises from USD 17 047 in 2013 to USD 35 913 by 2040 (Figure 4). To put this into perspective, while APEC's average GDP per capita in 2013 is comparable to Malaysia (USD 17 446) or Mexico (USD 15 228), by 2040 it will be comparable to Chinese Taipei's (USD 40 368) and Japan's (USD 36 488) 2013 GDP per capita. Rising GDP per capita has historically lead to higher energy consumption per capita, through increased energy demand for transport, buildings, and industry as well as from higher living standards.

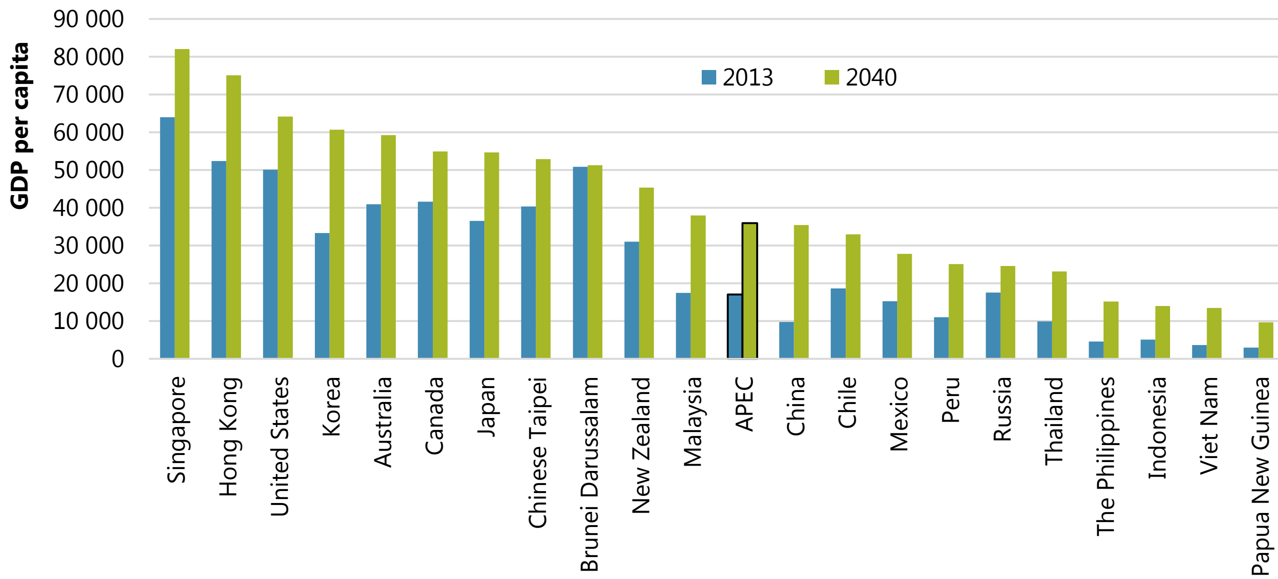
Figure 4 • APEC average GDP per capita, 1990-2040, 2012 USD PPP



Sources: UNDESA (2015), World Bank (2015a, 2015b), CEPII (2012) and APERC analysis.

Figure 5 shows the GDP per capita assumptions in 2013 and 2040 for each economy. The median growth rate of GDP per capita from 2013 to 2040 is 2.1%. While the median for South-East Asia (3.2%) and other Americas (2.2%) is relatively higher in comparison, other north-east Asia (1.3%) and Oceania (1.4%) are relatively lower. Although developed economies such as Singapore and United States still lead APEC in terms of GDP per capita, developing economies with a relatively low GDP per capita in 2013 are expected to have higher projected growth rates. This leads to income disparity across economies falling over the projection period.

Figure 5 • APEC GDP per capita by economy, 2013 and 2040, 2012 USD PPP



Sources: UNDESA (2015), World Bank (2015a, 2015b) and APERC analysis.

ENERGY PRICE

The Institute of Energy and Economics, Japan (IEEJ) provided the crude oil price assumption used in this Outlook. Given the different energy and economic positions of each economy, efforts were made to adjust domestic prices for each energy type accordingly. The energy price assumptions are shown in Table 1.

Table 1 • Energy price assumptions, 2013-2040

Fuel	2013	2014	2020	2030	2040
Crude oil (USD/bbl)	108	102	73	97	121
Natural gas in Japan (USD/MMbtu)	15.9	15.8	10.4	12.4	13.7
Natural gas in the US (USD/MMbtu)	3.6	4.3	4.4	5.4	6.6
Steam coal (USD/tonne)	110	95	86	103	128

Notes: The Outlook energy price assumptions are based on IEEJ's 2015 AWEO Reference Case and converted to USD 2012 PPP using World Bank PPP conversion factors; bbl = barrels; and MMbtu = million British thermal units.

Sources: IEEJ (2015) World Bank (2015a) and APERC analysis

Over the medium to long term, oil prices are expected to rise. On the demand side, oil consumption will continue to increase, especially for developing economies, as car ownership is well below saturation levels. On the supply side, oil production relies increasingly on deep water, arctic, oil sands and shale oil fields where marginal costs are higher.

KEY METHODOLOGIES

Seven sub-models constitute the Outlook model. Each sub-model has its own structure, including input data, calculations and output results. Input data consists of historical data, key assumptions, and other models output results.

MACROECONOMIC MODEL

The macroeconomic model forecasts GDP for each economy, which is defined as 'an aggregate measure of production equal to the sum of the gross values added of all resident, institutional units engaged in production (plus any taxes, and minus any subsidies, on products not included in the value of their outputs)' (OECD, 2002). The model uses a Cobb Douglass function to project the GDP for each economy (Equation 1).

Equation 1: Cobb Douglass GDP function

$$GDP = tfp * capital^{\alpha} * labor^{\beta}$$

where:

tfp = *total factor productivity: the real value of all goods produced in a year.*
$capital$ = *the real value of all machinery, equipment and buildings*
$labour$ = *the total number of person-hours worked in a year*
α & β = *output elasticities for capital and labour, respectively. These values are constants determined by available technology.*
$\alpha + \beta$ = *1*

The macroeconomic model forecast for each economy has two components. The first component involves collating historical *GDP*, *capital* and *labour* inputs to perform a regression analysis of the historical data using the software 'Stata' to formulate change patterns. Economies with similar socio-economic environments are grouped to reflect similar behaviours and patterns such as capital accumulation. In the second component, *tfp*, *capital* and *labour* are estimated for the first projection year (2014) based on the historical data and all the parameters deduced from the regression. This process iterates year by year until *GDP* for 2040 is forecasted.

Capital is an accumulation through a permanent-inventory process, where *capital* for each year is the gross fixed capital formation plus the depreciated historical capital accumulation (real value). The gross fixed capital formation rate is estimated from a savings rate, which is affected by GDP per capita, the age-structure of the population, as well as the cultural and social factors that are represented as historical savings rates. The historical capital depreciation rate is set at a constant value of 6% for all economies. The historical data is sourced from the World Bank, with the exception of data for Chinese Taipei which is based on its government's historical data and APERC estimations.

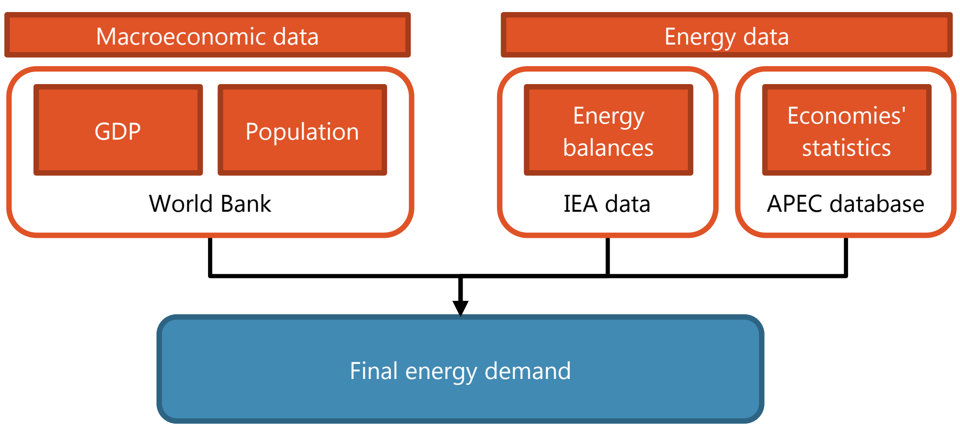
Labour is measured by the total demographic-weighted employed population. Different age groups and education levels are given different weights; for example, the working-age population, ranging from 15 to 60, has a higher activity rate than other groups. Education level is divided by primary, secondary and tertiary attainment, with more highly educated persons having higher weights. Male and female participation rates are also considered separately to account for regional differences in participation between the genders. Most of the data for *labour* is from CEPII model (CEP II, 2012), with the exception of data for Chinese Taipei which is based on its government's historical data and APERC estimations.

Tfp is the measure of an economy's long-term technological change or technological dynamism. It accounts for effects in total *GDP* output not caused by inputs of *labour* and *capital*. Some previous studies suggest that *tfp* growth can be explained by a catch-up effect, an education effect and an interaction between the two (CEPII, 2012). In the APERC model, some economies which currently exhibit lower *tfp* are expected to catch up in the projection period due to growing tertiary and secondary education rates.

BUILDINGS MODEL

The buildings model includes the residential, commercial and agriculture sectors' final energy demand, however as residential and commercial buildings represent the majority of final energy demand, the model is just referred to as the 'buildings model'. The model uses a top-down approach that projects future demand at an economy level based on aggregated energy statistics and energy demand elasticities by fuel for each economy.

Figure 6 • Top-down approach to modelling buildings and agriculture demand



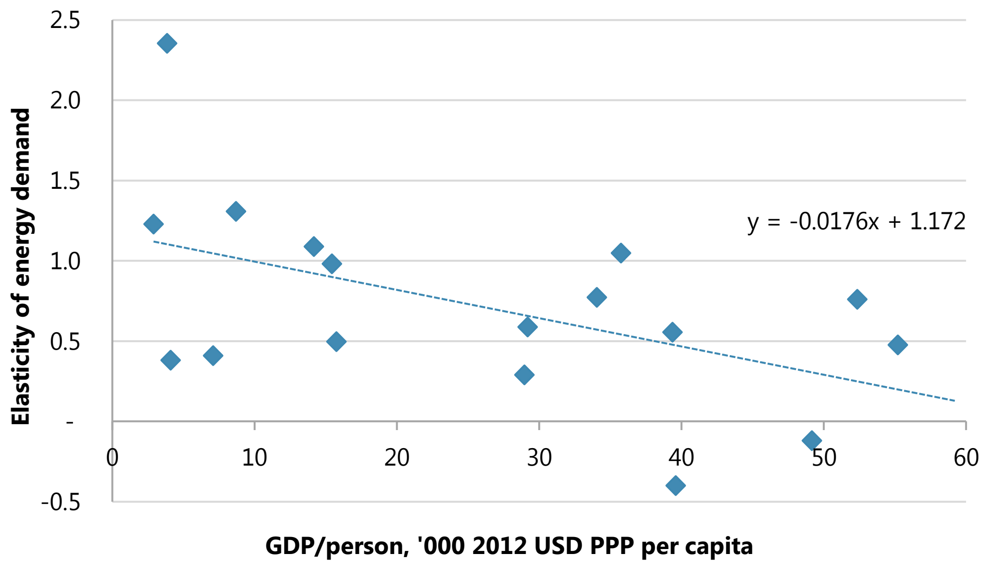
Source: APERC analysis.

Key consideration in the BAU

To project future residential and commercial energy demand, the concept of useful energy was introduced in the model. Different fuels have different coefficients in terms of the ratio between the energy input and useful energy output, for example, while a large amount of coal heat is lost (a low useful energy coefficient) electricity consumption is much more efficient (a high useful energy coefficient) (Chen and Samuelson, 2012). Through regression analysis, a linear correlation between the elasticity of useful energy demand and GDP (PPP) per capita in the residential

(Figure 7) and commercial sectors were found. This relationship was then used to project the future residential demand.

Figure 7 • Relationship between residential energy demand elasticity and GDP per capita by economy



Source: Chen and Samuelson (2012).

The above figure shows that growth of energy demand slows down as per capita GDP increases. The fuel mix in this sector tends to change slowly and depends on resource availability and energy policy.

Key considerations in the Alternative Scenarios

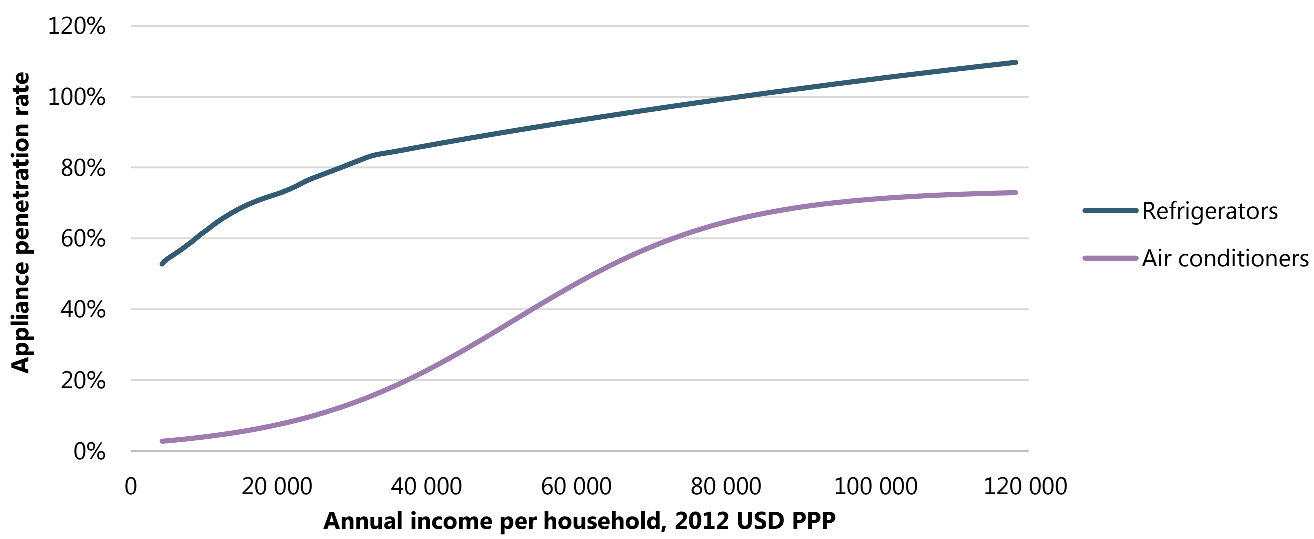
In order to estimate the Improved Efficiency Scenario's final energy demand for a sector, the model calculates and subtracts the estimated savings from the top down model estimated in the BAU Scenario.

In the Improved Efficiency Scenario, the buildings sector focuses on energy efficiency gains in residential and commercial sub-sectors. For this APERC used a bottom-up approach to estimate savings from 7 end uses of residential energy consumption and 4 end uses for the commercial sub-sectors. The end-uses include: cooling, refrigeration, lighting, washing machines, water heating, televisions, and stand-by. Heating and heating savings were not uniformly estimated for all economies due to data limitations, however it was estimated for the following five economies: Canada, China, Japan, Russia and the United States. In the commercial sub-sector the end-uses estimates include cooling, lighting, ventilation, and refrigeration.

This approach is based upon methodology first developed by the Lawrence Berkeley National Laboratory (McNeil et.al, 2008). This method uses the relationship of GDP per capita and access to appliances and energy services to estimate penetration rates of appliances and the energy demand per household for services. Other macroeconomic variables encompassed in the method that also influence appliance penetration include: electrification rates, urbanisation rates, and an assumed practical maximum rate of penetration.

Each of the appliances and end-uses has a different penetration shaped curve depending on their desirability and cost. An appliance that is seen as a necessity such as a refrigerator is highly desirable and will be generally acquired as soon as it is affordable for a household, as such an economy will near saturation at a relatively low income level. On the other hand, washing machines may be viewed more as a luxury than a necessity and penetration will be slower. Figure 8 shows this difference with estimated penetration rates for refrigerators and air conditioners in China.

Figure 8 • Penetration rates of appliances in China



Source: APERC analysis.

For climate-related energy demand (cooling and heating) the methodology included cooling degree days (CDD) and heating degree days (HDD) accordingly to estimate actual demand for this end use and, in the case of cooling, as a proxy to desirability. This way, economies with hot tropical weather will see air conditioners as a necessity and increase ownership faster than economies with temperate climates.

Under the Improved Efficiency Scenario, the average efficiency factors applied to each appliance are different from BAU where the existing efficiency rate was held constant throughout the period. The average efficiency factors for the Improved Efficiency scenario were sourced from McNeil et.al 2008. Efficiency factors vary for each region as each market is different in terms of development, size, and services demanded.

Table 2 • Residential and commercial end-uses and efficiencies modelled in the Improved Efficiency Scenario

Sector	Appliances	Range of efficiency (Highest in IES- Lowest in BAU)
Residential	Refrigeration	216 – 644 kWh/y
	Air conditioning	5.81 – 2.55EER
	Water heating	91% - 76%(HPWH – 2.5)
	Lighting	10W LED – 60W incandescent
	TV	102 – 261 kWh/y

	Washing machine	6 – 194 kWh/y
	Stand by	1 – 3 – 5 W per device
Commercial	Lighting	30% improvement
	Cooling	40% improvement
	Ventilation	20% improvement
	Refrigeration	34% improvement

Source: APERC analysis.

There is less data available for the commercial sector requiring a greater degree of econometric analysis in order to estimate demand for key end-uses. For this, the methodology uses a regression algorithm, to estimate energy intensity per square meter for commercial floor space. The estimation methodology first uses GDP per capita to estimate the square meters per commercial sector employee, and then uses the total number of commercial sector employees to estimate total commercial floor space for each economy. Once floor space is calculated the BAU commercial final energy demand estimated in BAU is applied to obtain energy demand per square meter.

The method then applies another algorithm to separate components of different end use energy demand, thus enabling the application of energy efficiency improvements for each end use.

INDUSTRY MODEL

The industry model is tailored for each economy to estimate industrial energy demand, which includes energy demand in different sub-sectors. These models are built based on a top-down energy intensity approach. Energy consumption is analysed in two elements, gross industrial output (monetary production amount) and energy intensity per output (Equation 2).

Equation 2: Industry energy consumption

$$E_{i,t} = EI_{i,t} * GIOR_{i,t}$$

where:

$E_{i,t}$ = *Energy consumption of sub-sector i in year t,*

$EI_{i,t}$ = *Energy intensity of sub-sector i in year t*

$GIOR_{i,t}$ = *Gross industrial output (2012 USD PPP) of sub-sector i in year t*

The merit of this approach is that the effects of future changes in the industrial structure and energy intensity can be assessed separately as they evolve under effects of different drivers. An industry’s industrial structure evolution reflects changes in roles of various sub-sectors due to geographical position, natural endowments and the developmental stage of an economy. An industry's energy intensity reflects the degree of technology progress, management modernisation and energy efficiency practices introduced into the sub-sector.

Energy demand elasticity per gross industrial output is projected in relation to the historical trend and changes in gross sectoral output and energy prices. The basic formula applied for calculation of energy intensity is shown below:

Equation 3: Industry energy intensity

$$\log\left(EI_{i,t}\right) = a + b\log\left(EI_{i,t-1}\right) - c\log(GIOR_{i,t}/GIOR_{i.t-1}) - d\log(P_t/P_{t-1})$$

where:

P_t = *energy price index in year t*

P_{t-1} = *energy price index in year t-1*

$\log(EI_{i,t})$ = *logarithm of energy intensity of sub-sector i at time t*

$\log(EI_{i,t-1})$ = *logarithm of energy intensity of sub-sector i at time t-1*

$\log(GIOR_{i,t}/GIOR_{i,t-1})$ = *logarithm of change in gross industrial output of sub-sector i*

$\log(P_t/P_{t-1})$ = *logarithm of change in energy price index*

a = *intercept*

b, c, d = *factor sensitivities*

Sub-sectors are grouped into ten industry sectors: iron and steel; chemicals and petrochemicals; non-metallic minerals (including cement), machinery, food and tobacco, paper and pulp, mining of metals and quarry, non-ferrous metals, construction and others. However, the 'non-energy' sub-sector is handled separately and is discussed at the end of this section.

Economies are divided into three categories in consideration of the availability of energy data by sub-sector and economy-specific industrial structure:

- Sub-model A: 6 economies (BD, HKC, MAS, PNG, SIN, VN[1]) with a simple industry structure in terms of energy consumption, or lack of appropriate sub-sectoral data;
- Sub-model B: 4 economies (CDA, CHL, NZ, PE) with only a limited number of industries and analysis on major energy consuming industrial sub-sectors is implemented; and

[1] AUS=Australia, BD=Brunei Darussalam, CDA=Canada, CHL=Chile, PRC=China, HKC=Hong Kong, China, INA=Indonesia, JPN=Japan, ROK=Korea, MAS=Malaysia, MEX=Mexico, NZ=New Zealand, PNG=Papua New Guinea, PE=Peru, RP=The Philippines, RUS=Russia, SIN=Singapore, CT=Chinese Taipei, THA=Thailand, US=The United States, VN=Viet Nam

- Sub-model C: 11 economies (AUS, PRC, CT, INA, JPN, ROK, MEX, PH, RUS, THA, US), with a variety of industrial activities backed by detailed sectoral data and analysis for all 10 industrial sub-sectors is implemented.

Historical input data (1990-2013) comes from a variety of sources:

- Energy data is sourced mainly from the IEA Energy Statistics 2015 for all economies except for PNG, which uses APEC Energy Statistics 2013 and the APEC Energy Database, and
- Industrial value added/gross output: sourced from the WB database and other sources.

The model platform uses the Simple-E software, developed by IEEJ and managed by the Asian Research Institute, Inc. (http://www.asiam.co.jp/). It is compatible with Excel and provides functions of database, econometric analysis, modelling, model simulation/projection and optimisation in a consolidated package.

Estimation of gross industrial output

Though diverse among economies, industrial production, which is a key driver for energy consumption, is expected to continue to grow in APEC through 2040 as population grows and economies continue to develop.

GDP elasticities of industrial sector output, or gross industrial output, are diverse among economies reflecting the different status of economic development, and the strengths, limitations or comparative advantages of industrial development.

Among industrial products, demand for steel and cement are known to be pro-cyclical in relation to the construction cycle of the industrial base and general infrastructure. Demand for these products surge during the high-speed development or 'take-off' stage of an economy, peak when certain development is achieved and settle down to an equilibrium level once an economy reaches a matured development stage. In addition, as an economy grows, greater supply of scrap steel for electric furnace occurs. This is modelled in the projection of outputs for the iron & steel and non-metallic minerals sectors. Outputs of other sectors are projected considering the historical trends in elasticity over total industrial production or GDP.

In nine middle-income economies, the three most energy-intensive industries (iron and steel, chemicals and petrochemicals, and non-metallic minerals) will play significant roles in supporting infrastructure development coupled with fast urbanisation and rural modernisation, subject to the above mentioned industry life cycle. Other less energy-intensive industries (food and tobacco, paper and pulp, machinery, non-ferrous metals, etc.) will also grow substantially to meet requirements from expanding population with increasing income.

In regards to the twelve high-income economies, as their industries are already in a mature stage, no remarkable shifts will occur in industrial structure. Generally, the share of the industry sector in relation to GDP is observed to decline in many economies as the prominence of the service sector increases, especially among those poor in natural resources and less populous economies such as Singapore and Hong Kong.

Estimation of energy intensity

Energy intensity of industrial sub-sectors largely depends on the production technology, volume and composition of industrial products and energy market structure. It will be affected by energy efficiency policies, in particular, those related to the promotion of advanced technology, energy demand-supply management and energy price regulation.

Analysis of APEC statistical data also shows that the APEC's average energy intensity in the industry sector fell on average by -1.4% per year during the period of 1990-2012, while this improved slightly to -0.7% per year for the later period of 2005-2012. The slowdown seen after 2005 can be mainly attributed to the structural change towards a greater share of energy-intensive industries in China and developing economies.

Declines in energy intensity per sub-sector output are assumed for all industry sectors and economies as a general trend. Table 2 below shows the projected average annual declines in elasticity of energy intensity over GDP by for each group of economies, which reflects the combined effects of sectoral energy efficiency improvements and structural changes.

Table 2 • GDP elasticity of energy intensity reduction in APEC economies

Economy groups by income*	GDP elasticity of energy intensity reduction, average 2013-2040
Low middle-income economies (INA, PNG, PH, VN)	0.1-0.2
Upper middle-income economies (PRC, MAS, MEX, PE, THA)	0.1-0.8
High-income OECD economies (AUS, CDA, CHL, JPN, ROK, NZ, USA)	0.5-1.1
High-income non-OECD economies (BD, HKC, SIN, CT, RUS)	0.3-4.2

Notes: Economy abbreviations used are from the APEC publishing guidelines; * according to the World Bank classification as of Jan 2015.

Source: APERC analysis.

The above elasticities assume that energy intensity reductions shall be pursued by implementing all policies and measures currently planned; deploying existing best available technologies (BATs) in larger capacities as well as increased process integration for new production facilities. They assume improving production techniques, the development and installation of new technologies and equipment/plants that deliver improved energy efficiency, enable fuel/feedstock switching, and promote more recycling and reuse, especially in iron and steel, paper and pulp, and chemical and petrochemicals.

Estimation of energy demand

Industrial energy demand by fuel type is estimated separately for combustible fuels, electricity and heat in consideration of significant differences in mode of consumption. Combustible fuels include coal, oil, natural gas and combustible renewables. Fuel mix composition among the combustible fuels is estimated taking into account elements such as industry development status, technical characteristics in use, comparative fuel prices, environmental and climate issues, etc.

Energy demand for non-energy use includes feedstocks for chemical industries and consumption of materials in other sectors such as asphalts for road construction, lubricants and grease for motor vehicles, ships, trains, machines and industrial processes, wax and solvents. Demand for chemical feedstock is projected in relation to the estimated future chemical production incorporating chemical plant project plans. Other non-energy demands are projected in relation to GDP.

Improved Efficiency Scenario implementation

In the Improved Efficiency Scenario, APEC industrial energy demand is estimated assuming the adoption of highly efficient equipment/systems and best practices in industry. Additional efficiency gains in the Improved Efficiency Scenario over the BAU Scenario are assumed (Table 3).

Table 3 • Assumption of additional energy intensity reduction in industry sub-sectors over the BAU scenario

	2016-2040	AAGR
Iron and steel	-10%	-0.44%
Chemicals and petrochemicals	-10%	-0.44%
Non-metallic minerals	-10%	-0.44%
All other sectors (less energy-intensive sectors)	-20%	-0.93%

Source: APERC analysis.

Due to the limited availability of data by industry sub-sector, industrial energy demand forecast simulations were run for 15 economies, excluding Brunei Darussalam, Hong Kong, Papua New Guinea, Singapore, Viet Nam and Malaysia.

TRANSPORT MODEL

The transport model projects the evolution of each vehicle technology and fuel use for the 21 APEC member economies from 2013 to 2040 in the BAU and Improved Efficiency Scenarios.

The vehicle fleet is divided into light-duty vehicles (curb weight under 3 tonnes), heavy-duty vehicles (above 3 tonnes) and motorcycles. These three types are further categorised by fuel and technology, e.g. gasoline, hybrid gasoline, used imported gasoline, and non-conventional plugin hybrid gasoline. There are two technologies for motorcycles; gasoline ICE and electric motorcycles. This vehicle fleet model utilises a system dynamics approach – using the STELLA modelling software – and consists of vehicle ownership, vehicle stock turnover, vehicle consumer choice, and vehicle travel elasticity sub-models. Energy demand for a vehicle type for a vintage year is a product of the number of vehicles, travel distance, and average fuel consumption. Input data consists of:

1. Macroeconomic data (population and GDP);
2. Vehicle data (government data on vehicle stock, sales by technology and age distribution);
3. Retail fuel price data; and
4. For historical energy data, IEA statistics (Energy Balances of OECD Countries, Energy Balances of non-OECD Countries) and for PNG only the APEC Energy Statistics 2013 and the APEC Energy Database.

Transport model sub-models

The vehicle ownership sub-model uses a Gompetz growth model. Growth in the vehicle fleet is modelled by the interaction between vehicle ownership per capita and income per capita (Dargay et al., 2007) with varying elasticity. An S-shaped function is utilised, where parameters are long run equilibrium vehicle ownership level, per-capita income, saturation level of vehicle ownership and other parameters obtained from historical data.

This sub-model has been developed by APERC, for more information, please refer to Leaver et al. (2011) on the prediction of light vehicle saturation levels in developing APEC economies. Vehicle saturation levels are obtained from literature review and reflect the land use and transport infrastructure developments suggested by economy experts.

The vehicle stock turnover sub-model is used to determine the number of vehicle retirements or scrapping. It relies on historical data and determines the annual retirements in each of the vehicle age groups. The input data consists of economies' vehicle stock structure, i.e. vehicle stock by vehicle technology and vehicle age.

Survival rate of a vehicle is a probability that, after entering the market, the vehicle is operable at certain age. The survival rate is defined by an S-shape curve 'Weibull distribution' function depending on vehicle age, scrappage start age, failure rate, and characteristic service life for all vehicle types. Annual vehicle sales are determined by subtracting the surviving stock (i.e. vehicle stock in previous year minus vehicle retirement) from expected vehicle stock in each year. Vehicle sales in the base year are used to validate the sub-model.

The vehicle consumer choice sub-model is based on a logit choice approach and models the consumer vehicle-buying decision-making process. It is assumed that consumers make a decision to purchase a vehicle based on (1) the consumer rational choice of owning and operating the vehicle and (2) their intrinsic non-rational preference for one vehicle type over another. The latter reflects consumers' factoring of the availability of refuelling infrastructure, vehicle's "green image", vehicle performance and customer's cultural preferences.

The logit *beta* values describe consumers' choice elasticity to fuel cost, vehicle purchase price, driving radius, convenient medium distance destinations, possible long distance destinations, reluctance to drive a vehicle, and a fleet diversity factor. The logit value for a vehicle type is a sum of products of elasticities and fractional differences of the above factors. The market share of a vehicle technology is then determined as the ratio between a vehicle's technology logit value and the sum of all vehicles' logit values (Train, 2008).

The vehicle travel elasticity sub-model projects the annual vehicle mileage based on short- (1-yr horizon) and long-run (5-10 year horizon) elasticities for fuel cost, per capita GDP, and number of vehicles per capita. Typically, long-run elasticities are larger in magnitude than short-run ones. For example, if fuel prices increase consumers can reduce non-essential travel in the short-run, but there may be more significant long-run adjustments such as moving closer to work.

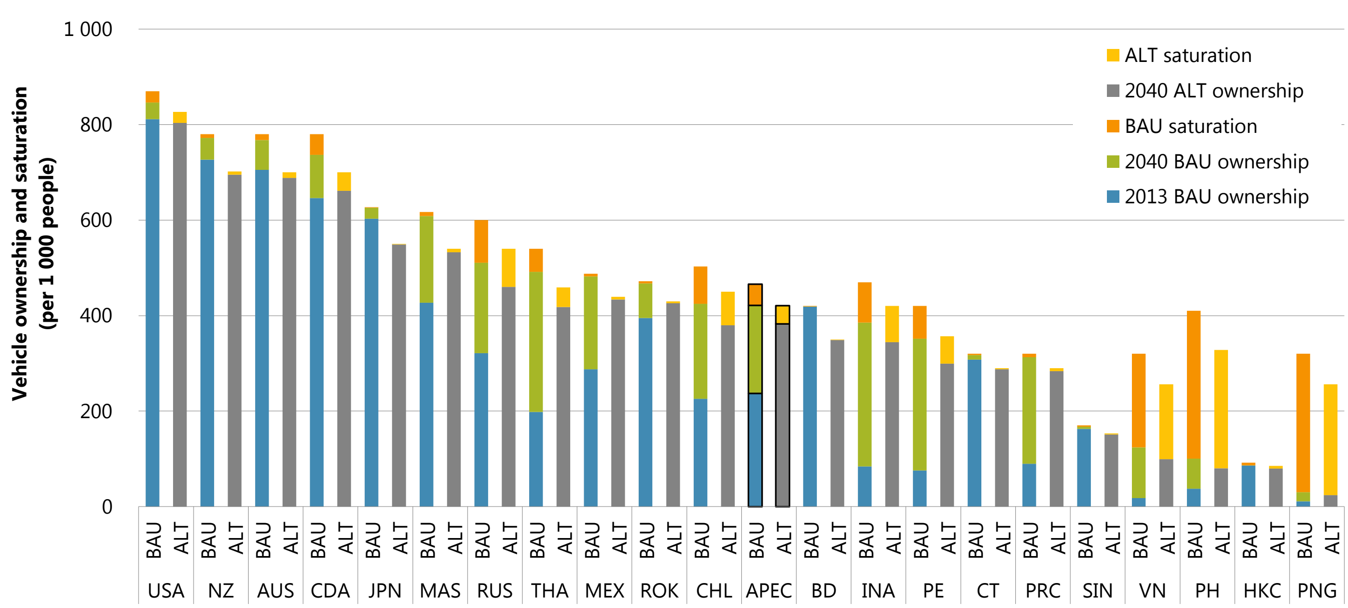
The annual vehicle travel is calculated based on the base year annual travel and changes in fuel cost, GDP per capita and vehicle ownership per capita, based on the above elasticities and for each vehicle type. Developed economies are expected to show higher sensitivity to the cost of driving, due to lower sensitivity to changes in GDP and vehicle ownership per capita. The fuel costs are expressed in fuel cost per km of an internal combustion vehicle to harmonise the price signal across all vehicle technologies, therefore vehicles with lower fuel per km cost are expected to have greater travel demand.

Key considerations in the BAU and Improved Efficiency Scenarios

GDP and population growth are the key drivers for growth in number of vehicles as well as new vehicles' fuel economy improvement rate. The estimation of the latter is based on reports from economies and international organisations, such as Global Fuel Economy Initiative (GFEI), and Technology Roadmap for Fuel Economy of Road Vehicles IEA (2014). Under the BAU, fuel economy in non-OECD APEC economies is assumed to improve at a lower rate than in the OECD, whereas in the Improved Efficiency Scenario, fuel efficiency is assumed to improve faster than the BAU due to improved technology exchange, leading non-OECD and OECD economies to have the same improvement rates. It is assumed that commercialised vehicle technologies such as hybrid electric vehicle (HEV) are available in all economies, except PNG. However, economies' policies define the penetration rate of new energy efficient vehicles and biofuel blend rates, otherwise, the latter is assumed to remain at the current level over the Outlook period.

Vehicle saturation is the maximum level of vehicle ownership in each economy, and is affected by urban form expressed by the urban density parameter. Under the BAU, in line with global historical data, it is assumed that urban density declines at 1.7% per year. In the Improved Efficiency Scenario, however, it is assumed to remain constant or even increase, due to city expansion management and improving public transport systems. This leads to a 5-20% lower level of vehicle saturation in the APEC region as compared to the BAU (see Figure 6).

Figure 9 • Vehicle saturation and vehicle ownership under the BAU and Improved Efficiency Scenarios.

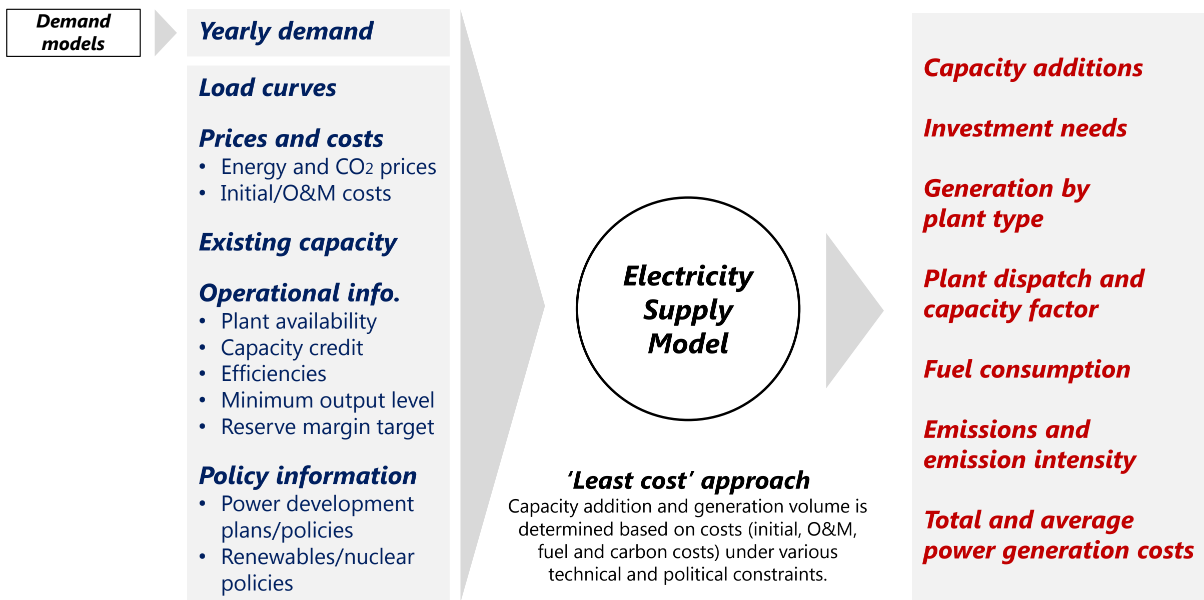


Note: Economy abbreviations used are from the APEC publishing guidelines. ALT = Improved Efficiency Scenario
Source: APERC analysis.

ELECTRICITY MODEL

The electricity model aims to optimally satisfy the electricity demand for the demand models (industry, transport and buildings model) (Figure 10). The electricity model assumes that annual electricity demand is met and enough capacity is installed to meet the peak load plus reserve margin criteria. This is a bottom-up model described as a linear programming problem, which determines capacity expansion and operation of each technology option based on cost-minimisation under technical and political constraints.

Figure 10 • Inputs and outputs of the electricity supply model



Source: APERC analysis.

The objective function is described in Equation 4. The model minimises the discounted total electricity system cost (net present value) in the selected economy over the outlook period. APERC's cost assumption relies primarily on

Equation 4: Minimum present value of total electricity system cost

$$min.\ J = \sum_y \left\{ TC_y \times \frac{1}{(1+\gamma)^{y-2013}} \right\}$$

where:

J = *net present value of total electricity system cost*
y = *year index*
TC_y = *annual electricity system cost in year y*
γ = *discount rate*

each economy's assessments as well as on IEA analysis (IEA, 2014). The investment analysis for transmission and distribution network is explained further.

Equation 5: Annual electricity system cost

$$TC_y = \sum_p \left(I_{p,y} + F_{p,y} + O_{p,y} + C_{p,y}\right) + \sum_{st}\left(IS_{st,y} + OS_{st,y}\right)$$

where:

TC_y = *annual electricity system cost in year y*

y = *year index*

p = *power plant index*

st = *storage facility index*

$I_{p,y}$ = *annualised capital cost of power plant type p in year y*

$F_{p,y}$ = *annual fuel costs of power plant type p in year y*

$O_{p,y}$ = *annual fixed and variable O&M costs of power plant type p in year y*

$C_{p,y}$ = *annual carbon penalties for emissions in power plant type p in year y*

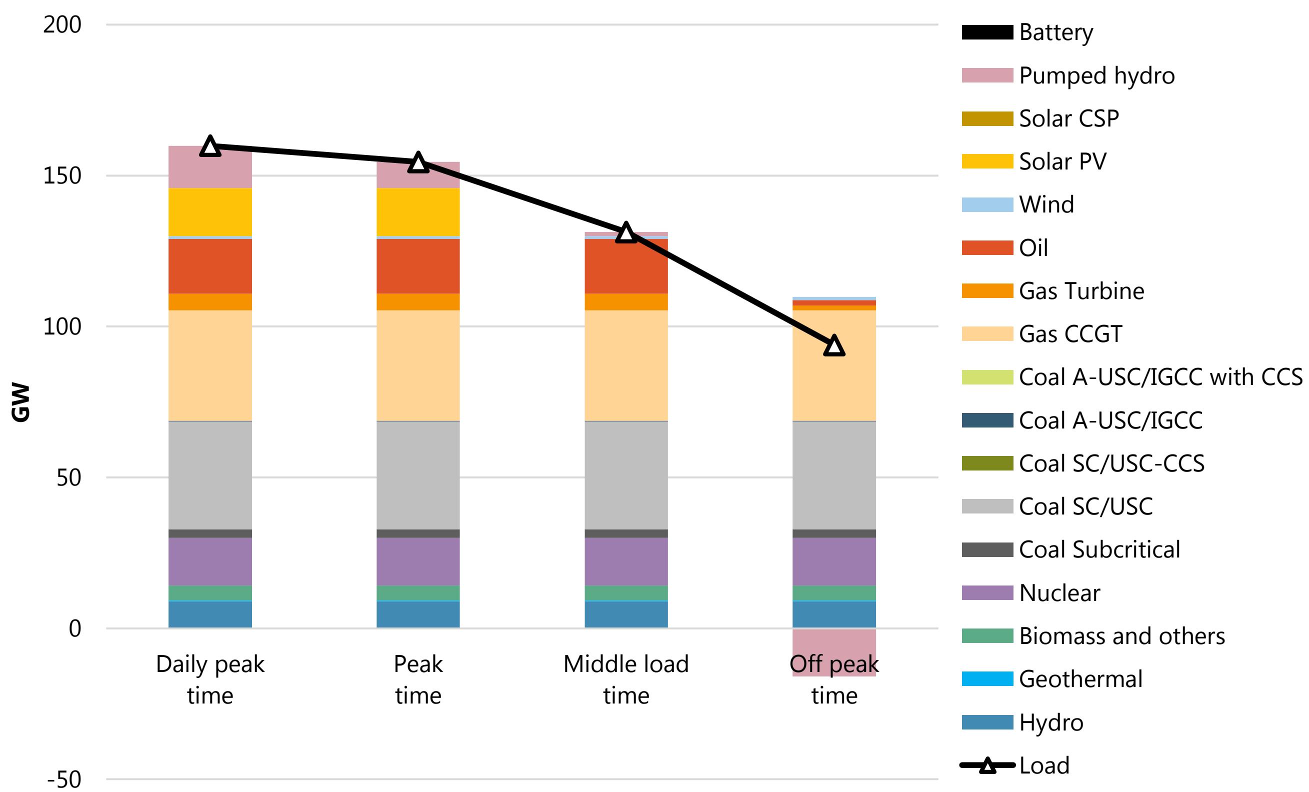
$IS_{st,y}$ = *annualised capital cost of storage type st in year y*

$OS_{st,y}$ = *annualised O&M costs of storage type st in year y*

APERC analysis considers relevant energy policies, as a set of constraints, in line with scenario definitions (see Table 4.1 in Volume I, Chapter 4). The following generation technologies are considered in the BAU: nuclear, coal subcritical, coal supercritical/ultra-supercritical (with and without CCS), advanced coal technologies (with and without CCS), gas turbine, combined-cycle gas turbine, oil-fired, hydro (large and small scale), onshore wind, offshore wind, solar photovoltaics (PV) and concentrating solar power (CSP), geothermal, and biomass/others. As for storage facilities, the model incorporates pumped hydro and battery storage. Assumptions for power plant lifetimes are as follows: 30-60 years for nuclear, 40-60 years for fossil fuel-fired plants and 25 years for solar and wind, based on economy specific regulations and historical operation information.

Here, it is important to note that nuclear and renewables capacity is subject to government policies and recent development trends. Therefore, in APERC analysis, the electricity supply model determines the fossil fuel-fired capacity, and dispatches power generation and storage technologies considering representative yearly or daily load duration curves (1-4 types in each economy, depending on data availability) as shown in Figure 11. As the model employs a least cost approach, it dispatches generation plants in the order of variable cost considering operational aspects (e.g. maximum availability). Variable costs vary by economy mainly due to local resource availability. In general, nuclear, coal and gas show relatively low variable costs among the fuel sources (except for renewables). These plants supply base load and middle load demand. When these types are not sufficient, high variable cost peaking units, such as oil-fired turbines, are operated to meet the peak load. Economies with storage facilities utilise them to reduce generation with high marginal cost by charging low-cost electricity and discharging at 'net' peak-load hours ('net' load = load - renewables output). These storage facilities contribute to levelling 'net' load for more economical electricity system operation.

Figure 11 • Example power plant and storage dispatch considering representative daily load duration curve



Notes: PV=Photovoltaics, CSP=Concentrating Solar Power, CCGT=Combined-cycle Gas Turbine, A-USC=Advanced Ultra Super Critical, IGCC=Integrated Coal Gasification Combined Cycle, CCS=Carbon Capture and Storage, and USC=Ultra Super Critical.

Source: APERC analysis.

As for variable renewables, the model approximately considers their long- and short-term output variation[2], and estimates the need for backup measures. Diurnal output characteristics of solar PV as modelled are shown in Figure I.11. The example shows an electricity system with mid-day peak, when solar PV output is at its maximum (it is modelled to appear only in peak time slot in this example). The model also makes a choice of backup reliability measures, including ramping operation of flexible generation, storage and curtailments, based on cost optimisation. In general, ramping up/down is the most-cost effective option, then storage or curtailments are selected after that.

[2]'Short-term' renewable variation usually refers to 'less than twenty minutes' fluctuation.

The projections for combined heat and power plants (CHP) are considered in a separate sub-model. The sub-model assumptions are based on CHP market penetration, CHP policy assessment and potential.

Key considerations in BAU and Alternative Scenarios

For BAU projections, APERC incorporated existing electricity supply policies, such as an economy's or utilities' power development plan and power plant project information, in the model as a set of constraints. For example, the BAU capacity additions are constrained to follow the trends in these plans or actual projects (for key assumptions, see Table 4.1 in Volume I, Chapter 4). The BAU also takes into account emissions policy which is implemented during the projection period (such as a carbon tax in Japan implemented in 2012 (MOE of Japan, 2012)). APERC assumes that the trend of these existing policies continues over the projection period.

APERC obtains input data, such as load curves, existing capacity and costs, referring to each economy's statistics/assessment[3] as well as IEA analyses (IEA, 2014). APERC also uses the Platts database (Platts, 2015) in order to estimate age profiles of existing power plants for retirement assumptions, and to disaggregate power plant capacity by technology if technology-divided data is not available in economy's statistics.

The Alternative Scenario (named Alternative Power Mix Scenario) uses the electricity model described above to integrate different premises concerning the use of high-efficiency coal technologies, higher shares of natural gas, and an expansion of nuclear energy in the configuration of the electricity generation systems of each APEC member economy. Therefore, within the concept of the Alternative Power Mix Scenario there are four specific fuel-driven cases: Cleaner Coal, High Gas 50%, High Gas 100% and High Nuclear.

The Cleaner Coal Case assumes that stricter environmental standards on carbon emissions in combination with technological advances will favour the gradual adoption of more efficient technologies in new coal-fired power plants built over the outlook period. To that end, this case includes 13 member economies with significant levels of current coal-based capacity, which are further divided in two major categories depending on the overall level of maturity of their coal demand in their electricity systems and the relative size of their respective use of coal for electricity in volumetric terms.

The first group (Group A) comprises seven mature coal-using economies (Australia, China, Japan, Korea, Chinese Taipei, Russia, and the United States) while the second group (Group B) comprises the remaining six developing coal-using economies (Chile, Indonesia, Malaysia, the Philippines, Thailand and Viet Nam). For the Group A, the Cleaner Coal Case assumes that all the new coal-based power plants built after 2020 will be equipped with Advanced Ultra Super Critical (A-USC) or Integrated Gasification Combined Cycle (IGCC), and after 2030 all new plants will also add carbon capture and storage systems (CCS). Similarly for Group B, all the new coal-based power plants will use Super Critical (SC) or Ultra Super Critical (USC) technologies, which will include CCS after 2030.

The High Gas Cases (50% and 100%) are based on the hypothesis that a larger share of natural gas in the electricity mix will replace coal capacity additions starting from 2020, and was applied on 13 member economies where BAU results indicated a considerable additions of coal-based generation (Australia, Chile, China, Indonesia, Japan, Korea, Malaysia, the Philippines, Russia, Chinese Taipei, Thailand, the United States and Viet Nam). The High Gas Case

[3]For example, METI (2015) for Japan and EIA (2013) for the United States.

deliberately assumes that either half or the full amount of new coal additions is replaced with gas-based generation. The High Gas 100% Case and High Gas 50% Case respectively distinguish between these levels of gas substitution.

Finally, the High Nuclear Case assumes an expansion of nuclear energy for electricity generation based on the potential magnitude of development over BAU in incumbent economies. This case encompasses 11 member economies; in nine of them (China, Indonesia, Japan, Korea, Malaysia, Russia, Thailand, USA and Vietnam) an expansion of their nuclear power generation would occur because of economic and environmental advantages combined with a decreasing dependence on fossil fuels.

Only in Mexico and Chinese Taipei, the expansion of generation would not occur as a result of additional capacity, but because of appropriate maintenance and refurbishments that would extend the lifetime of their current nuclear power plants beyond the timeframes in BAU settings. Furthermore, while Canada is another user of nuclear energy at the time being, it was excluded from this Scenario as it actually plans to retire 22% of its capacity by 2040 (equivalent to 3.2 GW), running counter to the premises in the High Nuclear Case.

RENEWABLES MODEL

The renewables model is used to estimate the amount of renewable energy consumed under the High Renewable Scenario. This scenario considers more factors and is different from the BAU, where only historical trends and committed projects are taken into account.

The renewables model consists of two sub-models, the renewables power sub-model and the biofuels sub-model. The renewables power sub-model mainly estimates generation capacity and output of hydro, wind, solar, biomass, geothermal and ocean, with the objective of reaching the APEC doubling goal in 2030. In the biofuels sub-model possible maximum bioethanol and biodiesel demand and supply are estimated for APEC.

Renewables power sub-model

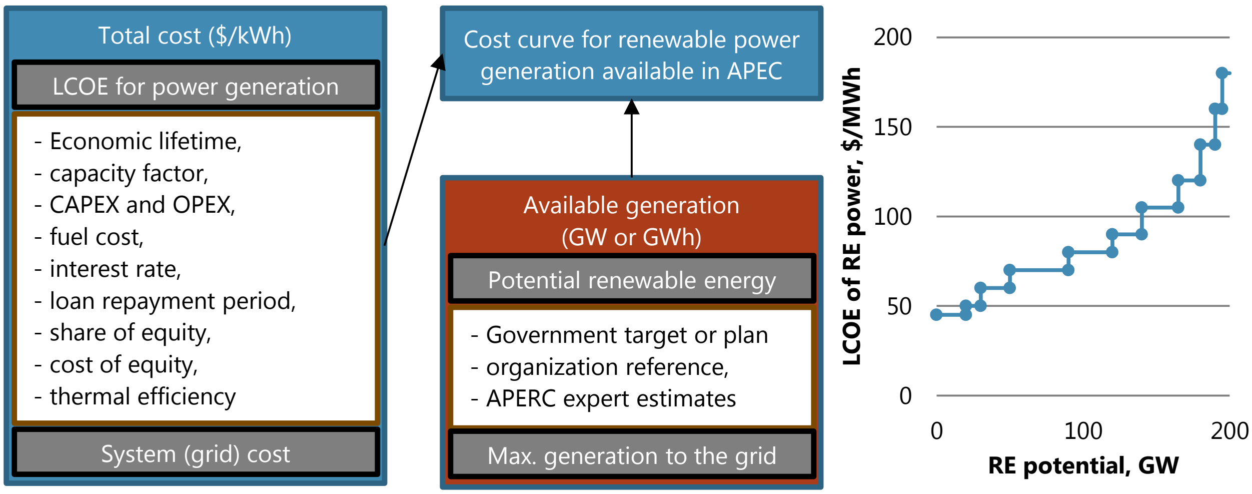
The High Renewables Scenario assumes that APEC economies fully meet their own renewables targets in power generation, and also undertake the development of any additional renewables generation needed to meet the APEC doubling goal[4] based on a least-cost approach. Additional renewables generation choices are made by considering the levelised cost of electricity (LCOE) and the economic potential[5] for each renewables technology in each economy. Post-2030, renewables' share in power generation continues to increase, in line with available economic potential of economies. Anticipated technological advances that will improve the performance and capacity factors of renewables technologies have been taken into consideration in determining these renewables capacity additions.

[4] As renewable potential and electricity demand are specific to each APEC economy, doubling the regional renewable share in power generation does not imply doubling renewables in each economy.

[5] Economic potential is the proportion of the technical potential that can be utilised economically, which takes into account costs and other socioeconomic factors (IRENA, 2014)

For each renewables type (i.e. hydro, wind, solar, biomass, geothermal and ocean) the economic potential and LCOE is determined for each economy. Due to resource or policy restrictions in certain economies, the economic potential is set at 0 for some renewables types in these economies. Figure 12 shows the cost curve formation process.

Figure 12 • Cost curve formation in the renewables power sub-model



Source: APERC analysis.

To determine the economic potential of renewables, factors such as technical renewable potential, government policies, targets, plans, and projections, and estimations from pertinent sources have been considered (e.g. REN21, 2014).

LCOE is determined by capital costs, fixed and variable operations and maintenance (O&M) costs, fuel costs, financing costs, and resulting electricity generation. The data is sourced from individual economies, reports of international energy organisations (e.g. IRENA and IEA), and international financing institutions (e.g. World Bank). Different cost assumptions for capital costs, interest rates, O&M costs, and fuel costs are applied in each economy.

Equation 6: Levelised cost of electricity

$$LCOE = \sum_t \frac{(Investment_t + O\&M_t + Fuel_t) * (1+r)^{-t}}{\sum_t (Electricity_t * (1+r)^{-t})}$$

where:

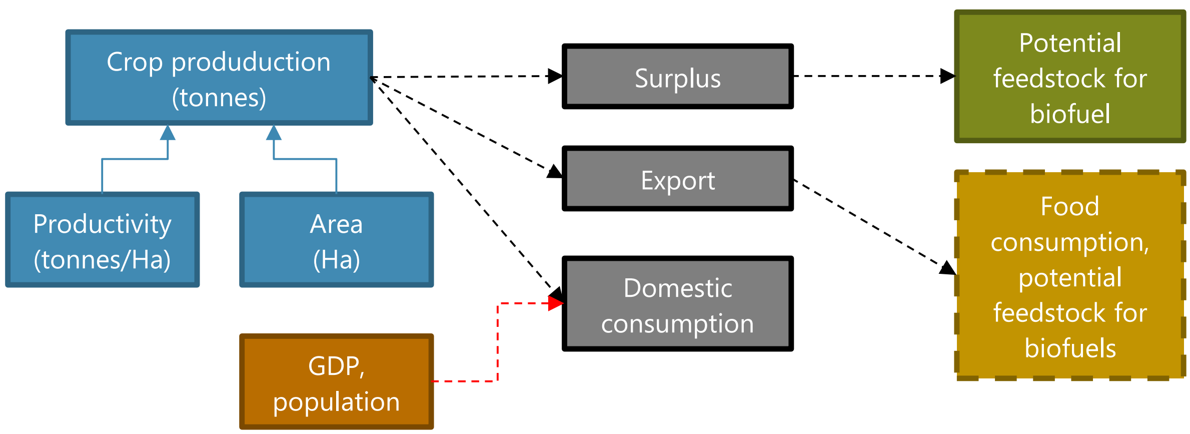
- $LCOE$ = *levelised cost of electricity*
- $Investment_t$ = *investment cost in year t*
- $O\&M_t$ = *operation and maintenance costs in year t*
- $Fuel_t$ = *fuel costs in year t*
- $(1+r)^{-t}$ = *the discount factor for year t*
- $Electricity_t$ = *the amount of electricity produced in year t*

An APEC-wide set of assumptions for loan repayment period as well as share and cost of equity was used. The formula to calculate LCOE is below:

Biofuels sub-model

In the biofuels sub-model, only 1st generation biofuels are assumed to be produced. Energy crops in the model include maize, rice, wheat, molasses, cassava, sorghum, sugar cane, coconut, soy bean, palm, rapeseed and sunflower. There are three stages to estimate the possible biofuels supply potential, shown in Figure 13.

Figure 13 • Supply potential estimation in biofuel sub-model



Note: Exports and food consumption are exogenous variables.

Source: APERC analysis.

In the first stage, energy crop potential for each economy is estimated. There are two ways to produce more energy crops, either by maximising the unutilised arable land or by enhancing the productivity of the existing land. Data from the Food Authority Organisation (FAO) is used to estimate the unutilised arable land. Those economies with a lower population density, such as United States, have high unutilised arable land, whereas economies with a higher population density have less. As for enhancing productivity, those economies with higher productivity levels per cultivated land will serve as a benchmark for increasing the productivity of other economies, based on the assumption that these techniques can be transferred. In this case, the economies are divided into two groups according to type of climate – 'continental climate economy' and 'tropical climate economy' – and one benchmark economy is selected for each group for each energy crop.

In the second stage, crop production in each economy is divided into domestic consumption, exports and surplus. The domestic consumption is estimated according to the GDP and population, while exports are influenced by crop price. GDP and population are taken from the macroeconomic model, while crop prices are forecasted based on the historical data obtained from UN statistics or the corresponding economy.

In the third stage, food consumption is excluded from surplus and exports. The model then assumes that all the remaining energy crops could be used as potential feedstock for biofuels supply potential.

After supply potential is obtained, the government blend target is taken into consideration to estimate demand and supply of biofuels in each economy under the following assumptions:

- **The economy has a mandated minimum blend rate and/or target on biofuels**. If the economy has no biofuels production, it is assumed that the minimum blend rate and/or target will be maintained. However, if there is sufficient biofuels supply potential in the High Renewables Scenario, then the blend rate (minimum or target) can be increased to a level which meets production.

- **The economy has no mandated minimum blend rate and/or target on biofuels**. No biofuels blend rate is considered, but if the economy has sufficient supply potential then a minimum biofuels blend rate is assumed to be set which matches supply potential.

SUPPLY AND ENERGY SECURITY ASSUMPTIONS

Supply assumptions (projecting fossil fuel production)

In our projections of the future production of fossil fuels in the APEC region, APERC has relied primarily on official government or government-sponsored projections from each economy. For economies where these are not available, APERC sought to find reliable independent sources. However, very few economy governments or independent sources make projections 25 years ahead, so a good deal of judgement on the part of APERC was required for the later years of the projection. Typically, the latter years' projections are based on historical trends, considering the resource availability. As for the Alternative Scenarios, production in a few major fossil fuel producing economies were adjusted to the forecast demand in order to avoid an oversupply situation.

Although we tried to make these long-term projections accurately based on available information, there still exists a high degree of uncertainty in the projections. Most APEC economies have not been well explored for oil and gas resources, so the full extent of their resource base is unknown. Furthermore, oil and gas exploration and production technology continues to improve, and by 2040 this progress could allow production of resources not currently considered economic.

Methodology in energy security

The energy security index devised by APERC is based on the Herfindahl–Hirschman Index, or HHI. It is an economic concept widely applied in competition law where market shares are compared. For energy security index purposes,

Equation 7: Herfindahl–Hirschman Index

$$H = \sum_{i=1}^{N} s_i^2$$

where:

s_i = *market share of fuel type i in the total primary energy supply*
N = *the number of fuel types*

this analytical method was chosen in order to measure the concentration of primary energy supply for each economy and region. This index is calculated as per Equation 7.

For *Outlook* purposes, the value of *H* varies from 0 to 1 as an indicator, where the lower the value the more diversified the primary energy supply (EC JRC, 2010; ERIA, 2012). This indicator is not used to cross-compare APEC economies, but could serve as a gauge to assess the current and future diversity of primary energy supply.

For primary energy self-sufficiency, APERC derived the formula from a methodology used by the Economic Research Institute for ASEAN and East Asia. (ERIA, 2012). The primary energy self-sufficiency is converted into a percentage as a way to indicate the level of self-reliance based on the domestic production against demand. This index is calculated according to:

Equation 8: Primary energy self-sufficiency

$$S_t = \frac{\sum_{p=1}^{N} E_p}{\sum_{d=1}^{N} E_d}$$

where:

S_t = *primary energy self-sufficiency in percent*
E_p = *primary energy production*
E_d = *primary energy demand for any particular fuel*
N = *the number of fuel types*

Derived from various organisations' definition on energy security, such as United Nations Development Programme (UNDP, 2000), each economies' self-sufficiency for a given fossil fuel was calculated as a percentage in order to indicate the level of imports that each economy would need. It is calculated based on:

Equation 9: Fossil fuel self-sufficiency

$$S_x = \frac{F_p}{F_d}$$

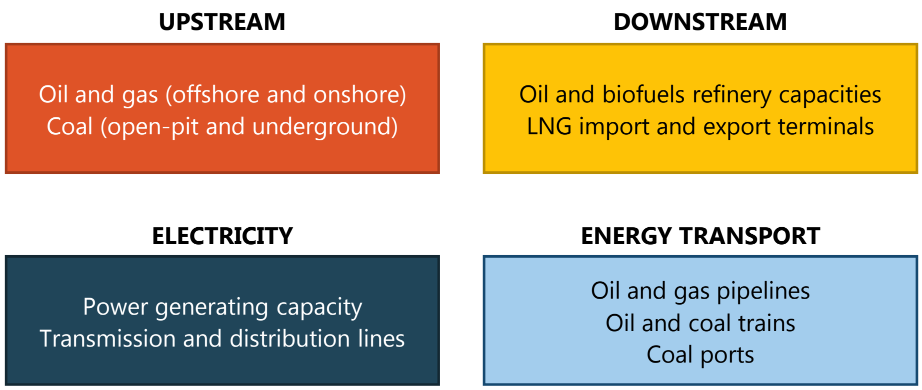
where:

S_i = *self-sufficiency in fossil fuel x in percent*
F_p = *fossil fuel production*
F_d = *fossil fuel demand for any particular fuel*

INVESTMENT MODEL

Investments are calculated based on the estimated capacity expansion requirements of an energy system by cost per unit of capacity. Energy systems are classified into four (4) sub-sectors, namely: upstream (oil, gas and coal extractions), downstream (refinery and LNG terminals), power (generation capacity, transmission and distribution networks) and energy transport (domestic transportation facilities for pipeline, railroads and coal ports). Shipping was not included in the investment estimates under the energy transport sector (Figure 14).

Figure 14 • Energy sector components



A cost range has been applied such that investments are computed using the lowest and highest cost per unit of energy facility/infrastructure capacity. This is to capture the variability in unit cost of similar energy facility/infrastructure across economies. If available, committed projects obtained from published sources or from economies' data were taken into account in the estimation of the capacity requirements.

For the upstream sub-sector, investments are computed on the annual production of oil and gas, which is segregated into onshore and offshore, while coal production is separated into open-pit and underground. The upstream investments are calculated as:

Equation 10: Upstream investments

$$Production\ Inew_{upstream,t} = \left[P_{t,onshore}(\%\ onshore) + P_{t,offshore}(\%\ offshore)\right] * ck$$

where:

$Production\ Inew_{upstream,t}$ = *new investment (annual) for the upstream sub-sector at time t*

P_t = *annual production from onshore and offshore (or open-pit and underground)*

ck = *capital costs: exploration and development costs (E&D) (USD/bbl for oil, USD/tonne for gas, and USD/tonne for coal)*

Different exploration and development (E&D) cost assumptions for onshore and offshore, and open-pit and underground were used for investment estimates in the upstream sub-sector.

In the downstream sub-sector, density/intensity has been utilised to estimate the additional capacity required for oil and biofuels refineries, as well as LNG import and export terminals. For oil and biofuels refineries, density/intensity is applied to final energy demand of oil, biodiesel and bioethanol. As most of the biofuels refineries are operating below nameplate capacity, density/intensity was set at 70% of nameplate capacity for some economies:

Equation 11: Oil or biofuels refinery investment

$$Refinery\ Inew_{downstream,t} = \beta C * \left(E_{d,t} - E_{d,t-1}\right) * ck$$

where:

$Refinery\ Inew_{downstream,t}$ = *new investment (annual) for a refinery at time t*

βC = *the additional capacity of oil or biofuels refinery per additional unit of demand ('000bbl per day capacity/oil demand) or (million litres per day capacity/biofuels demand)*

$E_{d,t}$ = *the volume of oil/biofuels demand at time t*

ck = *capital costs*

Meanwhile, application of density/intensity for LNG import terminals is linked with projected natural gas imports per economy, and for LNG export terminals with natural gas production estimates. LNG investments are calculated as:

Equation 12: LNG import terminal investment

$$LNG\ Import\ Terminal\ Inew_{downstream,t} = \beta C * \left(Imp_{ng,t} - Imp_{ng,t-1}\right) * ck$$

Equation 13: LNG export terminal investment

$$LNG\ Export\ Terminal\ Inew_{downstream,t} = \beta C * \left(P_{ng,t} - P_{ng,t-1}\right) * ck$$

where:

$LNG\ Terminal\ Inew_{downstream,t}$ = *new investment (annual) for an LNG terminal at time t*

βC = *the additional capacity of LNG import/export terminals per additional unit of natural gas import/export (million tonnes per year/gas import or export*

Imp_{ng} = *the volume of natural gas imports*

P_{ng} = *the volume of natural gas production*

Investments in power generation are computed per technology on a dollar per megawatt basis (USD/MW). Annual capacity additions in MW from the electricity optimisation model are used, while different cost assumptions are considered per technology. Capital costs for renewable energy, specifically for solar and wind, are assumed to be decreasing. The power generation capacity investment is calculated as:

Equation 14: Power generation capacity investment for each technology

$$Capacity\ Inew_{power,techA} = C_{addition,techA} * ck_{USD/MW}$$

where:

$Capacity\ Inew_{power,techA}$ = *new investment (annual) for power generation capacity of technology A*
$C_{addition,techA}$ = *the additional capacity of power generation of technology A*
$ck_{USD/MW}$ = *unit cost of technology*

New investments for transmission and distribution networks, due to increases in electricity generation, are calculated separately. Additional transmission requirements (km of transmission lines) for renewable energy, linking the source to the transmission network is also estimated and included in transmission investments. Likewise, generation from variable renewables exceeding 20% of total generation are assumed to entail additional transmission costs for grid integration per KWh of generation. The cost of refurbishment of existing and additional transmission networks, based on a 40 years useful life assumption, are also covered in transmission investments. The transmission and distribution network investments are computed as:

Equation 15: Transmission investment

$$Transmission\ Inew_{power,t} = \beta C(Gr_t - GR_{t-1}) * ck_{USD/km} + Re_{capacity,t} * ck_{add,USD/km} + G_{VRE,t} * ck_{USD/kWh} + TR_{refurb.t} * ck_{refurb,USD/km}$$

where:

$Transmission\ Inew_{power,t}$ = *new investment (annual) for power transmission*
βC = *additional length of transmission network required for each additional unit of generation (km/GWh)*
Gr = *the amount of electricity generated*
$ck_{USD/km}$ = *unit cost of transmission (USD/KWh)*
$Re_{capacity,t}$ = *renewable capacity addition at time t*
$ck_{add,USD/km}$ = *unit cost of excess electricity generation from solar and wind (USD/KWh)*
$Tr_{refurb,t}$ = *length of transmission network to be* refurbished at time *t*
$ck_{refurb,USD/km}$ = *unit cost of refurbishment (USD/KWh)*

Equation 16: Distribution investment

$$Distribution\ Inew_{power,t} = \beta C(Gr_t - GR_{t-1}) * ck_{USD/km}$$

where:

$Distribution\ Inew_{power,t}$ = *new investment (annual) for power distribution*
βC = *additional length of distribution network required for each additional unit of generation (km/GWh)*
Gr = *the amount of electricity generated*
$ck_{USD/km}$ = *unit cost of additional distribution network*

Domestic energy transport investments are computed for oil, gas and coal transport using existing capacity of pipelines, railroads, and coal ports. Capacity additions for pipelines are linked with the amount of production (for energy exporters) and imports (for energy importers), while railroads for oil and coal are based on demand (oil and coal). Coal port capacity estimates are associated with both exports and imports. The transport investment is computed as:

Equation 17: Energy transport investment based on demand

$$Energy\ Transport\ Inew_{demand,t} = \beta C\left(E_{d,t} - E_{d,t-1}\right) * ck$$

Equation 18: Energy transport investment based on production

$$Energy\ Transport\ Inew_{production,t} = \beta C(P_t - P_{t-1}) * ck$$

Equation 19: Energy transport investment based on imports

$$Energy\ Transport\ Inew_{imports,t} = \beta C(Imp_t - Imp_{t-1}) * ck$$

where:

$Energy\ Transporrt\ Inew_t$ = *new investment (annual) for energy transport*
βC = *additional capacity required for each additional unit of production/imports/exports*
ck = *capital costs*

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BUILDINGS MODEL

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