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Fossil Fuel Power Plants: Prospects for Potential Available Technologies and Thermal Plants in Latin America

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Presentation

The IDB with its Climate Change Strategy (2011) has taken a proactive approach to financing climate change mitigation and adaptation, including the promotion of renewable energy. The expectation is that, by 2015, the share of low-carbon sources in all power generation capacity funded by the IDB will be 93% of the total generation capacity.

A key component of the IDB's "Analytical Framework for Climate Change Action," which forms the basis of the Climate Change Strategy, is the commitment that the IDB adopt sector-specific principles to ensure that Bank-funded projects take into account the technological options and management practices currently available to guarantee adequate consideration of climate change impacts and the adoption of mitigation measures in relevant sectors. The Bank will continue to finance fossil-fuel-fired thermal plants but will be more selective regarding the type of technology used in projects proposed for funding in order to balance the environmental and economic benefits derived from the projects and impose more stringent Greenhouse Gas (GHG) Emissions Performance Standards (EPS) on funded projects. The Bank has first adopted a GHG emission guideline for coal-fired power plants[1] and with reference to this also a GHG emission guideline for other fossil-fuel power plants.[2]

Within this framework, the general objective of this study was to provide an overview of fossil-fuel-based electric power technologies other than coal-fired technologies (coal-fired technologies are the subject of a specific guideline that has already been adopted by the IDB) and an assessment of the relevance of these technologies in the future power generation mix in Latin America and the Caribbean resulting from new generation and retrofit investment in which the IDB may participate.

The Bank highly appreciates the support from the German Government within the Strategic Partnership, and the work by the consultants and authors. My special thanks go to Emmanuel Boulet and Paul Suding from my unit, who have supervised this work and driven the development of fossil fuel power GHG emissions guidelines in the Bank. We are

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[1] *Coal-Fired Power Plants, An Approach to Reconciling the Financing of Coal-Fired Power Plants with Climate Change Objectives*. 2009. A document of the Inter-American Development Bank.

[2] *Liquid and Gaseous Fossil Fuel Power Plants, An Approach to Reconciling the Financing of Fossil Fuel Power Plants with Climate Change Objectives*. 2012. A document of the Inter-American Development Bank.

thankful to the many other Bank colleagues who have provided comments to the draft guidelines, and to the editors who have made this highly technical work readable and enabled communication.

Janine Ferretti, Chief of VPS/ESG unit

I. Latin American and Caribbean electricity demand and the role of fossil-fuel power plants

This analysis will concentrate on Latin America, as the limited available information related to most of the Caribbean countries makes it very difficult to develop an overall LAC regional perspective in a consistent detail. The analysis will present a few comments on the regional evolution of the power generation capacity for public power services and the long-term perspective for the Caribbean sub-region based on available studies.

A. Historical evolution

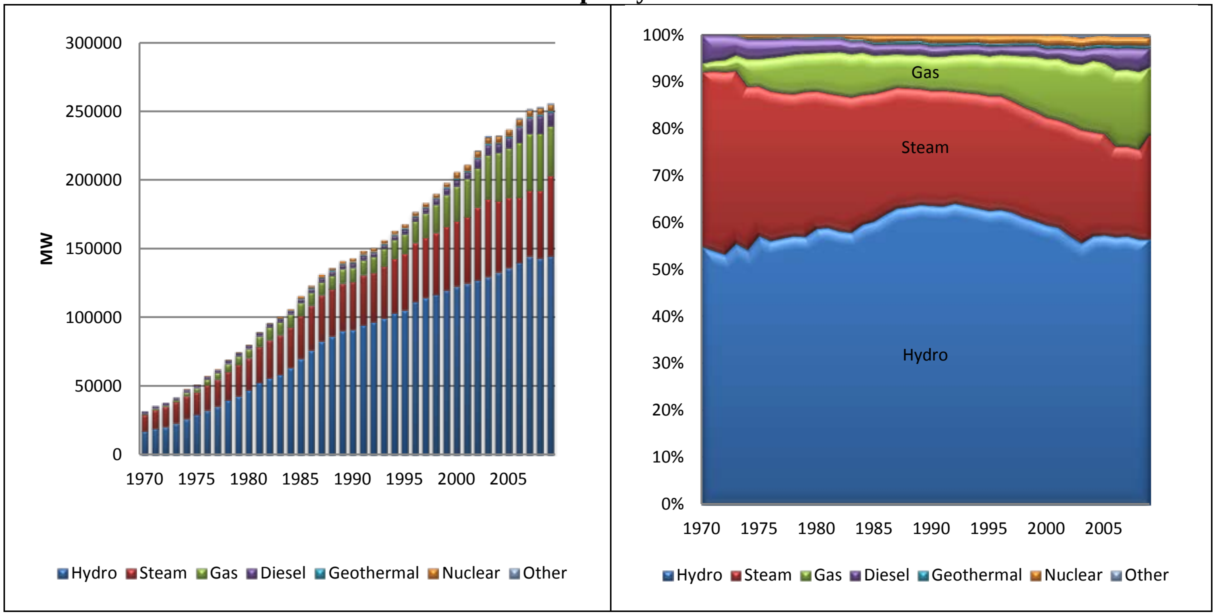
Over the last four decades, the total installed power generation capacity in Latin America has increased eightfold with the development of hydro resources primarily, the introduction of nuclear power plants in Argentina, Brazil, and Mexico, and the development of important geothermal plants in some Central American countries and Mexico. There has also been the remarkable development of gas-fired capacity, basically in combined cycle plants in the region's major economies that have natural gas reserves, resulting in a decline in the installation of steam plants[3] (see Chart 1).

Nevertheless, the development of gas-fired capacity has not been homogeneous, as the number of gas-fired thermal plants has increased in the Andean Countries, Mexico, Brazil, and the Southern Cone. Central America is a different case. In Central America, the number of diesel plants, mostly with medium-speed engines fuelled by heavy fuel oil, has grown from 11% of the total installed capacity in 1970 to 26% in 2009. The number of diesel-oil-fired gas turbines has grown from 4% to 13% over the same period. Despite the strong and sustained hydro and geothermal development in the first two decades of the period, that development subsequently slowed down, with the exception of Costa Rica, which has always been a country with renewable power generation. The renewable generation investment restarted in some countries in the 2000s, although at a slower pace.

[3] The OLADE-SIEE database does identify combined cycles that are included as steam plants, so the real figures will indicate a greater decrease in steam plants and a higher increase in gas plants.

Latin America is a hydro region; about 60% of its electricity is currently generated by hydroelectric plants. Although hydroelectric energy is already playing a major role in power generation, there is still a large unexploited hydro potential that will be developed; therefore, the high percentage of total power generation produced through hydroelectric energy will continue to be maintained, while taking into account environmental, climate, and settlement concerns regarding land use for large reservoirs and construction in protected areas.

Chart 1: Latin America: Evolution of installed capacity



Source: Based on data from OLADE-SIEE. Note: Gas and steam categories include the combined cycles.

In the region, the contribution of private cogeneration industrial facilities to the public interconnected systems is small, although there is frequent selling of surplus electricity to the public network by sugar mills in the sugar cane season.

There are also other cases of thermal optimization for internal use that may involve power cogeneration. For example, it has already been applied for internal energy and water use optimization in the hotel industry in some Latin American countries such as Mexico, or for district heating and cooling, which is no longer used in the region.

B. Long-term prospects

The power generation and installed capacity scenarios that will be presented in the following sections for the entire Latin American region and the sub-regional level are not business-as-usual scenarios based on historical structural trends of electricity demand.

On the contrary, they are the result of an integrated energy-demand analysis over the long term by sector and energy source, including electricity. In the analysis, there are built-in assumptions related to reducing the intensity of energy use through technologies in transportation (e.g., hybrid cars, electric cars, and a reduction in average general improvements in energy efficiency in transportation, industry, household, and commercial usage; structural changes through the introduction of new, more efficient usage of private vehicles due to the introduction of better public transportation alternatives); higher use of natural gas in industry, households, and commerce in many countries; substituting liquefied petroleum gas (LPG) and electricity for firewood in household and commercial usage in several countries, and substituting natural gas and electricity for LPG in others; and the introduction of biofuels such as ethanol and biodiesel into the transportation sector.

In general terms, as in most Latin American countries, there is still an important renewable energy potential for power generation (such as hydro, geothermal, and wind power), and, in many cases, there is the option of firing natural gas in efficient thermal plants, either coming from local reserves or from international markets via liquefied natural gas (LNG). It makes sense to increase electricity consumption by substituting other fuels for thermal uses. The resulting greater demand for power will be partially compensated for by higher energy efficiencies through the introduction of new technologies and better operational efficiency in relevant consumption sectors.

On the power generation side, the scenario reflects the priority given in most of the countries to power generation from renewable primary sources and efficient fuels such as natural gas, complemented in several cases by coal-fired plants and in other cases by nuclear power in the three countries that have that kind of generation (Argentina, Brazil, and Mexico).

1. General regional overview

Recent scenarios[4] foresee a growth of 100% to 150% in electricity demand in Latin America and the Caribbean (LAC) between 2007 and 2030, i.e., from 1,000 TWh in 2007 to between 2,000 and 2,500 TWh in 2030. This requires nearly a duplication of capacity from over 250 GW in 2009 to 480 GW in 2030, in addition to the replacement of obsolete or diminishing capacity.

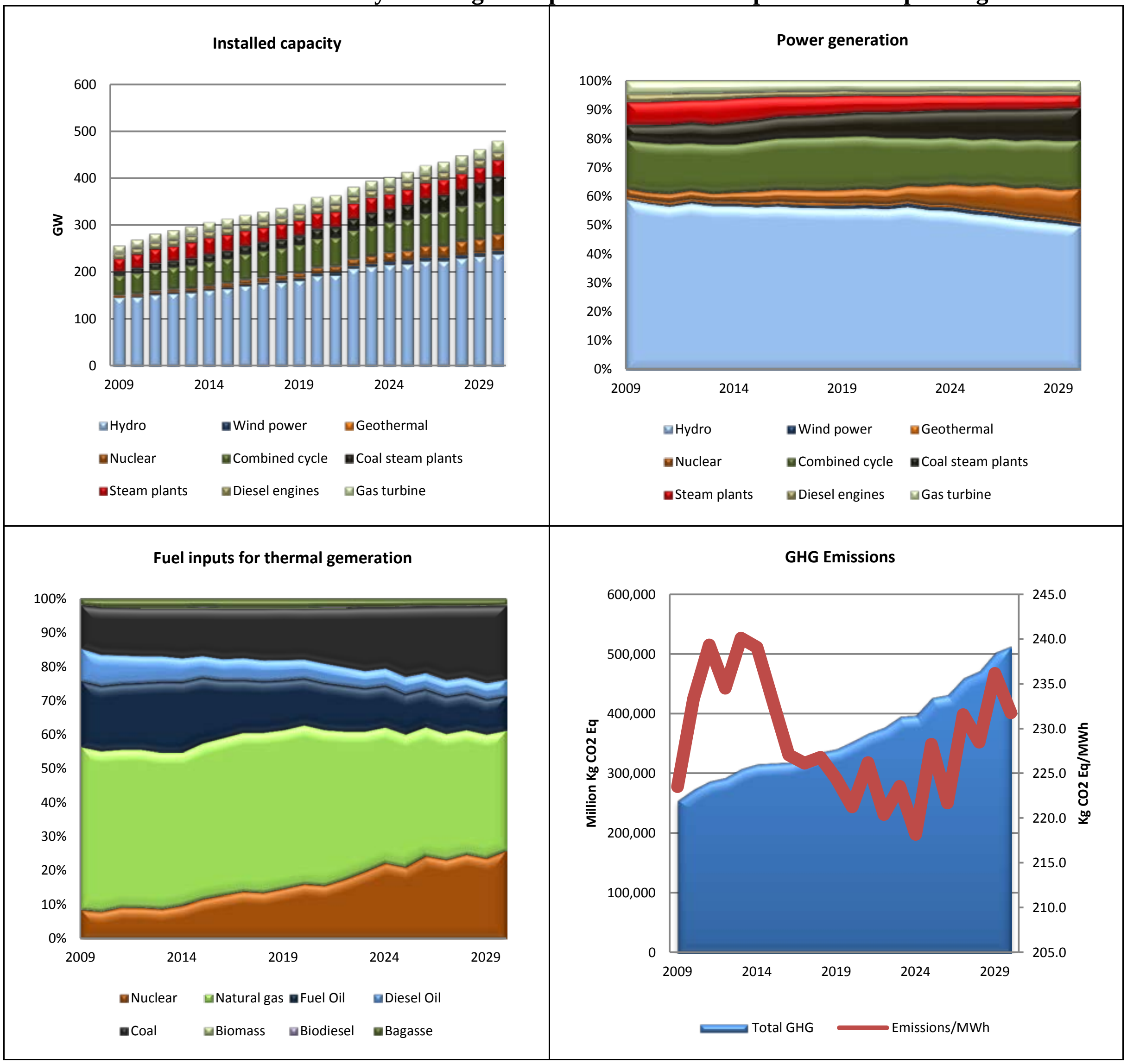
One option for promoting energy efficiency is keeping the growth of electricity consumption at bay. However, this may be countered if increasing concerns over climate change lead to increasing electricity use in transport, substituting it partially for the use of gasoline and diesel; substituting electricity for LPG in households (LPG is subsidized in many countries); and switching to electricity in the commercial and industrial sectors because of the availability of power from low-carbon sources (see Chart 2).

The countries and their respective generators of energy will select investments in additional capacity and replacement according to the local supply of natural renewable and fossil energy resources and their availability from imports; the economic benefits and risks; the environmental impact restrictions; the development strategies and eventual climate considerations; the access to technology; the sizes of plants; and the versatility within the national system and in integrated regional and interregional grids, along with the reliability of the energy sources and the time needed to construct energy-producing facilities.

In specific situations, such as islands like Barbados and other Caribbean countries (but not in the case of Trinidad and Tobago, which has important natural gas reserves and most of the power generation is gas-fired), the local availability of fuel oil might result in a preference for medium-speed diesel plants since their efficiency level is similar to that of steam plants, and the construction of this type of diesel plant is faster. Another special case of heavy fuel availability is Ecuador because of the refining structure. Nevertheless, the high operation and maintenance costs of these diesel plants and their shorter life may shift preferences to larger, efficient steam plants.

[4] Gomelsky, R. and Figueroa, F. et al. OLADE, LAC Energy Prospective to 2032.

Chart 2: Latin America: Summary of a long-term power scenario for public service power generation



Source: Based on R. Gomelsky, F. Figueroa et al. OLADE, LAC Energy Prospective to 2032.

Over the long term, beyond 2020/2030, large and small hydro participation in power generation will tend to be lower, increasing the participation of electricity generated by thermal plants, nuclear power, and coal, oil, and gas fossil fuels. Furthermore, a power supply based on a very high percentage of hydro generation, even under extreme hydrology conditions, is a very proactive planning assumption that leads to overinvestment and additional financial costs.

Other renewable energies still have large deployment potentials in power sectors all over Latin America. Wind energy is becoming increasingly competitive in more places where the resources are good: in the Southern Cone, in coastal Brazil and the Caribbean, and in the Mexican Isthmus.

Geothermal power has good prospects, also depending entirely on resource availability restricted to some sub-regions, especially in Central America.

Power generation from biomass will increase in regions where the resources are available in particular residues; the most relevant case is Brazil. Solar resources are ubiquitous, but the economics indicate concentrating first on specific markets where the electricity supply from other sources is costly, i.e., mostly in rural electrification, where solar resources are already playing an important role.

In any case, even though the share of renewable energies other than regular hydropower in power generation will increase, and may even increase markedly depending on support policies, this share will still be reduced compared with other resources. It should be noted that, if new renewable wind, geothermal, and solar energy constitutes 20% of overall power generation over the long term, it will be a rather impressive achievement.

Nuclear energy may become a competitive option over the long term if proliferation and waste cycle concerns are resolved satisfactorily. However, the generation of this type of energy might be limited to a few countries, especially those that already have nuclear plants in operation (Argentina, Brazil, and Mexico).

The reasons that countries and generators of energy may favor fossil-fuel-based thermoelectric plants are: (i) investment costs and easier financial structuring; (ii) supply security; and (iii) reliability considerations. In more countries, natural gas is becoming available from indigenous resources or imports, through pipelines, and through LNG chains. This increased availability and high-efficiency and low-emission technologies feed expectations of further expansion of natural gas in power generation.

However, price variability expectations may keep countries without domestic fossil fuel resources from engaging in long-term import schemes, but, in some cases such as Central American countries that are already fuel oil importers, the use of LNG will be a way to diversify the energy matrix by lowering costs and GHG emissions. Running optimizing power generation models for Central America shows that, particularly in a regional interconnected grid, LNG is a competitive option.

Among the fossil-fuel power technologies, coal is an option for larger unit sizes where indigenous resources can be used economically. However, imported coal can also be used when the international coal market offers competitive prices and also when environmental and climate change concerns are met. Chile is the one case in Latin America where coal is used for a large portion of power generation, mostly in the Grand North Interconnected System (SING) where most of the copper mining industry is concentrated, but also to a lesser extent in the Central Interconnected System (SIC). This situation will continue in the future according to the Chilean expansion plans. But this is not the only case of coal use. Coal plants are in operation in small countries such as Guatemala and the Dominican Republic, and there are coal plant projects in several Central American countries, Colombia, Argentina, and Brazil.

Annex I presents a comparison of some equipment scenarios in terms of cost and GHG emissions for Argentina, Brazil, and Mexico, which have the most diversified energy matrixes in the region, and for Chile, a country with extensive use of coal-fired steam plants.

In summary, there is a rather wide field of opportunities for non-coal, fossil-fuel power. It is conceivable that electricity generation from natural gas and the respective capacity of oil and gas plants may increase markedly during the coming 20 years of expansion, but the greatest increase will be expected primarily in the last portion of that period, when most of the hydro resources will become utilized. By the year 2030, about one-third of Latin America’s installed capacity will still be non-coal, fossil-fuel-fired thermal plants that will cover about one-fourth of electricity generation.

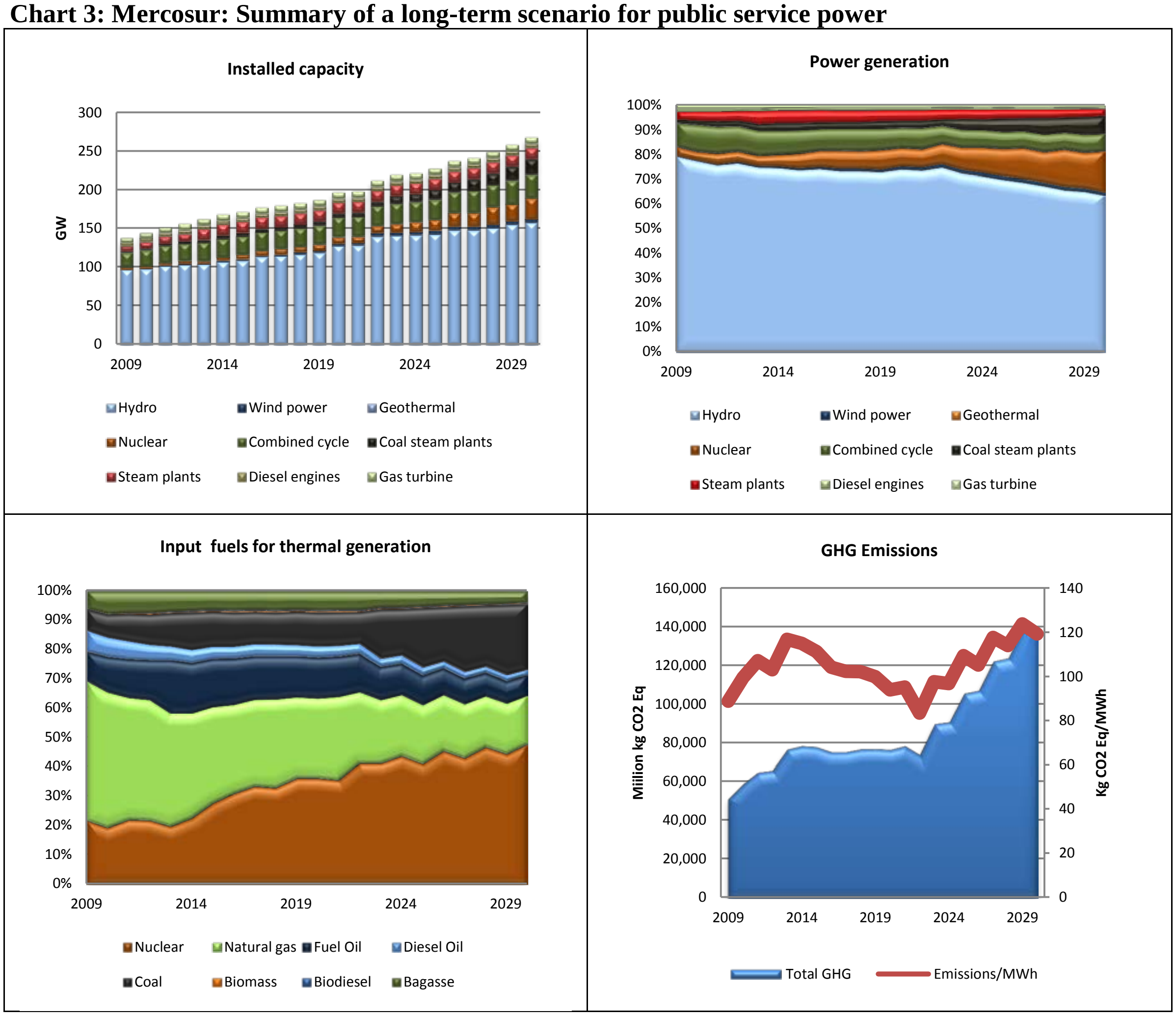
2. Sub-regional long-term prospects

The power sector differs from area to area in the various sub-regions of Latin America because of the availability of natural resources and the power generation technologies applied.

a) *Mercosur*[5]

Chart 3 summarizes what would result from the following at the sub-regional level: a moderated high-growth economic scenario with changes in the demand structure and increasing energy efficiency, and a power generation scenario with the exploitation of most economically attractive hydro sites, including new bi-national developments, an increase and then a decline in indigenous gas reserves, a moderate nuclear option, and some increase in the exploitation of coal reserves in Brazil.

Chart 3: Mercosur: Summary of a long-term scenario for public service power



Source: Based on R. Gomelsky, F. Figueroa et al. OLADE, LAC Energy Prospective to 2032.

Installed power generation capacity will almost double by 2030, and a major portion of the power generated will still be from hydro plants, although the percentage of these plants will

[5] Argentina, Brazil, Paraguay, and Uruguay.

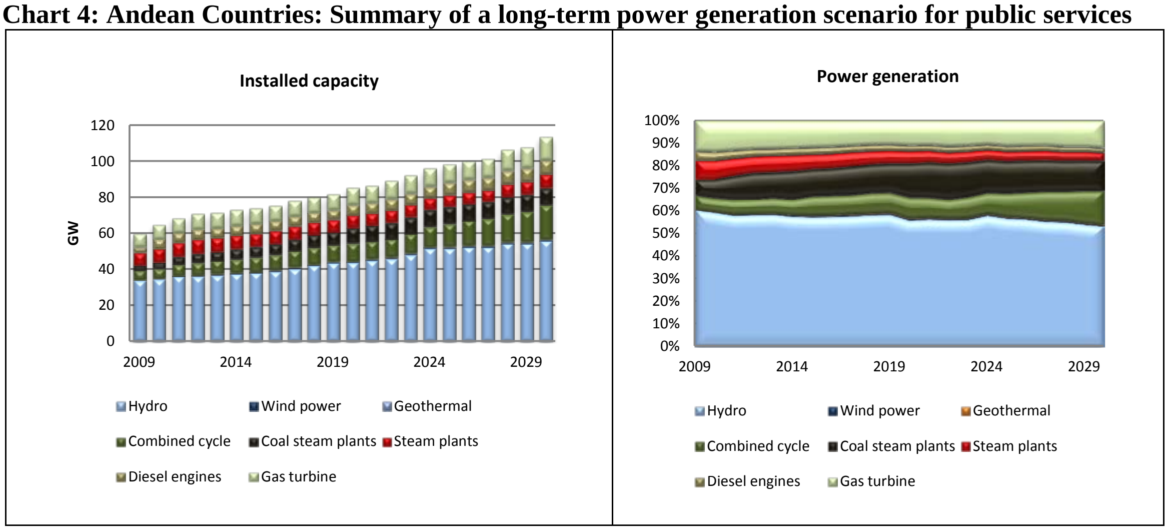
decline from 80% in 2009 to slightly above 60%. On the other hand, nuclear generation of power will increase considerably since, even with a moderate number of additional plants for new capacity, the nuclear plant's very high plant operation factor produces a higher amount of energy. Coal generation will also increase but at a slower pace.

Fuel input structure of the thermal power generation will change according to the changes in the power generation matrix, and GHG emissions will increase as new coal capacity comes on line. Specific emissions per MWh generated will decrease while the development of hydro and gas plants continues, but these emissions will increase starting in 2022 because of additional plants that will increase coal capacity. There will be some fluctuations in emissions because of the steps taken for capacity additions and the modeling of operation simulation.

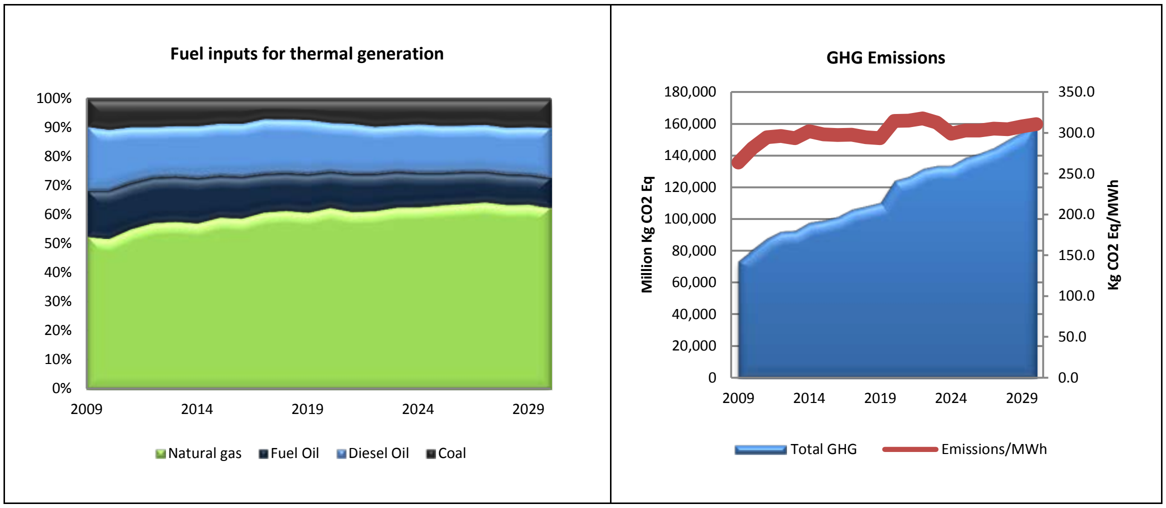
b) Andean Countries[6]

Chart 4 summarizes the results of a power generation scenario in the Andean Countries with moderated high growth economically, changes in the demand structure, and increasing energy efficiency.

Chart 4: Andean Countries: Summary of a long-term power generation scenario for public services



[6] Chile, Bolivia, Peru, Ecuador, Colombia, and Venezuela. It should be noted that, in the case of Venezuela, prospective models could not be created as they were in the other countries because of a lack of available information, making some rough estimates necessary.



Source: Based on R. Gomelsky, F. Figueroa et al. OLADE, LAC Energy Prospective to 2032.

The power generation scenario considers the exploitation of most economically attractive hydro sites, an increase in the utilization of indigenous natural gas reserves for power generation in some countries, and an increase in the capacity of coal plants and in coal plant power generation in Chile following the trends of its current expansion plans. Power generation from hydro plants will decline from 60% to 50% from 2009 to 2030 as combined cycle participation increases. The share of gas turbines in power generation will remain stable due to keeping this equipment in operation extensively in Bolivia for the purpose of firing natural gas and to a less extent in Peru, where there is increasing use and installation of combined cycles.

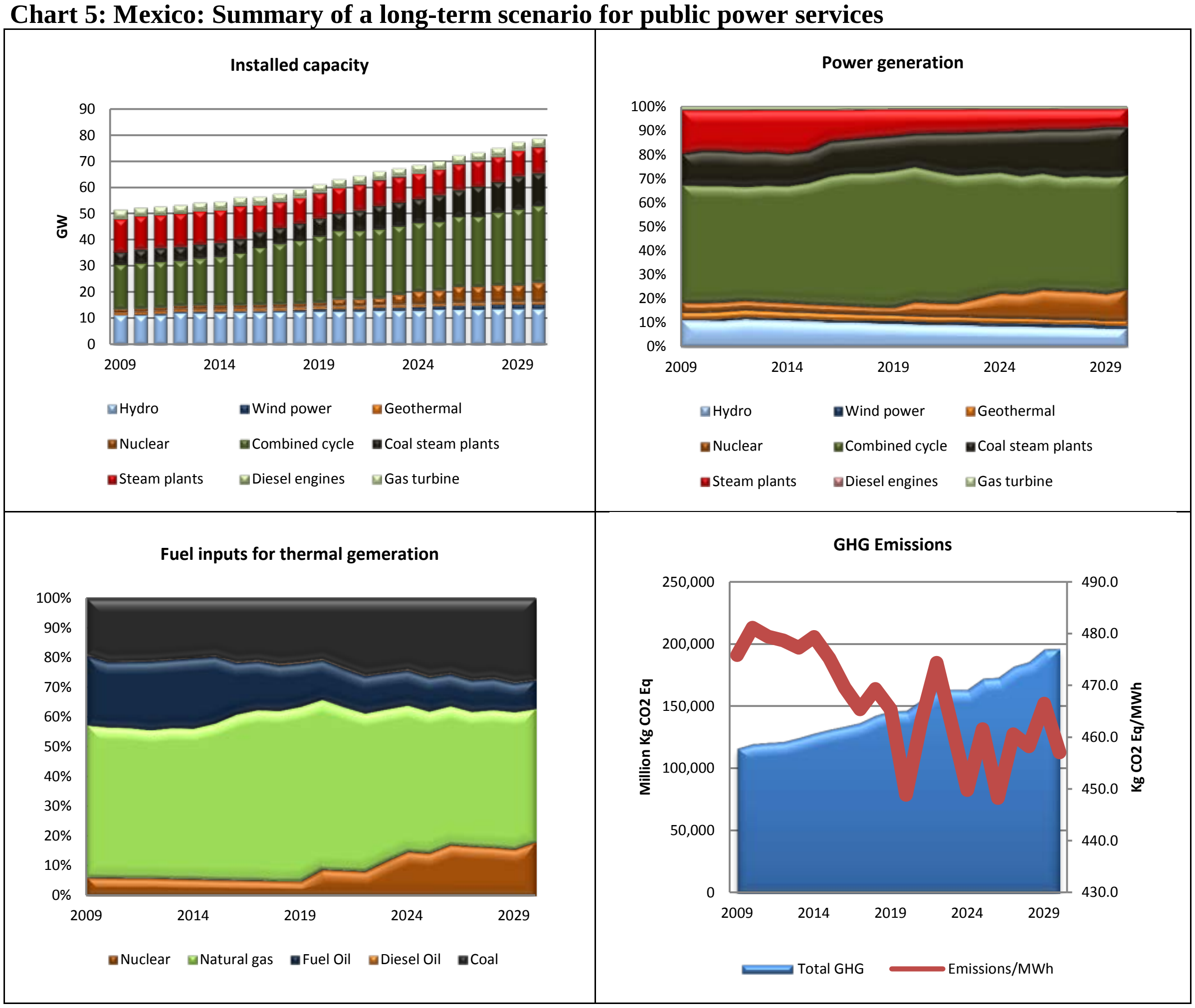
Although there has been some increase over the last few years in the installed capacity of medium-speed diesel plants, fuel-oil-fired plants, some diesel or steam plant projects that refine heavy residuals, or even crude oil steam plants in oil producing fields, this is not the general trend and is not considered in a long-term scenario, which indicates that a low number of diesel plants will participate in power generation.

Fuel input structure will stay stable, while natural gas will maintain a share ranging from 55% to 60% with the rest being diesel oil, fuel oil, and coal. Total GHG emissions in power generation will increase as the thermal generation share grows, but specific emissions per MWh will stay relatively stable showing only a minor increase.

c) *Mexico*

A power generation scenario for Mexico is shown in Chart 5, which considers a moderated high-growth economic scenario, changes in the demand structure, and increasing energy efficiency.

Chart 5: Mexico: Summary of a long-term scenario for public power services



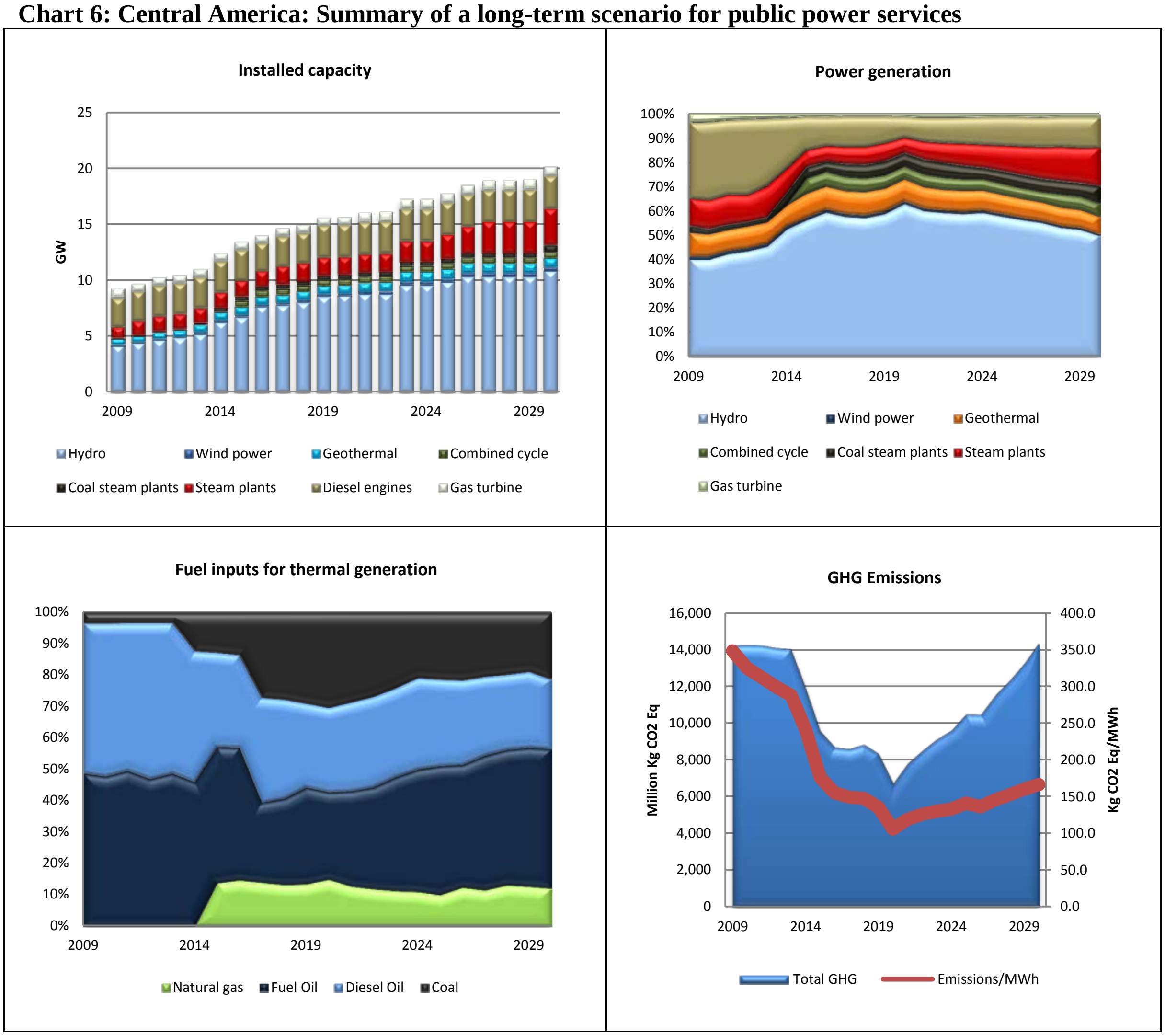
Source: Based on R. Gomelsky, F. Figueroa et al. OLADE, LAC Energy Prospective to 2032.

Mexico is the country that has the least significant remaining hydro potential in the entire region. By 2030, the hydro power plants in the country will generate a bit less power than the 10% generated in 2009. A major portion of power generation will come from gas-fired combined cycle plants. The share of steam plants will continue to decline as many plants will be retired, according to the refining investment strategy of moving toward high-conversion refineries that produce almost no fuel oil or heavy residuals. As most of the Mexican power generation is and will be thermal, total GHG emissions will increase, but emissions per MWh will decline and then reach a stable average as the core of the expanded generation capacity becomes gas-fired combined cycle plants. The large size of the Mexican power system requires constant additions, which produces a fluctuating effect in GHG emissions.

d) Central America[7]

A long-term power generation scenario for Central America is shown in Chart 6, based on a moderately high economic growth scenario and structural changes in energy demand.

Chart 6: Central America: Summary of a long-term scenario for public power services



Source: Based on R. Gomelsky, F. Figueroa et al. OLADE, LAC Energy Prospective to 2032.

[7] Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama.

Installed capacity will double in two decades. The scenario shows the effects of hydro plant development over the first half of that period and, then, the share of hydro plants in power generation declines because there is a slow down as there are few sites left for new construction. This, combined with the installation of combined cycles using natural gas (LNG) and a few new coal facilities, permits the substitution of heavy fuel-oil-fired diesel engines for power generation.

Total GHG emissions will decrease in the next decade considerably as the commissioning of new hydro and geothermal projects continues, and increase again in the second decade when fossil-fuelled thermal power generation is required again. The specific GHG emissions per MWh show a similar pattern, although the increase in specific emissions in the second half of the period will be lower than that of the total emissions.

e) The Caribbean

The Caribbean is a diverse sub-region from the social, economic, and energy standpoint. It has the country with the highest per-capita income in LAC (Trinidad and Tobago) and the country with the lowest per-capita income in LAC (Haiti).

Some of the countries have some oil and gas resources, such as Cuba, Barbados, Suriname, and Trinidad and Tobago. Trinidad and Tobago has very important natural gas resources and is one of the top 10 LNG exporters worldwide. The rest of the countries do not have fossil fuel resources. Cuba, the Dominican Republic, and Haiti have little hydroelectric potential, and it is almost all utilized. All of the Caribbean countries rely on non-conventional renewable energies that may be appropriate for some economic activities such as tourism but not for other industries with huge economic impacts such as mining (Jamaica and Suriname).

Some common factors shared by these countries are:

- They have a strong dependence on oil products to satisfy energy demands, with the exception of Trinidad and Tobago, where natural gas prevails as a major fuel in the energy matrix. Oil products account for a high portion of total energy consumption, ranging from 40% to 80% and averaging 50%.

- They have limited renewable energy resources, mostly the ones that can be exploited on a larger scale, such as hydroelectricity.
- They have important tourism industries, making the economic sector of commerce and service significant.
- In some countries, there is a very important mining industry that is highly intensive in the use of energy.
- The future scenarios show that oil will still be the main energy source for almost all of the Caribbean countries other than Trinidad and Tobago.
- LNG may be an option to diversify the energy matrix of some of the bigger economies of the region, such as the Dominican Republic, Cuba, and Barbados.

Because there is a lack of available and reliable detailed information concerning many of the countries in the sub-region, a breakdown of power generation by types of plants is difficult to summarize, although there are some factors that characterize the power sectors of the Caribbean countries. Most of the power generation in the Caribbean is fossil-fuel thermal.

The Dominican Republic has the most diversified power generation, with a small proportion of hydro plants; coal steam plants; fuel-oil steam plants; and even combined cycle plants importing LNG. Plans include increasing the capacity for importing LNG and adding more coal plants, among other types of plants.

Cuba also has a small hydro capacity; fuel-oil steam plants; and one oil combined cycle, having expanded distributed power generation throughout the island by means of both medium-speed, fuel-oil-fired diesel engines and high-speed diesel oil (light fuel oil) engines.

Trinidad and Tobago generates almost all of its electricity with natural gas, while the rest of the countries generate most of their power with oil products.

II. Relevant fossil-fuel power plant technologies and their impact on climate change

Relevant technologies are characterized by their thermodynamic cycles, operational temperatures, and pressures, which determine their efficiencies, the types of fuels that they may use (there are technologies that allow burning different fuels), their useful life, their ability to start up quickly or slowly, and investment and operational costs (fuel, fixed O&M, and variable O&M).

The fossil-fuel input may be solid (coal, wood, other biomass products such as sugar cane bagasse, and other agro industrial residues), liquid (oil products or liquefied solid fuel) or gaseous (natural gas, petroleum gas, or coal-like mine , coal-bed gas, high-furnace gas, coke gas, and refinery gases). According to the place where the combustion of fuel takes place, the thermal power generation plants can be grouped into external combustion plants (such as steam plants where fuel is fired in boilers to produce steam and the cycle is realized by water changing its physical parameters, or where fuel is fired inside a combustion chamber in gas turbines) and internal combustion plants with engines like the usual Otto cycle engine used in automobiles (generally not used for public service power generation) and the Diesel cycle engines that are used for a variety of applications in transportation and power generation.

The fluid (water or combustion gases or air) that realizes the thermodynamic cycle moves a rotating machine (turbine or motor) that, in turn, drives an electrical generator to produce alternate current through the physical electromagnetic induction law (Faraday).

Large power plants are operated within an interconnected electricity supply system, including a mix of different power plants, a transmission and distribution grid, and the consumers, which is usually considered a public service. Outside of the integrated grid, small power plants are operated to supply a limited number of customers or an isolated electricity grid, or to distribute power to isolated customers (e.g., in rural areas), which is also considered a public service.

However, there are also power plants that are owned, built, and operated by consumers themselves for receiving supplementary or back-up power, with or without connection to a grid. These plants are considered self-consumption or self-generation plants, although, in some cases, consumers may sell excess available power to the public grid.

Considering the technologies for power generation that are currently commercially available, there are only three basic thermodynamic cycles that are utilized: the Brayton cycle (gas turbines), the Rankine cycle (steam turbines), and the internal combustion cycles, such as the Otto cycle engines used in the automobile industry—which may have some applications in small back-power units but are not relevant for major power generation—and the Diesel cycle engines used in power generation both in public and self-generation services.

Table 1 presents different types of plant options for generating power and their characteristics according to their thermodynamic cycles, depending on applications, materials, technologies, the combination of cycles, working temperatures, and pressures.

Table 1: Main technologies for power generation only

Thermodynamic cycle	Type of plant	Main fuels	Efficiencies (1)	Unit sizes (2)	Dispatch (normal)	GHG emissions	Investment (USD$/KW) (3)	Non-fuel O&M	Useful life (years)
Gas turbines (Brayton cycle)	Aero-derivative	Gas (4) Diesel/LFO	25%-35%	5-20 MW	Peak	Medium (natural gas) High (diesel oil)	700-800	High	15
	Micro-turbines (new)	Gas Other	25%-35%	Less than KW Hundreds KW	Distributed generation	Low to medium	n.a	Low	n.a
	Power generation	Gas Diesel/LFO	25%-35%	Up to 200-300 MW	Peak	Medium (natural gas) High (diesel oil)	700-800	High	20
	Combined cycle	Gas	50%-60%	Above 150-200 MW	Base load Medium load	Low	1,200-1,400	Low	30
Steam turbines (Rankine cycle)	Condensing, simple or reheat	Gas Fuel Oil Coal Biomass	40%-45%	20-600 MW	Base load Medium load	Low (natural gas) High (fuel oil)	1,000-1,200	Medium	30-40
	Back-pressure	Fuel Oil Coal Biomass	25%-35%	5-50 MW	Base load	Low to medium	1,200-1,500	Medium-high	30
	Nuclear	Nuclear	30%-35%	Specific design	Base load	None	3,000-4,000	Very low	30-40
	Geothermal	Natural steam	30%	Specific design	Base load	None	2,000-2,500	Medium-high	30
Internal combustion (Diesel cycle)	Regular diesel engines	Diesel/LFO Gas	25%-30%	5 KW to 10-15MW	Peak-medium	High	800-1,000	High	20
	Medium-speed engines	Fuel Oil	35%-40%	Up to 30 MW	Medium	High	800-1,000	High	20

(1) There is a wide variation depending on age, de-rating by external conditions (i.e., altitude) and operations (dispatch), although there is a positive relationship between efficiency and size, mostly for large plants.[8]
(2) Only indicative.

[8] "Securing Energy Supply and Enlarging Markets through Cleaner Fossil Technology. A Review of the Power Sector in Latin America and the Caribbean, Evolution in the Market and Investment Opportunities for CFTs." March 2005. OLADE-CIEMAT.

(3) Only indicative; depends not only on technology and manufactures, but also on equipment and financial market conditions.
(4) Natural gas from a gas network (pipelines) or from a liquefied natural gas (LNG) re-gasification plant.
Source: Own analysis.

In Annex II, there is a brief technical description of thermodynamic cycles and the technologies currently used for thermal generation.

This overview comprises all major thermal power technologies, apart from the fossil-fuel-fired and nuclear-, geothermal-, and biomass-powered technologies, which are not subject to the guideline on fossil-fuel power plants under consideration. Although fired by fossil fuel, the coal power plant technologies are not considered further in this paper because the respective guideline[9] has already been adopted by the IDB. Some of the power generation technologies and thermodynamic cycles have other applications for non-electric power generation, such as those used in marine propulsion, airplanes, and fluid compression, which are not considered in this analysis.

The cogeneration applications are a positive consideration in this analysis, however. They are used by large customers, which, in many cases, sell excess power to the interconnected public network. The simultaneous generation of electricity and production of other energy products in a power plant increases the combined efficiency significantly. The heat production may reduce the power generation, but it produces other outputs such as steam in industrial joint electricity-heat production. These are called cogeneration plants. If there is a combined heat/cold and power production, known as tri-generation, the heat may be used in an absorption process to operate absorption chillers.

Focusing on natural gas, diesel (light fuel oil),[10] and (heavy) fuel oil, the technologies in question are presented in Table 2, with their standard and range of performance generally achievable both in terms of efficiency and the intensity of GHG emissions.

[9] *Coal-Fired Power Plants, An Approach to Reconciling the Financing of Coal-Fired Power Plants with Climate Change objectives*. 2009. A document of the Inter-American Development Bank.
[10] The diesel oil used for industrial uses and power generation is usually different from the diesel oil used in transportation, which is a lighter cut of hydrocarbons and is commercialized in several countries under a different name (gas oil).

Table 2: Energy efficiencies and GHG emissions of selected power generation technologies

Technology	Plant factor (%)	Efficiency Range (%) (1)	GHG emissions (kg CO2 Eq./MWh)(2)		
			Natural gas	HFO	Diesel (LFO)
Steam turbine, condensing	80%-85%	From 40%	505	697	667
		To 45%	449	619	593
Steam turbine, back pressure (3)	65%-70%	From 35%	577	796	762
		To 38%	531	733	702
Gas turbine	10%-15%	From 28%	721	n.a.	953
		To 36%	561	n.a.	741
Combined cycle	80%-85%	From 47%	430	n.a.	568
		To 60%	337	n.a.	445
Internal combustion regular diesel engine (4)	30%-50%	From 30%	673	n.a.	889
		To 33%	612	n.a.	808
Internal combustion medium-speed diesel engine (4)	50%-65%	From 38%	531	733	702
		To 42%	481	663	635

(1) Since efficiencies have just slight variations according to the type of technology used and there are only a few references found, a wide range of efficiencies for each type of plant was assumed that may include those variations in addition to the range of efficiency of the thermodynamic cycle itself.
(2) CO2 Emissions (kg/MWh)=(3.6/Efficiency (%))*CO2 from fuel (kg/Gigajoule of fuel consumed).
(3) Usually not used in power service networks.
(4) May need adaptations to use natural gas; usually are LFO or HFO fired.
Source: Own analysis based on information from IPCC[11] (GHG emissions by fuels per Gigajoule consumed).

Table 2 shows that natural gas has a clear advantage with respect to mitigating emissions. Where natural gas is not available, it is still possible to attain efficiencies as high as 40% to 50% and GHG emission levels as low as 600 kg CO2/MWh using petroleum products with the best available technologies.

Setting minimum- and maximum-range emissions in the kg CO_2/MWh threshold for each type of fuel and technology is recommended, as emissions are determined by the characteristics of fuels (the specific emissions per thermal energy of fuel used [kg CO2/Gigajoule]) and the efficiency of the plant (this covers any type of technology). This may provide a parameter that is easy to compare and control.

The total amount of GHG emissions of plants also depends on the load factor, i.e., the number of hours of full-capacity employment per year (as a ratio of all 8,760 hours).

The availability of natural gas provides the widest choice of technologies for the production of electricity from it as well as from petroleum products, as shown in Table 2. Gas technologies might be considered even in countries or areas with no gas reserves or current

[11] *Air pollution from electricity-generating large combustion plants. An assessment of the theoretical emission reduction of SO2 and NOX*. European Environmental Agency (EEA). EEA Technical Report No 4/2008.

pipeline connections as international pipelines are extended and there is a growing infrastructure for LNG. LNG is becoming more competitive with scale and presents a wide range of supply options. Today, it represents about 30% of natural gas trade globally. If the availability of natural gas is planned for the medium term, plants may be fuelled temporarily with light fuel oil (LFO) with appropriate planning.

From the information on efficiency and emissions, it may be concluded that the following power technologies might be the ones prioritized for financing by the IDB for public services:

From a climate change mitigation point of view:

- Natural gas combined cycle plants are clearly the most appropriate technology because of their efficiency and rather low specific GHG emissions.
- Large condensing steam plants with intermediate extraction, which is usual in interconnected power systems, may achieve efficiencies of 45%. Their specific GHG emissions in the case of natural gas firing are as low as 450-500 kg CO2/MWh, but they are still not comparable to those of gas turbine combined cycle (GTCC) plants.
- Single cycle gas turbines fired by natural gas are acceptable as a peak load device only, but the use of diesel oil in gas turbines may be accepted only when there is no possibility of obtaining a natural gas supply and where and when there is no other possibility for peaking.

If natural gas is not available in the short or medium term, fuel-oil-fired steam and internal combustion plants come into play:

  - Large steam plants may be justifiable if the best steam technology is applied complying with a 45% minimum efficiency and maximum specific GHG emissions of 700 Kg CO2/MWh. It may be convenient to analyze the inclusion of preparations to implement carbon capture and storage (CCS)[12] in the plant design as this technology develops and becomes cost effective.
  - The efficiency parameters of steam plants can be improved significantly if cogeneration is applied. This also permits raising the return on investment if income

[12] Metz, B., Davidson, O., and de Coninck, H. et al. (Eds.). 2005. "IPCC Special Report on Carbon Dioxide Capture and Storage." UK: Cambridge University Press.

from selling steam or other energy products increases more than additional expenditures for operating costs and energy input (or the loss of income from reduced electricity sales).

- Steam plants using back-pressure turbines may also be considered in the case of self-cogeneration. Compared to condensing turbines, back-pressure turbines may be less costly, although the ratio between power and heat is rigid. On the other hand, the extraction of heat from plants using condensing turbines is variable and can be adjusted to demand, and these plants are more efficient than those using back-pressure turbines.
- Internal combustion plants with medium-speed engines may achieve efficiencies similar to those of steam plants. With the use of heavy fuel oil, GHG emissions may reach less than 700 Kg CO2/MWh, which may be satisfactory. However, it is preferable to improve performance under a cogeneration arrangement.
- There are generation or cogeneration units based on internal combustion motors or gas or steam turbines that use locally available fuels, as in the case of the oil and gas extraction industry's on-site power generation fuelled by byproducts of the extraction (e.g., associated gas, coal bed gas, or mine gas) and supplying heat as well as electricity. Such plants may be highly recommended in particular when they put a GHG to use that might otherwise escape into the atmosphere or might be flared without generating useful energy.

The issue of conversion is to be considered especially carefully with dual or multiple fuel plants, steam plants, or even combined cycle (CC) plants. A plant with reasonably low emissions because of the use of a lower carbon fuel such as natural gas may be converted after approval or some years of operation to a fuel that has different and higher GHG emissions such as fuel oil.

In general, there is a relationship between efficiency and size mostly for large plants[13]; therefore, choosing larger unit sizes may be recommended. It should be considered, however, that the economies of scale may be lost because the larger investment required

[13] "Securing Energy Supply and Enlarging Markets through Cleaner Fossil Technology. A Review of the Power Sector in Latin America and the Caribbean, Evolution in the Market and Investment Opportunities for CFTs." March 2005. OLADE-CIEMAT.

would make the arrangement of a project or balance-sheet finance structure difficult, mostly in non-investment grade countries.

The following types of power plants should not be on a priority list:

- Internal combustion generators of any size driven by the Otto cycle and fuelled by gasoline.
- In general terms, self-generation without cogeneration is less efficient and should not be promoted, particularly the type of small diesel generators in buildings and industry. These are often used in electricity grids of low service quality to provide a back-up and supplementary supply of power. Public services have to be enhanced since a persistently low reliability of services may lead to the wider use of inefficient and polluting private systems on a permanent basis. This issue is a matter of concern for several reasons, including climate change, and is dealt with by the IDB country programs.
- Remote diesel generators as part of off-grid electrification of any size, given that the IDB is giving priority to promoting renewable energy and alleviating the local environmental and economic problems stemming from diesel generators. In the LAC region, there are local energy resources to meet local demand, such as small and micro hydro, wind, and solar devices for rural electrification. These resources are already in use but have to be increased.
- In some special cases, thermal steam plants that are crude-oil-fired are used as a power supply for oil companies in oil exploitation fields in areas where there is no public service power supply. For example, this type of plant currently exists in the Oriente region of Ecuador. There are also projects that use heavy residuals from refineries, as in the Shushufindi refinery in Ecuador. These can be steam or medium-speed engine plants. These kinds of projects should not be promoted through IDB financing. Burning associate gas to generate electricity is a better energy solution that lowers GHG emissions. In the case of refineries, the highest added value may arise from investing in conversion to reduce heavy residuals, with a power supply from the interconnected grid and emergency back-up from steam plants or conventional diesel plants.

It should not be overlooked that reducing GHG emissions is not only a matter of the characteristics of power plants and technologies, but also of maintenance and operational practices, as well as dispatch needs, at any given moment. Even when correct planning is carried out and the right type of plant is built, the wrong maintenance may lead to operation of the equipment outside of its efficient design parameters. The same effect may occur as a consequence of the dispatch below the design's most efficient output.

In that sense, in almost all of the countries, there are requirements for obtaining an environmental license for the operation of any kind of power generation plant. The license is usually given after the presentation and approval of an environmental impact study, both at the project design stage and after construction. But control of the environmental issues involved in a commercial operation is not always carried out. The IDB may be required to establish some conditions for IDB borrowers to comply with related to maintenance practices and the use of fuels in commercial operations.

III. Conclusions

The main conclusions are summarized as follows:

- It is recommended that minimum efficiency and maximum GHG emission requirements be considered for each type of plant that may be prioritized for IDB financing.

- The power technologies that may be prioritized for financing by the IDB for public services are:
    - Natural-gas-fired combined cycle plants, which are the most efficient and the best from the GHG emissions standpoint, even in areas with no gas reserves since there is an increasing market for LNG.
    - Large condensing steam plants with intermediate extraction, which is usual in interconnected power systems, are efficient, but, with respect to GHG emissions, only plants using natural gas should be eligible according to the new financing parameters. This includes cogeneration plants to supply industrial power and sell heat surplus to the power network. If natural gas is

not available, efficient steam plants using liquid fossil fuels may be eligible if they comply with minimum efficiency and maximum emission parameters

  - Steam cogeneration plants linked to agro-industrial processes that sell power to the interconnected grid. Biomass is not a fossil fuel but a renewable fuel, but biomass-fired cogeneration steam plants are efficient, may sell relevant amounts of power to the public grid, and permit the use of residues that otherwise might negatively affect the environment, mostly through water and soil pollution. This type of pollution has very important negative environmental effects even though it does not involve GHG emissions.
  - Back-pressure steam plants may also be considered not in terms of self-cogeneration, but to the extent that they may use fossil fuels or biomass and have enough capacity to deliver energy to the power network. However, it is preferable to give priority to condensing turbines as they are more efficient in generating power.
  - Generation or cogeneration units based on internal combustion motors or gas or steam turbines that use locally available fuels, as in the case of the oil and gas extraction industry's on-site power generation fuelled by byproducts of the extraction (e.g., associated gas, coal bed gas, or mine gas) and supplying heat as well as electricity, mainly when they put a GHG to use that might otherwise escape into the atmosphere or that would be burned without generating useful energy.

- The following types of power plants should not be on a priority list:
  - Internal combustion generators of any size driven by the Otto cycle and fuelled by gasoline
  - In general terms, self-generation without cogeneration is less efficient and should not be promoted, particularly the type of small diesel generators in buildings and industry. These are often used in electricity grids of low service quality to provide a back-up and supplementary supply of power. Public services have to be enhanced.
  - Remote diesel generators as part of off-grid electrification of any size, given that the IDB is giving priority to promoting renewable energy and

alleviating the local environmental and economic problems stemming from diesel generators. In the LAC region, there are local energy resources to meet local demand, such as small and micro hydro, wind, and solar devices for rural electrification. These resources are already in use but have to be increased

- Regarding the size of power plants, there is a relationship between efficiency and size mostly for large plants.[14] It should be considered, however, that the economies of scale may be lost because the larger investment required for larger unit sizes would make the arrangement of a project or balance-sheet finance structure difficult, mostly in non-investment grade countries.

- The investment decision-making process has to change:
    - Environmental issues are not really part of a project's selection process; the key objective is to minimize cost.
    - What does an optimum or economically adapted system mean? Is it really the least investment and operational cost?
    - The reality is that "optimum" exists only on paper; the actual systems are far from "optimum."
    - Optimum actually might be the investment plan that is financially viable (bankable) and environmentally sound.
    - If we want clean energy, we should be prepared to pay for it.
    - The role of financial institutions such as the IDB may be very important to changing the decision-making process.

- Dispatch rules also have to be revised:
    - GHG emission reduction is not only a matter of the characteristics of power plants, technologies, and fuels, but also of maintenance and operational practices and dispatch needs at any given moment.

[14] "Securing Energy Supply and Enlarging Markets through Cleaner Fossil Technology. A Review of the Power Sector in Latin America and the Caribbean, Evolution in the Market and Investment Opportunities for CFTs." March 2005. OLADE-CIEMAT.

- Even when correct planning is carried out and the right type of plant is built, the wrong maintenance may lead to operation of the equipment outside of its efficient design parameters. The same effect may occur as a consequence of the dispatch below the design's most efficient output.
- Correct control of the environmental issues involved in a commercial operation is not always carried out. A similar issue may arise when an efficient plant is used for commercial operations burning a fuel that has different and higher GHG emissions.

- The IDB might be required to establish some conditions for IDB borrowers to comply with related to maintenance practices and the use of fuels in commercial operations.

- Thermal generation will still be necessary, particularly fossil-fuelled generation:
  - Latin America is already a hydro region. Although hydroelectric energy is playing a major role in power generation, there is still a large unexploited hydro potential that will be developed, taking into account some environmental concerns regarding land use for large reservoirs and avoiding the construction of power plants in protected areas.
  - There are some cases where the remaining hydro potential is limited (i.e., Mexico), but, in any case, over the next two to three decades, hydro development may reach its limits because of the availability of technically and economically attractive sites, even in countries with huge hydro potential such as Brazil or Costa Rica. After that, the role of thermal power in meeting the electricity demand will increase in most of the countries.
  - There is always a need to count on thermal support to ensure a sufficient energy supply during dry seasons, which may become more frequent and more sustained as a consequence of climate change and because of the lack of hydro basin/forest resources management.
  - Over the long term, beyond 2020/2030, hydro participation in power generation will tend to be lower. Furthermore, a power supply based on a very high percentage of hydro generation, even under extreme hydrology

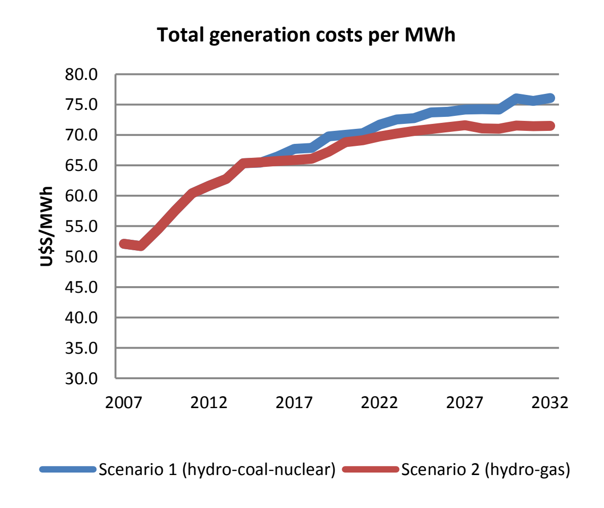
conditions, is a very proactive planning assumption that leads to overinvestment and additional financial costs.

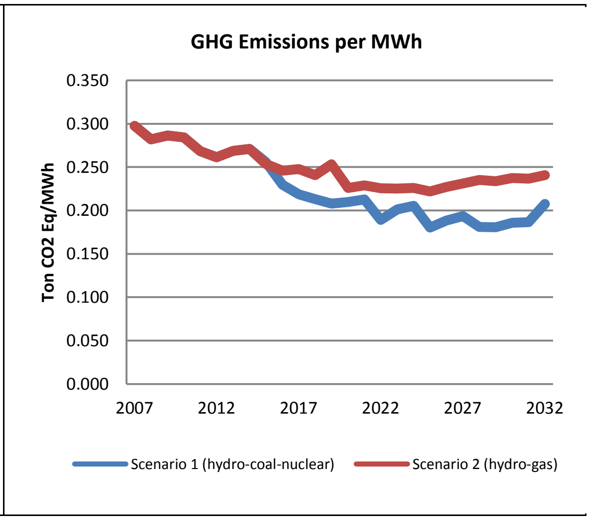
- There is a rather wide field of opportunities for non-coal, fossil-fuel power. It is expected that electricity generation from natural gas and the respective capacity of oil and gas plants may increase markedly during the coming 20 years of expansion but mostly in the last portion of that period, when most of the hydro resources will become utilized.

Annex I: Comparison of different equipment scenarios in selected countries

A. Costs and GHG emissions of different technologies: the case of diversified generation matrix countries

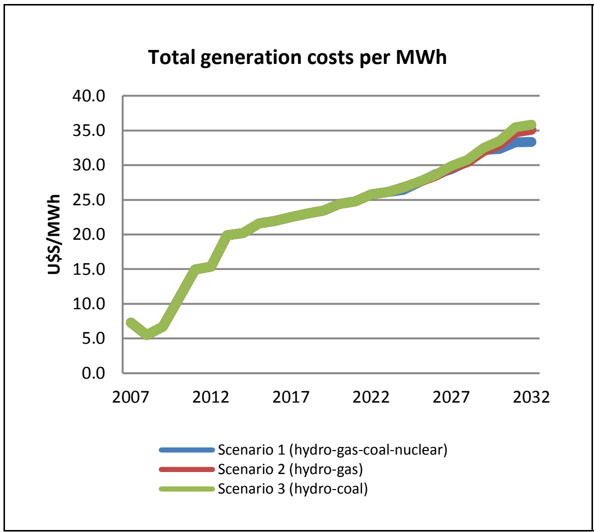
Argentina

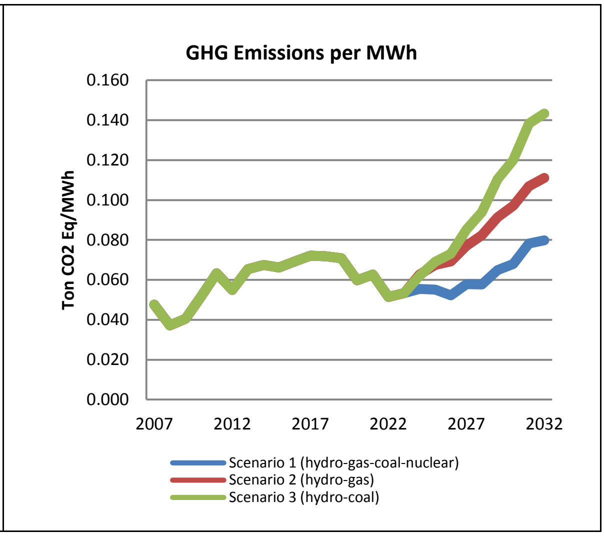




Source: Based on R. Gomelsky et al. World Bank, LAC Power Sector Scenarios to 2032.

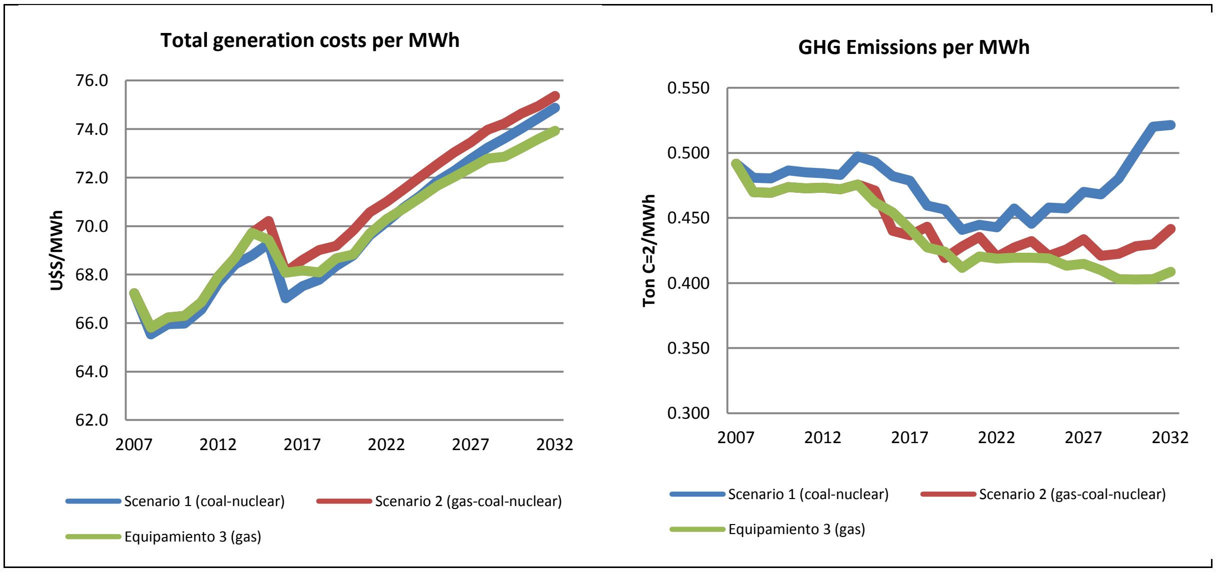
Brazil





Source: Based on R. Gomelsky et al. World Bank, LAC Power Sector Scenarios to 2032.

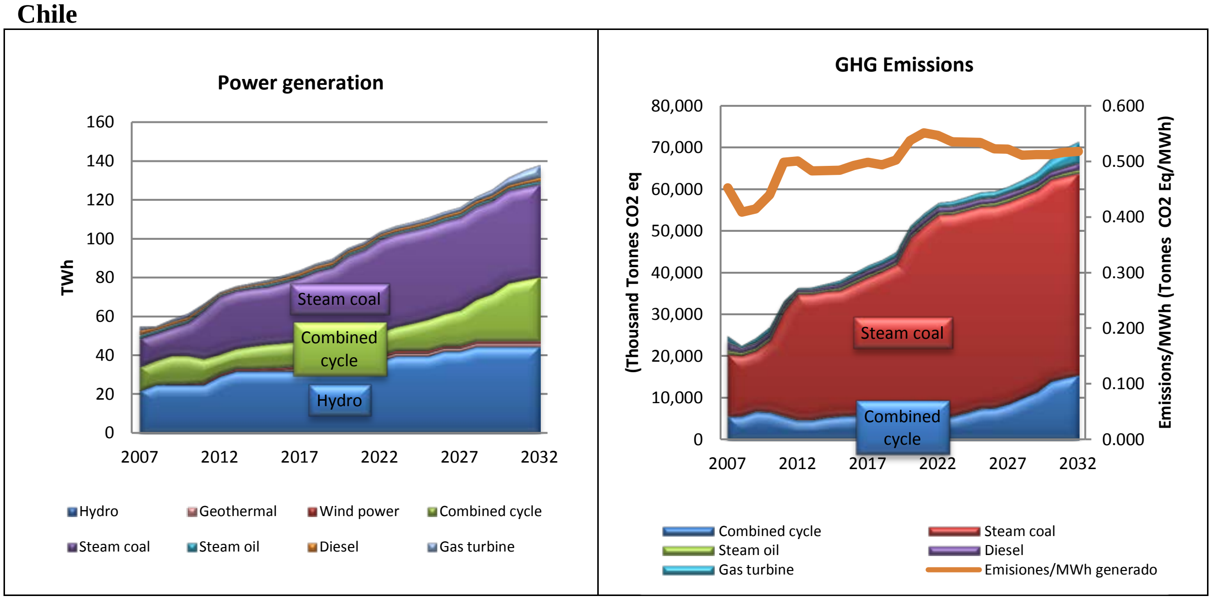
Mexico



Source: Based on R. Gomelsky et al. World Bank, LAC Power Sector Scenarios to 2032.

B. Costs and GHG emissions of different technologies: the case of high coal and gas thermal generation

Chile



Source: Based on R. Gomelsky et al. World Bank, LAC Power Sector Scenarios to 2032.

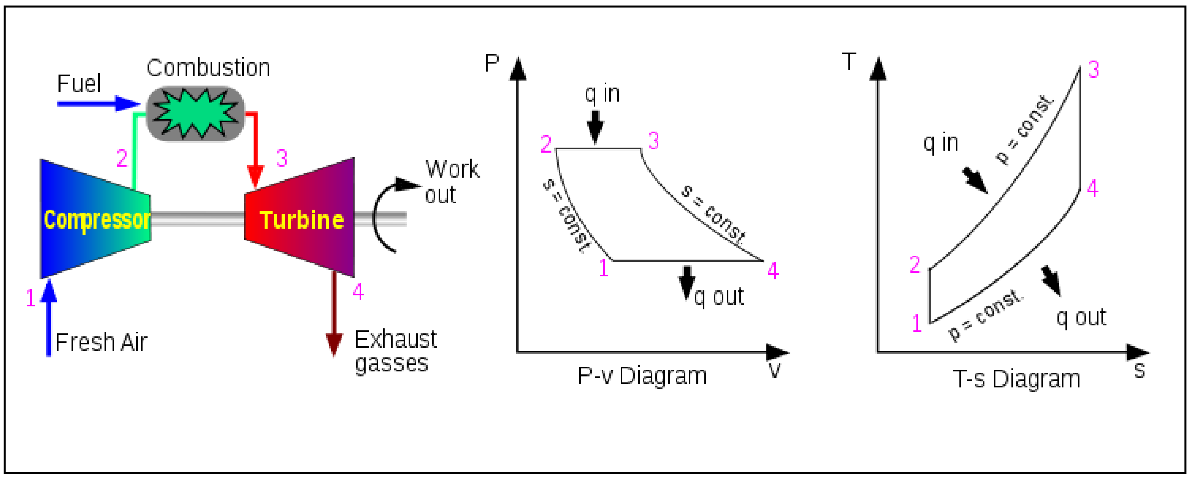
Annex II: Fossil-fuel power plant technologies[15]

A. Gas turbines

1. The Brayton cycle

Gas turbines are described thermodynamically by the Brayton cycle (see diagram A1), in which air is compressed isentropically (that is, at the same entropy or energy level, as shown in the T-S temperature-entropy diagram below), combustion occurs at constant pressure, and expansion over the turbine occurs isentropically back to the starting pressure.

Graphic A1: The Brayton cycle



Notes: P: Pressure; T: Temperature; V: Volume; S: Entropy; q: Heat

As with all cyclic heat engines, higher combustion temperature means greater efficiency. The limiting factor is the ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand heat and pressure. Considerable engineering goes into keeping the turbine parts cool. Some turbines also try to recover exhaust heat, which otherwise is wasted energy. Recuperators are heat exchangers that pass exhaust heat to the compressed air, prior to combustion. The combined cycle designs pass waste heat to the steam turbine system, and combined heat and power (cogeneration) use waste heat for hot water production.

[15] The summary description of thermodynamic cycles is based on several references quoted in Wikipedia; "Securing Energy Supply and Enlarging Markets through Cleaner Fossil Technology," op. cit.; manufacturers' web sites; Ecoelectric S.A., Ecuador.

Mechanically, gas turbines can be considerably less complex than internal combustion piston engines. Simple turbines might have just one moving part: the shaft/compressor/turbine/alternative-rotor assembly, not counting the fuel system. However, the precision required in manufacturing the components and the temperature-resistant alloys necessary to achieve high efficiency often make the construction of a simple turbine more complicated than that of a piston engine.

More sophisticated turbines (such as those found in modern jet engines) may have multiple shafts (spools), hundreds of turbine blades, movable stator blades, and a vast system of complex piping, combustors, and heat exchangers.

As a general rule, the smaller the engine, the higher the rotation rate of the shaft(s) needs to be to maintain top speed. Turbine blade top speed determines the maximum pressure that can be gained; this produces the maximum power possible independently of the size of the engine. Jet engines operate around 10,000 rpm and micro turbines around 100,000 rpm.

2. Aero-derivatives and jet engines

Air breathing jet engines are gas turbines optimized to produce thrust from the exhaust gases, or from ducted fans connected to the gas turbines. Jet engines that produce driving force primarily from the direct impulse of exhaust gases are often called turbojets, whereas those that generate most of their propulsion from the action of a ducted fan are often called turbofans. Gas turbines are also used in many liquid propellant rockets. The gas turbines are used to power a turbo-pump to permit the use of lightweight, low pressure tanks, which saves considerable dry mass.

Aero-derivative gas turbines are also used in electrical power generation due to their ability to start up, shut down, and manage load changes more quickly than industrial machines. But the useful life of these turbines may be shorter than that of the industrial turbines due to the high speed. They are also used in the marine industry to reduce weight.

3. Industrial gas turbines for power generation

Industrial gas turbines differ from aero-derivative gas turbines in that the frames, bearings, and blading are of heavier construction. Industrial gas turbines range in size from truckmounted mobile plants to bigger, complex systems. They can be particularly efficient, up to 60%, under a combined cycle arrangement with steam plants, but their own efficiency is usually lower than that of other thermal power plants.

These turbines can also be run in a cogeneration configuration: the exhaust is used for space or water heating, or drives an absorption chiller for cooling or refrigeration. Such engines require a dedicated enclosure, both to protect the engine from the elements and the operators from the noise.

The construction process for gas turbines can take as little as several weeks to a few months, compared to years for base load power plants, although their supply may take considerably more time according to the waiting lists of orders to the suppliers. The other main advantage of these turbines is the ability to be turned on and off within minutes, supplying power during peak demand.

Since single cycle (gas turbine only) power plants are less efficient than steam or combined cycle plants, they are usually used as peaking power plants operating several hours per day normally, depending on the electricity demand, the generating capacity of the region, the efficiencies of installed plants and fuel costs, and the available capacity of other sources that dispatch centers may have at any given time; therefore, in some cases, gas turbines are used more intensively because of suboptimal dispatch. In areas with a shortage of base load and load following power plant capacity or low fuel costs, a gas turbine power plant may operate regularly during most hours of the day, but this is not an economical way to operate the power system.

A large single cycle gas turbine typically may have an output of 100 to 300 megawatts of power and have 35% to 40% thermal efficiency, although the smaller turbines may have significantly lower efficiencies (25% to 33%) depending on age and location.

4. Micro turbines

Micro turbines are becoming widespread for distributed power and combined heat and power applications. They are one of the most promising technologies for powering hybrid electric vehicles. They range from hand-held units producing less than a kilowatt to commercial-size systems that produce tens or hundreds of kilowatts.

Part of their success is due to advances in electronics, which allow unattended operation and interfacing with the commercial power grid. Electronic power switching technology eliminates the need for the generator to be synchronized with the power grid. This allows the generator to be integrated with the turbine shaft and to double as the starter motor.

Micro turbine systems have many advantages over reciprocating engine generators, such as a higher power-to-weight ratio, extremely low emissions, and few moving parts or just one moving part. An advantage is that micro turbines may be designed with foil bearings and air-cooling operation without lubricating oil, coolants, or other hazardous materials. Micro turbines also have the further advantage of having the majority of the waste heat contained in the relatively high temperature exhaust making it simpler to capture, whereas the waste heat of reciprocating engines is split between their exhaust and their cooling system. However, reciprocating engine generators are quicker to respond to changes in output power requirements and are usually slightly more efficient, although the efficiency of micro turbines is increasing. Micro turbines also lose more efficiency at low power levels than reciprocating engines do. When used in vehicles, the static efficiency drawback is negated by the superior power-to-weight ratio—the vehicle does not have to move a heavy engine and transmission.

These turbines accept most commercial fuels, such as gasoline, natural gas, propane, diesel, and kerosene as well as renewable fuels such as E85, biodiesel, and biogas.

Micro turbine designs usually consist of a single stage radial compressor, a single stage radial turbine, and a recuperator. Recuperators are difficult to design and manufacture because they operate under high pressure and temperature differentials. Exhaust heat can be used for water heating, space heating, drying processes, or absorption chillers, which create cold for air conditioning from heat energy instead of electric energy.

Typical micro turbine efficiencies are 25% to 35%. When micro turbines are in a combined heat and power cogeneration system, efficiencies of greater than 80% are commonly achieved.

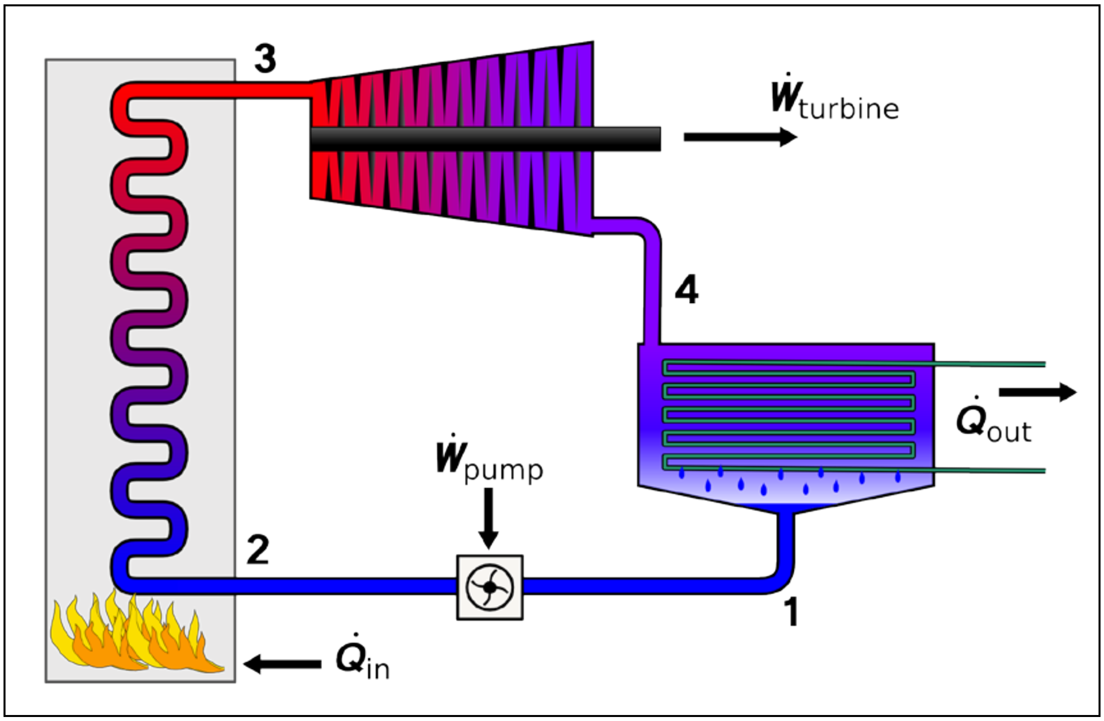
B. Steam turbines

A steam turbine is a turbo machine that transforms thermal energy from a steam flow into mechanical energy by exchanging energy between the working fluid (steam) and the rotor, the core of the turbine that has specially shaped blades to produce the energy interchange. Steam turbines are present in various power cycles that use a fluid that can change its physical phase, usually water. The most important one is the Rankine cycle, which generates steam in a boiler at high temperature and pressure. The internal energy of the steam is converted into mechanical energy in the turbine that is usually used to drive a generator that produces electricity. There are two different parts in a turbine: the rotor and the stator. The rotor has wheels with blades fixed to its axis (this is the mobile part of the turbine), and the stator also has blades, but is fixed to the carcass of the turbine.

1. The Rankine cycle

The Rankine cycle converts heat into work (see diagram A2). The heat is supplied externally to a closed loop, which usually uses water. This cycle generates about 80% of all electric power used throughout the world, including virtually all solar, thermal, biomass, coal, and nuclear power plants. The cycle is named after William John Macquorn Rankine.

Graphic A2: The Rankine cycle



The diagram A2 shows the Rankine cycle, the steam-operated heat engine model most commonly found in power generation plants. Common heat sources for power plants using the Rankine cycle are the combustion of coal, natural gas and oil, and nuclear fission.

A pump is used to pressurize the working fluid received from the condenser as a liquid instead of as a gas. All of the energy in pumping the working fluid through the complete cycle is lost, as is all of the energy of vaporization of the working fluid, in the boiler. This energy is lost to the cycle in that first phase; no condensation takes place in the turbine. All of the vaporization energy is rejected from the cycle through the condenser. But pumping the working fluid through the cycle as a liquid requires a very small fraction of the energy needed to transport it as compared to compressing the working fluid as a gas in a compressor.

2. Types and sizes

Steam turbines are made in a variety of sizes ranging from small (<0.75 kW) units rarely used as mechanical drives for pumps, compressors, and other shaft-driven equipment to

1,500 MW turbines used to generate electricity. There are several classifications for modern steam turbines.

Non-condensing or back-pressure turbines are most widely used for process steam applications. The exhaust pressure is controlled by a regulating valve to suit the needs of the process steam pressure. These turbines are commonly found at refineries, district heating units, pulp and paper plants, and sugar cane industry and desalination facilities, where large amounts of low pressure process steam are available.

Condensing turbines are most commonly found in electrical power plants. These turbines exhaust steam in a partially condensed state to a condenser at a pressure well below atmospheric.

Reheat turbines are also used almost exclusively in electrical power plants. In a reheat turbine, steam flow exits from a high pressure section of the turbine and is returned to the boiler, where additional superheat is added. The steam then goes back into an intermediate pressure section of the turbine and continues its expansion.

Extracting-type turbines are common in all applications. In an extracting-type turbine, steam is released from various stages of the turbine, and is used for industrial process needs or is sent to boiler feed-water heaters to improve overall cycle efficiency. Extraction flows may be controlled with a valve, or left uncontrolled.

3. Efficiency

The efficiency of the Rankine cycle is usually limited by the working fluid. Without the pressure reaching super critical levels for the working fluid, the temperature range that the cycle can operate over is quite small: turbine entry temperatures are typically 565°C (the creep limit of stainless steel), and condenser temperatures are around 30°C. This gives a theoretical Carnot efficiency of about 63% compared with an actual efficiency of 42% for a modern coal-fired power station. This low turbine entry temperature (compared with a gas turbine) is why the Rankine cycle is often used as a bottoming cycle in combined-cycle gas turbine power stations.

The working fluid in the Rankine cycle follows a closed loop and is reused constantly. The water vapor with entrained droplets often seen billowing from power stations is generated by the cooling systems (not by the closed-loop Rankine power cycle) and represents the waste energy heat (pumping and vaporization) that could not be converted to useful work in the turbine. Note that cooling towers operate using the latent heat of vaporization of the cooling fluid. The white billowing clouds that form in cooling tower operation are the result of water droplets that are entrained in the cooling tower airflow; they are not, as commonly thought, steam. While many substances could be used in the Rankine cycle, water is usually the fluid of choice due to its favorable properties, such as nontoxic and un-reactive chemistry, abundance, and low cost, as well as its thermodynamic properties.

One of the principal advantages that the Rankine cycle holds over other cycles is that, during the compression stage, relatively little work is required to drive the pump, the working fluid being in its liquid phase at this point. By condensing the fluid, the work required by the pump consumes only 1% to 3% of the turbine power and contributes to a much higher efficiency for a real cycle.

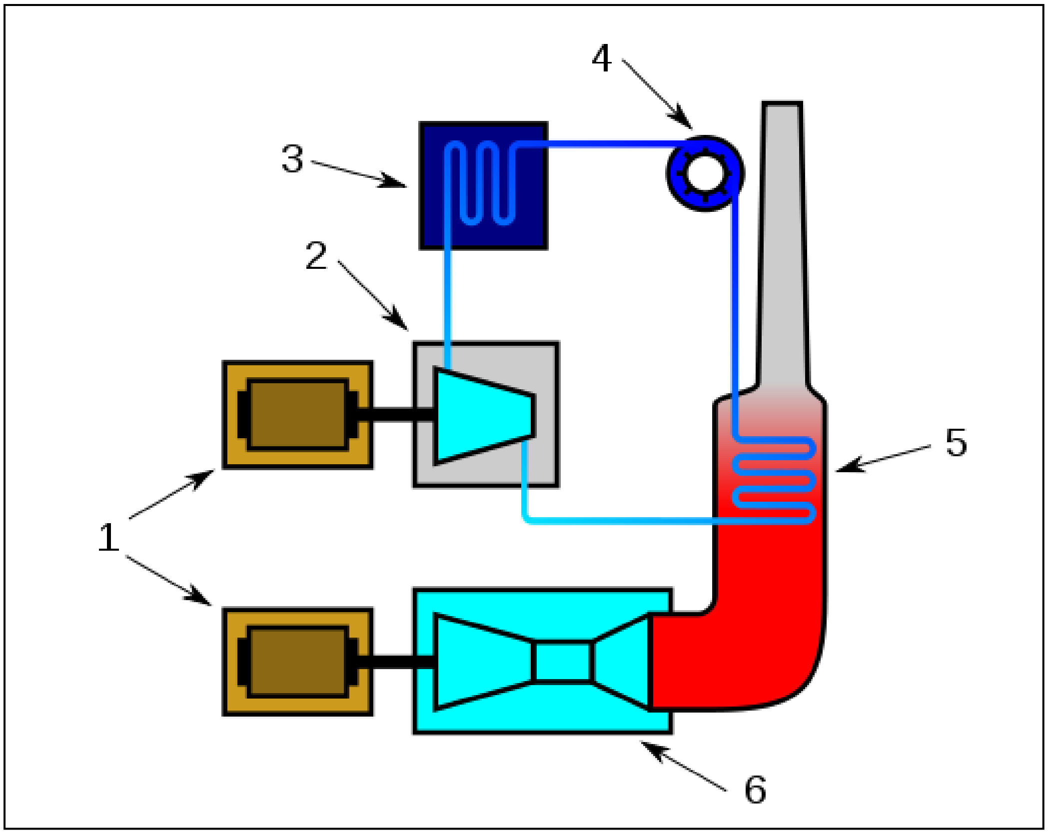
C. Gas turbine-steam turbine combined cycle

A combined cycle is characteristic of a power-producing engine or plant that employs more than one thermodynamic cycle (see diagram A3). Heat engines are only able to use a portion of the energy that their fuel generates (usually less than 50%). The remaining heat (e.g., hot exhaust fumes) from combustion is generally wasted. Combining two or more thermodynamic cycles, such as the Brayton cycle and the Rankine cycle, results in improved overall efficiency.

1. The combined cycle power plant

In a combined cycle power plant (CCPP) or a combined cycle gas turbine (CCGT) plant, a gas turbine generator generates electricity, and the waste heat is used to make steam to generate additional electricity via a steam turbine. This last step enhances the efficiency of electricity generation. Most new gas power plants in North America and Europe are of this type. In a thermal power plant, high-temperature heat as input to the power plant, usually from the burning of fuel, is converted to electricity as one of the outputs and to low-temperature heat as another output. As a rule, in order to achieve high efficiency, the temperature difference between the input and output heat levels should be as high as possible. This is achieved by combining the Rankine (steam) and Brayton (gas) thermodynamic cycles.

Graphic A3: The combined cycle power plant



In a thermal power station, water is the working medium. High pressure steam requires strong, bulky components. High temperatures require expensive alloys made from nickel or cobalt, rather than inexpensive steel. These alloys limit practical steam temperatures to 655°C, while the lower temperature of a steam plant is fixed by the boiling point of water. With these limits, a steam plant has a fixed upper efficiency of 35% to 42%.

An open-circuit gas turbine cycle has a compressor, a combustor, and a turbine. For gas turbines, the amount of metal that must withstand the high temperatures and pressures is small, and lower quantities of expensive materials can be used. In this type of cycle, the input temperature of the turbine (the firing temperature) is relatively high (900°C to

1,400°C). The output temperature of the flue gas is also high (450°C to 650°C). It is, therefore, high enough to provide heat for a second cycle, which uses steam as the working fluid (a Rankine cycle).

In a combined cycle power plant, the heat of the gas turbine's exhaust air is used to generate steam by passing the air through a heat recovery steam generator (HRSG) with a live steam temperature between 420°C and 580°C. The condenser of the Rankine cycle is usually cooled by water from a lake, a river, a sea, or cooling towers. This temperature can be as low as 15°C.

2. Typical size of CCGT plants

For large-scale power generation, a typical set would be a 400 MW gas turbine coupled with a 200 MW steam turbine, giving 600 MW. Nevertheless, combined cycles of lower capacity can be installed, let's say above 200 MW.

3. Efficiency of CCGT plants

By combining both gas and steam cycles, high input temperatures and low output temperatures can be achieved. The efficiency of the cycles increases because they are powered by the same fuel source. Therefore, a combined cycle plant has a thermodynamic cycle that operates between the gas turbine's high firing temperature and the waste heat temperature from the condensers of the steam cycle. This large range means that the Carnot efficiency of the cycle is high. The actual efficiency, while lower than this, is still higher than that of either plant on its own.

The commercial availability of a CCGT "pure power" (i.e. non-CHP) plant with 60% LCV basis efficiency is quite genuine and commercial, not just 'in the laboratory'. This is the GE 'high-tech' steam-cooled H Class turbine[16]. The first H Class System located at BP Baglan Bay refinery in Wales has been in commercial operation since September 2003 and has achieved significant operating experience. Siemens and Mitsubishi MHI are also both on the point of introducing 60% LCV systems. However, a more common 'state of the art' for

[16] GE Energy: http://www.gepower.com/prod_serv/products/gas_turbines_cc/en/h_system/index.htm

the new-build market today is 58% LCV efficiency. The overall gas CCGT ‘fleet average’ is probably c.53%.

D. Internal combustion Diesel engines

The Diesel cycle is the thermodynamic cycle which approximates the pressure and volume of the combustion chamber of the Diesel engine, invented by Rudolph Diesel in 1897. It is assumed to have constant pressure during the first part of the combustion phase (V2 to V3 in the diagram, below). This is an idealized mathematical model: real physical Diesels do have an increase in pressure during this period, but it is less pronounced than in the Otto cycle.

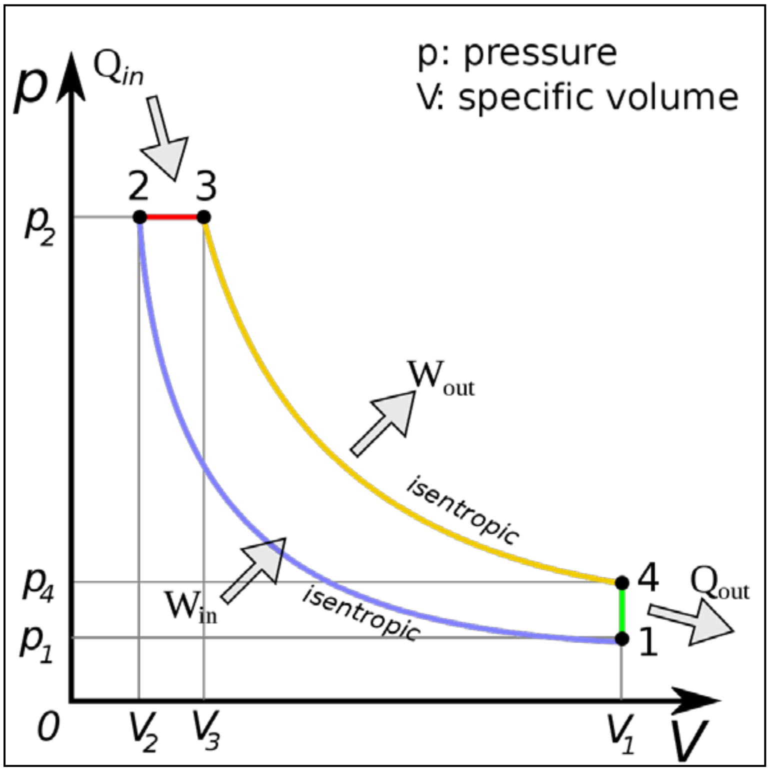
The ideal Diesel cycle follows the following four distinct processes:

- Process 1 to 2 is isentropic compression
- Process 2 to 3 is reversible constant pressure heating
- Process 3 to 4 is isentropic expansion
- Process 4 to 1 is reversible constant volume cooling (green)

The Diesel is a heat engine: it converts heat into work. The isentropic processes are impermeable to heat: heat flows into the loop through the left expanding isobaric process and some of it flows back out through the right depressurizing process, and the heat that remains does the work.

- Work in (W_{in}) is done by the piston compressing the working fluid
- Heat in (Q_{in}) is done by the combustion of the fuel
- Work out (W_{out}) is done by the working fluid expanding onto the piston (this produces usable torque)
- Heat out (Qout) is done by venting the air

Graphic A4: Internal combustion Diesel engines



E. Cogeneration

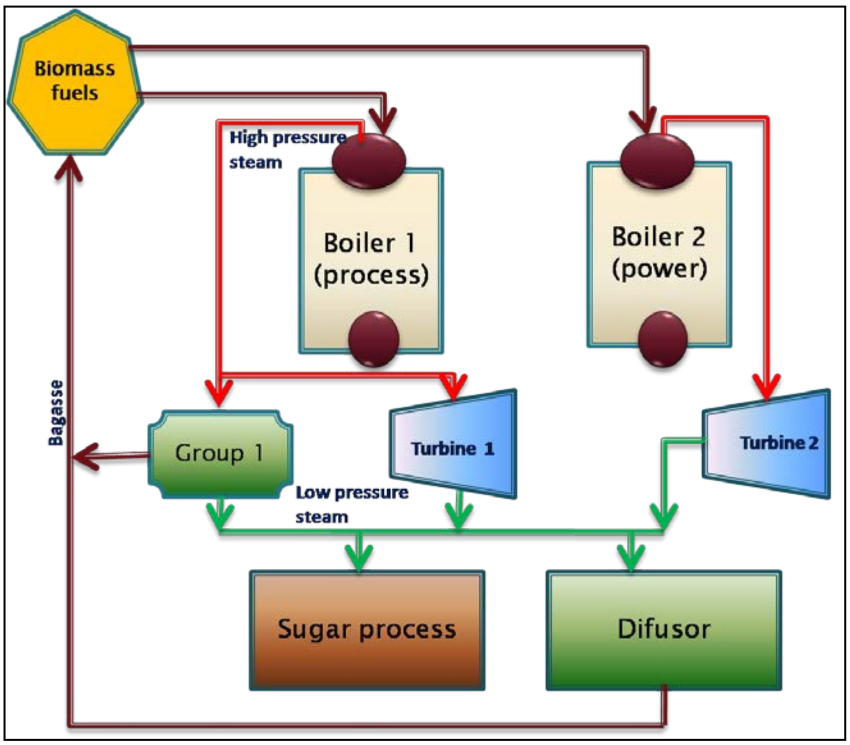
Cogeneration i.e. combined heat and power (CHP) is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat. All power plants must emit a certain amount of heat during electricity generation. This can be released into the natural environment through cooling towers, flue gas, or other means. In contrast, CHP captures some of the by-product heat for heating purposes, either very close to the plant for industrial uses as low pressure steam or as hot water for district heating with temperatures ranging from approximately 80°C to 130°C. (see diagram A5)

By-product heat at moderate temperatures (212-356°F/100-180°C) can also be used in absorption chillers for cooling. A plant producing electricity, heat, and cold is sometimes called a trigeneration plant or, more generally, a polygeneration plant.

Cogeneration is a thermodynamically efficient use of fuel. In the separate production of electricity, some energy must be rejected as waste heat, but, in cogeneration, this thermal energy is put to good use.

Cogeneration has been regularly used for a long time in sugar mills to generate electricity and uses residual heat in expanded low pressure steam for the sugar production process. A typical arrangement may be that which is indicated in the following chart, corresponding to a real case of a back-pressure steam turbine plant linked to a sugar mill in Ecuador.[17] The power plant uses different kinds of biomasses to produce power and steam for the sugar mill, and the plant sells electricity to the power market.

Graphic A5: Cogeneration



[17] Ecoelectric, Province of Guayas, Ecuador.