LARGE SCALE INTEGRATION OF RENEWABLE ENERGY SOURCES FOR POWER GENERATION IN COLOMBIA: A SENSIBLE ALTERNATIVE TO CONVENTIONAL ENERGY SOURCES

SCENARIO: 2010 - 2050

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To my parents Patricia and Hugo

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EXECUTIVE SUMMARY

The aim of this dissertation is to answer the research question, whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources such as hydropower, natural gas and coal. This dissertation examined the use of new technologies powered by renewable energy sources in the long term with a planning horizon of 2010 to 2050.

Colombia is energy self-sufficient today. However, natural gas proved reserves are expected to last only until the year 2020, and oil until the period 2018 to 2020 depending on the evolution of demand and production rates. The portfolio of technologies of the Colombian electricity sector consists mainly of hydropower and fossil fuel power plants powered by natural gas and coal. The total capacity of the Colombian power system amounts to 14,367 MW as of 2010. Hydropower has a share of 67.7%. Accordingly electricity generation is dominated by hydropower with 67% and 77.8% of the total production by 2010 and 2011 respectively (56.9 TWh and 58.6 TWh). Coal and most notably natural gas complete the production.

Excluding large hydropower plants (power plants over 20 MW), the share of renewable energy sources in the portfolio of technologies amounts to 3.89% (560 MW). Small hydropower plants account for 96% of this capacity. This is a very modest participation of renewable energy sources and in particular of other sources apart from hydropower.

The power sector in Colombia is characterized by its dependence on hydropower, the seasonality of hydropower production in particular by periodic extreme weather conditions such as strong El Niño events, the volatility of fossil fuel prices due to natural gas supply deficits because of transport restrictions and fossil fuel prices coupled with international oil prices and the volatility of electricity prices driven by the contribution of hydropower. Figure 1 shows the contribution of energy sources in electricity generation over the last 15 years and the effect of El Niño on hydropower generation (dotted circles) and electricity spot prices.

These facts in combination with the expected scarcity of natural gas and the increase of demand for energy sources are all drivers prompting the quest for alternative energy sources in Colombia.

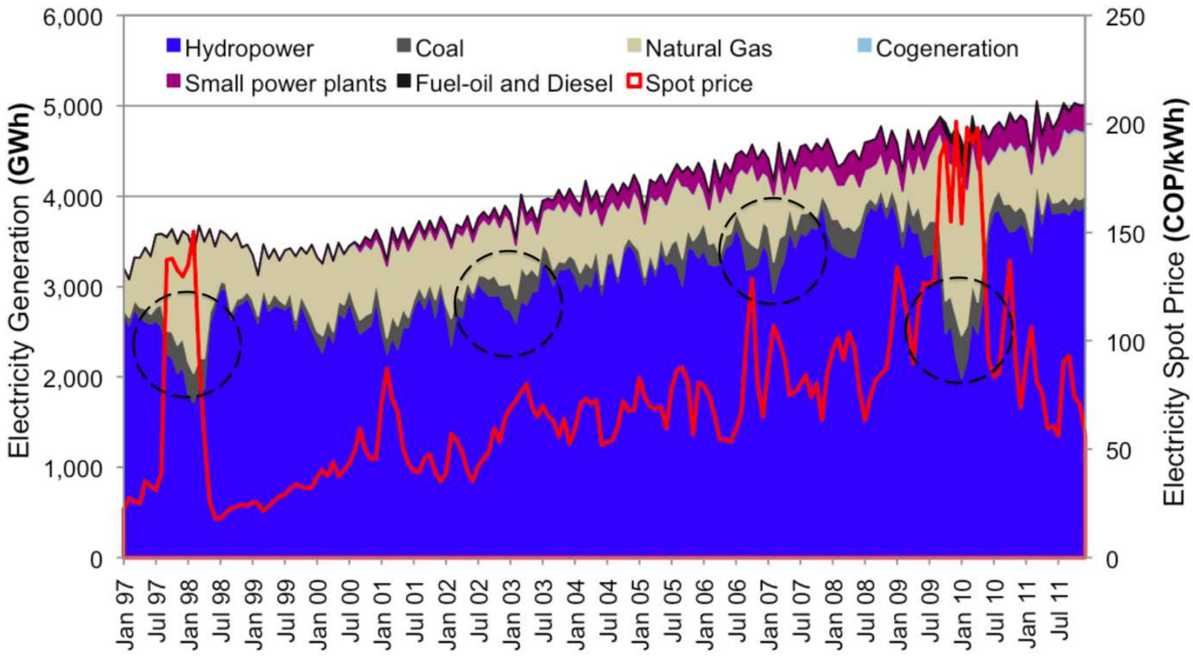

Figure 1 Contribution of hydropower and thermal power plants in power generation

Higher shares of electricity coming from fossil-power plants may affect security of supply by relying on scarce energy sources, such as natural gas, which may have to be imported at some point. A shift to more power technologies using coal, which is abundant, will drastically increase the current low CO_2 emission of the power sector.

The questions remain, which other energy sources apart from hydropower, natural gas and coal could also help to achieve a more balanced and diversified portfolio of power generation technologies, and furthermore, how does Colombia start making a suitable transition to a more reliable, competitive and environmentally friendly power generation system.

Colombia has the potential to use advanced energy technologies powered by renewable energy sources such as wind energy, biomass, geothermal, and solar energy. Renewable energy sources and the technologies for their transformation are already part of power systems in many countries. In addition, diverse studies for future energy supply (energy scenarios) published at a global and national level include the use of renewable energy sources.

Power systems with almost or full 100% renewable energy sources are technically possible. Hydro dominated power systems with storage reservoirs such as those in Colombia could be complemented for instance with intermittent sources such as wind and solar energy and dispatchable technologies with biomass and geothermal energy sources. This may lead to a power system fully supplied by renewable energy sources in Colombia. In addition, the economic advantages of a mature technology such as hydropower combined with technologies powered by other renewable energy sources which are commercially available and continue reducing costs of investment and operation may offer an attractive economic alternative to the overall power system. This could be more noticeable in a scenario of growing prices of fossil fuels and scarcity of natural gas in Colombia.

An analysis of how power generation in Colombia may unfold, including the use of renewable energy sources is therefore of high importance. This dissertation presents such an analysis. Based on the main research question above, the objective of this dissertation is to test the following hypotheses:

(1) Renewable energy sources can fully substitute fossil fuel energy sources and can turn the hydropower based power system in Colombia into a 100% renewable energy system.

(2) The introduction of renewable energy sources in Colombia can be part of the least cost alternative for the expansion of the Colombian power system.

This dissertation is divided into a logical sequence of sections which follows the scientific approach taken to reach the objective. The core analysis is the simulation of the expansion of power generation in Colombia. For that a review of energy modelling techniques and a selection of suitable energy models were conducted. The potential of renewable energy sources in Colombia was also examined, which was complemented with a description of state of the art technologies for electricity supply powered by these sources. To simulate the expansion of the Colombian power sector, a prognosis analysis was essential for all data required for the energy models until 2050 such as the existing and new portfolio of technologies for electricity supply, their investment and operation and maintenance costs and technical parameters, fuel costs, electricity demand, availability of fossil fuel resources such as natural gas and coal, and emission factors of fossil fuels.

Subsequently the simulation of the expansion of the Colombian power sector was conducted with the energy models selected. The results of the simulation were put in the context of the Colombian power sector emphasizing why renewable energy sources should be part of the Colombian power sector. In addition other issues such as Colombia’s dependency on hydropower, relative CO_2 emissions and climate change as well as integration of renewable energy sources in the Colombian context for the power sector were addressed.

Regarding the selection of a suitable energy model, two energy bottom-up models were selected, which differ from their approach to simulate power generation systems. The model LEAP was used to explore energy futures. In that way an expansion of the Colombian power system with current energy sources (business as usual scenarios) was compared to an expansion scenario with both a modest and significant penetration of renewable energy sources (renewable scenarios). In contrast, the optimization model MESSAGE was used, which identifies autonomously the least cost expansion path for the power system.

Renewable energy sources including biomass, large and small hydropower, geothermal, solar and wind energy were assessed for Colombia. In particular a detailed assessment of the future potential for biomass was conducted. The analysis suggests that every source assessed apart from Geothermal due to lack of information has a potential above the current installed power generation capacity in Colombia (14.4 GW as of 2010). Hydropower is and will continue to be a main energy source for electricity production given its huge potential. The potential of other renewable energy sources suggest that they can become an important contributor of electricity at a large scale and may displace fossil fuel energy sources and decrease the high dependence on hydropower.

In the prognosis analysis for the time horizon 2010 - 2050, it was essential to determine the development of the investment and operation and maintenance costs of all power technologies. The cost projection for new technologies powered by renewable energy sources was based on the experience curve approach. With respect to a projection of the electricity demand and fossil fuel prices, the official projections were taken and completed based on the same methodology.

The results of the simulation with LEAP and MESSAGE in respect to the shares of new technologies powered by renewable energy sources for the planning horizon from 2010 to 2050 in Colombia are summarized in Figure 2. The scenario analysis approach with LEAP shows higher shares of renewable energy sources apart from hydropower from 2020 to 2040 in comparison with the least cost approach of MESSAGE. This suggests the somehow aggressive introduction of renewable energy sources by LEAP leading to higher overall costs.

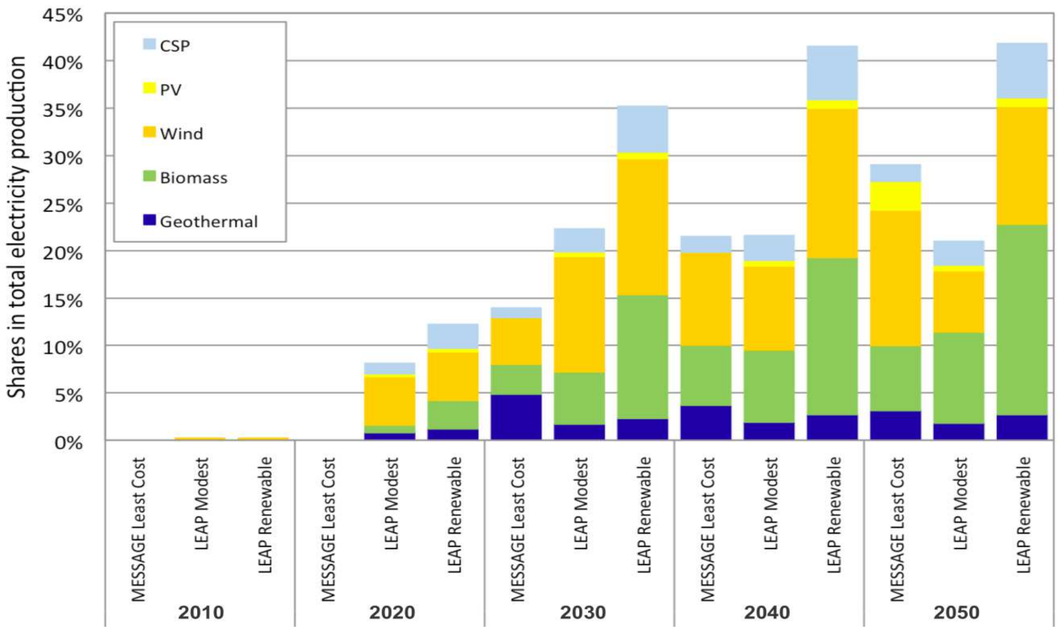

Figure 2 Renewable energy sources share in power generation. Results from LEAP and MESSAGE

An analysis of these results was conducted by means of the net present value approach. In the accounting framework model LEAP the entrance of renewable energy technologies in all scenarios resulted in an increase of the overall cost of the power system. The overall cost of renewable scenarios (modest and renewable) are between 19.7 and 24.4 billion in 2006 USD, suggesting that BAU scenarios in LEAP without new renewable energy sources are the least cost alternative. The overall cost of the BAU scenarios in LEAP are between 18.9 and 19.8 billion in 2006 USD.

On the other hand, the simulation with the optimization model MESSAGE performed with the same parameters suggests that despite all sensitivities renewable energy technologies will enter the system by their own economic and technical merits in an ideal market as the optimization model assumes. In this case the overall costs of the optimization results are between 13.1 and 15.1 billion in 2006 USD.

The combination of the two model techniques proved to be essential to arrive at more precise conclusions. The results of LEAP’s scenarios helped to understand the cornerstones of the expansion. For instance the BAU scenarios showed what shape the power sector may take if new technologies powered by renewable energy sources are not allowed to become part of the system causing much higher emissions of CO_2 and a higher dependence on hydropower and fossil fuels. The results of the simulation with MESSAGE found least cost expansion paths that include renewable energy technologies. Thus, the least cost approach suggests that renewable energy technologies will be competitive upon entering the system.

Therefore, the results of the simulation with MESSAGE suggest that new technologies powered by wind, geothermal, biomass and solar energy will be introduced at a large scale in the Colombian power sector by their own technical and economic merits. This was accomplished without driving their entrance by either forcing the expansion or giving any economic incentive to improve their competitiveness.

In that sense there is a period from 2015 to 2030 in which the conditions are given for renewable energy technologies to be part of the Colombian power system with diverse energy production shares depending on the evolution of economic and technical parameter as simulated with the sensitivity analysis. Thus, the results suggest new renewable energy technologies will contribute to diversifying the supply of electricity in Colombia. Fossil fuel sources will be displaced as the main energy sources completing hydropower production by other renewable energy sources.

Figure 3 shows a pathway of the expansion of the Colombian power sector according to the simulation with MESSAGE (reference case with low prices for fossil fuels and low investment costs for renewable energy technologies) to better illustrate how renewable energy sources will enter the Colombian energy mix over the time horizon of the analysis and the importance of hydropower in electricity production.

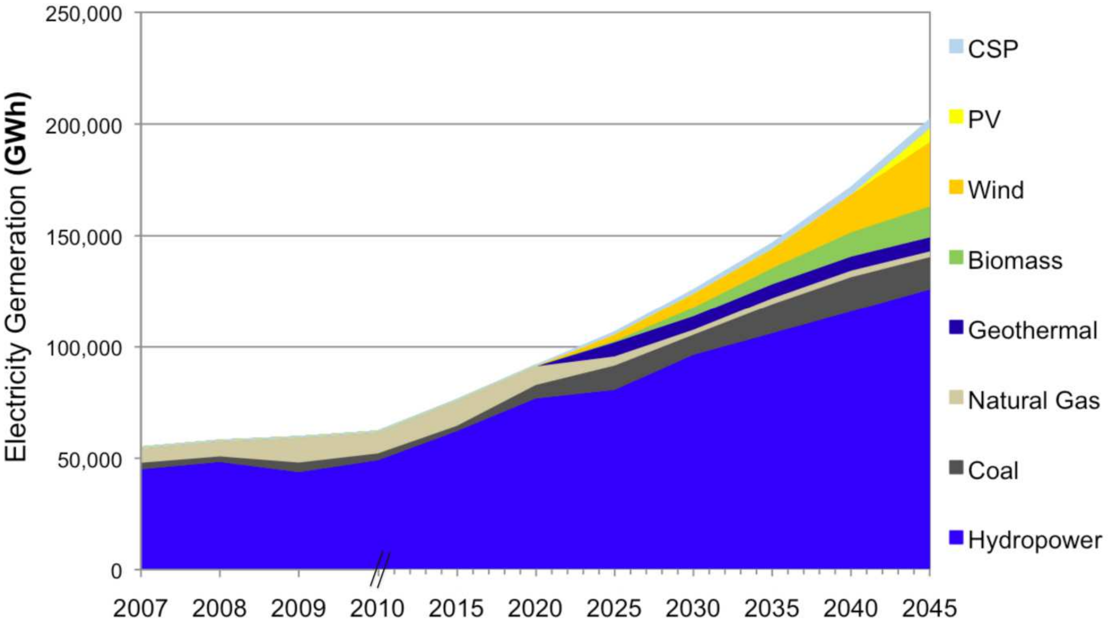

Figure 3 Least cost electricity generation for the reference case

The most promising new renewable technology is powered by wind energy. In all sensitivities in the model, wind energy reached a significant share in electricity generation over 10% after

2040. In addition, the maximum potential of 10 GW set in the simulation is reached after 2040. This suggests the potential to continue expanding the system with wind energy by increasing and further developing suitable sites in Colombia. In all scenarios conventional geothermal technology was introduced as well as biomass. In contrast solar technologies such as concentrated solar power and photovoltaic have a relatively modest contribution to the system.

The results show an expansion path does not reach a 100% renewable system until 2050 including large hydropower. Despite an important decrease of fossil fuel sources for power generation over the years, the system still needs these sources to be part of the least cost solution. In other words, the results suggest that during the time horizon in the analysis, the Colombian power system will not turn into a 100% renewable system based on market forces. However, it is worth noting the combination of existing and new hydropower plants with the introduction of technologies powered by wind, geothermal, biomass and solar turning gradually the heavy based hydropower system in Colombia over the years into a diversified renewable energy system. Thus, the current share of up to 80% of the electricity supply coming from hydropower plants will be reduced to approximately 60%. The introduction of new renewable energy sources together with hydropower will increase the share of all renewable energy sources to 90% as shown in Figure 4.

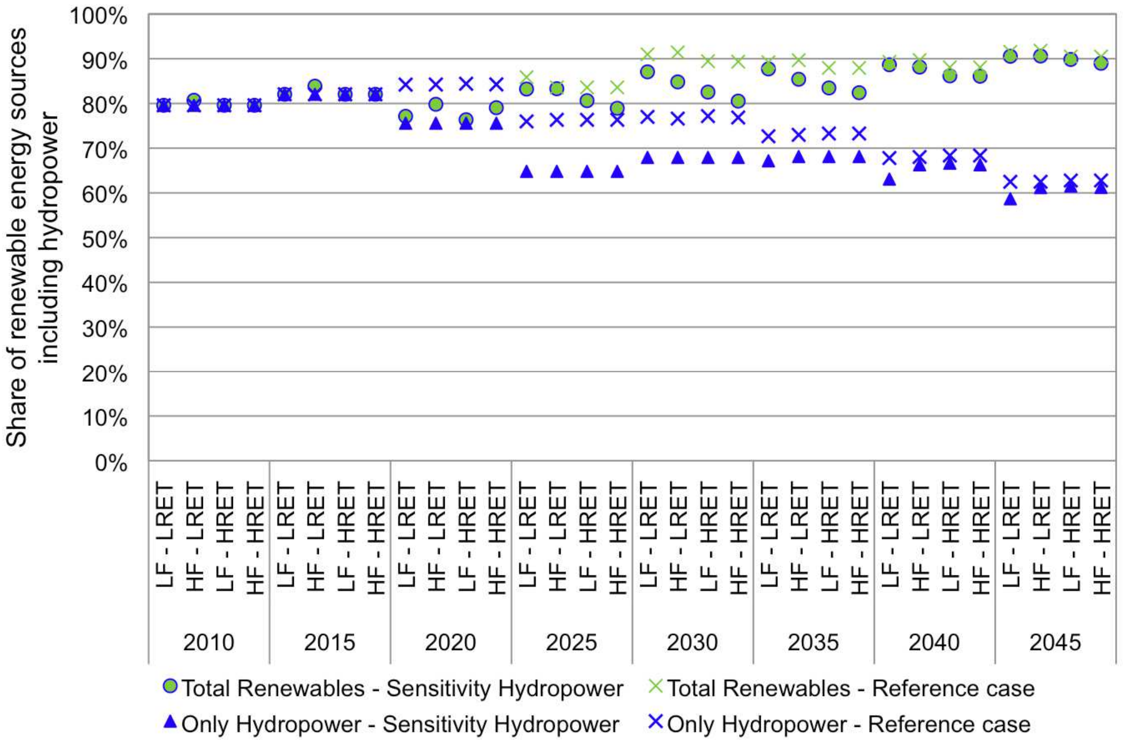

Figure 4 Total share of renewable energy sources vs. total hydropower share in electricity generation

Renewable energy technologies do not fully substitute or avoid the use of fossil fuel sources. In spite of this the share of gas is drastically reduced, whereas coal will continue to have a small share in the system. The results from analyses performed with MESSAGE and LEAP showed that Colombia will rely on imported natural gas from 2018 onwards. Renewable energy sources will contribute to decrease the dependence on natural gas for the power sector and to release carbon resources to supply international markets and thus improving the Colombian's balance of payments.

A logical effect of reducing the participation of fossil fuel energy sources in the Colombian power sector is the avoidance of CO_2 emissions. Otherwise the emissions of CO_2 will surpass today's levels. This situation was simulated with the BAU scenarios in LEAP. The optimization results suggest that emissions will be below 12 million tonnes of CO_2 eq. per year during the time horizon of 40 years due to entrance of technologies powered by renewable energy sources. This shows the immense potential of renewable energy technologies including large hydropower to maintain current emission levels over the next 40 years despite electricity demand growth. Between 388 and 671 million tonnes of CO_2 eq. or between 556 and 731 million tonnes of CO_2 eq. for a scenario with lesser contribution of hydropower can be avoided.

In summary, the results of this dissertation found least cost expansion paths that include renewable energy technologies, which will be competitive to enter the Colombian power system. The results suggests that the Colombian power system may be transformed from a system heavily based on hydropower to a system composed of a more diversified portfolio of technologies and energy sources such as wind, geothermal, biomass, solar and hydropower. State of the art coal and gas fossil fuel power plants will also be introduced into the power system. A 100% renewable system by 2050 was not obtained. Therefore fossil fuel energy sources are not fully substituted but they will be displaced as main energy sources after hydropower.

Finally this dissertation closes the analysis with a discussion of the theoretical results of the simulation and what should be considered in practice. The least cost approach of the simulation does not necessarily reflect the power market environment that new technologies face in reality. Therefore it is recommended that bias of market rules towards some technologies should be abolished to ensure a level playing field for all technologies in the Colombian power system. In that way, power markets allow new technologies to be part of the system at the time of their competitiveness.

Regarding the technical integration of new technologies into the system, it is also recommended to conduct an assessment of the potential of hydropower to accommodate intermittent sources such as wind energy due to hydropower’s storage capacity and strong complementarity of wind energy during dry seasons to improve the firm energy of the system. In respect to solar energy technologies such as CSP and PV, an assessment of the potential of solar power should be conducted to attend the demand at Colombia’s Caribbean coast, where high temperatures are connected to higher consumption of electricity driven by the use of air conditioning systems. That makes solar technologies ideal for daily and seasonal operation matching peak and intermediate loads. Such a contribution releases other energy sources to cover these loads and could also optimize the grid operation.

For technologies such as geothermal and biomass, the lack of information about the availability and quality of associated resources should be overcome. The use of solid residues from sugar plantations in particular the collection, disposal and transport, should be assessed in detail. These technologies are key since they are not intermittent, therefore contributing to the supply of firm energy into the system.

Finally the results of this dissertation should be complemented with a study to determine transmission expansion and enforcements to make sure that the Colombian power system can pull the potential and profit fully from new energy technologies powered by renewable energy sources.

ABREVIATIONS

BAU: Business as usual scenario

BIGCC: Biomass Integrated gasification combined cycle

CDM: Clean Development Mechanism

COP: Colombian Pesos

CREG: Comisión de Regulación de Energía y Gas (Regulatory Commission for Electricity and Gas)

CSP: Concentrated solar power

DANE: Departamento administrativo nacional de estadística (Colombian bureau of national statistics)

ECOPETROL: Colombia’s state oil company

ENSO: El Niño-Southern Oscillation

ESMAP: World Bank Energy Sector Management Assistance Program

GDP: Gross domestic product

GHG: Greenhouse gases

IAEA: International Atomic Energy Agency

IDEAM: Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (Institute of Hydrology, Meteorology, and Environmental Studies of Colombia)

IEA: International Energy Agency

IGCC: Integrated gasification combined cycle

IPCC: Intergovernmental Panel for Climate Change

LEAP: Long range energy alternatives planning system

LR: Learning Rate

MESSAGE: Model for energy supply strategy alternatives and their general environmental impact

NATURGAS: Asociación Colombiana de Gas Natural (Colombian Natural Gas Association)

NG: Natural Gas

NPV: Net present value

O&M: Operation and Maintenance

PV: Photovoltaic

RET: Renewable energy technologies

SSPD: Superintendencia de Servicios Públicos Domiciliarios. (Superintendency for Residential Public Services)

UNFCCC: United Nations Framework Convention on Climate Change

UPME: Unidad de Planeamiento Minero-Energética (Colombia’s Energy Mining Planning Unit)

USD / US$: United States Dollars

LIST OF UNITS

AC	Alternate current
CO_2	Carbon dioxide
DC	Direct current
GJ	Giga joule
GW	Giga watt
GWh	Giga watt hour
kg	Kilogram
kV	Kilovolts
kWh	Kilowatt hour
m	Meter
m/s	Meter per second
m^2	Quadrat meters
m^3	Cubic meters
MBTU	Million BTU
MJ	Mega joule
Mt	Mega tonnes
Gm^3	Giga cubic meters
MW	Megawatt
MWh	Megawatt hour
TWh	Terawatt hour

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1. INTRODUCTION

This dissertation examined the use of new technologies powered by renewable energy sources to generate electricity on a large scale in Colombia. The core analysis of this study was a simulation of power generation in Colombia by means of energy models to assess the convenience of having alternative energy sources. The simulation was conducted in the long term with a planning horizon of 2010 to 2050.

This introductory chapter presents the background of this dissertation study, the research question and explains the significance of the dissertation. A description of the methodology is also included. The chapter concludes by noting the delimitations of the study.

1.1 BACKGROUND OF THE STUDY

The law 697 of 2001 enacted by the Colombian Congress promotes the rational and efficient use of energy and promotes the use of non-conventional energy sources. The law mandates that the State must establish all necessary regulations and conditions to fulfil the purpose of this law thereby achieving project implementation, assuring sustainable development and creating awareness of the rational use of energy and know-how of non-conventional energy sources. In addition the decree 3683 of 2003 was enacted giving instructions to issue the required regulations by Colombian institutions to fulfil the law 697 of 2001.

The definition of sustainable development adopted by Colombian law is development which leads to economic growth, improvement of quality of life and social welfare which does not exhaust the renewable natural resources base and worsen the natural environment or the right of future generations to use it to meet their own needs.

The law shows that Colombia embraces the concept of sustainable development in its energy policy, which should transform the energy system. Such a transformation depends on the actions and decisions made today and in the coming future. Sustainable development, today, is a well accepted world-wide term since the introduction of the Brundtland report (WCED, 1987) and the adoption of its definition by the United Nations thereafter.

The Colombian energy sector has been a liberalised market since 1994 and still continues with the process of liberalisation of all markets, giving the private sector the main role, introducing competition and thereby minimising state participation. The total energy supply, including international markets, is dominated by coal with a share of 45.1%, oil with a 37% share, natural gas with a 10.4% share, hydropower with a 3.9% share and wood and bagasse with a share of 3.4% as of 2010. 91% of coal production, 12% of gas production and 56% of oil production are bound for exports (UPME 2011).

The country is energy self-sufficient today. However, natural gas proved reserves are expected to last only until the year 2020, and oil until the period 2018 to 2020 depending on the evolution of demand and production rates (UPME 2009, p. 147, UPME 2011a, p.144). Currently, substantial efforts are being made to increase production and to explore new reserves, oil being the most critical. In contrast, coal resources are plenty. With current exploitation rates and proved reserves, it is predicted that Colombia can supply international markets and the internal demand for 100 years (UPME 2010, p.68).

The portfolio of technologies of the Colombian electricity sector consists mainly of hydropower and fossil fuel power plants powered by natural gas and coal. Hydropower has a share of 67.7% of the total capacity (14.367 MW) followed by natural gas with 27.3% and coal with 4.9% (UPME 2011b, p. 50-52). Electricity generation is dominated by hydropower with 67% and 77.8% of the total production by 2010 and 2011 respectively (56.9 TWh and 58.6 TWh). Coal and natural gas complete the production. Natural gas covered 20.1% and 13% and coal 6.3% and 2.8% by 2010 and 2011 respectively (XM 2011).

Excluding large hydropower plants (power plants over 20 MW), the share of renewable energy sources in the portfolio of technologies amounts to 560 MW including the wind park Jeripachi with a capacity of 18.4 MW. Small hydropower plants account for 96% of this capacity (XM 2011). This is a very modest participation of renewable energy sources and in particular of other sources different from hydropower.

Electricity generation in Colombia is dependent on the availability of the water resources, which are influenced by Colombia’s seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO). ENSO causes extreme weather conditions (droughts and floods respectively), which have a significant impact on hydropower generation. In addition the vulnerability of Colombia to climate change may affect adversely the contribution of hydropower (Ideam 2010, p.186).

These fluctuations of hydropower generation lead to power generation price volatilities in the spot market (UPME 2003, p.16; Ayala 2003, p.79; Corpoema 2010, p.4-4 and 4-5). As a result fossil fuel power generation varies substantially affecting the cost per kWh. Therefore a high dependence on hydropower requires a shift to a more balanced portfolio of generation technologies (Larsen et al 2004, p.1777; Ayala 2003; p.81).

Volatility is also faced by fossil fuel power plants due to natural gas supply deficits because of transport restrictions and fossil fuel prices coupled with international oil prices. Consequently, power plants making use of natural gas face a situation of restrictions in high demand periods and competition with residential, industrial and transport sectors for the use of natural gas (UPME 2010, p. 39-40).

A high dependence on hydropower may induce blackouts and rationing under severe drought conditions as experienced in Colombia in 1992 (Ayala 2003, p.3). The contribution of thermal power plants has avoided such a scenario since then. However, higher shares of electricity coming from fossil-power plants may affect security of supply by relying on scarce energy sources, such as natural gas, which may have to be imported at some point. A shift to more power technologies using coal, which is abundant, will drastically increase the current low CO_2 emissions and other pollutants such as SO_x and NO_x of the power sector. In that regard Colombia approved the United Nations Framework Convention on Climate Change (UNFCCC) in Law 164 in 1994 and approved the Kyoto Protocol in Law 629 in 2000. Recently in December 2011, the conference of the parties at the Durban Climate Change Conference decided on the introduction of a new protocol, another legal instrument or an agreed outcome with legal force from 2020 to hold the increase in global average temperature below 2 °C or 1.5 °C above pre-industrial levels (UNFCCC 2011).

Electricity demand in Colombia has increased at an average rate of 3% in the last 7 years (UPME 2011b, p.37), with fluctuations due to the global economic crisis which occurred between 2008 and 2009 as well as extreme weather conditions. The official electricity demand projections forecast annual growth rates between 3% and 4% up until the year 2030 (UPME 2011b, p.31). Countries like Colombia experience higher growths in their economies and population so primary energy use is expected to continue to increase.

Colombian’s dependence on hydropower, the seasonality of hydropower production, the volatility of electricity prices, the volatility of fossil fuel prices, the scarcity of natural gas, and the increase of demand for energy sources are all drivers prompting the quest for alternative energy sources in Colombia. In contrast to a transformation of the power sector only driven by environmental externalities as most of industrialised countries, these economic drivers take precedence in the Colombian power sector.

The questions remain, which other energy sources apart from hydropower, natural gas and coal could also help to achieve a more balanced and diversified portfolio of power generation technologies, and furthermore, how does Colombia start making a suitable transition to a more reliable, competitive and environmentally friendly power generation system.

By looking at the recently released indicative electricity plan of the Colombian Mine and Energy Planning Agency (UPME), the expansion required for the period 2010 – 2025 is based mostly on investments in hydropower (6.087 MW) and fossil fuel power plants with natural gas and coal (760 MW and 864 MW respectively) (UPME 2011b, p.96 – 102). This is a business as usual expansion of the power system which uses the same conventional energy sources in the mid-term.

A key strategy for a more sustainable energy future is the use of renewable sources, the rational use of energy and the adoption of advanced energy technologies for example for power generation such as wind power, biomass direct combustion and gasification, binary and flash geothermal, photovoltaic and concentrated solar power. Therefore technological choices become an important issue.

Renewable energy sources are defined as any form of energy from solar, geophysical or biological sources that are replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy sources in the natural environment include resources such as biomass (e.g. sugar cane residues, rice husks, and cacao), solar energy, geothermal heat, hydropower, tides and waves, ocean thermal energy and wind energy (IPCC 2011, p. 11). Various types of renewable energy technologies can supply electricity. Renewable technologies for power generation are to a greater or lesser extent already available in the market. Colombia possesses renewable energy sources that can be exploited for electricity generation.

Renewable energy sources and the technologies for their transformation are already part of power systems in many countries. The introduction of wind and solar technologies worldwide has experienced a high growth in the last 10 years. Their average annual growth rate (AAGR) of electricity production corresponds to 27.1% and 38.1% respectively. Biomass has an AAGR of 7% whereas hydropower has an AAGR of 2.3% (Observ’er and EDR 2011, p.7). In addition, diverse studies for future energy supply (energy scenarios) published at a global and national level include the use of renewable energy sources.

This has been noted by a recent analysis from the IPPC’s authors in their Special Report on Renewable Energy Sources and Climate Change Mitigation, where 164 recent global energy scenarios were reviewed indicating a substantial increase in the deployment of renewable energy by 2030, 2050 and beyond and consequently a growth widespread of these sources over the world (IPCC 2011a, p. 794-795). The shares of renewable energy in primary energy supply reach 43% and 77% in 2030 and 2030 respectively for scenarios with the highest renewable energy shares (IPCC 2011a, p. 803). Regarding electricity generation, it was found that renewable energy sources for power generation develops more quickly in comparison to renewable energy sources for other uses such as heating, cooling and transport (IPCC 2011a, p. 816).

From four illustrative scenarios selected by the IPPC's authors for their review, which comprise a wide range of modeling architecture, demand projections and technology portfolio for electricity supply, it was found that shares of renewable energy sources range from 24% to 95% worldwide by 2050 (IPCC 2011a, p. 818). A similar conclusion was also obtained from a previous analysis of energy scenarios before 2007, which shows important shares of renewable energy for power generation ranging from 25% to 70% globally in 2050 (Hamrin et al 2007, p.7).

At the European level, a recent analysis of energy scenarios for the power sector by 2050 was conducted by the German Advisory Council for the Environment. The shares of electricity with renewable energy sources in Europe are between 20% and 42% for reference scenarios and between 34% and 100% for scenarios with the goal of decarbonising power systems by 2050 (SRU 2011, p.67). A high decarbonised power system is achieved with high shares of renewable energy sources, e.g. a 100% renewable system or a combination of renewable sources with nuclear power and fossil fuel power plants with carbon capture storage.

Power systems with almost or full 100% renewable energy sources in the European studies include very small shares of fossil fuel sources for grid stabilization purposes or imports of renewable energy electricity from Africa or other regions (SRU 2011, p.65). The high shares of renewable energy sources are also explained in some cases by the grade of implementation of energy efficiency measures to decline electricity demand (SRU 2011, p.63).

At a national level, the German Advisory Council for the Environment in its study Pathways to a 100% Renewable Power Supply, showed the options for Germany to reach a power system fully supplied by renewable energy sources by 2050 (SRU 2011, p.31). The study concludes that a 100% renewable system with domestic renewable energy sources is technically possible. Intermittent electricity supply from wind and solar photovoltaic are backed up by dispatchable biomass technologies and compressed air energy storage CAES. By considering an exchange of electricity with Scandinavian countries it was found that the option of using pump storage hydropower plants in Norway would maximize the use of wind energy and will greatly reduce the use of biomass and CAES to back up the intermittency. The use of pump storage hydropower plants proved to be the most cost efficient system in terms of the overall cost of investments and cost per kWh by 2050 (SRU 2011, p.105).

The use of the hydropower potential of Norway for the case of Germany evidences the advantages in terms of cost and flexibility for a full integration of renewables with hydropower. Hydro dominated power systems with storage reservoirs such as those in Colombia could offer the opportunity to deal with the intermittency of renewable energy sources such as wind and solar technologies. Alternating for instance wind and hydropower generation depending on the availability of the wind and hydro resources could provide a virtual storage reservoir for wind energy (Mason et al 2010, p. 3975; IPCC 2011b, p. 627) and may lead to improvements in the ability of hydropower to provide more firm energy (IPCC 2011b, p.634; ESMAP 2010, p.41-42). In addition, the flexibility of hydropower provides a balancing option in the power system (IPCC 2011, p.628). The integration of a high penetration of wind and hydropower systems is technically feasible (Acker et al 2012, p. 11). The combination of variable renewable sources and resources from larger geographical areas could be beneficial in reducing variability (IPCC 2011b, p.635). This may be the case in Colombia thanks to the dispersion of hydropower plants and other potential renewable sources across the country.

A 100% renewable system dominated by hydropower with reservoirs is technically possible. This was shown in an analysis conducted for New Zealand. Between 53% and 60% of power generation coming from hydropower is complemented with a combination of technologies using variable sources such as wind and solar and base load technologies using biomass and geothermal energy (Mason et al 2010, p.3983).

With regard to the costs of renewable energy technologies for power generation, all global energy scenarios show important reduction of cost for these technologies due to their international expansion, related scale effects and expected further development (SRU 2011, p.70; IPCC 2011, p. 816). This trend has been observed in the last years and has been described by means of learning curves in several studies (Neij 2008, p. 2200; European Commission 2006; IPCC 2011a, p.846). In addition, the integration of renewable energy sources may lead to savings due to their lower operation and maintenance costs and avoidance of fossil fuel costs.

Studies conducted for Germany show that the inclusion of renewable energy sources for power generation reduces the electricity generation and transmission cost of supply due to learning effects and increasing fossil fuel costs. These reductions take place at some point in the future (between 2029 and 2044 in the scenarios of the German Advisory Council for the Environment) in comparison to a system without a high penetration of renewables (IPCC 2008, p. 142; SRU 2011, p.180).

Colombia has a heavy based hydropower system that delivers up to 80% of electricity generation from this renewable energy source, the potential to continue expanding with hydropower is still high (ESMAP 2007, p.18). In addition Colombia possesses the potential to produce power with other renewable energy sources, which have not been exploited.

A combination of hydropower with reservoirs complemented with intermittent sources such as wind and solar energy and dispatchable technologies with biomass and geothermal energy sources may lead to a power system fully supplied by renewable energy sources in Colombia. In addition, the economic advantages of a mature technology such as hydropower combined with technologies powered by other renewable energy sources which are commercially available and continues reducing costs of investment and operation may offer an attractive economic alternative to the overall power system. This could be more noticeable in a scenario of growing prices of fossil fuels and scarcity of natural gas in Colombia.

An analysis of how power generation in Colombia may unfold, including the use of renewable energy sources, which addresses the issues presented above for the Colombian power sector, is needed. An analysis that explores different pathways of how power generation in Colombia may develop over time is of significance to the energy sector and may give additional inputs on how to provide guidelines and corresponding energy policies to shape the electricity sector, especially regarding the role that new technologies powered by renewable energy sources may play in Colombia. This dissertation presents such an analysis.

1.2 PROBLEM STATEMENT

This dissertation aims to answer the research question, whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources such as hydropower, natural gas and coal.

Based on the main research question above, the objective of this dissertation is to test the following hypotheses:

(1) Renewable energy sources can fully substitute fossil fuel energy sources and can turn the hydropower based power system in Colombia into a 100% renewable energy system.

(2) The introduction of renewable energy sources in Colombia can be part of the least cost alternative for the expansion of the Colombian power system.

1.3 SIGNIFICANCE OF THE STUDY

The approach of this dissertation differs from the classic approach used for the official planning analysis of the Colombian Mine and Energy Planning Agency (UPME), by including the use of renewable energy sources for electricity generation in the long term and by employing the use of scenario analysis.

A contribution to existing studies is the inclusion of a quantitative analysis with a planning horizon from 2010 to 2050. Power investment decisions are made with the long-term in mind and because the life span of power technologies ranges from 20 to 60 years, the inclusion of the long term in the analysis is fundamental. In doing so power generation based on renewable energy sources can be better compared to conventional energy sources. This comparison helps to make clear the effects of having renewable energy sources for electricity generation over the long term.

The pathways derived from the analyses, which detail how power generation in Colombia may develop over the time horizon, provide additional information that help energy policy makers define guidelines and corresponding energy policies to shape the electricity sector.

Last but not least, the analyses and findings of this dissertation may be applicable to other countries, where hydropower also represents a dominant supplier of the electricity system, such as those countries within the range of the Andes Mountain Range in South America.

1.4 METHODOLOGY:

1.4.1 Type of research

This dissertation is based mainly on quantitative analyses. By means of energy models simulating electricity generation in Colombia, the pathways of the electricity sector from 2010 to 2050 will be assessed. The results of the simulation show power technologies employed, their production and energy sources needed to cover the electricity demand over the time horizon. In that sense this dissertation is an evaluative study in which the introduction of new technologies and energy sources in the electricity supply are judged based on their own economic and technical merits.

Since the core analysis is the simulation of power generation in Colombia, a review and selection of suitable energy models to address the research question of this dissertation were performed as fully discussed in Chapter 3. In addition to the energy models, the collection of data to be entered into the models demanded a quantitative analysis, in particular for the projection of technology costs, electricity demand and fossil fuel prices as presented in Chapter 6.

1.4.2 Structure of the study

This dissertation is divided into a logical sequence of sections which follows the scientific approach taken to reach the objective. Chapter 2 provides an overview of the Colombian power sector. Chapter 3 introduces the theory of energy modelling to define the technique and selection of models to simulate the introduction of new power technologies in Colombia.

Chapter 4 examines the potential of renewable energy sources in Colombia, which is complemented with a description of state of the art technologies for electricity supply powered by these sources in Chapter 5. Chapter 6 is a prognosis analysis for all data required for the energy models until 2050 such as the existing and new portfolio of technologies for electricity supply, their cost and technical parameters, electricity demand, availability of natural gas and coal energy sources, and emission factors of fossil fuels.

The definition of the scenarios of possible pathways of the power sector in Colombia is presented in Chapter 7. A screening analysis of the scenarios with the energy model LEAP is conducted in Chapter 8 and an optimization approach with the energy model MESSAGE is conducted in Chapter 9 according to the theoretical approach defined in Chapter 3 in order to obtain the results of how the Colombian power system could be expanded.

These quantitative results of the simulation with the energy models are put in the context of the Colombian power sector in Chapter 10 emphasizing why renewable energy sources should be part of the Colombian power sector. In addition, climate change issues as well as integration of renewable energy sources in power systems and policies for their integration are analysed.

Finally, conclusions are drawn and recommendations are provided from the results of the dissertation in Chapter 11, where the research question and the objective of this dissertation are discussed.

1.5 DELIMITATIONS OF THE STUDY

The focus of the dissertation is on generation planning. The expansion of the Colombian power system is examined as a whole to determine the power technology mix, size and timing of entrance of new power technologies. The behaviour of the technology and their energy sources in the system is analysed according to the Colombian demand profile. It is not the objective of this dissertation to simulate the behaviour of single power plants in the power market to determine their optimal dispatch schedule and economics in the wholesale market, which is more related to the operation of the system.

The expansion of the power system is related to the capacity and expansion of the transmission network. The optimal location of power technologies to supply electricity to load centers goes through an analysis of the location of energy sources, availability and/or infrastructure for their transportation and the optimal point in the transmission network to connect the new power plants. An expansion of the power sector due to growing demand also requires investments for upgrading the network and adding new lines to transport electricity from generators. Such an analysis is beyond the scope of this dissertation

.

2. COLOMBIA'S ELECTRICITY PICTURE

This chapter serves as a preamble to the dissertation to provide a brief overview of Colombia and introduces the Colombian power sector in order to acknowledge what an energy model should simulate for the case of Colombia. Further analyses of the Colombian power sector are conducted in the following chapters of this dissertation.

2.1 COUNTRY BRIEF

Colombia's total area is 2,070,408 km^2, which is constituted by 1,141,748 km^2 of mainland and 926,660 km^2 of territorial waters. Colombia’s mainland area is divided into five natural regions, Caribbean, Pacific, Amazonia, Orinoco and Andes. Island regions are located in the territorial waters of the Caribbean. An outstanding feature of the mainland are the ranges of the Andes in three major divisions, west, central and east; separated from each other by their valleys of the Cauca and Magdalena rivers, with maximum altitudes between 4,700 and 5,400 m above sea level (IDEAM 2010, p.45). The political and physical map of Colombia is shown in Figure 2-4 and Figure 2-5

Colombia is located on the equator in the north-west corner of South America. The region is influenced by the Intertropical Convergence Zone (ITCZ), a zone of trade-wind convergence that encircles the earth, which plays a large role in the controlling of weather patterns over Colombia including the distribution of rainfall in space and time and cloud cover. The diverse topography of Colombia produces a variety of climate patterns ranging from hot temperatures to perpetual snows. In general, the coastal areas of the Pacific and the Caribbean as well as the regions of the Orinoco and Amazonia have a warm and tropical climate. The ranges of the Andes have a cool climate throughout the year (IDEAM 2010, p.45).

In political terms, Colombia is a democratic republic with three executive branches, executive, legislative and judicial. The executive branch is led by the President. The legislative branch comprises the Senate and the House of Representatives elected by popular vote. The President is also elected by popular vote. The territory is divided administratively into 32 Departments, which are in turn subdivided into municipalities (Proexport 2011, p.5).

The population amounted to 46,044,601 (2011 estimate) (DANE 2012). Approximately 25 million people are under 30 years of age. The Andean region is home to 75% of the population, and the Caribbean region to 21%. The seven largest cities hold 34% of the total population, and have higher demographic growth rates than the rest of the country. Colombia is the second most populous country in South America and the fourth in the Americas. The official language is Spanish (IDEAM 2010, p.45).

Colombia's GDP per capita has almost tripled since 2003 from 2,233 USD to 6,153 USD in 2011. The GDP per capita amounts to 9,300 USD adjusted by the Power Purchase Parity in 2010. In real terms (2005 USD), the GDP per capita has increased 32% from 2003 to 2011 (Proexport 2012, p.40). The goal of the Central Bank is to keep the Consumer Price Index (CPI) between 2% and 4% in the long term. The CPI amounted to 3.7% in 2011 (Banco de la República 2012).

The total energy supply in Colombia consists of coal with a share of 45.1%, oil with a 37% share, natural gas with a 10.4% share, hydropower with a 3.9% share and wood and bagasse with a share of 3.4% as of 2010. The country exports 91% of coal production, 56% of oil production and 12% of gas production (UPME 2011). However, natural gas proved reserves are expected to last only until the year 2020, and oil until the period 2018 to 2020, depending on the evolution of demand and production rates (UPME 2009, p. 147, UPME 2011a, p.144). Coal resources are plenty and is predicted that Colombia can supply international markets and the internal demand for 100 years (UPME 2010, p.68).

Currently, substantial efforts are being made to increase production and to explore new reserves, oil being the most critical. A further analysis of natural gas and coal resources and demand projections is conducted in section 6.7 and section 6.8 respectively.

2.2 COLOMBIA'S POWER SECTOR

The power sector in Colombia is a liberalized market, where the main chain activities generation, transmission, distribution and retailers are separated. Retailers and large consumers acquire their electricity in the wholesale market, which is driven by supply and demand. Transactions in the spot market accounted for 21.2% of total energy commercialized in the electricity market in 2011. Bilateral contracts between generators and consumers amounted to 78.8% (XM 2012).

The market participants are constituted by 41 generators, 69 retailers, 29 grid operators and 9 transmission operators as of 2011. The wholesale market operator is XM (XM 2012). The role of the Colombian state is restricted to regulation, planning and control activities by the Regulatory Commission for Electricity and Gas (CREG), the Energy Mining Planning Unit (UPME) and the Superintendency for Residential Public Services (SSPD) (UPME 2011a, p.98).

In relation to the electricity generating industry, electricity supply in Colombia is differentiated between generators connected to the National Grid (SIN), and generators of

Non-Interconnected Areas (ZNI). The national grid consists of 24,405.8 km of transmission lines (XM 2012). Figure 2-6 shows a map with current transmission lines in Colombia.

The portfolio of technologies of the Colombian electricity sector consists mainly of hydropower and fossil fuel power plants powered by natural gas and coal. The total power capacity in Colombia amounted to 14,367 MW in 2010. Hydropower has a share of 67.7% of the total capacity followed by natural gas with 27.3% and coal with 4.9% as of 2011 (UPME 2011, p. 50-52). Table 2-1 shows the capacities by energy sources from 2003 to 2010. The total capacity has increased by approximately 740 MW from 2009 to 2010 by the addition of a new hydropower unit of 660 MW and other small power plants.

Table 2-1 Capacities in MW and shares in the Colombian power sector

	Hydropower		**Coal**		**Gas**		**Wind**		**Others**		**Total**
Year	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*
2003	8,839	67.0	692	5.2	3,656	27.7	0	0.0	13	0.1	13,200
2004	8,923	66.5	692	5.2	3,766	28.1	20	0.1	16	0.1	13,417
2005	8,948	67.0	694	5.2	3,682	27.6	20	0.1	14	0.1	13,348
2006	8,956	67.4	700	5.3	3,585	27.0	18	0.1	20	0.2	13,279
2007	8,997	67.1	700	5.2	3,675	27.4	18	0.1	20	0.1	13,410
2008	9,002	66.8	700	5.2	3,739	27.7	18	0.1	20	0.1	13,479
2009	9,036	66.7	700	5.2	3,759	27.8	18	0.1	30	0.2	13,543

Source: Data from XM 2011.

While the share of capacities has been constant over the years, the electricity production share reveals a completely different picture. The share of electricity generation in Colombia is dominated by hydropower. 67% of the total production by 2010 (56.9 TWh) was delivered by hydropower plants, this increased to 77.8% of the total production by 2011 (58.6 TWh). Coal and natural gas complete the production. Natural gas covered 20.1% and 13% and coal 6.3% and 2.8% by 2010 and 2011 respectively (XM 2011). Figure 2-1 shows the contribution of energy sources to total electricity generation from 1997 to 2011.

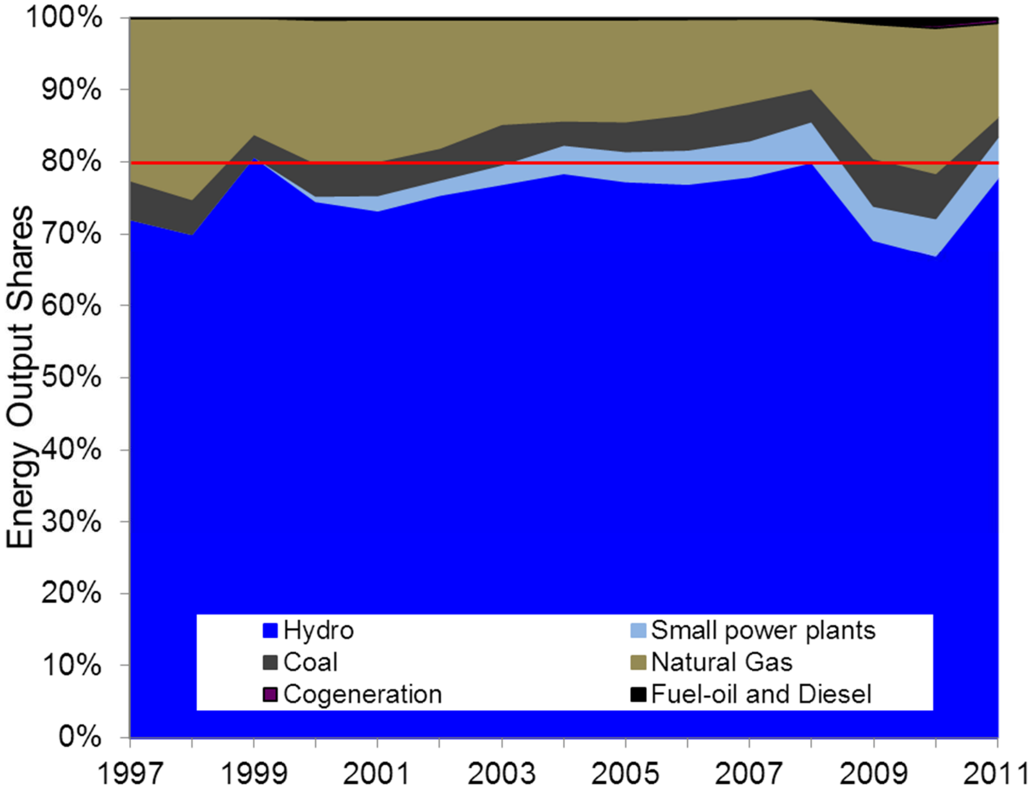

Figure 2-1 Shares of in electricity generation in Colombia

Source: Data from XM 2011.

Electricity generation in Colombia is dependent on the availability of water resources, which are influenced by Colombia's seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO). The ENSO can cause extreme weather conditions (droughts and floods respectively) over the region. This situation has a significant impact on hydropower generation. The resulting fluctuations of hydropower generation lead to power generation price volatilities in the spot market (UPME 2003, p.16; Ayala et al 2003, p.79; Corpoema 2010, p.4-4, 4-5). As a result, fossil fuel power generation varies substantially, which affects the cost per kWh. Figure 2-2 shows electricity generation and spot price development in Colombia.

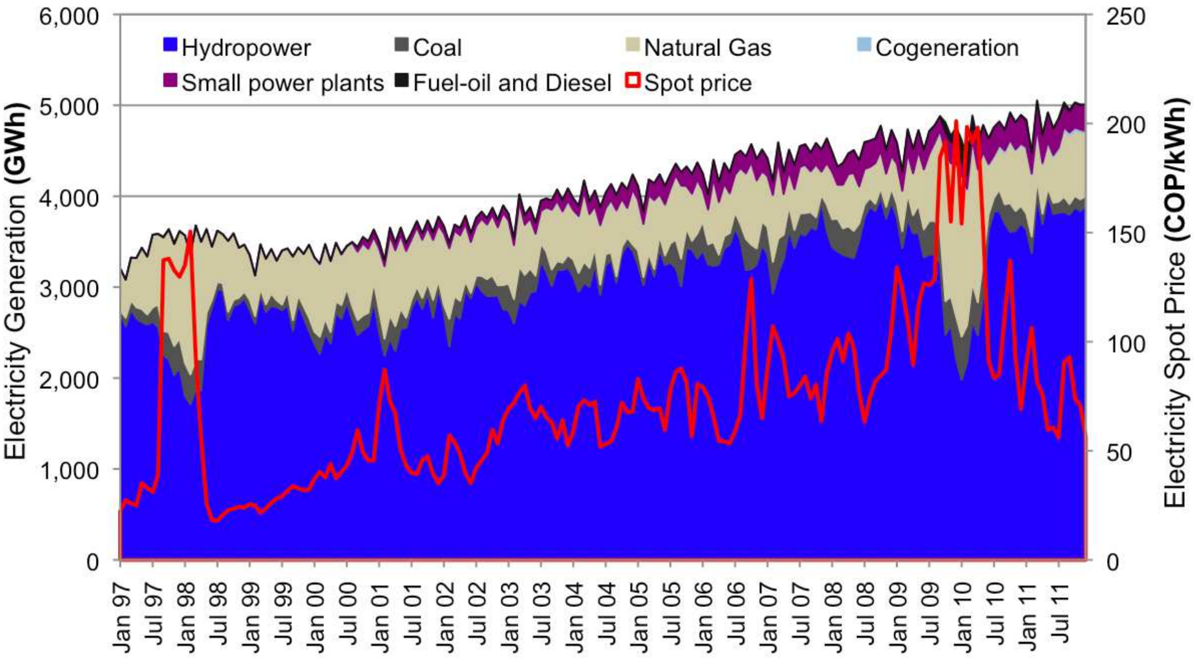

Figure 2-2 Electricity generation and electricity spot price in Colombia

Source: Data from XM 2012.

Electricity demand in Colombia has increased at an average rate of 3% in the last 7 years (UPME 2011, p.37), with fluctuations existing between 2008 and 2009 due to the global economic situation paired with extreme weather conditions. The official electricity demand projections forecast growth rates between 3% and 4% up until the year 2030 (UPME 2011, p.31). Figure 2-3 shows the increase of demand and GDP over the last years.

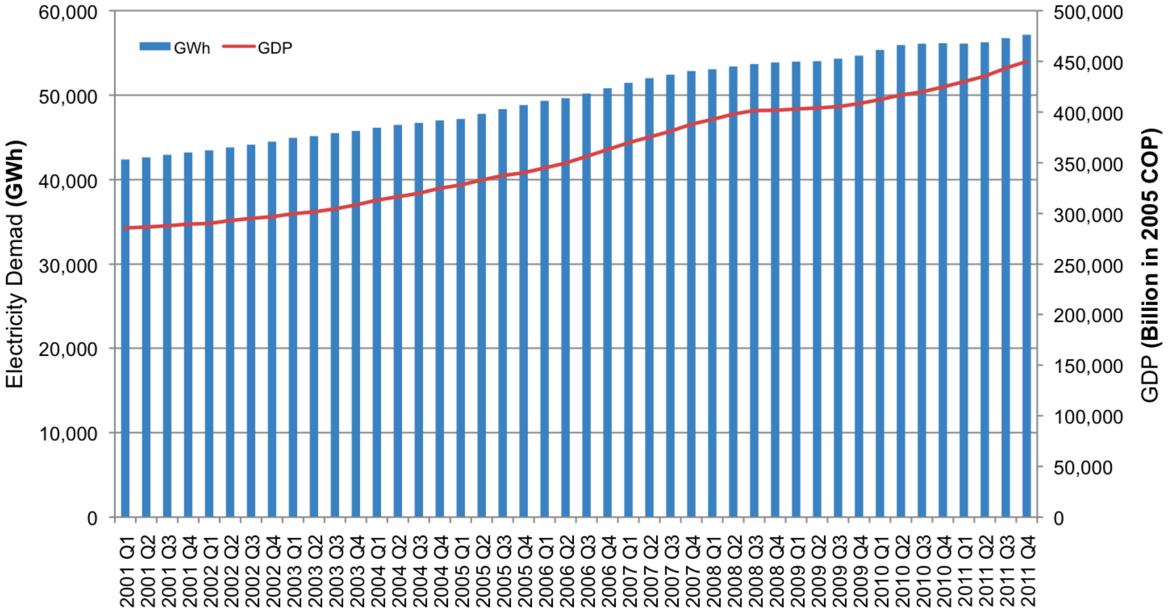

Figure 2-3 Electricity demand and GDP growth in Colombia

Source: Data from XM 2012 and Banco de la República 2012. COP = Colombian Pesos.

A more detailed assessment of the Colombian electricity power sector is performed, and is described in the following chapters of this dissertation, in particular in the prognosis analysis (Chapter 6) and in the analysis of renewable energy in the context of the Colombian power sector (Chapter 10).

This overview of the power sector in Colombia demonstrates what an energy model should be capable of; that is, a simulation of the delivery of electricity from different power technologies to cover a growing demand. A review and selection of suitable energy models for the simulation is described in the next chapter.

Figure 2-4 Political map of Colombia

Source: IGAC 2012

Figure 2-5 Physical map of Colombia

Source: IGAC 2012a

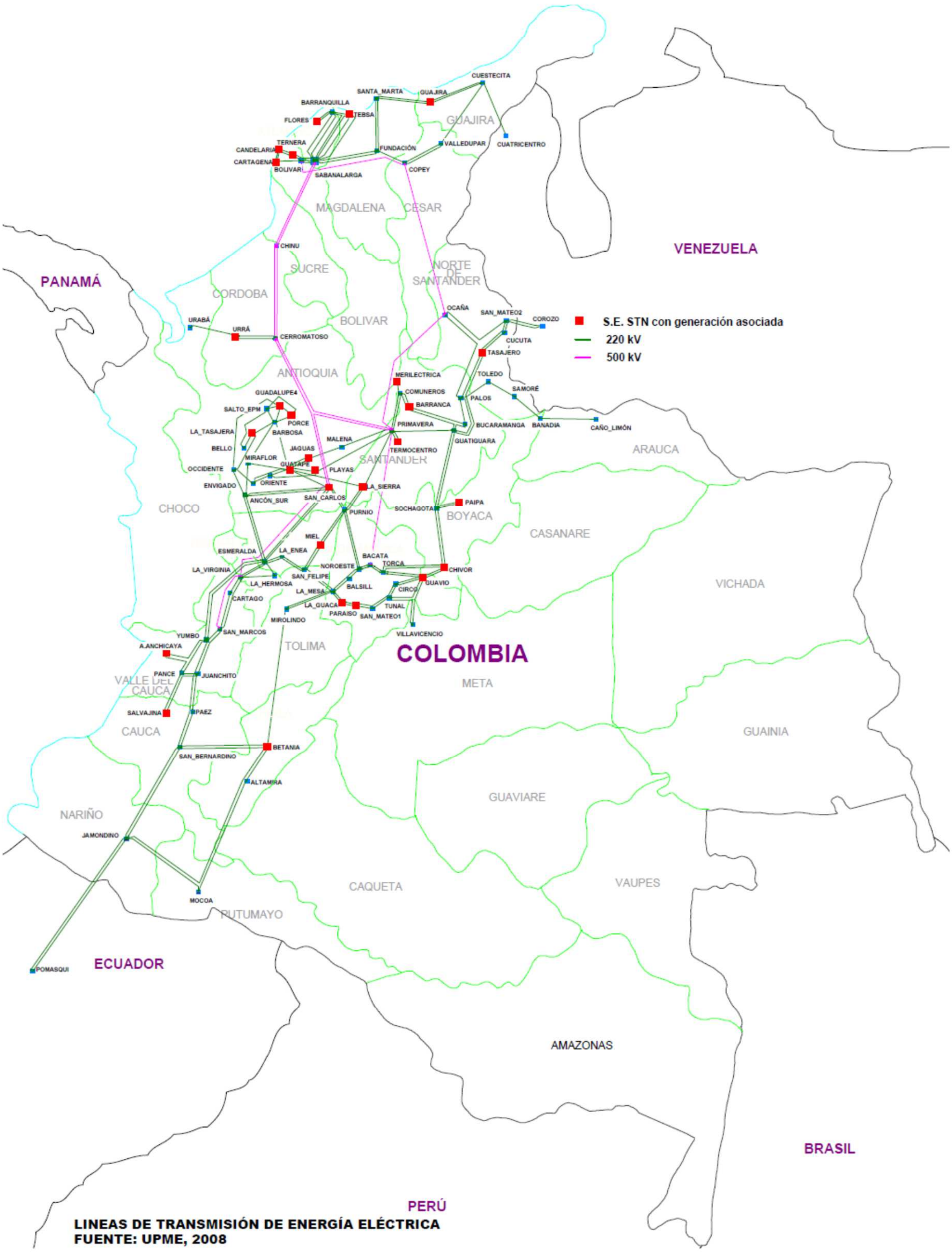

Figure 2-6 Transmission lines of the national grid (SIN)

Source: UPME 2011c

3. ENERGY MODELING

A review and selection of suitable energy models for the simulation of large scale integration of renewable energy sources for power generation in Colombia is conducted in this chapter. The chapter begins with the rationale of power generation planning. A literature review of modeling of energy systems that tackle the issues of power generation planning is conducted in order to select the model classes that better suit the objective of this dissertation. The methodology to conduct the quantitative analysis for this dissertation closes this chapter.

3.1 POWER GENERATION PLANNING

Electricity is an economic good with unique features in comparison with other commodities; it cannot easily be stored[1] and therefore has to be consumed as it is produced. What is demanded has to be available, ready for delivery and compatible with the quality requirements of the grid. A real time balance between supply and demand takes place by coordinating generators and demand centers, all connected by the same transport system. Although there are variations such as independent power production not relying on the grid and distributed generation (small scale independent production at low voltages), the major bulk of electricity is conceived in such a system.

The demand for electricity varies on all time scales: hourly, daily (day and night), seasonally (e.g. winter and summer) and yearly (e.g. more consumers, economy boom or recession). The electricity needs of consumers shape the demand according to their energy practices and income. In a broader sense, the performance of the economy, population growth, grade of industrialization, location of consumers and access to electricity (physically and economically) define the volume of the demand and its shape in a given period.

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[1] Pump storage plants, hydrogen production, and compressed air energy storage are examples of technologies which transform electricity in other forms of energy to make storage possible.

A general challenge is having the necessary power generation and transmission capacity at disposal in order to cope with both demand fluctuations and growing demand. From the generation-side, the key questions are: a) what kind of technologies are needed, b) how many of them are needed, c) when is the optimal time for new power plants to enter into operation and d) at what cost. To exemplify this in more detail, a load duration curve representing the demand is shown in Figure 3-1 (Stoll 1989, p.486 and p.503; SEI 2006, p.103).

A load duration curve plots capacity required per hour (the power demand) against the number of hours in a year. Load duration curves sort the demand from the highest to the lowest value of a year. Thus, a cumulative graphical representation of the number of hours in which the power demand exceeds a given value is obtained. The load duration curve improves schematically the representation of both power requirements and dispatch of different types of power plants.

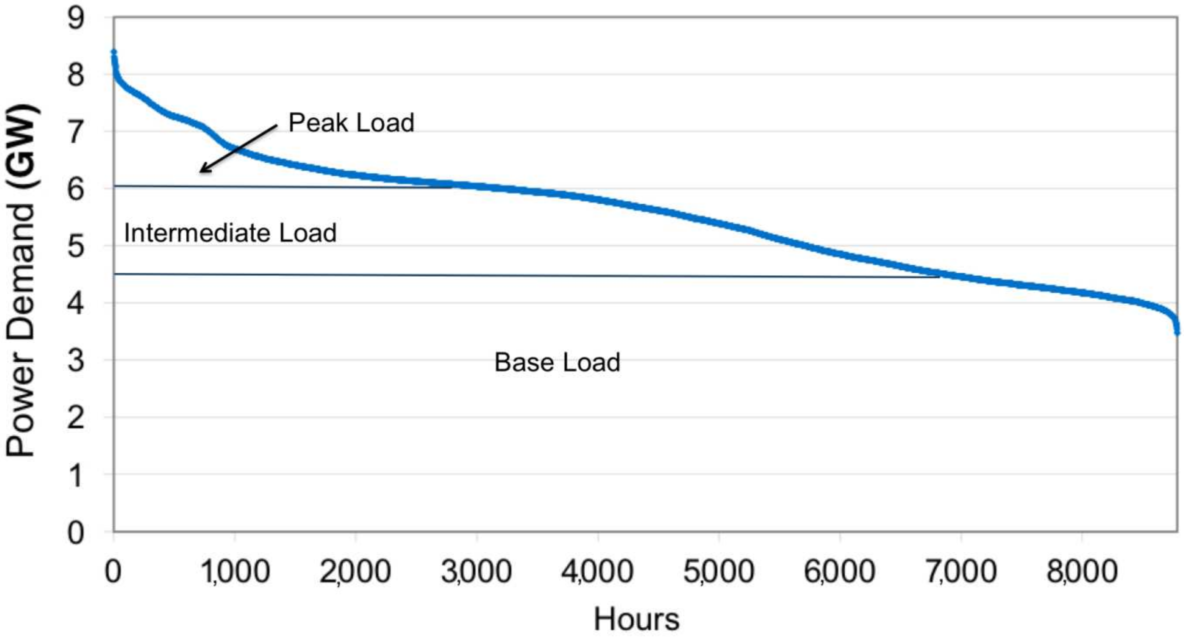


Figure 3-1 Load curve

Source: Data from XM 2007.

From Figure 3-1 three main levels can be distinguished. The first level, called the base load, requires generation technologies to serve full time. In contrast, a peak load level is needed to serve high load demands that occur at given hours (e.g. at 7 pm in Colombia). The intermediate load level is in between.

The selection of a power plant to a load is a decision combining the technology's technical features and costs. Base load power plants, for instance, have low variable generation cost and do not change production to match fluctuating power demand. In contrast, higher variable cost power plants such as combined cycle plants are better suited to match fluctuating power demand and are typically used to serve the intermediate load. High variable cost peaking power plants such as combustion turbines are more responsive, run more easily and are faster on line so they serve peak loads.

Identifying the optimal type of technology to deliver electricity to a given load at the *least cost* can be explained using a screening curve analysis which combines the economic merits of different types of generation technologies and the number of hours at which they can operate to determine their suitability to attend base, intermediate or peak loads (Stoll 1989, p.501; Stoft 2002, p.34).

A screening curve analysis is exhibited in Figure 3-2. The economic merits of the technologies are shown in the levelized annual cost curve. This curve plots the capacity factor and the levelized annual cost of every technology. The capacity factor is the ratio of a given output of a power plant over a period of time and its output if it had operated at full nameplate capacity the entire time. The levelized cost is the result of a cash flow analysis over a given time horizon where all costs are annualized at different capacity factors.

The intersection of the levelized cost curve of the coal and combined cycle unit shows that the coal unit is able to operate at capacity factors over 55% per year (more than 4,818 hours) at lower costs than the combined cycle unit. Therefore, the coal unit can serve the base load of the electricity demand optimally from an economic point of view. In this case, approximately 2,500 MW of coal units are needed for base load as shown by a projection of the intersection between the load duration curve and the 55% capacity factor.

The coal power plant has a high capital cost that is counteracted by the low operation cost. Below 55%, the coal power plant is not competitive. The combined cycle power plant performs better at capacity factors between 15% and 55%. Despite a lower capital cost, the combined cycle power plant has a higher operation cost than coal. The gas turbine power plant serves the peak periods, it has a very low capital cost but high operational cost.

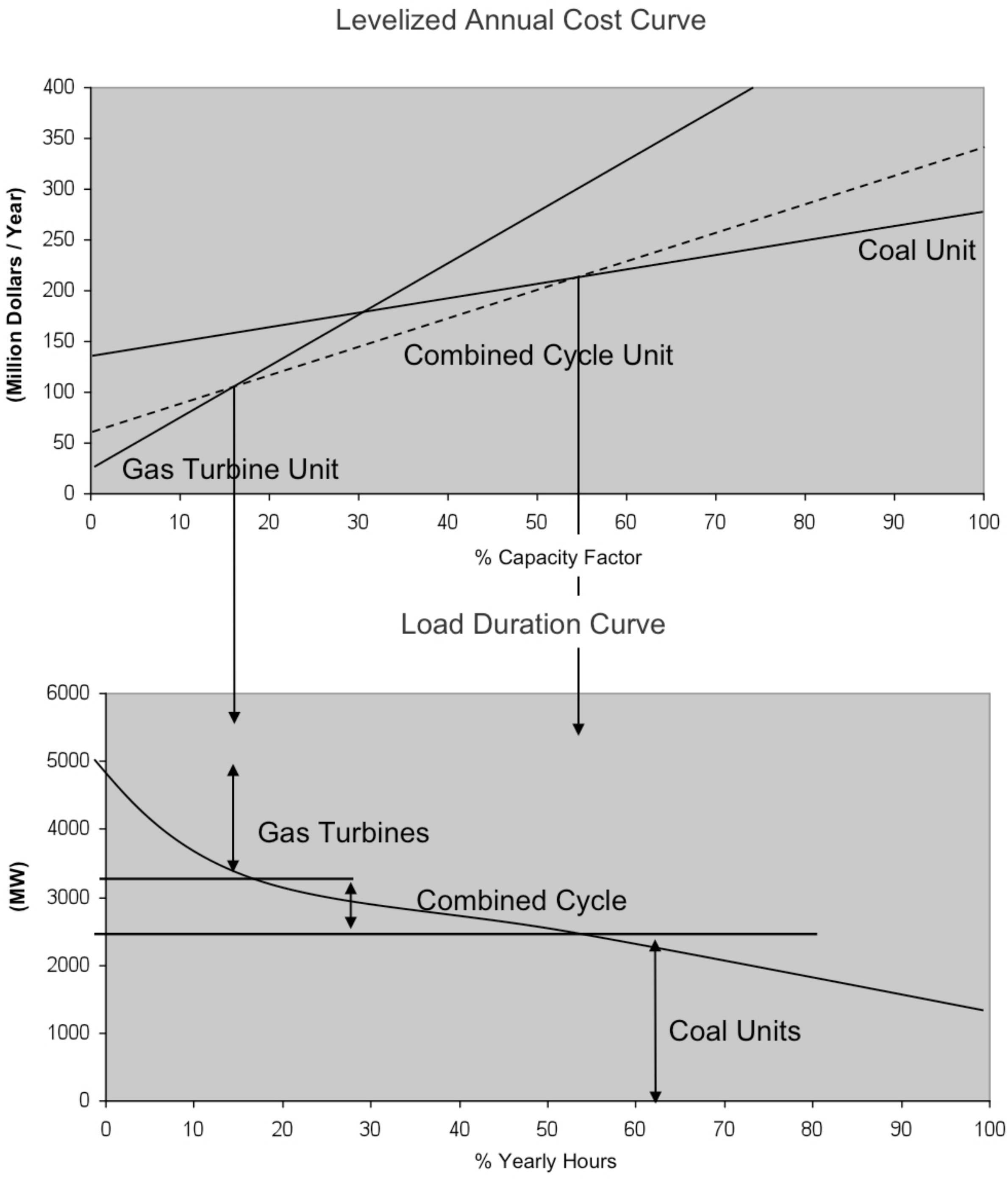


Figure 3-2 Screening curve

Source: Modified from Stoll 1989, p.503.

The screening curve analysis shows schematically in a very simplified way the generation mix concept in which technologies based on their merits serve the different loads in the load duration curve. This analysis must be further improved to include needed future power generation expansion over a time horizon, replacing of old units, environmental criteria, forced and scheduled outage rates of power plants, intermittency of energy production, etc. The next sections will introduce the techniques available that include these aspects and allow a simulation of the delivery of electricity of an entire power system over the years.

3.2 MODELING OF ENERGY SYSTEMS

A model of a system or a process is a mathematical representation of the system's functioning to make possible the understanding of how the system works and behaves under various conditions or scenarios (Tester et al 2005, p.275). The core analysis of this dissertation is to simulate the expansion of the Colombian power sector over the long-term. A model therefore must be designed or selected that integrates power supply, electricity transport and demand to weigh diverse portfolios of generation technologies. This allows the assessment of impacts of technological choices on the economy, environment and society.

The development of energy models can be traced back to the early 1970s where the oil price shock made necessary the design of energy policies to find ways of reducing dependence on oil. Since then, a variety of models have been developed. In the late 1980s the inclusion of global warming in the analysis to assess CO_2 mitigation strategies and other energy pollutants such as sulphur dioxides, nitrogen oxides and particulate matter became essential. Cost was no longer the main driver in energy analysis, society and environment factors had become also relevant (Messner 1997, p.293; Lesourd J.B. at el 1996, p.xxxi; Diakoluaki et al 2005, p.860).

In the section to follow a literature review of energy models is presented. The objective of this review is to identify the model class that better suits the objective of this dissertation. An analysis of suitable models is later detailed in Sections 3.3 and 3.4.

3.2.1 Model classes

Energy models can be classified under different criteria such as the theoretical foundation, the time horizon, and data requirements. In general an energy model does not belong to a single category. From a broad perspective models belong to two classes (Messner 1997, p.292; Koch et al 2003, p. 45):

i) Technology oriented optimization and simulation models known as *Bottom-Up Models* and ii) economy oriented models with an emphasis on energy as a sub sector of the overall economy known as *Top-Down Models*.

Bottom-up models are often referred to as energy system models or end-use models. Top-down models are also known as energy-economic models or macro or econometric models. Models combining the two approaches, hybrid models, are also found linking technology oriented models with the overall economy.

The top-down analysis is a macroeconomic approach to model energy-economy interactions and the costs of changing those interactions. In a bottom-up analysis the energy analysis is a disaggregate approach to model energy supply and demand. Supply and demand are altered to find alternatives and their corresponding costs. Bottom-up and top-down models were conceived and designed through disciplines, for different purposes and lead to very different conclusions as noted by Wilson and Swisher in their top-down versus bottom-up analysis (Wilson et al 1993, p.249).

A further classification of energy models according to the theoretical approach better explains the basic methodological differences between bottom-up a top-down approaches (Heaps 2002, p.2; Alfstad 2005, p.44; Mäkelä 2000, p.17; Koch et al 2003, p.71; Wilson et al 1993, p.250):

i) General equilibrium models
ii) Optimization models
iii) Simulation models

The *General Equilibrium Model* is a top-down model since macro-economy factors dictate the main parameters (e.g. level of income). Here supply and demand functions describe the market relations. The equilibrium is found in the intersection of the two curves indicating the market optimum between price and quantities. Elasticities are included to account for changes in quantities due to variation in prices. The energy sector is then represented with the help of production functions based on capital and labor, which do not allow for a detailed description of technological alternatives. Thus, the behavior of consumers and producers are simulated under various signals such as energy prices, income levels, and policies. As a result the energy prices are found endogenously. A *Partial Equilibrium Model* is used when the analysis is for one sector, e.g. the energy sector. General equilibrium models are useful to analyse the relationship between the energy sector and the overall economy. Examples are LEAN, and NEWAGE (Koch et al 2003, p. 50).

In an *Optimization Model* the energy systems are represented by the technical, economic and environmental features of technologies. Unlike the general equilibrium models, the optimization model requires as input of what constitutes the supply (energy resources and technologies) which is available and a portfolio of new technologies. This structure makes it a bottom-up model. Thus, the model selects the suitable mix of technologies according to the parameters given by the modeler. This is achieved by an optimization routine based on linear or dynamic programming to maximize or minimize an objective function, normally the least cost energy supply under various constraints such as technology availability, emissions caps, mandated renewable energy shares, reserve margins, etc. Demand is given mostly exogenously in the model. Optimization models are prescriptive rather than descriptive (ERC

2008, p.2) since the optimization routine with the objective function and constraints set by the modeler finds the solutions instead of indicating the model what the outcome should be as it is found in accounting framework models. Optimization models are useful for questions of technological choice. Examples are MARKAL, MESSAGE and RAINS models from IIASA, IKARUS, PERSEUS, E3NET and WASP (Koch et al 2003, p. 65-66; Lund 2008, p.83-84).

Similarly, *Accounting Framework Models or Simulation Models* are represented by technical, economic and environmental features of the single technologies and hence, belong to a bottom-up model. While the optimization model is controlled by the objective function and its constraints in the mathematical formulation because it uses a prescriptive approach, the accounting framework models on the other hand use exogenously specific outcomes set by the modeler, the descriptive approach. Thus, technological development is an input into the model, e.g. the rate of penetration of wind energy in the system which differs from the learning curve approach in an optimization problem where the rate of penetration is endogenously determined. In that way other objectives apart from the least cost goal can be taken into account in the analysis such as social and environmental factors. The advantage is that the model can integrate detailed expertise to shape the results making the model ideal for scenario analysis examining possible futures. This is a major difference with models making use of historical data, time series analysis, to accomplish a forecast analysis as general equilibrium models do. The model carries out an accounting balance for the flow of energy from resources, extraction, and transformation until end users consumption. Accounting framework models are useful to analyze the implications of policy objectives. Examples of this approach are the models LEAP, GEMIS and EnergyBALANCE (Koch et al 2003, p. 70; Lund 2008, p.83-84).

A further classification of energy models can be performed according to the treatment of the energy demand. A *Partial Equilibrium Model* (the term partial is used because the analysis is for one sector; the energy sector) calculates balance prices against supply and demand curves of energy; therefore the demand is endogenously calculated, whereas in fixed demand models the demand is an exogenous variable determined by the model user (Märkelä 2000, p.18).

Static, Quasi-Dynamic or Dynamic Models are also other classification categories. Static refers to the representation of one point in time in the analysis (e.g. peak load). Quasi-dynamic optimizes the energy system for a given period of time and the results become the input for the second period. The dynamic model optimizes the solution for the time horizon instead (Märkelä 2000, p.19).

Furthermore a distinction between *middle- and long term analysis and short term forecasting* can be made. The middle and long term modeling are found in parametric models like the ones described above where the data is based on various sources such as literature, official statistics, policies, modeler assumptions and judgments whereas the short term models make use of econometric models based on statistical analysis of time series data (Märkelä 2000, p.19).

3.2.2 Model for the long term of power generation planning

After introducing the model classes, a suitable model class can be selected that addresses the research question whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources.

Bottom-up or top-down

The modeling of technological choices for supply alternatives requires the handling of extensive data. The degree of detail required is high and the specific technical and economic features of technologies must be modeled: resources available and transformation rates, fuel extraction; technology efficiencies, capacity, availability, transmission and distribution losses, investment and operation and maintenance costs, fuel prices, etc. From that rational a bottom-up approach must be used. A bottom-up model can be combined with a top-down model to examine macroeconomic effects.

With respect to the demand in a bottom-up model, this can be endogenously obtained or exogenously given in the model. When calculated endogenously a bottom-up model differentiates itself from top-down models by calculating the demand based on an engineering approach by means of energy intensities of end use technologies instead of the macroeconomic approach of a top-down model (income and prices).

Equilibrium, optimization, or accounting framework models

Equilibrium models belong to the top-down model class and they are therefore suitable for macroeconomic questions instead of focusing in detail on the supply or demand technologies. In contrast, the bottom- up approach of optimization and accounting models are adequate models, since they allow an engineering approach by including the present stock of technologies, their life-span, future options to both replace and expand the stock of demand and supply technologies. As explained before, optimization and accounting models differentiate themselves from their theoretical approach. The approach that is most suitable depends on the research questions, the information available and the modeler proficiency with the theory (Heaps 2002, p.6-7).

Short, middle or long-term

The issue of power generation planning implies by itself the long term. Investment decisions must be made with technologies with life spans ranging from 10 to 50 years or more. A portfolio of technologies over a time horizon is the output of the model. In addition, the incorporation in the analysis of climate change issues demands time horizon analysis up to 100 years. For these reasons an analysis for the long term should be conducted.

The modeling of technological choices for supply alternatives is the core analysis required by this dissertation. The engineering approach of bottom up models is therefore the suitable model class. Thus, a bottom-up model is ideal for addressing the research question. However, bottom-up models tackle the power generation planning issue in a different way. Thus a more detailed analysis of the two models, the accounting framework model and the optimization model, is necessary in order to select the best approach. This will be discussed in detail in the next sections.

3.3 ACCOUNTING FRAMEWORK MODEL

An energy balance is the basis of an accounting framework model. An energy balance is a systematic representation of the energy flow from its extraction, transformation to its final consumption (Munasinghe 1993, p.37). It is an energy network that shows all energy carriers, transformation and transport technologies as well as the sectors demanding energy as depicted in the hypothetical example conducted with LEAP as shown in Figure 3-3 and Table 3-1 below:

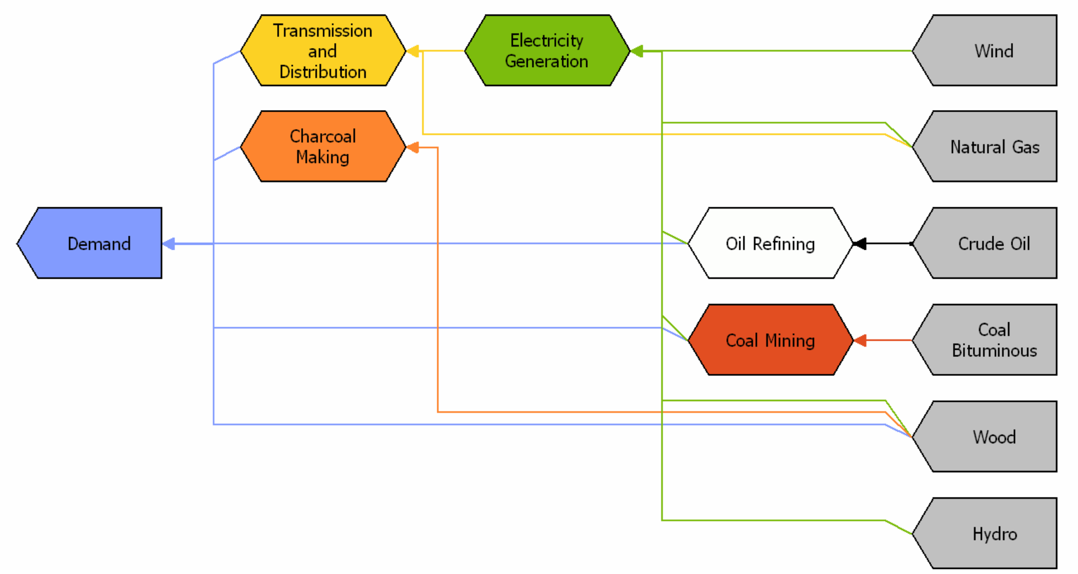


Figure 3-3 Energy chain example

Table 3-1 Energy Balance Reference Scenario example

Scenario Reference Year 2000 - Units in Million Gigajoule								
	Electricity	**Oil Products**	**Solid Fuels**	**Crude Oil**	**Natural Gas**	**Hydro-power**	**Biomass**	**Total**
Production	0	0	0	0	0	20	81	101
Imports	0	0	125	218	4	0	0	346
Exports	0	0	0	0	0	0	0	0
Total Primary Supply	***0***	***0***	***125***	***218***	***4***	***20***	***81***	***447***
Coal Mining	0	0	-25	0	0	0	0	-25
Oil Refining	0	174	0	-218	0	0	0	-44
Charcoal Making	0	0	0	0	0	0	-32	-32
Electricity Generation	58	-51	-86	0	0	-20	0	-98
Transmission and Distribution	-9	0	0	0	0	0	0	-9
Total Transformation	**50**	**123**	**-110**	**-218**	**0**	**-20**	**-32**	**-208**
Household	18	13	0	0	3	0	33	68
Industry	20	22	14	0	0	0	16	72
Transport	1	78	0	0	0	0	0	79
Commercial	10	10	0	0	0	0	0	20
Total Demand	***50***	***123***	***14***	***0***	***3***	***0***	***49***	***239***
Unmet Demand	0	0	0	0	0	0	0	0

As the name implies the flow of energy must be balanced as shown in the last row in Table 3-1. Production must equal consumption as follows (IEA 2005, p.I.3):

$$P + I - X \pm DS = L + C_f \quad [1.]$$

Where:

P = Total Indigenous Production
I = Imports
X = Exports
DS = Stock Changes
L = Losses and consumption in the transformation sector
C_f = Final Consumption

The left side of the equation [1] corresponds to the domestic supply which represents the resource requirements; the transformation sector -L- comprises the conversion of primary forms of energy to secondary fuels as well as losses in the transportation. The final consumption C_f represents the different sectors demand for energy.

By manipulating the values of one of the energy forms at any stage, the effect on the overall energy system can be seen. For instance the penetration of renewable energy sources for electricity generation such as wind and solar, so that a displacement of a conventional power plant makes it possible to allocate natural gas and coal resources for other uses. Improvements of transformation efficiencies, better consumption practices, etc. are some examples of how an energy balance can be modified to determine the effect on the energy system.

That makes an accounting framework model descriptive by entering a change defined by the modeler. The model is thereby suitable for scenario analysis. For a long term exercise, an energy balance calculation is performed, e.g. per year, and the accounting process is performed from final energy demands up to production. Table 3-2 shows the energy balance for the year 2030 of the example introduced in Figure 3-3 and Table 3-1 above, where a higher demand of electricity, oil and solid fuels increases imports substantially.

Accounting framework models are “What If” tools that examine the implications of a scenario by altering and adjusting the balance. Scenarios are constructed based on assumptions for a set of potential futures (Energy Research Centre 2008, p.2; Heaps 2002, p.9). These models have no degrees of freedom, there is only one equation for every variable and therefore only one feasible solution can be found (ERC 2008, p.1; Messner et al 2000, p.400).

Table 3-2 Energy Balance Scenario 2030

Scenario Reference Year 2030 - Units in Million Gigajoule								
	Electricity	**Oil Products**	**Solid Fuels**	**Crude Oil**	**Natural Gas**	**Hydro-power**	**Biomass**	**Total**
Production	0	0	0	0	0	22	105	127
Imports	0	561	622	251	17	0	0	1,451
Exports	0	-100	0	0	0	0	0	-100
Total Primary Supply	***0***	***461***	***622***	***251***	***17***	***22***	***105***	***1,479***
Coal Mining	0	0	-124	0	0	0	0	-124
Oil Refining	0	201	0	-251	0	0	0	-50
Charcoal Making	0	0	0	0	0	0	-51	-51
Electricity Generation	225	-160	-484	0	0	-22	0	-441
Transmission and Distribution	-27	0	0	0	0	0	0	-27
Total Transformation	***198***	***41***	***-609***	***-251***	***0***	***-22***	***-51***	***-694***
Household	110	30	0	0	7	0	30	177
Industry	64	45	13	0	1	0	24	147
Transport	6	423	0	0	0	0	0	429
Commercial	19	4	0	0	9	0	0	32
Total Demand	***198***	***502***	***13***	***0***	***17***	***0***	***54***	***785***
Unmet Demand	0	0	0	0	0	0	0	0

In that sense the accounting framework does not find the optimal flow of energy in the energy chain as it is performed by other mathematical model techniques (Munansinghe et al 1993, p.70). The accounting framework models do not assume perfect competition, are simple, transparent and flexible and require less data than optimization models. However they do not automatically identify least-cost systems (Heaps 2002, p11).

3.4 OPTIMIZATION MODEL

A classical optimization model is composed of an objective function and its constraints. The objective function is what the model must target: minimum cost, minimum production of emissions, maximization of income, etc. as appropriate. The constraints help the objective function to concentrate on the set of combinations that are realistic; they control the objective function by instructing what it is permitted.

The objective function makes the optimization model different from the accounting framework model. The outcome is not an input into the model but rather the result of the mathematical routine of the model, e.g. the rate of penetration of a new technology is not given, the optimization model based on the cost and technical features of the technology determine when and how much enters the market. The solution must meet the objective (e.g. least cost) and the constraints (e.g. cap on emissions).

Power generation planning in the long term is an excellent example to show what an optimization model is capable of. In Figure 3-4 below the existing power system must be expanded for the next 20 years. Three sets of technology alternatives are at disposal: a thermal steam power plant (ST), a combined cycle (CC), and a gas turbine (GT). Assuming a new unit is needed per year, the alternative generation plans up to the 20th year amount to 3 billion. If the objective is to minimize the cost of expansion, the optimization procedure finds the best combination.

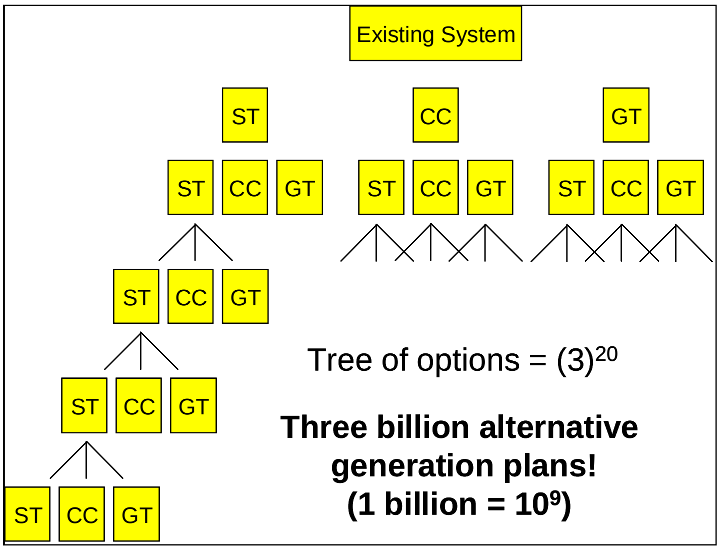


Figure 3-4 Power expansion tree

Source: Modified from Stoll 1989, p.513.

Regarding the optimization procedure, there are multiple mathematical techniques at disposal to find the best solution. The most widely used techniques are based on linear programming (Messner et al 2000, p.401; Munasinghe 1993, p.73). In linear programming a variety of techniques are employed such as dynamic programming, integer linear programming and mixed integer programming. Optimization models may also include more than one objective function. That is the optimization focuses on more than one target. A classical example is including both the minimum cost of expansion and the minimum possible emissions as targets in the optimization problem (Mavrotas et al 2005, p.191).

The complexity of these models requires a good understanding of optimization techniques and their mathematical grounds. For that reason, the command of optimization models demands more effort than accounting framework models. Before introducing briefly the optimization techniques, an example of a classic linear programming problem needs to be introduced aimed at understanding the basics of optimization techniques.

Linear programming example:

A utility has a contractual agreement to deliver 1,000 MW of electricity per hour. Two power plant technologies are available with a total capacity of 1,300 MW with the following features:

Table 3-3 linear programming example

Power Plant	**Capacity** *(MW)*	**CO_2 Emission Factor** *(tCO_2/MWh)*	**Variable Cost** *($/MWh)*
Combined cycle	500	0.40	43
Coal steam cycle	800	0.74	33

In addition the utility has a cap of 640 tonnes of CO_2 per hour. Assuming that the utility cannot trade the excess power, the least cost dispatch must be found. In this very simple example it can be seen that the least cost dispatch without the CO_2 restriction is 800 MW of the coal power plant and the remaining 200 MW with the combined cycle, since the coal power plant has a lower variable cost. To find the adequate dispatch of both power plants, the optimization procedure begins as follows:

Objective function formulation:

If y_1 and y_2 are the amount of power to be delivered by the combined cycle and the steam cycle respectively, the total power cost is the sum of the total variable costs of both plants:

Minimize: $K = 43y_1 + 33y_2$ [2.]

Constraints formulation:

The objective is constrained by the total demand, the maximum capacities and a CO_2 cap.

$y_1 + y_2 \geq 1000MW$ [Demand constraint] [3.]

$y_1 \leq 500MW$ [Capacity constraint] [4.]

$y_2 \leq 800MW$ [Capacity constraint] [5.]

$0.40y_1 + 0.74y_2 \leq 640tCO_2$ [CO_2 constraint] [6.]

And non-negativity constraints must also be added:

$y_1, y_2 \geq 0$ [7.]

Graphical interpretation:

A graphical interpretation of the problem is executed by plotting all constraints and taking into account the inequalities as depicted in Figure 3-5. The solution is found in the region that the constraints have left out. This region is called the feasible area of solution as indicated in the figure below by the points A, B, C. Inside the feasible area are found all possible combinations of y_1 and y_2 that fulfill the constraints. The objective function is also plotted by solving for y_2:

$$y_2 = \frac{K}{33} - \frac{43}{33}y_1 \text{ [8.]}$$

This equation is a line with a slope of -43/33 that can be moved along the feasible area by changing K to find the solution, where the optimum can be found in one of the corners. Figure 3-5 shows that the objective function that yields the minimum cost is found at A. The optimum coordinate therefore is 295 MW from the combined cycle and 706 MW from the coal power plant. The demand and CO_2 constraints were completely fulfilled (by substituting the values of y_1 and y_2 in the constraints the result is equal to the right side of the constraint) which make them *binding* constraints whereas the capacity constraint are fulfilled with values lower than their right side. In this case, the constraints are said to be *non-binding*. In the example, this means that the full capacity of the power plants was not delivered.

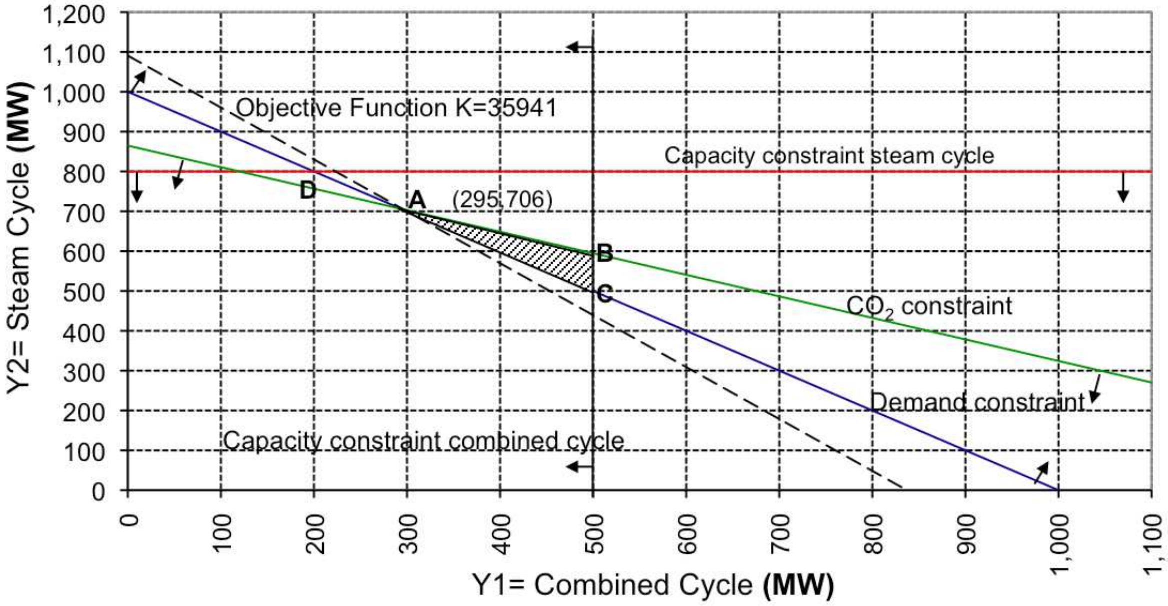


Figure 3-5 Linear optimization example

Since this example has only two variables the optimization could be solved graphically. A graphical representation with three variables requires plotting the constraints in three dimensions. A variable number exceeding three thus cannot be represented graphically anymore. As it will be seen, a power planning optimization problem can easily have hundreds of variables. Therefore, mathematical optimization techniques have to be used. Before entering into that topic, an important feature of linear programming needs still to be introduced, that is the “dual” property of a linear programming problem.

The linear programming formulation (objective functions and constraints) shown in the example is called the *primal*, which can be converted into what is called its *dual*. For each constraint in the primal, there is one variable in the dual. If the objective function of the primal is to be minimized, then its dual is to be maximized. The dual of the example is shown below:

Maximize: $1000x_1 + 500x_2 + 800x_3 + 640x_4 = G$ [objective function] [9.]

Subject to:

$x_1 - x_2 + 0.43x_4 \leq 43$ [10.]

$x_1 + x_3 + 0.33x_4 \leq 33$ [11.]

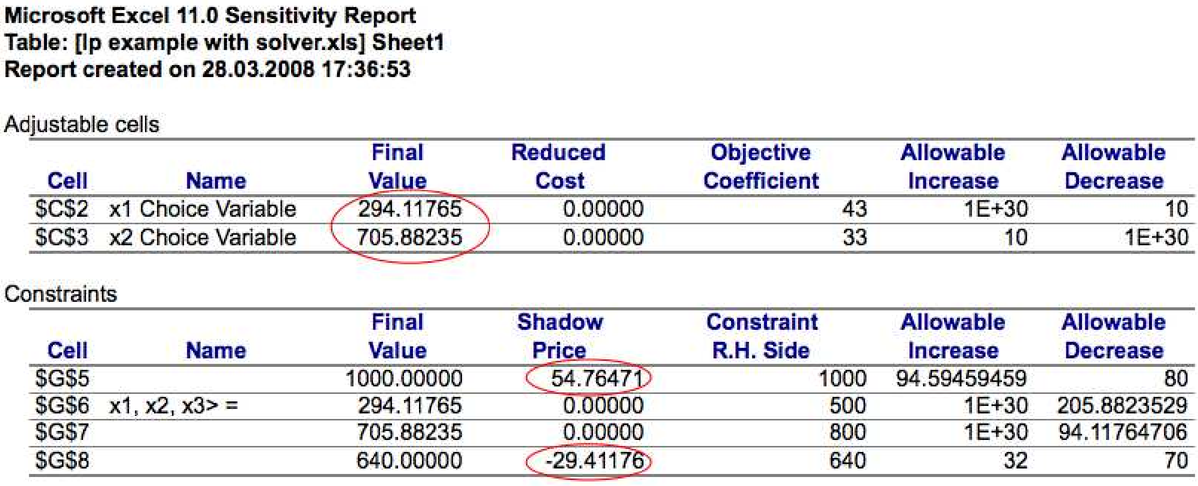
$x_1, x_2, x_3, x_4 \geq 0$ [12.]

The solution of both the primal and the dual give the same result in their respective objective function. In a dual formulation, the constraints that are binding in the primal will have a non-zero result in their variables. A value of zero will be obtained in the dual variable, if the constraint in their primal was non-binding indicating that the variable is not constraining the optimal solution. The dual formulation can be seen as a sensitivity analysis that indicates the worth of an additional unit of the binding variables to the objective function: The rate of change in the objective function for an increase in the right hand side in one unit of the constraint. These rates are called *shadow prices* (Rau 2003, p.119; Munansinghe et al 1993, p.76; Schwarze 2005, p.93).

Shadow prices indicate the marginal value of a constraint to the reduction or increase of the objective function. This marginal value represents the marginal price of energy delivery.

The dual solution of the example shown in Table 3-4 was obtained with the Excel solver routine, which uses the Simplex Method for linear problems. The final value column shows the optimal solution for the objective function. In the column shadow price two values different from zero were found. The positive shadow price indicates that an increase of one unit of the demand constraint of 1,000 MW on the right-hand side will increase the objective function, the cost of dispatch, to 54.76 $. Correspondingly, the relaxing of one tonne of CO_2 in the constraint will decrease the cost of dispatch by 29.41 $ as indicated by the negative shadow price.

Table 3-4 Linear optimization results with Excel solver



Microsoft Excel 11.0 Sensitivity Report
Table: [lp example with solver.xls] Sheet1
Report created on 28.03.2008 17:36:53

Adjustable cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
C2	x1 Choice Variable	294.11765	0.00000	43	1E+30	10
C3	x2 Choice Variable	705.88235	0.00000	33	10	1E+30

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
G5		1000.00000	54.76471	1000	94.59459459	80
G6	x1, x2, x3> =	294.11765	0.00000	500	1E+30	205.8823529
G7		705.88235	0.00000	800	1E+30	94.11764706
G8		640.00000	-29.41176	640	32	70

The *simplex method* was developed by George Dantzing in 1947. The algorithm tests the points of the feasible area boundaries moving from corner to corner until finding the optimal values that maximize or minimize the objective function. In 1984, Narendra Kamarkar introduced his *interior point algorithm* which instead of moving along the boundaries, moves through the interior of the feasible area heading to the optimal corner (Hamacher et al 2006, p.82).

In energy planning the size and type of power technology requires a linear model that allows variables such as capacity and the number of new units to be integer values. This can be handled by *integer and mixed integer linear programming*. Integer linear programming set all values of the decision to be integers while mixed in integer linear programming some variables are integers and others are real variables. The most widely used solution is the *Brach and Bound method* introduced by Land and Doig in 1960. Another technique available includes the *cutting-plane method* of Ralph Gomory, developed in 1958 (Sierksma 2002, p.241; Rao 1996, p.670).

Dynamic Programming is also an optimization technique for multistage decision problems such as the one for generation planning. Generation planning involves a study time horizon of, e.g. 40 years, with an inventory of diverse technologies, which becomes a tree of infinite combinations of technologies as depicted in Figure 3-4. The tree can be described as an infinite number of stage processes connected in series so that the output of one stage is the input of the succeeding stage. The problem then becomes a multistage decision problem. The dynamic technique looks for the optimal path in the tree that yields, e.g. the minimum cost. The minimum cost of stage 1, year 1, is added to the minimum cost of the second stage process, year 2, and so on until stage n, year 40.

This procedure is comparable to a PERT, Program Evaluation and Review Technique, in project management to analyse the tasks involved in completing a given project, especially the time needed to complete each task, and identifying the minimum time needed to complete the total project. It is worth mentioning that multistage problems can also be solved by the optimization techniques already mentioned (Stoll 1989, p.516; Rao 1996, p.616).

Integer and mixed integer linear programming and *Dynamic Programming* techniques are well documented in the literature and optimization solvers are commercially available. A detailed description of these mathematic techniques is beyond the scope of this dissertation. However, its understanding is essential to command any optimization model.

Finally, a technique that has been also applied in generation planning is *multi-objective optimization*. As its name implies, more than one objective function is formulated. As the energy sector has experienced dramatic transformations such as liberalization and the introduction of sustainability related issues in energy planning, the assessment of only one objective function may overlook other objectives that tackle environmental and societal aspects such as atmospheric pollution, greenhouse gas emissions GHG, effects on employment, public health, etc. Instead of formulating constraints for environmental or social aspects, they are modeled by additional objectives.

Mathematically the results are a set of efficient solutions and corresponding efficient combinations of the multiple objective problem. This allows the modeler or decision makers to weigh different possibilities so that a trade-off between the objectives takes place (Mavrotas et al 2005, p.203). The techniques used are further developments of the techniques already mentioned as the simplex or Brach and Bound method. Multiple criteria decision models making use of multi-objective mixed and linear programming have been developed to assist the modeler with selecting a final decision that involves conflicting objectives (Diakoulaki et al 2005, p.191).

In the following a review of the accounting framework model LEAP and the optimization model MESSAGE is introduced. The Long-range Energy Alternatives Planning system (LEAP) is a software tool for integrated energy-environment and greenhouse gas mitigation analysis (SEI 2006, p.1). LEAP has been developed by the Stockholm Environment Institute - Boston in the United States of America. The software is an accounting framework model.

The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is an engineering optimization model used for medium to long-term energy system planning, energy policy analysis, and scenario development (IAEA 2004, p.1-1). The program was developed by the International Institute for Applied Systems Analysis –IIASA- in Austria.

An analysis on how these programs simulate a power sector has been conducted in order to assess their suitability to address the research questions at hand.

3.5 LEAP: LONG-RANGE ENERGY ALTERNATIVES PLANNING SYSTEM

LEAP is a scenario-based energy-environment modeling tool. As an accounting framework model, the modeling is based on the accounting of how energy is consumed, converted and produced in a given region or economy. LEAP is not only a model to simulate energy supply but also for projecting demand. LEAP is especially suitable to address energy policies and their impact on the energy system and environment by looking at different scenarios with a variety of assumptions related to technology, population and economic development (SEI 2006, p.1).

The first step is to enter the energy chain into the program, starting with the demand. LEAP can calculate endogenously the demand by giving the energy intensities for all possible end-uses (e.g. the energy intensity of electric stoves for cooking which multiplied by the number of households yields the electricity demand for cooking in the residential sector) so the total demand is the sum of the product of all energy intensities and number of end-uses. The demand can also be a direct function of income or prices (e.g. demand is directly linked to GDP rates).

To simulate the power sector in LEAP, the energy chain must be defined from energy resource extraction, technologies for their transformation, individual or groups of power plants and transmission and distribution infrastructure linking the demand sectors (*see* Figure 3-6). Every component of the energy chain has to be entered into LEAP with their technical features such as fuels to be converted, capacities, efficiencies, capacity factors, and their economic parameters, such as fuel costs, capital and O&M costs.

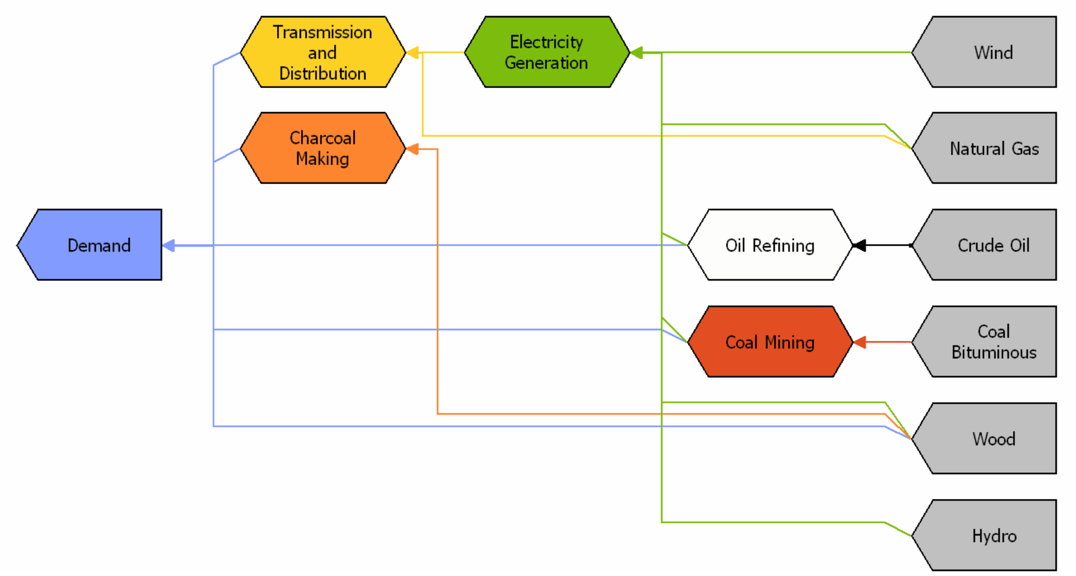


Figure 3-6 Energy chain in LEAP

After completion of this procedure a reference scenario is set in the program, from which the scenario analysis is carried out by altering the parameters of the reference scenario such as improving the transformation efficiency, replacing old technologies, including demand side management improvements, etc.

The program bases its calculations on a system load curve which is required to simulate electricity demand to determine capacity additions and dispatch of power plants by merit order or running costs (SEI 2006, p.102). The load curve must be specified as a percentage of the peak load versus the cumulative hours. LEAP allows a maximum of 9 bars to specify the curve as depicted in Figure 3-7. The bar represents the volume of energy needed for that section of the load curve. The load curve can be defined for every year in the time horizon.

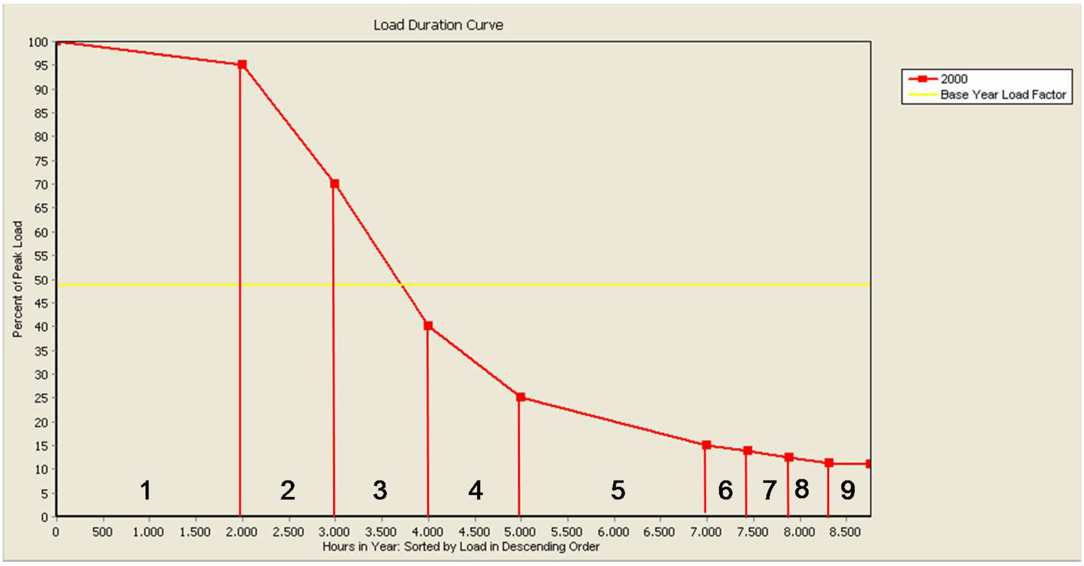
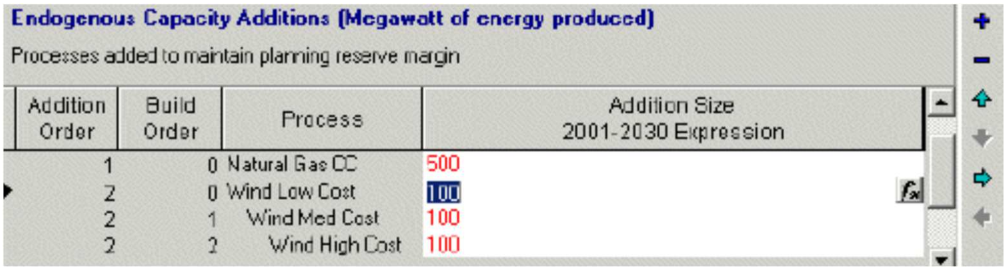


Figure 3-7 Load curve in LEAP

The user can also construct a seasonal supply curve to take into account seasonality of power production. A hydropower plant, for instance, may be dispatched as base load (merit order=1) in a wet season and as a peak load in a dry season. Up to 4 sections or “seasons” can be defined in the supply curve.

Regarding the expansion of the system to meet growing demand, that is the addition of new capacity in the system, is defined by the user directly or indirectly by instructing LEAP to add new power plants by using an addition order. When the user defines the expansion directly, the amount of power required per year to satisfy the demand and a reserve power margin must be known. For instance, an existing power system of 2,300 MW in the year 2000 can supply electricity above the minimum planning reserve margin of 35 % until 2004. After this point to keep the margin a coal power plant of 500 MW needs to be added. In that case, the user needs to enter the expansion plan.

An endogenously expansion with LEAP requires to enter a list of power plants to create an *addition order* set by the user. The expansion will be performed accordingly. In addition, a build order can be set in order to take into account available or cheaper technologies that will be built first as shown in Figure 3-8.



Endogenous Capacity Additions (Megawatt of energy produced)

Processes added to maintain planning reserve margin

Addition Order	Build Order	Process	Addition Size 2001-2030 Expression
1	0	Natural Gas CC	500
2	0	Wind Low Cost	100
2	1	Wind Med Cost	100
2	2	Wind High Cost	100

Figure 3-8 Capacity additions in LEAP

Source: SEI 2006, p.112.

As shown in Figure 3-8, the natural gas combined cycle power plant is added. As demand increases or existing units are phased out the next power plant, wind low cost, is added. The addition order continues until the wind high cost wind power plant is added to the system. To continue meeting the demand of the coming years, this addition order is duplicated again as many times as required until the final year of the evaluation. It is worth noting that this is only a simulation of capacity expansion defined by the user. LEAP does not automatically build the least cost configuration of plants based on marginal costs and does not use any optimization methodology (SEI 2006, p.1).

Similarly, the dispatch requires the definition of a *merit order* of power plants to fill the bars in the load curve as shown in Figure 3-7. The plant with the lower merit order value will attend the base load whereas the higher merit order value is for peak power plants. An example of a merit order list defined directly by the user is shown in Table 3-5:

Table 3-5 Merit Order in LEAP

Technology	Merit Order
Oil Comustion Turbines	3
New Oil	3
New Coal Steam	2
Biomass	2
Wind	2
Natural Gas	2
Existing Coal Steam	2
Hydropower	1

Power plants with equal merit order are dispatched together in proportion to their available capacity. The merit order can also be defined endogenously by the model. In that case the power plants are dispatched by running costs. The running cost is determined as follows:

$$RunningCost_i = VariableOMCost_i + \frac{FuelCost_i}{Efficiency_i} \quad [17.]$$

Where *i* is the year of the time-horizon being modeled.

In summary, the user can control the modeling of the power sector by defining the addition order for the expansion and the merit order for the dispatch in the load curve. Additionally, existing capacity can be entered.

3.6 MESSAGE: MODEL FOR ENERGY SUPPLY STRATEGY ALTERNATIVES AND THEIR GENERAL ENVIRONMENTAL IMPACT

MESSAGE is a mixed integer programming model, which optimizes an objective function under a set of constraints that define the feasible region of all possible solutions of the problem (IAEA 2004, p.1-1). To solve the model, the program uses standard solvers such as GLPK, OSLV2, OSLV3, CPLEX, and MOSEK (IAEA 2004, p.1-1).

MESSAGE is a program to evaluate alternative energy supply strategies. First, the energy chain of the system under consideration must be defined. The energy chain or network represents the energy from the demand to the resources. Thus, a detailed description of the energy system includes the energy forms at each level of energy chains; technologies producing, transforming or using these energy forms and the energy resources. All of this has to be defined by the user for the energy system to be modeled. Figure 3-9 is a schematic presentation of the degree of detail that the program can model. The demand is an exogenous variable to be entered into the model.

First, the levels (vertical lines in the figure depicting the resource level and transformation of energy forms from primary use to final demand) and their energy forms (e.g. the primary gas, oil and coal at the primary level) must be specified. Subsequently, technologies must be entered. They are defined by their inputs and outputs, efficiency, capacity and operation features, among other factors. Similarly, current and expected costs of resources and technologies are entered into the program. In addition, the model allows accounting of existing capacities of different technologies and the implementation of an inventory of future technologies for the expansion and replacement of old units. Therefore, a time horizon of the energy system must be chosen, defining the base year and the terminal year.

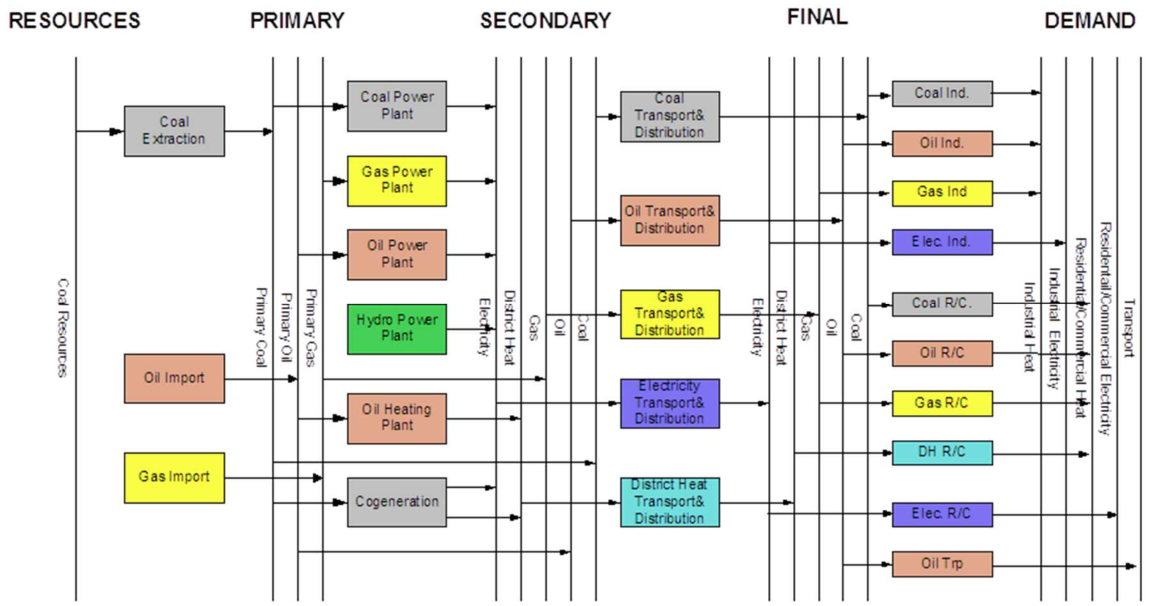


Figure 3-9 Energy chain in MESSAGE

Source: IAEA 2004. p. 1-2.

Regarding an energy carrier like electricity, the demand is modeled by means of load curves. The program allows subdividing each year into an optimal number of parts called the load regions. In this way demand fluctuations are considered.

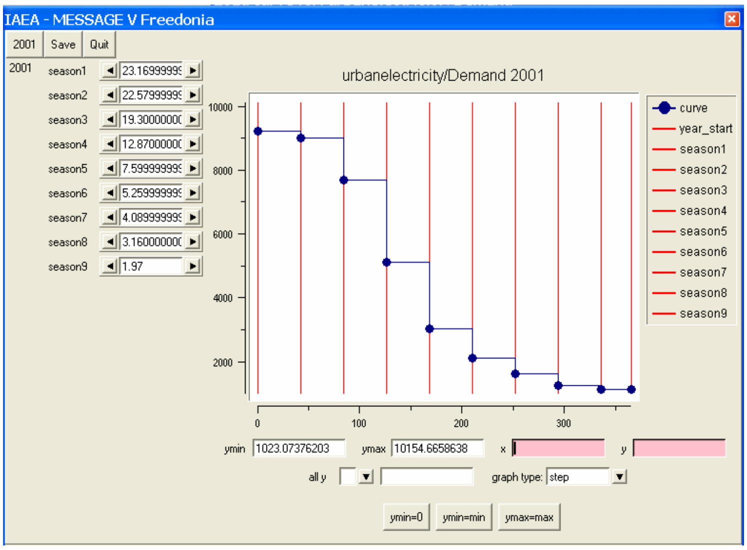
Limits and bounds on technologies can be set. These restrictions refer to maximum capacity that can be built or the maximum and minimum levels of output from a technology. The values of the limits and bounds on technologies and resources can be given in absolute terms or as dynamic limits (e.g. growth rates) so that a future development can be controlled by imposing certain limits. Also relationships between technologies or between technologies and resources can be given such as maximum share of wind energy in total electricity generation, maximum limits of atmospheric pollutants, etc.

Once the energy chain and the limits and bounds on the technologies are set, the model generates the mathematical formulation to be solved with one of the solvers. The program checks the feasibility of the generated matrix, which represent the objective function and restrictions and proceeds to run the solver. Subsequently the results are obtained. The objective function by default is the minimization of the total system costs which includes investments costs, operation costs and any penalty defined for the limits and bounds, and relations.

In the optimization process, the model calculates the new capacity requirement taking into account the existing capacities and their retirement time, according to the objective function and restrictions previously defined.

3.6.1 Modelling of the power sector with MESSAGE

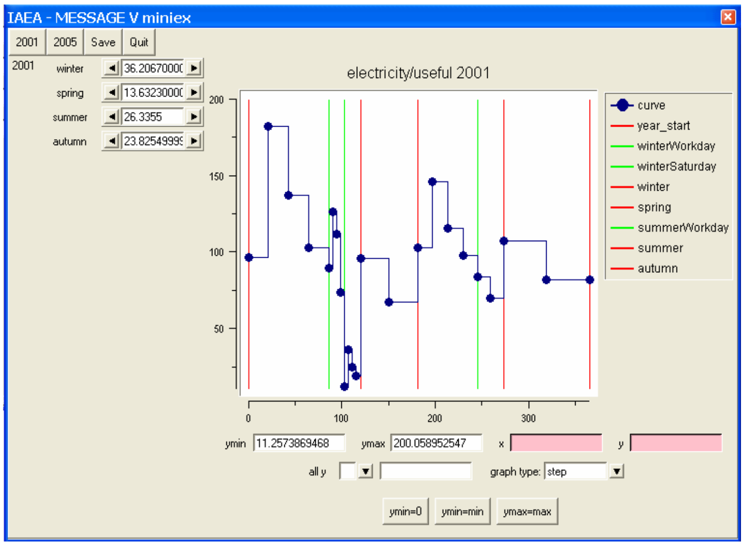
For modeling the power sector in MESSAGE, an electricity demand curve can be modeled. This modeling can be performed by either a load curve, which shows the peak power and minimum required capacity or by load regions, where patterns of the energy demand at a specific time of the year take place. This is illustrated in Figure 3-10 and Figure 3-11:



2001
season1 23.1699999
season2 22.5799999
season3 19.3000000
season4 12.8700000
season5 7.59999999
season6 5.25999999
season7 4.08999999
season8 3.16000000
season9 1.97

ymin 1023.07376203
ymax 10154.6658638
x
y
all y
graph type: step

Figure 3-10 Load curve in MESSAGE



2001
winter 36.2067000
spring 13.6323000
summer 26.3355
autumn 23.8254999

ymin 11.2573869468
ymax 200.058952547
x
y
all y
graph type: step

Figure 3-11 Load regions in MESSAGE

The load curve is useful to have yearly results without taking into account seasonal or pattern changes per se (the peak power is known but not the time when it happens) whereas the load regions make possible to consider seasons, types of days or time of a day, thereby, enhancing the analysis by detecting the time of year where there is a surplus or shortfalls of energy carriers, storage potentials, intermittency of power delivery from renewable energy sources such as wind and solar, identifying hydropower fluctuations, etc. A load curve can be entered for every year in the time horizon.

The program optimizes the expansion and dispatch of power technologies for every segment of the load curve or load region (areas under the curve between red and green vertical lines) for the time horizon according to the least cost objective function and constraints. In other words, a merit cost analysis of power technologies is accomplished taking into account the energy chain resources, extraction, transformation, transport and distribution and sectors demand. Subsequently low short-marginal costs will deliver energy for the base load until dispatching costly peak load power technologies. This is equivalent to a merit order dispatch. Regarding the expansion, the optimization routine selects technologies to be added to the system based on the lowest long-marginal cost.

The following section delineates the mathematical formulation of the power planning problem in order to understand how, from a theoretical point of view, energy planning can be described by means of linear programming in an optimization model. That is the core of MESSAGE, and its understanding is essential to handle the data, to guide and control the optimization routine and to interpret the results.

3.6.2 Mathematical formulation

The mathematical formulation presented here is the theoretical backbone of the energy planning problem in optimization models (Mazer 2007, p.141; IAEA 2004a, p.36; Mavrotas et al 2005, p.199; Antunes 2003, p.619). In order to facilitate its comprehension, only the essential variables and equations are introduced:

The electricity demand is described by a load curve in a planning horizon as depicted in Figure 3-12.

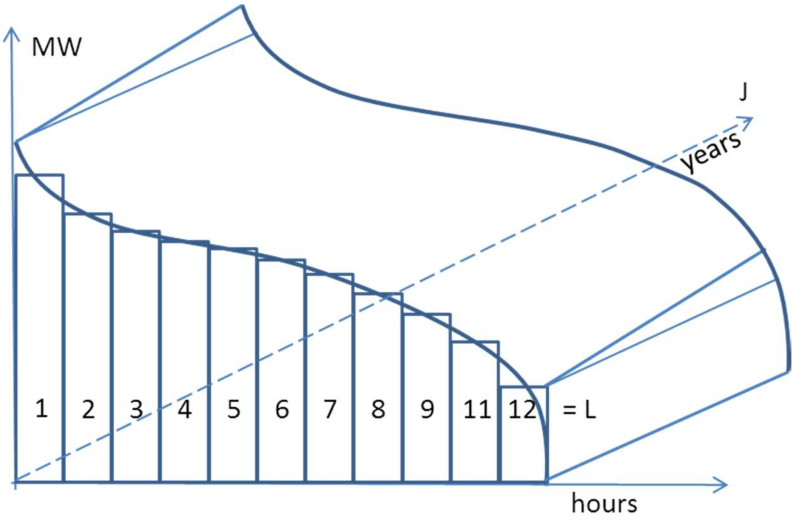


Figure 3-12 Load curve

L is the number of bars in the load curve. The demand grows over the time until the terminal year J. To cover the demand an inventory of power units are at disposal as shown in Table 3-6.

Table 3-6 Power generation inventory

Inventory Power Units	
1. Steam Cycle	ST1
2. Steam Cycle	ST2
3. Combined Cycle	CC1
4. Cobined Cycle	CC2
5. Hydropower	H1
6. Hydropower	H2

Objective function:

The aim of the objective function is to find the combinations of power generation units which have the least cost. An inventory of power generation units is therefore required:

$$Minimize\ K = \sum_{k=1}^{M}\sum_{j=1}^{J}\sum_{i=1}^{L} DF * [VC * MWh] + \sum_{k}^{M}\sum_{j}^{J}\sum_{i}^{L} DF * [INV * MW] \quad [13.]$$

Where:

DF= Discount factor

$$DF = \prod_{j=1}^{J}\left[\frac{1}{(1+DR)}\right] \quad [14.]$$

The discount factor is the net present value of all cost in the time horizon.

K = Net present value of total costs
DR = Discount rate
VC = Variable cost –fuel cost, maintenance and operation cost
MWh: = Output of power unit
INV = Investment cost
MW = Capacity new power unit
L = Load regions (bars)
J = Years
M = Type of technologies

The first term on the right side of the objective function is the Net Present Value (NPV) of the O&M costs and the second term is the NPV of investments, that is, the new units added to the system all over the time horizon.

Demand balance constraint:

The sum of the energy production of all technologies must be at least the required demand in a load region before transmission and distribution losses for every year. For the sake of clarity, the pure power planning problem is kept as simple as possible otherwise the equation has to be much further extended as well as the objective function to account for the complete energy chain from resources up to demand in given sectors.

$$\sum_{k=1}^{M} MWh \geq D_{L,J} \quad [15.]$$

Where:

MWh = Output of power unit
$D_{L,J}$ = Demand in a load region L in a given year J

Capacity balance constraint:

This is the output power of a type of technology in a given year for any load region which cannot exceed the total output affected by its plant factor.

$MW_k - \sum_{1}^{j} PF * MW * I \leq PF * MW_0$ for every technology M, load region L, and years J [16.]

Where:

MW_k	=	Total capacity required in a load region for a given technology
MW	=	Capacity new power unit
I	=	Number of plants of a given technology (integer number) installed in previous years
MW_0	=	Capacity in the first year of the time horizon
PF	=	Plant factor

For instance, the power required in summer, one of the defined load regions, is 800 MW peak. An existing hydropower plant of 300 MW becomes the variable MW_0 which is the contribution of this plant to the load region. PF and MW_0 are known and entered as input into the program. Assuming a maximum of 300 MW of hydropower is allowed in the system for the first year (via a restriction), the second term of the equation becomes zero because there is no addition of a hydropower plant previously and the right hand side of the constraint is equal to 300 MW with a plant factor of one. Thus, the optimization routine is constrained to a maximum of 300 MW of hydropower, now the value of MW_k, which can be available in the first year. The optimization routine continues the analysis for all technologies until the 800 MW peak demand of the load region is reached.

As demand increases, existing power plants may not cover the demand. For instance, in the year 2015, the variable MW_k would be the total contribution of hydropower in a load region for that year. Assuming the optimization routine had decided to expand the system with hydropower plants before 2015, the sum of the existing capacity at the initial year, 300 MW of hydropower, and the number of new hydropower plants added to the system in the previous year equal the total hydropower capacity MW_k for that year. That can be clearly seen when the second term is moved to the right hand side of the constraint. With this procedure, the amount of power delivered from a particular technology in a load region in a given year is controlled according to what the technology can deliver and the previous additions over the time horizon.

These constraints, among others, such as minimum expansion reserve margins, capacity caps, CO_2 emission restrictions, etc. can be added to control the objective function. In that way the modeler controls the optimization routine and defines how the simulation should find the energy mix of the system.

3.7 SELECTION OF MODEL FOR COLOMBIAN POWER SECTOR

The model to be selected should be able to successfully address the research question, whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources, and the objective of this dissertation study to prove the following hypotheses:

(1) Renewable energy sources can fully substitute fossil fuel energy sources and can turn the hydropower based power system in Colombia into a 100% renewable energy system.

(2) The introduction of renewable energy sources in Colombia can be part of the least cost alternative for the expansion of the Colombian power system.

The model should therefore be able to simulate the contribution of renewable energy sources to diversify the supply of electricity within the Colombian power sector considering the energy resources available, existing and future portfolio of technologies, the seasonality of electricity production from intermittent sources such as hydropower, and the increase of electricity demand over the years. In addition, the model should include an analysis of overall cost of the power system based on the technical and economic performance of the single power generation technologies and their energy sources.

The bottom up models reviewed, LEAP and MESSAGE, provide the necessary engineering approach to simulate the contribution of power technologies to cover electricity demand in the long term. The question arises whether the accounting framework and/or the optimization approach should be selected. The main difference between the two models lies on the cost analysis and flexibility to simulate alternative scenarios for the expansion of a power system.

In that sense, the accounting framework model includes cost-benefit analysis that makes possible the construction of a Business as Usual (BAU) scenario and other explorative scenarios to achieve certain goals. The model provides flexibility, simplicity and expedited results due to its more descriptive approach. To find a least-cost alternative in an accounting framework model, the modeler must perform an iterative procedure by running the program repeatedly until the solution is consistent and realistic.

In the optimization model the scenario approach is based on the least cost. The outcome is found endogenously. It does not mean that a desired outcome cannot be modeled as in the accounting framework model. A constraint forcing the program to have, e.g. a certain amount of capacity from a given technology makes it possible. Figure 3-13 highlights the methodological differences between the two models:

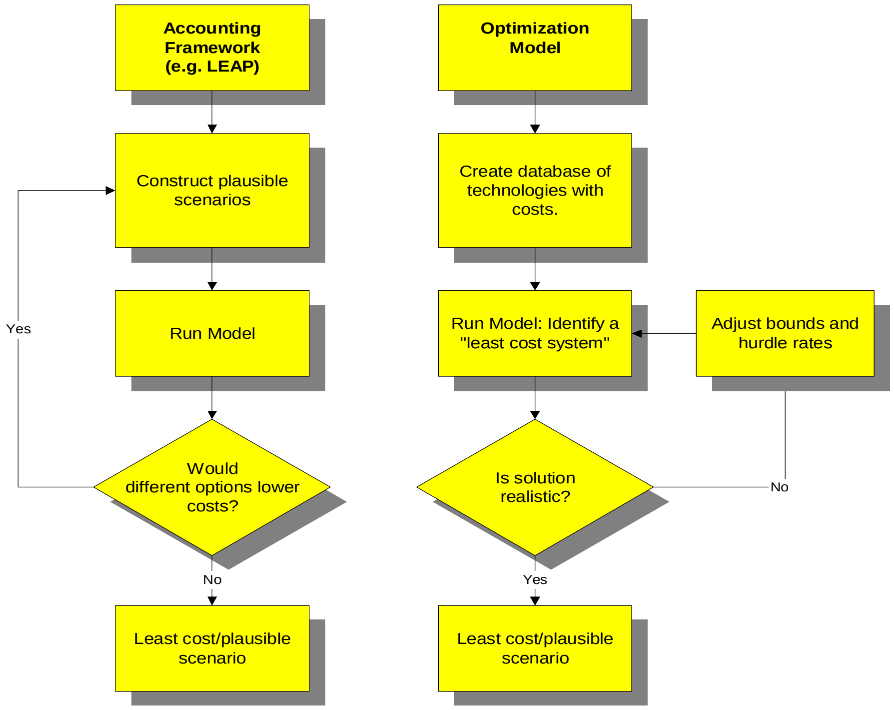


Figure 3-13 Accounting framework and optimization model comparison

Source: Heaps 2002, p.8.

Figure 3-13 suggests that both models find the least-cost solution. Since the accounting framework uses an iterative procedure, the result might not be exactly the least cost solution as the optimization approach will find. In both cases, however plausible scenarios are found by either the iterative process in the accounting framework or the manipulation of the constraints (bounds and hurdles in Figure 3-13) in the optimization model.

By using the optimization model, short and long term marginal costs of power generation technologies will define the expansion of the system. This approach corresponds to the rationale for power generation planning under ideal market conditions based on the economic merits of the different types of generation technologies. If a power technology is not competitive enough, it will not be added to the existing portfolio and will not be part of the output of the model. A scenario that does not follow that logic would not be addressed by the least cost approach.

If only the account framework model were used, the simplicity and flexibility for exploring energy futures would not be restricted to the least cost approach. However a least cost alternative is dependent on the ability of the modeler to find plausible scenarios through the iterative procedure.

Relying on solely one model and not making use of the advantages that both in combination may bring looks as if an opportunity to synergize the two models is dismissed. Therefore, for the purpose of achieving the most comprehensive result, this dissertation will be using both models to answer the research question at hand.

Thus, the account framework model will be used as a “what if” tool to obtain an insight into BAU and alternative scenarios to identify overall costs and other effects such as CO_2 emissions and open a debate of what might be a realistic result. Later the optimization model may proceed by refining the scenarios and find least cost supply alternatives, in doing so, the model is used as a “how to” tool to minimize the costs (ERC 2008, p.4).

For the modeling of the large scale use of renewable energy in this dissertation, the models LEAP and MESSAGE have been obtained, which have been employed in several energy planning exercises worldwide and used for energy scenario analysis like those made by the Intergovernmental Panel on Climate Change (IPCC) to assess energy global issues (IPCC 2007, p.68; IPCC 2000, p.29). The institutions holding the copyrights of these models have granted the author permission to use their software for the purpose of this study. The version 1.0.3.0 IAEA 2002-2004 adapted from IIASA’s MESSAGE Model was used. The simulation with LEAP was conducted with the versions of the year 2009.

The following chapters focus on the potential of renewable energy sources in Colombia, and the technologies for their transformation. Afterwards a prognosis analysis is conducted for all data required for the energy models LEAP and MESSAGE which constitutes the foundation for the simulation of the Colombian power sector.

4. POTENTIAL OF RENEWABLE ENERGY SOURCES IN COLOMBIA

Colombia possesses renewable energy sources that can be exploited for power generation. The aim of this chapter is to determine the potential of these sources to become an important contributor to the Colombian power sector on a large scale. Wind energy, solar energy, geothermal energy, hydropower and biomass, which can be exploited with proven commercially available technologies, are analyzed. The geographical location of these sources is included in the analysis. For the use of biomass, current figures were upgraded to estimate the future potential. A summary of the main findings closes this chapter.

4.1 WIND ENERGY POTENTIAL

The best wind resources in Colombia are found at the Caribbean coastal state of La Guajira as illustrated in the Colombian wind map in Figure 4-2 (areas marked in yellow and orange) based on a resolution of 10 x 10 km at 10 meter height (UPME, IDEAM 2006, p. 11). A potential of 22 GW has been estimated in that state alone (ESMAP 2007, p.27). According to a study performed by the Energy Sector Management Assistance Program (ESMAP), a technical trust fund administered by the World Bank, the offshore wind resources in the area are among the best in South America. The ESMAP suggests that the offshore wind resources are similar to those in the Patagonia region of Chile and Argentina, where their offshore regions have been classified with class 7 winds over 10 m/s. (ESMAP 2007, p.27).

In order to have a figure of the wind energy potential to be used in the energy models a wind park size of 50 MW was assumed to determine a maximum potential based on the area required for that size. Assuming a grid size of 5 x 5 turbines, 2 MW per turbine and a spacing between them in the wind direction of 8 diameters and 4 diameters in its perpendicular, a land area of 4.1 km^2 would be required as shown in Table 4-1. La Guajira possess an area of 20,842 km^2. One percent utilization of that area for wind energy development would allow the implementation of 2,500 MW based on the wind park area.

Table 4-1 Wind park area

Total Power [MW]	50
Diameter Ø [m]	80
Rows	5
Width (Rows x 4Ø) [m]	1,600
Long (Rows x 8Ø) [m]	2,560
Area Wind Park (WxL) [m^2]	4,096,368
Turbine V80 Vestas 2MW [Units]	25
Area Wind Park [km^2]	4.10

Source: Turbine data from Vestas 2011, p12.

In order to have a reference figure on how much area can be used for wind energy, a comparison with a well-established market for wind energy was conducted. Germany's northern-most state, Schleswig-Holstein, possesses one of the best German wind resources as compared to the rest of the country. Schleswig-Holstein had an installed capacity of 3,007 MW as of December 2010 (DEWI 2011, p.39) with 15,799 km^2 and a population density of 179 inhabitants per km^2 (Schleswig-Holstein 2011). In contrast La Guajira has a population density of 39.2 Inhabitants per km^2 (DANE 2009, p.132) for an area of 20,842 km^2. Schleswig-Holstein has a share of 11% of the total installed capacity in Germany which amounts to 27,204 MW with a total of 21,585 wind turbines as of December 2010 (DEWI 2011, p. 32).

For the simulation with the energy models, it will be assumed that between 2% and 4% of the area in La Guajira is available for wind energy. This equates to a wind energy potential between 5,000 and 10,000 MW. This figure does not consider other suitable onshore locations at the Caribbean coast and other regions (*see* Figure 4-2) or the offshore potential in Colombia. A capacity of 10,000 MW at the coast of Colombia with its excellent wind resources is a rather conservative figure.

The only Colombian existing wind park is Jeripachi in La Guajira. Jeripachi has been in operation since 2004 and has a power capacity of 19.5 MW. With the monthly data available since the operation date, the park shows an average capacity factor of 32.8% in the last 8 years. The last months of the year are the periods with less generation. Figure 4-1 shows the generation per month from 2004 to the present date. This monthly intermittency and the capacity factor will be technical parameters for the energy models.

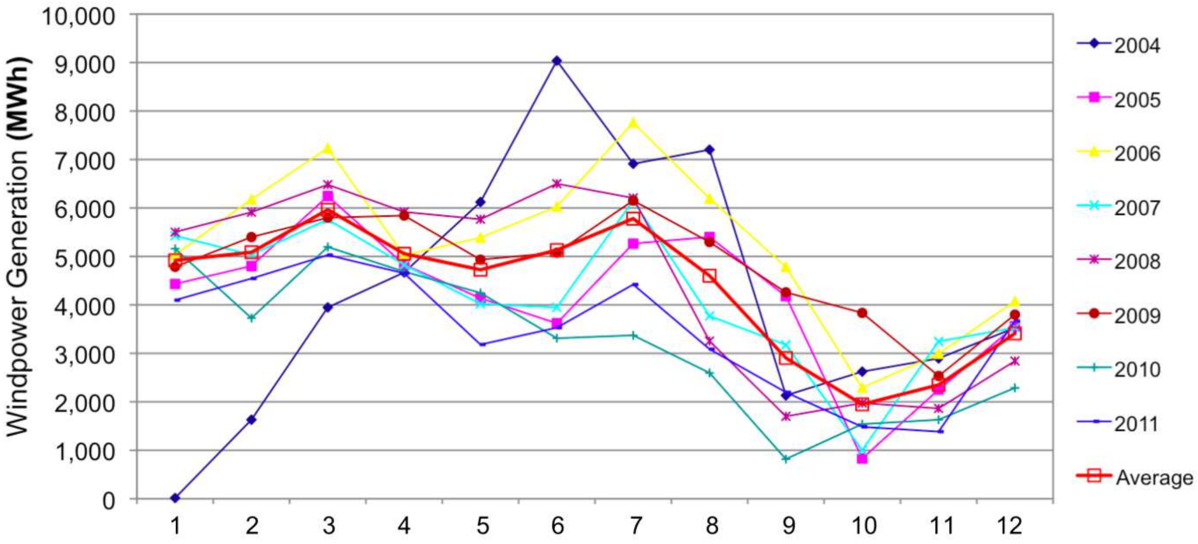


Figure 4-1 Jeripachi wind park monthly generation at monthly intervals for the years 2004 - 2011

Yearly average shown in red. Source: Data from XM 2012.

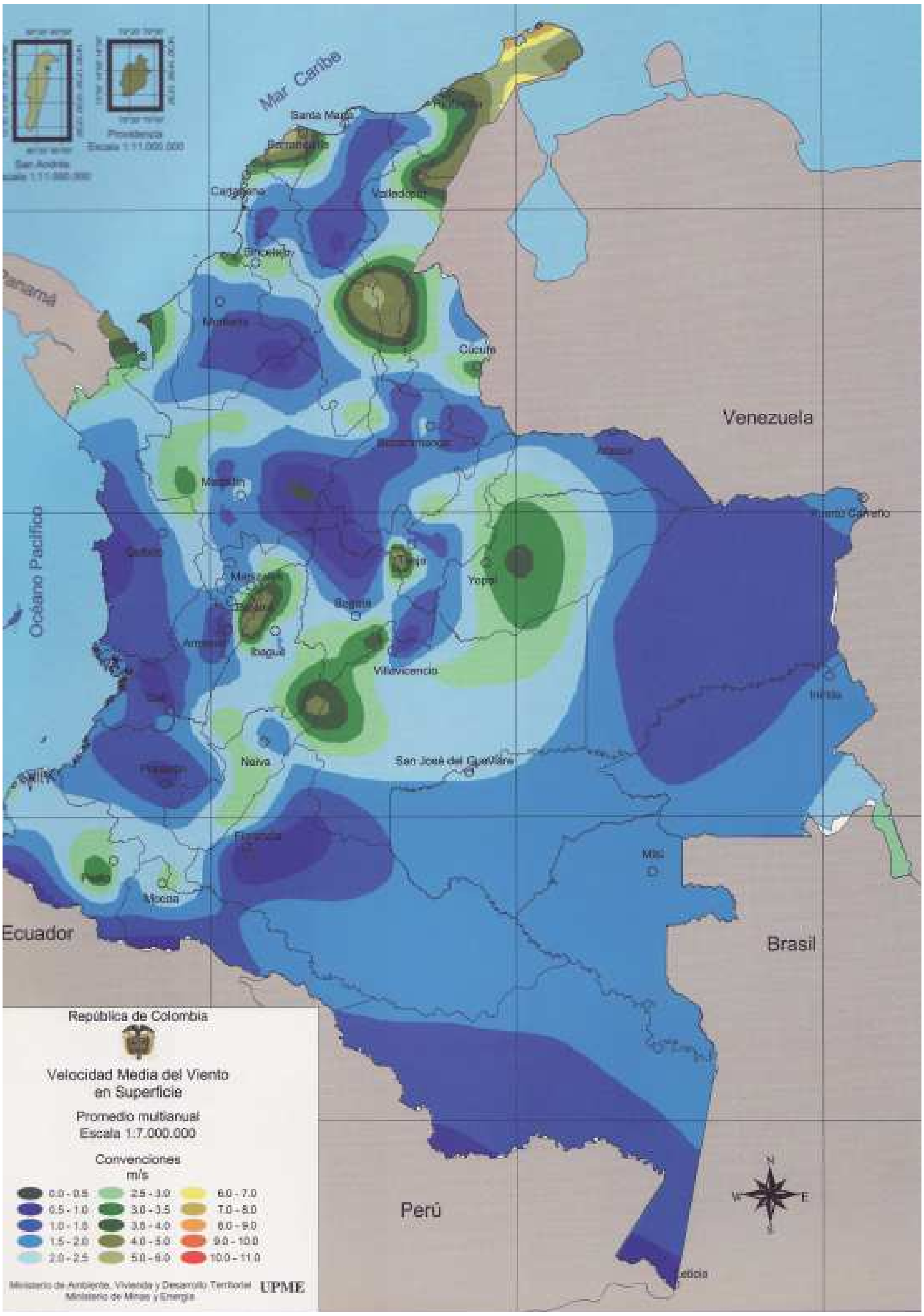


Figure 4-2 Colombian wind map. Annual average speeds in m/s at 10 m height

Source: UPME, IDEAM 2006, p. 3.

4.2 SOLAR POTENTIAL

Colombia benefits from a significant solar potential due to its location in the tropics close to the equator (12°26'46'' N, 4°13'30'' S). The Caribbean coast and the northeast area of the oriental planes at the Orinoco basin are the most promising areas for solar applications due to the potential as shown in the Colombian solar map in Figure 4-4 (areas marked in yellow and orange).

For great scale utility solar power plants, the Caribbean coast and in particular its northeast State of La Guajira show the highest solar average availability in Colombia. The Caribbean coast has an average availability of 1,825 kWh/m^2/year (UPME, IDEAM 2005; p.20) and La Guajira has an average of 2,190 kWh/m^2/year (UPME, IDEAM 2005; p.20). La Guajira is comparable in its solar availability to other global locations renowned for solar development such as California with 2,555 kWh/m^2/year (NREL, 2008), the Middle East and sub-Saharan Africa with 2,200 kWh/m^2 (EPIA 2011, p.32). The high solar availability might make the La Guajira region not only suitable for PV applications but also for concentrated power solar technologies (CSP). This is further supported by the number of hours with direct radiation observed at the Caribbean coast (UPME, IDEAM 2005; p.57).

Based on average radiation per month (in kWh/m^2) reported for the Guajira region (UPME, IDEAM 2005; p.28-39) and assuming a photovoltaic module with 15% efficiency (150 W/m^2 at ISO standard conditions of 1,000 W/m^2) and an inverter efficiency of 90% and additional system losses of 3%, Figure 4-3 shows the generation yield per square meter that can be obtained in the region. By comparing these figures per month with an ideal generation of a photovoltaic module of 150 W/m^2 during 8,760 hours, a capacity factor between 24.4 % and 26.5% was obtained.

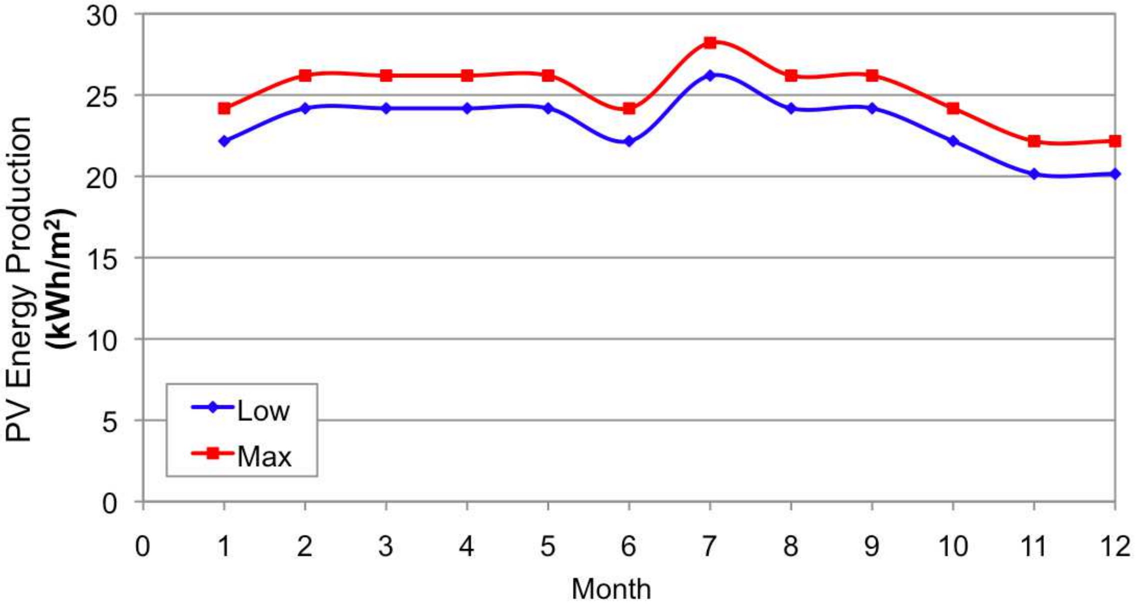


Figure 4-3 Monthly average radiation in La Guajira

Source: Data from UPME, IDEAM 2005; p. 28-39.

Assuming 1.3 ha for a 1 MW photovoltaic solar park with polycrystalline modules a land area of 0.65 km^2 would be required for a solar park of 50 MW as shown in Table 4-2. For CSP technologies a trough power plant of 150 MW with heat storage requires 1.47 km^2 for the solar field and 4.98 km^2 for the whole installation (NREL 2003, p. 4-4).

Table 4-2 Solar park area

Capacity [MW]	50
Solar Module [kW/m^2]	0,15
Module area required [m^2]	333,333
Module area required [Ha]	33.3
Total area PV Plant, modules and Balance of Plant [Ha]	65
Area Wind Park [km^2]	0.65

La Guajira possesses an area of 20,842 km^2. One percent utilization of that area for solar photovoltaic park developments would allow the implementation of 16,000 MW. In terms of capacity this result is higher than the total Colombian installed power generation (14,367 MW as of 2011). However, such a capacity would not deliver the amount of electricity required due to low capacity factors and intermittency of production. For the installation of CSP power plants, 1% utilization of the area could comprise 41 units of 150 MW amounting to 6,150 MW.

For the simulation with the energy models, maximum capacities will be defined in the scenario analysis and a capacity factor of 25.5 % will be assumed.

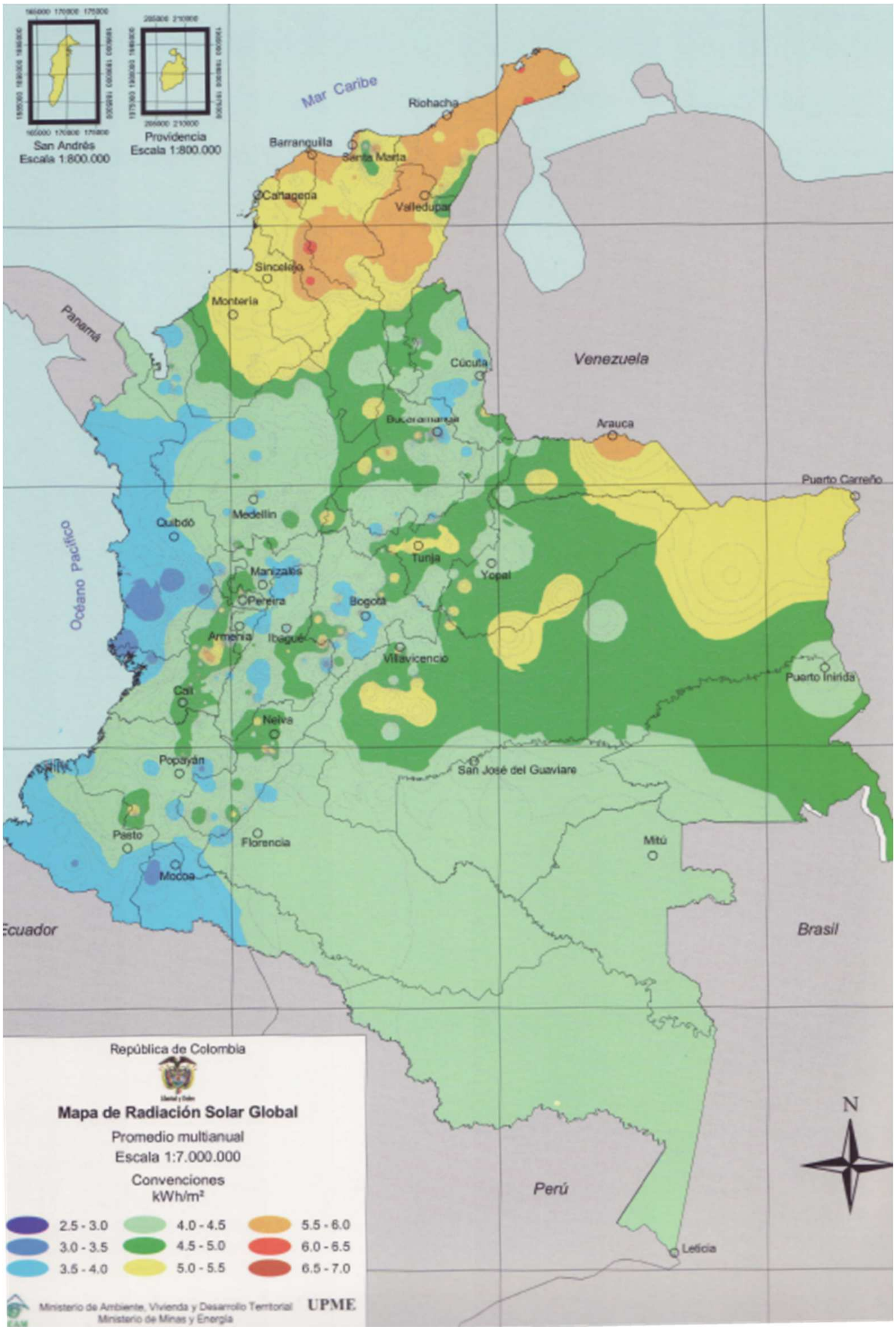


Figure 4-4 Colombian solar map

Multiannual average in kWh/m^2. Source: UPME, IEAM 2005; p.40.

4.3 GEOTHERMAL

Colombia possesses the potential to produce power with geothermal resources. Due to the seismic and volcanic activity of the plate boundaries, specifically those in the Pacific Ocean, the geothermal activity at the Andes Mountain Range is high, where high temperature fields are present (Friedleifsson et al 2008, p.63). Unfortunately, a figure showing the potential for geothermal power generation in Colombia has not been determined.

In a study achieved by the Energy Sector Management Assistant Program (ESMAP) in 2007, geothermal energy was included as a renewable energy source that may have a potential in Colombia. The study quotes four areas with potential according to previous analysis performed at the former Colombian Institute of Electrical Energy and the Latin American Energy Organization: i) Azufral, in the south department of Nariño, which is a Volcanic area with potential reservoirs, ii) Cerro Negro-Tufino located at the border with Ecuador, where the Chiles Volcano may have reservoirs with temperatures around 225°C at 5-10 km depth and iii) La Paipa region located at the Oriental range and iv) the area in the Macizo Volcánico Ruiz-Tolima (ESMAP 2007, p.33).

Table 4-3 and Figure 4-5 illustrate the potential areas and locations for geothermal power in Colombia. Figure 4-6 is a geothermal map of Colombia showing geothermal hotspots according to their temperatures at 3 km depth. The red hotspots correspond to areas which possess geothermal hotspots reaching temperatures of 370 °C. These areas are listed in Table 4-3.

Table 4-3 Potential areas for geothermal power

Area	Department	Potential
Chiles-Cerro Negro	Nariño	High
Azufral de Túqueres	Nariño	High
Doña Juana	Nariño	Unknown
Grupo Sotará	Cauca	Unknown
Puracé	Cauca	Unknown
Machía	Huila	High
Cerro Bravo	Nariño	High
Nevado del Ruiz – Santa Isabel	Caldas	High
Cerro España	Caldas	High

Source: ESMAP 2007, p. 33.

Figure 4-5 Geothermal potential regions

Source: ESMAP 2007, p.34.

Grants will be employed amounting to 3.75 Million US dollars from the Fund for the World Environment, the Colombia Ministry of Mine and Energy and the power producer ISAGEN to make possible the first geothermal power plant in Colombia. Feasibility studies will be conducted in different sites of the Macizo Volcánico del Ruiz for a power plant of 50 MW (UPME 2011).

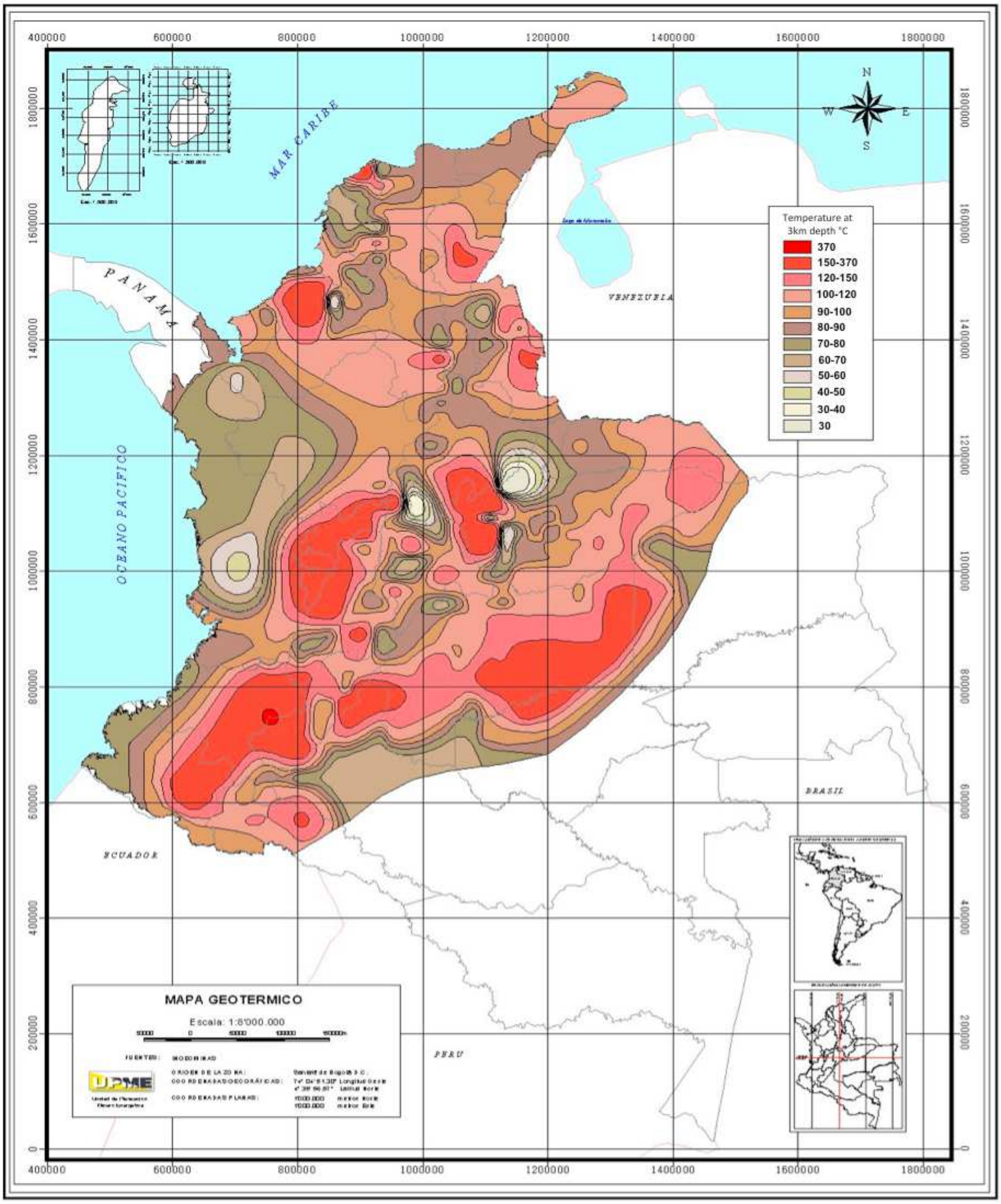


Figure 4-6 Colombian geothermal map

Temperatures at 3 km depth in °C. Source: Modified from MME 2008.

4.4 HYDROPOWER

The total hydropower potential for Colombia has been estimated at 93,000 MW (ESMAP 2007, p.18) from which 9,000 MW are already exploited from large hydropower plants as of 2010 (UPME 2011a, p. 113). The contribution of hydropower to electricity generation in Colombia is dependent on the availability of water resources, which is influenced by Colombia’s seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO). The ENSO causes extreme weather conditions over Colombia (droughts and floods respectively). In addition the vulnerability of Colombia to climate change may affect adversely the contribution of hydropower (Ideam 2010, p.186). This issue is further detailed in the analysis of renewable energy in the context of the Colombian power sector (Chapter 10).

In addition a potential of 25,000 MW has been identified for small hydropower (run-of-river units) of 20 MW (ESMAP 2007, p.18). Figure 4-7 shows the Colombian hydropower map. The dark blue areas correspond to regions with high potential naturally located in the mountainous regions of the country. This confirms the vast hydropower resources still available and why the power sector will continue relying on this source of energy.

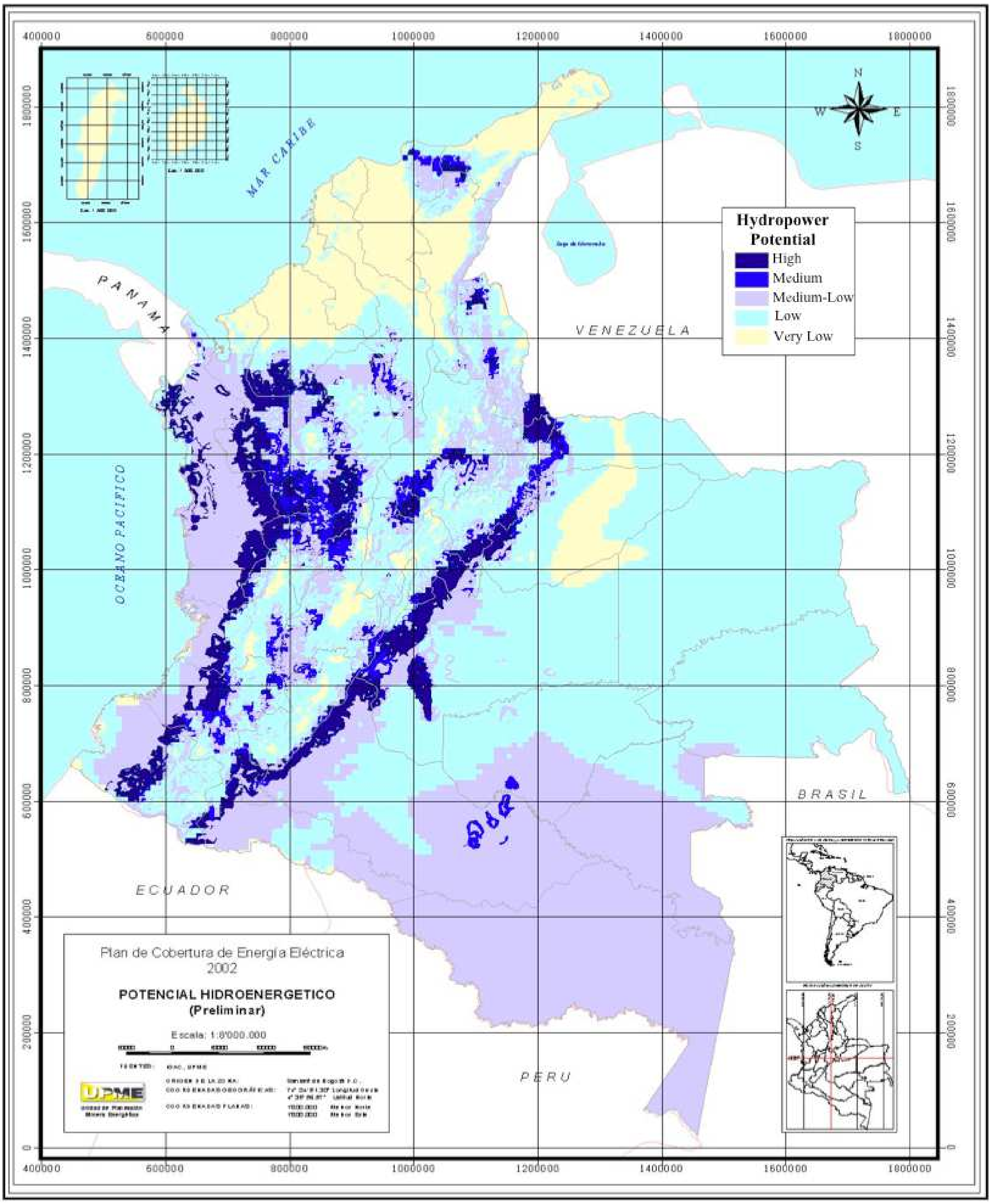


Figure 4-7 Colombia hydropower resources map

Source: Modified from from MME 2008.

4.5 BIOMASS POTENTIAL ASSESSMENT IN COLOMBIA

In 2003, the Colombian Mine-Energy Planning Unit (UPME, 2003) identified the theoretical potential of energy that can be produced through dedicated energy crops and the utilization of agricultural and agro-industrial residues. The theoretical potential calculated was 15 GW, where 4 GW for electricity and thermal energy applications was estimated. In order to have an indication of the future biomass potential for power generation, an upgrade of these figures with current data and a prediction of the future potential was conducted as part of the analysis for this dissertation.

From current agricultural crops 13 potential crop species were identified, which are suitable to be used as energy dedicated crops to produce ethanol or biodiesel. In addition, residues such as biomass for combustion were also considered. Table 4-4 introduces the potential crops and their residues. Rice is the only crop, which is not used to produce any biofuel, but its residues (rice husk) can be used as biomass for combustion.

Table 4-4 Energy Crops in Colombia

Name	**Species**	**Biomass Resource**	**Utilization**	**Type**
Cacao	*Theobroma cacao*	Dedicated energy crop	Biodiesel	Annual
Coconut Palm	*Cocos nucifera*	Dedicated energy crop	Biodiesel	Permanent
		Agricultural residue	Biomass for combustion	
Cotton	*Gossypium hirsutum*	Dedicated energy crop	Biodiesel	Annual
		Agricultural residue	Biomass for combustion	
Maize	*Zea mayz*	Dedicated energy crop	Ethanol	Annual
Oil Palm	*Elaeis guineensis*	Dedicated energy crop	Biodiesel	Permanent
		Agricultural residue	Biomass for combustion	
Peanut	*Arachis hypogaea*	Dedicated energy crop	Biodiesel	Permanent
Potato	Solanum tuberosum	Dedicated energy crop	Ethanol	Annual
Rice	Oryza sativa	Agricultural residue	Biomass for combustion	Annual
Sesame	Sesamum orientale	Dedicated energy crop	Biodiesel	Annual
Soja	Glycine max	Dedicated energy crop	Biodiesel	Annual
Sorghum	Sorghum bicolor	Dedicated energy crop	Ethanol	Annual
Sugar cane	*Saccharum officinarum*	Dedicated energy crop	Ethanol	Annual
		Agricultural residue	Biomass for combustion	
Yucca	*Manihot esculenta*	Dedicated energy crop	Ethanol	Annual

Source: UPME 2003, p. 113-114.

Colombia has a land area of 114,174,800 ha, where the land use is distributed as shown in Figure 4-8. 57.7 million ha of the land (50%) is forested, while only 4% (4.2 million ha) is being cultivated (CCI-MADR 2007, p.18). The share of the identified energy crops occupied in 2006 amounted to 2.4 million ha (57% of the agricultural area) as shown in Figure 4-9. Maize is the energy crop that occupies the largest extension of area with 616,552 ha in 2006 followed by rice and sugar cane with 455,412 ha and 429,312 ha respectively (CCI-MADR 2007, p.18).

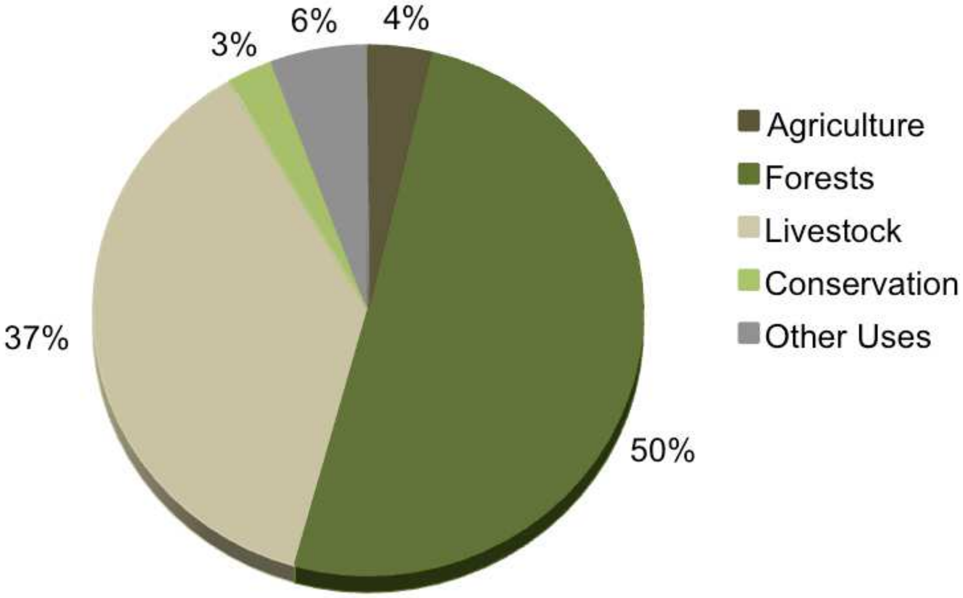


Figure 4-8 Land use distribution in Colombia

Source: CCI-MADR, 2007, p.18.

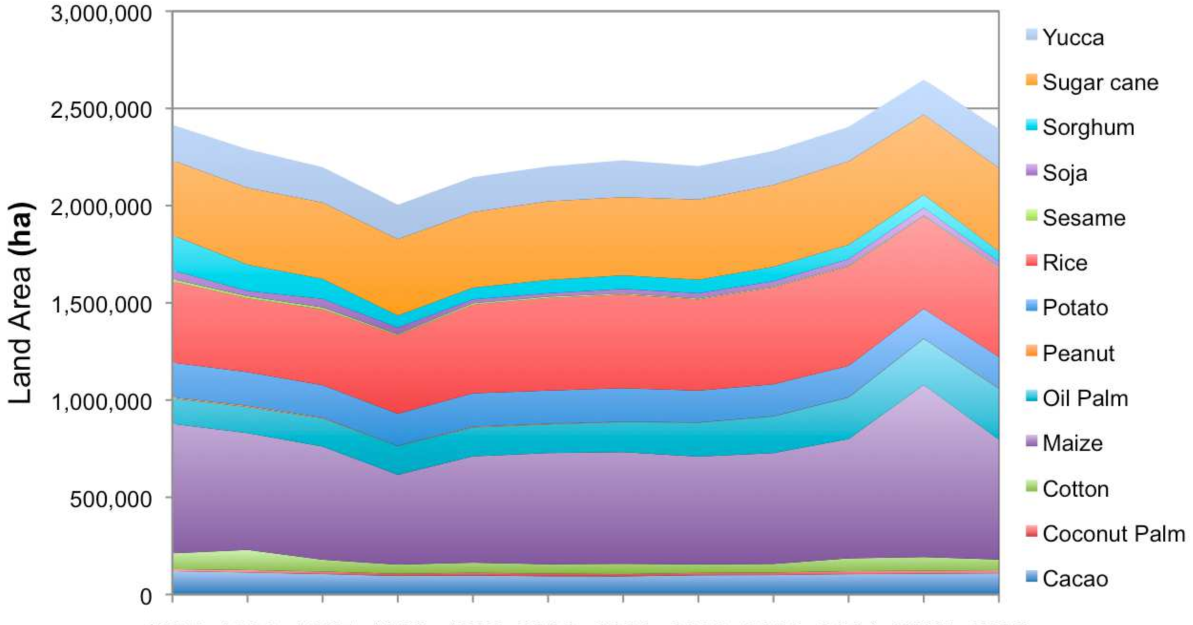


Figure 4-9 Area occupied by energy crops

Source: CCI-MADR 2007, p.18.

The Ministry of Agriculture states that Colombia is overusing 28.2 million ha in livestock that could be used for agriculture and forests. Currently, 42.5 million ha are used for livestock, which can be redistributed as shown in Figure 4-10 to boost the country's agricultural potential. In that way 17.3 million ha can be allocated for agriculture, while 9.1 and 1.5 million ha can be allocated for forests and conservation of natural resources respectively (Arias 2008, p. 13).

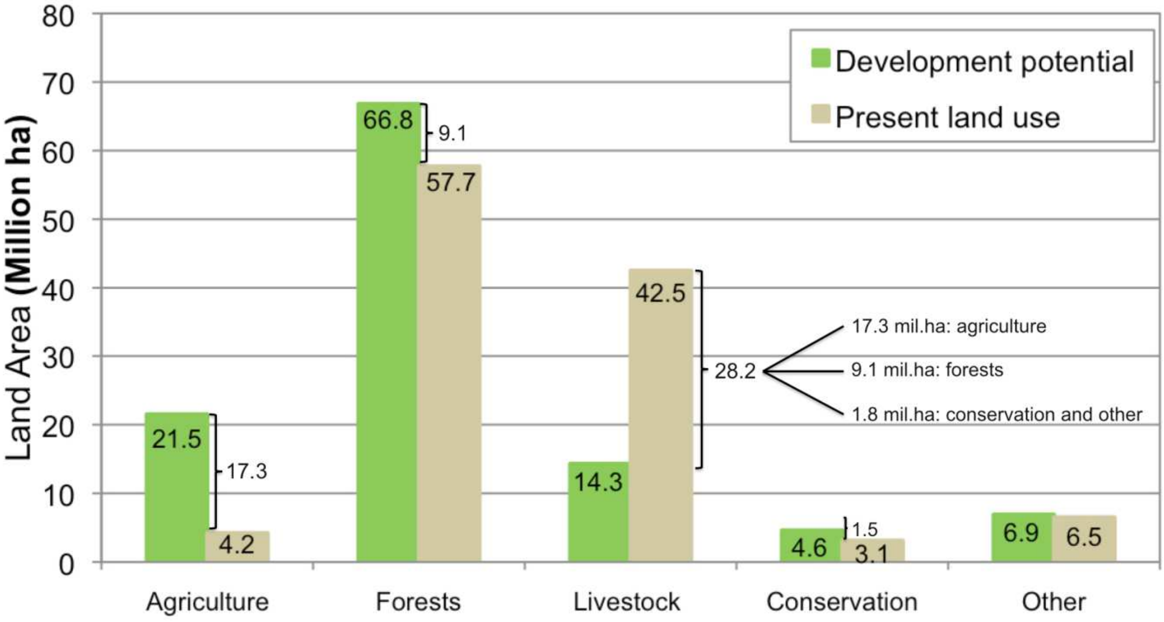


Figure 4-10 Present and development potential of land use

Source: Modified from Arias 2008, p. 13.

The Ministry also identified the potential area that can be allocated for the development of energy crops (Arias 2008, p. 13). From the 17.3 million ha that can be used for agriculture, 10.9 million ha (63%) can be dedicated to energy crops with the aim of producing biofuels at a great scale. Consequently, current areas being used for oil palm, cacao and sugarcane can be substantially increased as shown in Table 4-5:

Table 4-5 Current and potential area for the development of energy crops

Energy Crop	**Current Area** *(ha)*	**Potential Area** *(ha)*
Oil Palm	364,343	3,273,282
Cacao	111,496	3,753,308
Sugarcane	477,797	3,898,221
Total	953,636	10,924,811

The potential area can be slowly adapted within the next 40 years given the possibility of increasing the energy potential that can be obtained through dedicated energy crops.

In summary, the electricity potential from biomass may be much higher than the figure obtained by the Ministry study as of 2003 (4 GW), which might make biomass a vast energy source to be considered for power generation. The potential and optimal crops for power generation will be determined based on the same theoretical approach used by the Ministry.

An assessment of the geographical distribution of biomass potential regions was also conducted by the Ministry as shown in Figure 4-11. The figures show the potential areas for oil palm, sugarcane, rice and wood energy. Unlike other renewable energy sources like wind and solar which are mainly located at the coast and more specifically in the La Guajira region, biomass sources are distributed all over the country, which improves their implementation in optimal regions close to demand centers.

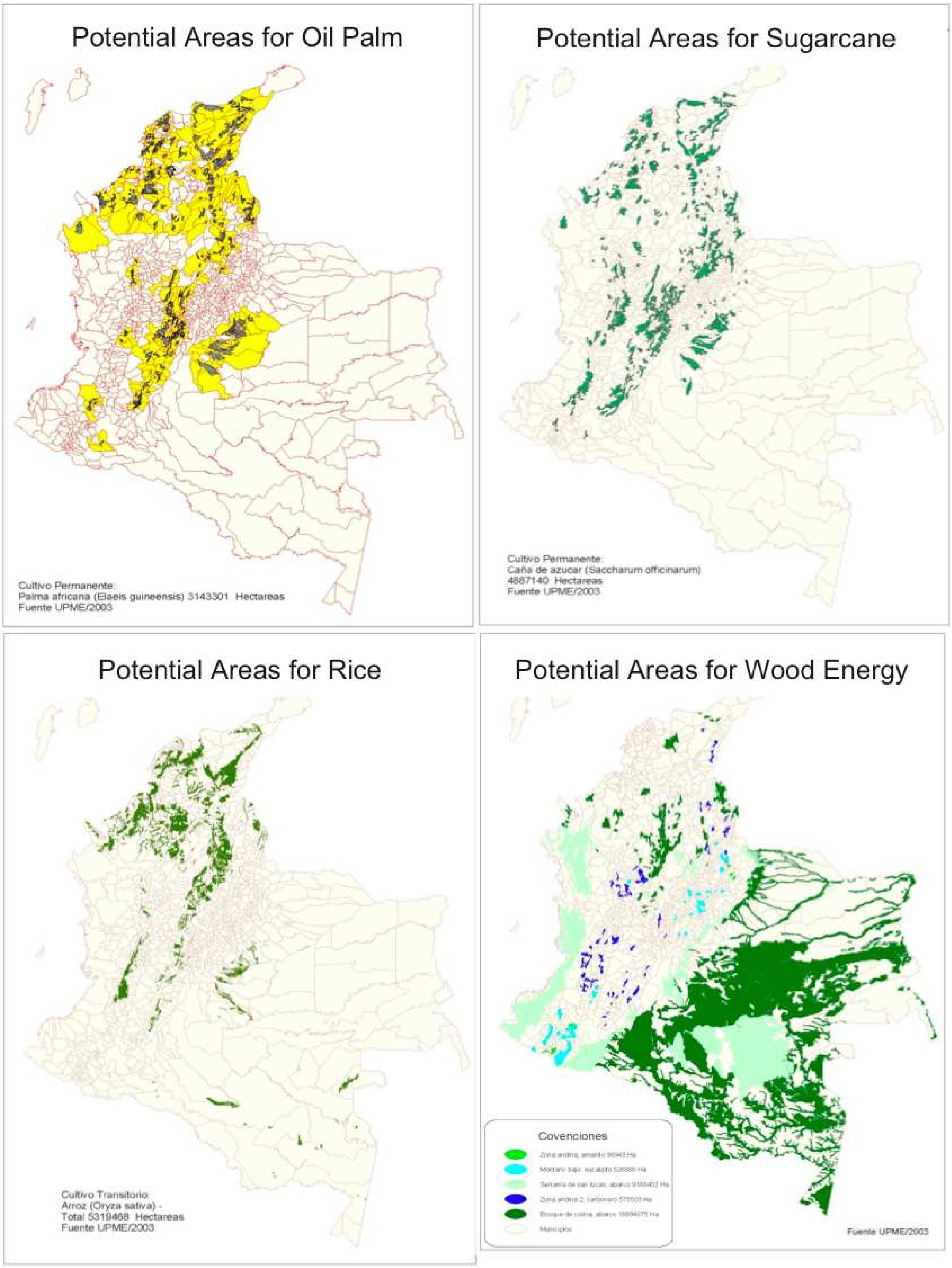


Figure 4-11 Potential biomass distribution

Source: MME 2008.

4.5.1 Theoretical potential

For the calculation of current and future theoretical potential with biomass resources, the methodology applied is as follows.

$$CP_i = CY_i * Ha$$

$$EP_i = CP_i * ES_i * HV_i * K$$

$$TP = \sum_i^n EP_i$$

Where:

CP = Crop Production in tonnes per year, which results from the amount of cultivated hectares [Ha] and the crop or yield performance per hectare [CY].

CY = Crop performance in tonnes per hectare in a year. This performance is reported by the national agricultural statistics (CCI-MADR, 2007) as well as the type of crop and number hectares.

i = type of crop

Ha = Area cultivated in hectares

EP = Energy potential of a given crop *i* in MW

ES = share of a crop that can be utilized for energy purposes in percentage. For instance 28% of sugar cane harvested is solid residues that have an energy potential.

HV = Heating value of a given type of crop in kilojoules per kilogram

K = Unit conversion to obtain MW per year. ($3.1708*10^{-8}$)

TP = Theoretical potential in MW.

n = Amount of energy crops

With this methodology and based on current information from 1995 to 2006 as shown in Figure 4-9, the historical theoretical energy potential from dedicated energy crops in the form of biodiesel and ethanol was obtained for these years, as well as the use of their agricultural or agro industrial residues (*see* Table 4-4) as depicted in Figure 4-12.

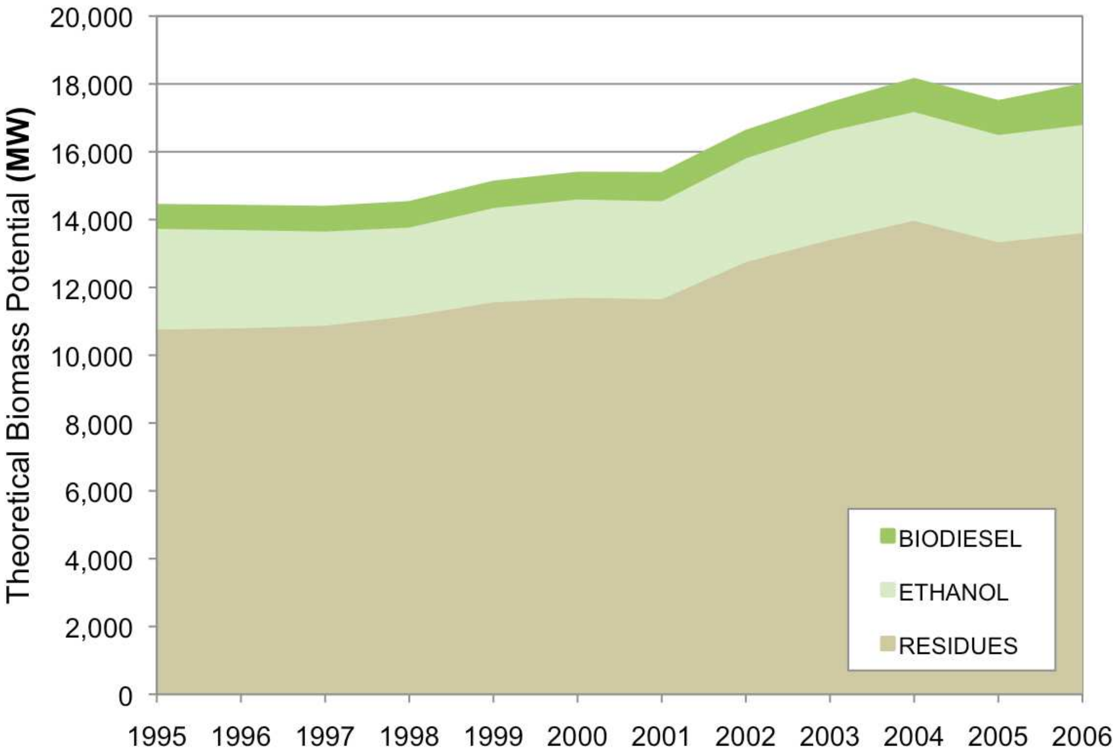


Figure 4-12 Historical theoretical potential from biomass

The theoretical potential for 2006 corresponds to 18 GW, where the utilization of agricultural and agro industrial residues have the highest share with 76% (13.7 GW), while the production of ethanol and biodiesel correspond only to 18% (3.2 GW) and 6% (1.1 GW) respectively. The shares have been maintained throughout the years and the variations are driven by the fluctuations of the cultivated area of every potential energy crop.

The tendency is positive and is expected to increase, given the fact that the Colombian government has the intention to keep in progress the agricultural expansion and give priority to the development of energy crops (Arias 2008, p. 53).

4.5.2 Future theoretical potential

By assuming an agricultural expansion for palm oil, cacao and sugarcane over the next 40 years, as shown in Table 4-5, new potential areas for the development of energy crops (10.9 million ha) will be available as suggested by the Colombian government. By applying the methodology introduced in Section 4.5.1, the theoretical energy potential rises from 18 GW (*see* Figure 4-12) in 2006 to 185 GW by 2050. The results are shown in Figure 4-13 for every crop.

The utilization of agricultural and agro industrial residues holds the highest share representing 80% of the total potential energy due to agricultural expansion as predicted for the year 2050 (*see* Figure 4-13). The agricultural expansion considers only the previously mentioned crop species, since the Colombian government has given priority to them as they represent great opportunities for foreign markets. This does not mean that rice, cotton or other potential crop species will not provide a source for energy production in the future as they might develop to have a greater potential as compared to current figures.

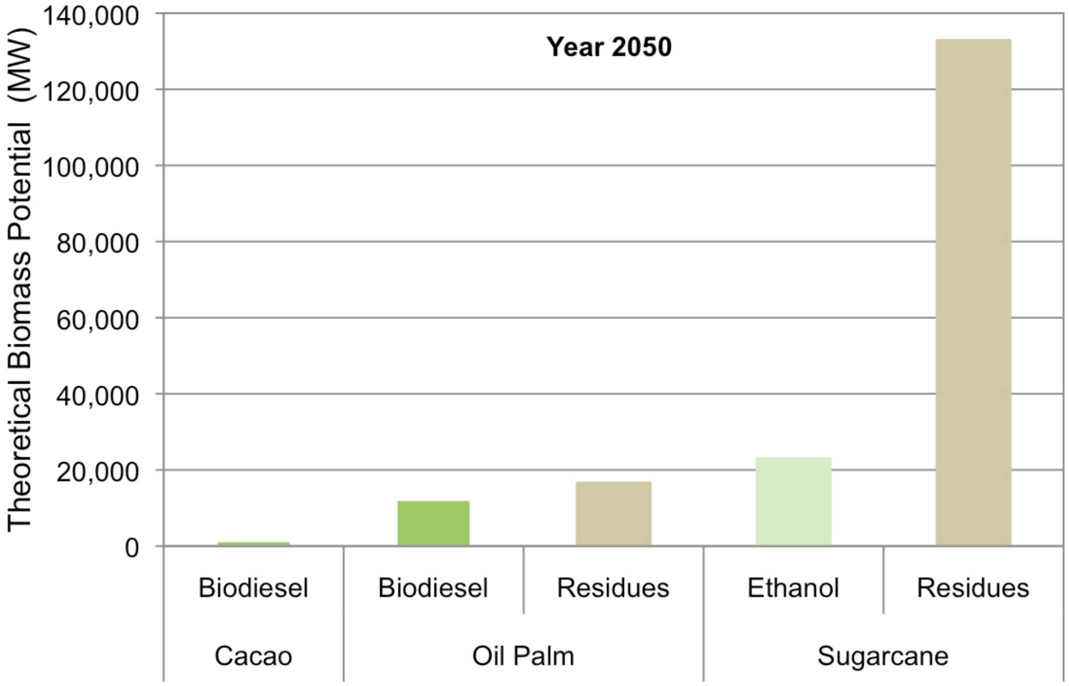


Figure 4-13 Theoretical potential from biomass in 2050 due to agricultural expansion

The potential of biodiesel and ethanol that can be produced is not considered as an energy source to produce electricity, since the use of biodiesel and ethanol is intended in the automotive sector for internal consumption and foreign markets.

Regarding residues from sugarcane and oil palm, the utilization of sugarcane harvesting residues has a great theoretical potential of 97.5 GW. The Figure 4-14 shows the future theoretical potential from these residues.

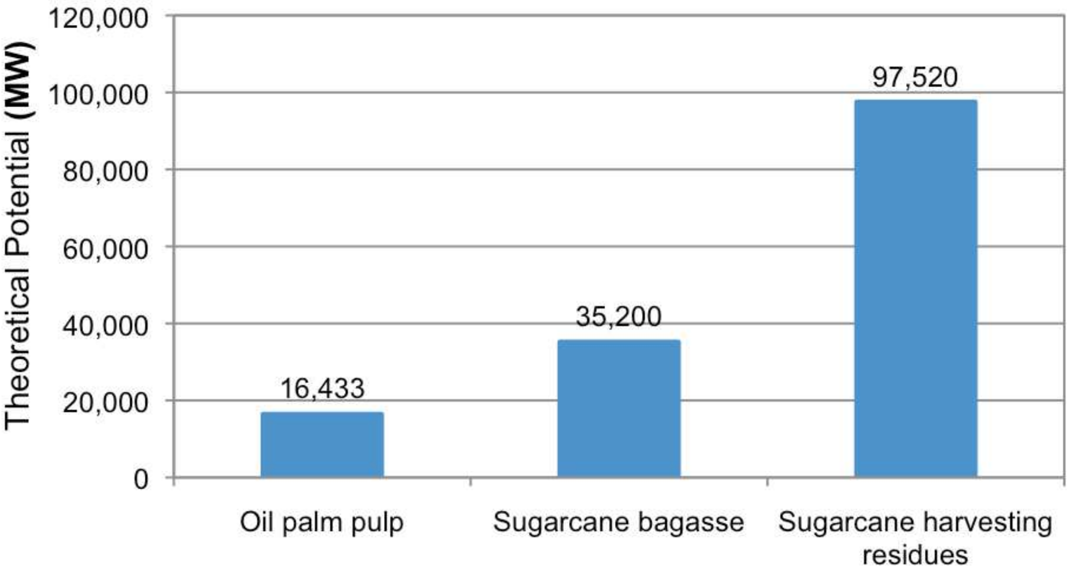


Figure 4-14 Future theoretical potential from residues

As described in the next subchapter under residues, an energy potential in the short term (year 2010) of 200 MW was determined for power generation that can be provided by the sugar sector. This value is equivalent to 1.8% of the theoretical potential from sugar cane, bagasse and residues together, in 2006 (11.16 GW). If this percentage is applied to the theoretical potential from sugarcane bagasse and residues in 2050 (132 GW) there will be an actual potential of producing 2.3 GW by cogeneration facilities.

4.5.3 Availability of energy crops for power generation

The current theoretical potential was obtained for all crops listed in Table 4-4. The future theoretical potential was determined for key crops given their potential for foreign markets. However, the availability to use these crops for power generation in Colombia depends on their demand for other markets, food competition, exports, etc. For that reason an analysis of the three categories of energy sources from biomass was conducted as follows:

Biodiesel:

Biodiesel is obtained through cacao, coconut, cotton, palm oil, peanut, sesame and soybeans with a theoretical potential of 1.1 GW by 2006. However the market for the oil and fruit of some of the plantations such as coconut, sesame, cacao and peanut is intended for human consumption and the production of additional goods (UPME 2003, p. 97). Coconut palm and palm oil present the highest yield, showing a great potential for biodiesel production. On the other hand the remaining energy crops present lower yields and high food competition.

Therefore palm oil plantations are the most feasible option for biodiesel production. The theoretical potential for palm oil is 972 MW in 2006, which may contribute to power generation in areas not connected to the grid. This might be possible under a scenario of removal of subsidies for diesel and the development of plants for biodiesel production and plantations located near these areas (UPME 2003, p. 97).

The use of biodiesel for electricity generation connected to the grid is not considered as a feasible option in the short term, since biodiesel has currently a very competitive market in the automotive area, besides the possibility of exporting the surplus.

Ethanol:

There is significant potential for ethanol production mainly from sugarcane and potato. Ethanol can be obtained from five species (Sorghum, Potato, Yucca, Sugar Cane, and Maize). From these five species, sugarcane and potato have the highest yields (UPME 2003, p.72).

Ethanol is produced globally and from different crop sources. In Brazil ethanol is produced mainly from sugarcane, in the United States mainly from maize and in Russia mainly from potatoes and sugar beets. The use of other crops such as yucca and sorghum requires basic research on the crop cycle and crop management and also the costs related to the conversion process (UPME 2003, p.98).

In 2001 the Colombian government issued Law 693, which established that gasoline must contain a 10% ethanol blend and by 2006 a 25% blend. When the law was issued, there were no ethanol production facilities and it was not until October 2005 when two distilleries began to produce sugarcane based ethanol. At the moment ethanol is produced in mills, which are energy self-sufficient. The mills use bagasse which is a byproduct remaining after crushing and extracting juice from sugarcane and through cogeneration they generate the energy needed for processing. The surplus bagasse-based power is sold to the national electric grid (Asocaña 2008, p. 37).

According to the Sugar Cane Producers Association (Asocaña 2008, p. 37) the growing demand for sugar cane should not affect Colombian food exports and food security because the cane for future ethanol production will come from new cropland and unproductive pasture land.

Ethanol may not be used to generate electricity as the market is intended for the automotive sector. On the other hand there is a potential to generate electricity by using the residues derived in the ethanol processing as well as the agricultural residues after harvesting.

Residues:

Within the classification of residues, there are a variety of products such as rice and cotton husk, residues from harvesting sugarcane, sorghum and maize as well as cacao and oil palm pulp. Although there was a theoretical potential of 13.7 GW in 2006, there are many subjects that have to be taken into consideration which require additional research such as the cultivation techniques, residues collection, other demands and utilization processes. Figure 4-15 shows the theoretical energy potential from different residues.

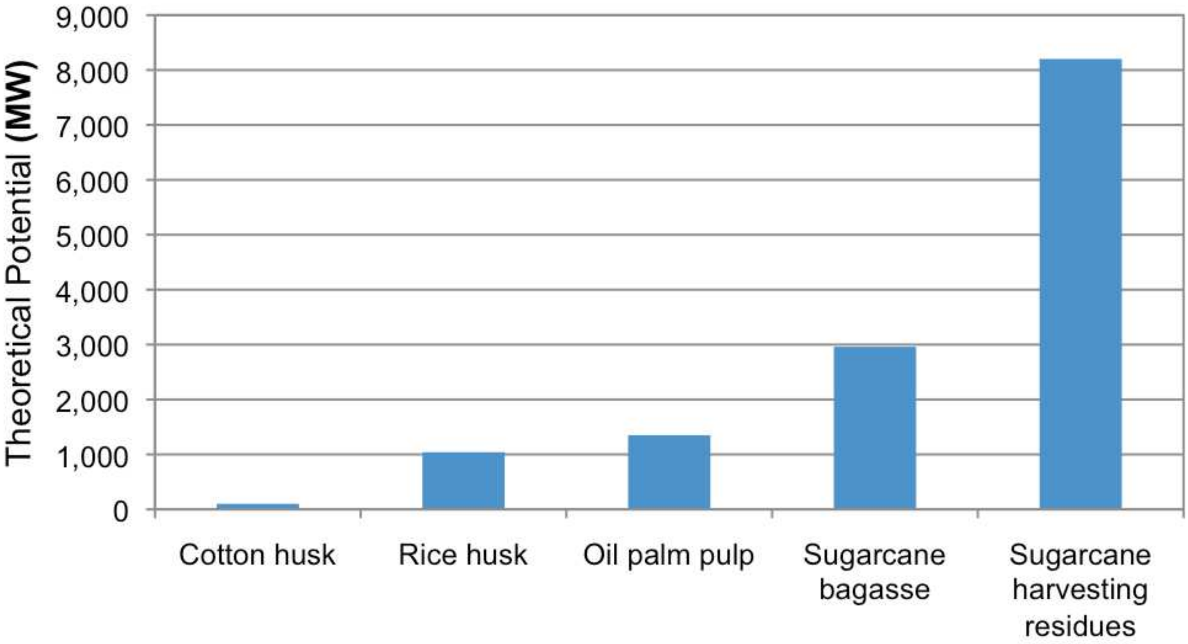


Figure 4-15 Theoretical potential from residues in 2006

Harvesting residues from sugarcane has the highest potential being able to produce 8.2 GW which represents 60% of the total energy potential.

The Study of the Colombian Mine-Energy Planning Unit (UPME 2003) conducted investigations with the objective to identify the present use of residues from the different energy crops. It was found that the residues that come from coconut palm such as the fiber and the shell, which are reported in the literature as an energy product, are not available due to the non existence of a processing industry, which could be able to gather and concentrate the residues allowing its use for energy purposes. The coconut is mainly consumed as fresh fruit and for that reason this residue was not considered in the calculation of the energy potential (UPME 2003, p.103).

The utilization of rice husk is considered as an excellent opportunity for the development of cleaner production and the utilization of industrial wastes. In Colombia, the production is gathered in rural areas adjacent to the mills, causing environmental problems associated with the dispersion of dust and husk. Although some of the husks are sold for use in barns, stables, poultry and gardening work, the market is unable to consume it all (UPME 2003, p. 107-108 and AENE 2006, p.10).

The husks are not always available near the cultivation area. Sometimes the rice is transported and processed in mills in other parts of the country and the husks are then available for cogeneration projects, as the mills have a strong demand for electrical and thermal energy for drying, threshing, sorting and packing (UPME 2003, p. 99). The energy potential for rice husk utilization is 1 GW, which can be obtained in the long term.

The bagasse is currently used in the mills to generate the energy needed for processing. The surplus bagasse-based power is sold to the national electricity grid (Asocaña 2008, p. 37). According to the Sugar Cane Producers Association, there is a potential of 200 MW that can be provided by the sugar sector in the short term by 2010 (Asocaña 2008, p.23 and 38). Even though the cost of production of bagasse-based electricity is higher than that of coal-based or hydroelectric-based electricity, the final price (after tax, commercialization, and transportation costs) that the mills would have to pay for conventional electricity would be higher than that of bagasse-based electricity (Asocaña 2008, p. 23). On the other hand, the residues of sugar cane after harvesting are not currently being use for energy purposes.

Oil palm pulp is consumed within the same plantation and in oil extraction plants to produce steam that is consumed in the process. The energy potential of oil palm pulp was equivalent to 1 GW in 2006. This potential is not considered available for other uses in the same industry, but the installation of cogeneration systems, replacing boilers and industrial furnaces currently used, will improve process efficiency (UPME 2003, p. 104).

4.5.4 Power generation potential

With the results obtained due to agricultural expansion (*see* Figure 4-13 and Figure 4-14) a power generation potential can be obtained by selecting from the theoretical potential the energy crops that can be available to transform them into electricity.

The use of agro-industrial residues for power generation such as oil palm pulp and sugarcane bagasse has a great potential for cogeneration projects, which produce electricity and thermal energy (e.g. steam or hot water) for their industries. Eventually their surplus of electricity will be available for the national power system. It does not mean that power plants cannot be erected only for electricity generation as it may be the case by using residues of sugar cane of fields after harvesting. Other residues from other species such as cotton and rice husks may be available in the future. On the other hand, the use of alcohols or biodiesel will be mainly used for transport sector and foreign markets, although the use of bioethanol for power production might be an option.

For that reason the power generation potential is calculated only for residues of the expected three most promising crop species: Oil palm pulp, sugarcane bagasse and sugarcane harvesting residues. Based on the theoretical potential of these residues, the power generation potential will be obtained by considering the losses of the transformation of the energy content of the residues into electricity.

The direct combustion of biomass (fluidized bed combustion) and the biomass integrated gasification combined cycle IGCC are the technologies to be employed for power production with biomass. The efficiencies reported by the literature today are 40% for direct combustion and 42% for IGCC, which are expected to be improved in the future (*see* Table 6-18 in Chapter 6). In order to have a conservative estimation, a constant efficiency of 40% will be assumed. The power generation potential will be calculated as follows:

$$CP_i = TP_i * \eta / 1000$$

Where:

CP = Power generation potential of a given energy crop in GW

i = Type of crop

TP = Theoretical potential of a given crop in MW

η = Electrical efficiency. 40% is assumed for all processes.

Table 4-6 exhibits the input data and the results.

Table 4-6 Power generation potential CP from residues

Specie	TP 2006 *(MW)*	TP until 2050 *(MW)*	Process	Electrical Efficiency *(η)*	CP 2006 *(GW)*	CP up to 2050 *(GW)*
Oil palm pulp	1,350	16,433	Cogeneration	40%	0.54	6.57
Sugarcane bagasse	2,961	35,200	Cogeneration	40%	1.18	14.08
Sugarcane harvesting residues	8,202	97,520	Combustion	40%	3.28	39.01
Total	12,513	149,153			5.01	59.66

The potential for power generation with only these key selected species grows from 5 GW to 59.7 GW. These residues are better utilized in cogeneration projects, where overall efficiency is much higher by also delivering thermal energy. That may be the case for almost all applications with oil palm pulp and sugar bagasse. In that case surplus electricity will be injected into the grid. In contrast, sugarcane harvesting residues can be 100% available for power generation which amounts to 39 GW. It is worth noting that other residues from species such as cotton and rice might also be available. How much of that potential can be present in the Colombian power system is a question of the energy policy and economics and technical performance of the technology, which will be a task in the simulation with the energy models.

These indicative results show that biomass resources have a vast potential to be exploited and constitute an important energy source to be used for power generation.

4.5.5 Price Residues

In order to assess the feasibility of biomass as an energy source, the price of biomass must be known. A literature review of available sources results in the following prices:

Table 4-7 Biomass prices

Species	Price[4] *(USD/Tonne)*	Heating Value *(MJ/Tonne)*	Energy Price *(USD/GJ)*
Eucalyptus[1]	37.74	18674.49	2.021
Rice Husks[2]	95.33	13905.64	6.858
Sugar cane bagasse[2]	12.23	8894.12	1.374
Sugarcane harvesting residues[3]	6.85	16743.74	0.409

Sources:

1. (UPME 2005, p.11.30).
2. (UPME 2003, p.125). 181.18 COP/kg for Rice Husks and 23.24 COP/kg in December 2001were inflated with IPP (Production inflation index) agriculture and with official exchange rate in 2005 (1.2269 and 2331.7 COP/USD)
3. (Betancur et al 2003, p.47). 14.06 COP/kg in February 2003 was inflated with IPP agriculture and with official exchange rate in 2005 (1.1351 and 2331.7 COP/USD)
4. Prices in 2005 US Dollars

Eucalyptus was included as an example of dedicated energy crops with wood. Rice husks are the most expensive source, whereas the residues price from the sugar industry shows the most favourable prices. As noted before, the sugarcane harvesting residues are at disposal, are not fully being used and are the cheapest. The price for sugarcane harvesting residues was calculated for a distance of 10 km. Despite the fact of low prices, the current option today has been the use of some of these residues in cogeneration projects, where the additional income by selling thermal energy make some projects attractive.

The use of these resources for exclusively power generation will have to compete with conventional sources. Today the regulatory framework for cogeneration projects has not given the necessary incentive to raise the cogeneration potential available and currently no promotion for projects generation with renewable energy sources exists (UPME 2003, p.105; Betancur et al 2003, p.10).

4.6 SUMMARY

Table 4-8 summarizes the renewable energy source potential for power generation in Colombia.

Table 4-8 Renewable energy sources potential in GW

Energy source	Potential	Region
Agriculture residues	5 to 59	Pacific and Andean region
Large hydropower (> 20 MW)	84	Andean region
Small hydropower (< 20 MW)	25	Andean region
Geothermal	Unknown	Potential regions in south and middle Colombia
Solar PV	16	PV potential for the state of Guajira with 1% utilization of its area. Other regions at the Caribbean coast have also good conditions
Solar CSP	6	CSP potential for the state of Guajira with 1% utilization of its area
Wind	22	On-shore potential for the state of Guajira. Other regions at the Caribbean coast have also good conditions

This information constitutes the resource basis for the simulation in the energy models. The potential for almost every source is above the current installed power generation capacity in Colombia (14.4 GW as of 2010). Hydropower is and will continue to be a main energy source for electricity production given its huge potential. The potential of other renewable energy sources suggest that they can become an important contributor of electricity at a large scale and may displace fossil fuel energy sources and decrease the high dependence on hydropower. The chapter that follows introduces the power technologies available to transform renewable energy sources into electricity.

5. RENEWABLE ENERGY POWER TECHNOLOGIES

The objective of this chapter is to provide an overview of power technologies that can transform the Colombian renewable energy sources into electricity on a large scale. Not only are their functioning and technical features introduced, but also their market development in recent years, as well as prospects for further innovations and current costs.

Conventional energy technologies such as hydropower, gas turbines and coal power plants are not discussed in this chapter, since they are well-known technologies already supplying electricity in Colombia. However, the development of their technical features and costs will be included in the prognosis analysis of the next chapter.

5.1 PHOTOVOLTAIC

5.1.1 Physics

The photovoltaic technology directly transforms solar energy into electricity. This is possible due to the properties of semi-conductor materials in which their electrons can be stimulated to produce a current of electrons, which are directed through a magnetic field created between the semiconductor through other materials such as boron and phosphorus. This stimulation is caused by the solar irradiance (light) on the electrons of e.g. crystalline silicon of a solar cell. Materials with this property are silicon (Si), gallium arsenide (GaAs), cadmium telluride (Cdte) and copper indium diselenide (CulnSe2).

The functional principle of a solar cell is illustrated in Figure 5-1. Every silicon atom in the material is bound with their outer electron shell to other neighbouring silicon atoms. The outer electron shell has 4 electrons forming a binding pair of electrons (valence electrons) with the other atoms (4 pairs with 8 electrons). The photons contained in the light are able to break that crystalline structure, the bonds between the electrons, releasing electrons and leaving ‘holes’. This, by itself, is not enough to make possible the generation of electricity, since the electricity current in pure semiconductors is very small. To improve the number of charge carriers (electrons and holes) the silicon structure has to be “contaminated” –impurity of the structure- with doped atoms in the crystalline structure (GSES 2005, p.18; IPCC 2011a, 351; SESAM 2002, p.6)

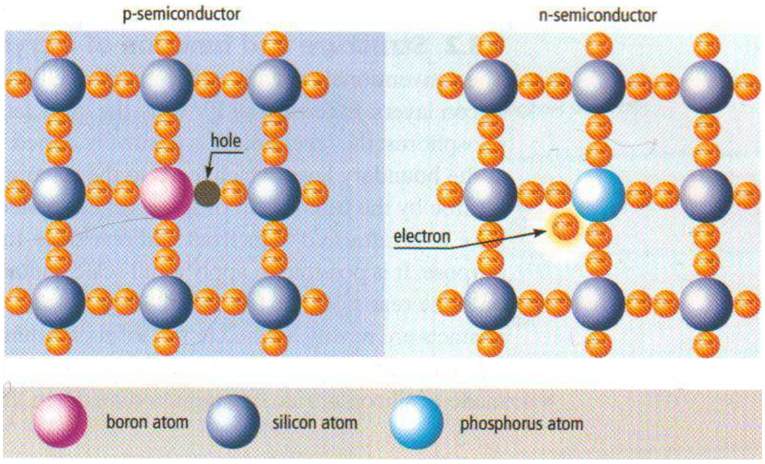


Figure 5-1 Solar cell principle

Source: GSES 2005, p.18.

The doped atoms are phosphorus or boron each with one more electron or fewer electrons in their outer shell respectively. The silicon crystalline structure has a surplus of electrons, if doped with phosphorus or a shortfall of electrons, if doped with boron as shown in Figure 5-1. A solar cell then has the so called n-doping (surplus of electrons) and p-doping (shortfall of electrons or holes) semiconductor layers, which are connected to form a p-n junction. This makes possible a diffusion of electrons at which the free electrons from the n-material recombines to the p-material (recombination). During this process a transition area is created, where atoms which did not recombine are left. Thus, the p-doping layer in the transition area will have electrons, which did not find a hole and for that reason negatively doped atoms remain. In the n-doping layer, positively doped atoms remain. The outcome is an area with few remaining free charge carriers, which is called the space charge zone. In the space charge zone an electricity field is created (voltage). (GSES 2005, p.18; SESAM 2002, p.8)

This photovoltaic effect makes it possible to create a current of electrons as soon as an open circuit is maintained by having constant light and a connection to a load as shown in Figure 5-2.

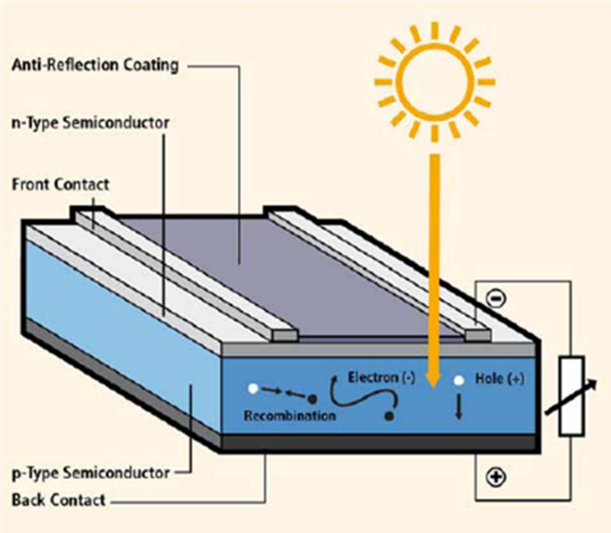


Figure 5-2 Photovoltaic effect of a solar cell

Source: IPCC 2011a, p. 23.

5.1.2 Technical properties

Photovoltaic cells can be distinguished according to their material and manufacturing process. This defines also their technical properties. Two main categories are found: the crystalline silicon cells and thin layer cells (*see* Figure 5-3).

Regarding the material, the crystalline silicon cells can be classified as mono-crystalline, poly-crystalline cells and ribbon sheets. By the thin film cells the typical types of material are amorphous silicon, cadmium telluride, copper Indium/gallium, diselenide disulphide and multi-junction cells.

Thin layer module

Crystaline module

Figure 5-3 Crystalline and thin layer cells

Main differences between the two types of cells are cell thickness, amount of material employed in cell manufacturing, energy consumption in cell production, cell efficiency, performance as shown in Table 5-1. These features have an effect on the cost.

Table 5-1 Features of crystalline and thin layer cells

Feature	Crystalline	Thin Layer
Cell thickness (µm)	200-300	1-6
Semiconductor material consumption (kg/kWp)	16	0.2
Primary energy consumption (MWh/kWp)	8-15	4-7
Connection	Internal	External
Efficiency (%)	11 – 19	4-12
Area needed per kW for Modules (m^2)	7 – 8	10 -15

Sources: GSES 2005, p. 31-32 and EPIA 2011, p.25.

Despite the lower efficiency of thin layer cells, a better performance under certain conditions can be reached. Thin layers are less sensitive to shading and have a better performance at higher temperatures.

The cells are placed in a PV module to be used as a power generation device. A PV module connects the cells, typically 60 cells in a crystalline module, protects them against corrosion, fragility and humidity; giving the construction the necessary robustness and modularity to be used as a power generation technology. In addition, the aim of a module is to achieve the maximum energy yields at the lowest possible cost. The module is designed to reach a given voltage and current. Higher voltages and currents are determined by means of a series and parallel connection of the solar cells in the module and between the modules. A typical solar module delivers, e.g. 7A at 32V which equals a capacity of 224 W.

In a photovoltaic solar power plant, the series connected modules are described as a string and the number of the strings determines the overall voltage, which corresponds to the input voltage of the connected inverter. In a grid connected system several strings are connected in parallel, thereby increasing the electricity output. Figure 5-4 illustrates a photovoltaic power plant configuration and Figure 5-5 shows a picture of a utility scale photovoltaic power plant.

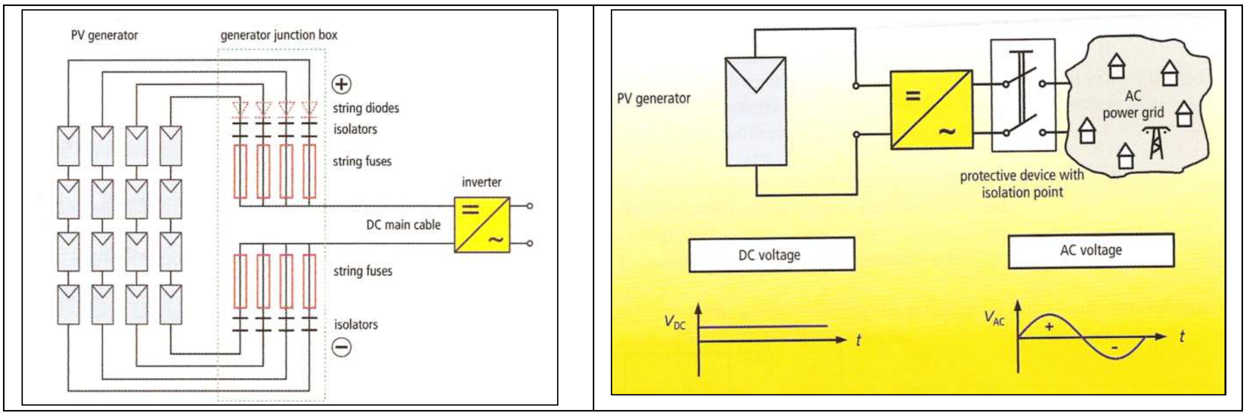


Figure 5-4 Photovoltaic solar power plant configuration

Source: GSES 2005, p. 81, 83.

Figure 5-5 Utility great scale photovoltaic power plant

The output of the individual strings is collected by a generator junction box. A photovoltaic solar power plant comprises several junction boxes. The junction box then delivers, at a given voltage and current, the DC electricity generated by the PV modules to the inverter (DC-AC converter), which converts the DC electricity into AC electricity and adjusts the frequency for the grid. A transformer is normally included in the inverter to match the voltage of the grid (e.g. 20 kV or 33kV).

5.1.3 Market development

Based on data available as of May 2011, the global total installation of photovoltaic systems reached at least 37 GW. A strong growth of installations has been seen in the late three years. The worldwide market is mainly driven by Europe (70% of the global market), Germany being the most important market in the world.

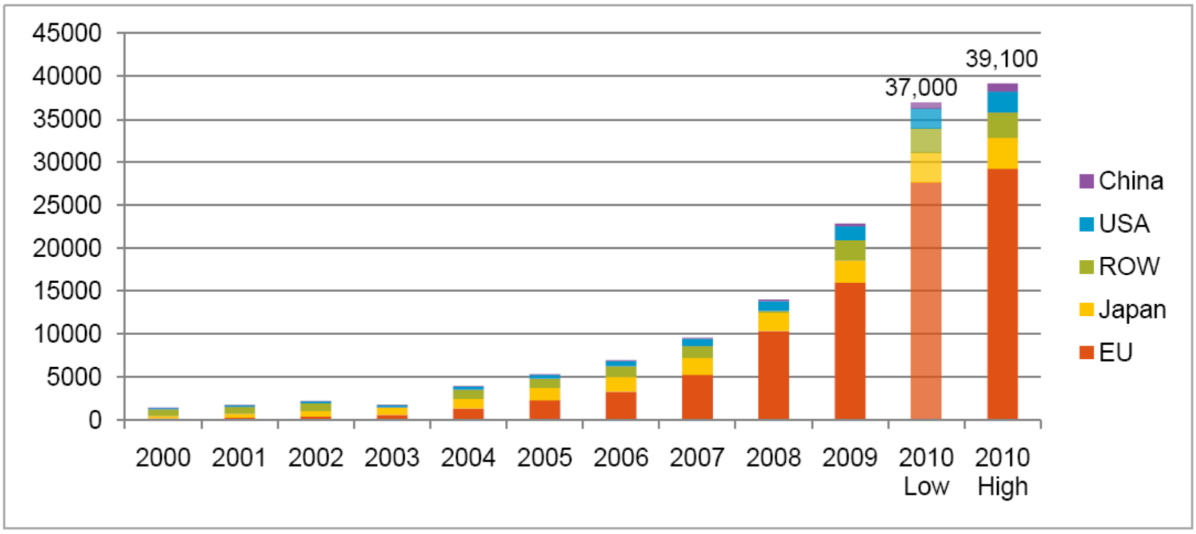


Figure 5-6 PV global market figures in GW

Source: EPIA 2011a, p.3.

Silicon continues to dominate the market with a share of 70%. CdTe thin layer technologies account for 13% of the market share. The share of silicon is expected to shrink as the share of thin layers technologies continues to grow and new technologies, such as concentrator PV enter the market (EPIA 2011).

5.1.4 Road map

According to the European Photovoltaic Industry Association (EPIA) and the Solar Europe Industry Initiative, the cost of PV needs to be further reduced to reach competitiveness with conventional sources of electricity. Through technological innovation such as higher efficiencies, economies of scale, improved production processes, better performance and an extended life of PV systems that goal can be achieved.

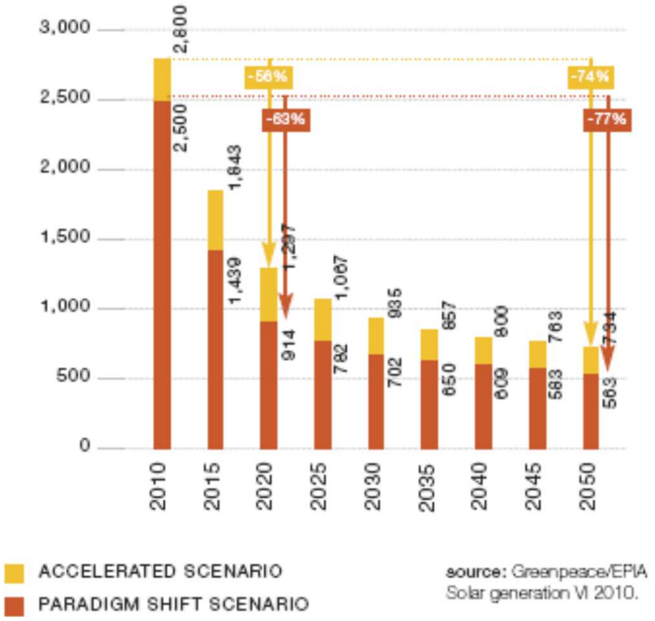
Table 5-2 Features of crystalline and thin layer cells

		2007	**2010**	**2015**	**2020**
Turnkey price large systems *(€/Wp)*		5	2.5-3.5	2	1.5
PV Electricity generation cost in southern EU *(kWh)*		0.30 - 0.60	0.14 - 0.20	0.10 - 0.17	0.07 - 0.12
Typical PV module efficiency range *(%)*	Crystalline silicon	13-18%	15-19%	16-21%	18-23%
	Thin Films	5-11%	6-12%	8-14%	10-16%
	Concentrators	20%	20-25%	25-30%	30-35%
Inverter lifetime (years)		10	15	20	>25
Module lifetime (years)		20-25	25-30	30-35	35-40
Energy payback time (years)		2-3	1-2	1	0.5

Source: EPIA 2011 p.39.

5.1.5 Current cost

Current cost for large PV systems based on the German market today is between 2,500 EUR/kWp (3,310 USD/kWp) and 2,800 EUR/kWp (3,708 USD/kWp) (EPIA 2011, p.31), including converters and balance of plant items equipment and installation costs. A further decrease in price for the coming decades is dependent on the installed capacity in the future. The forecast of the EPIA and Greenpeace shows quick price reductions over the coming ten years. Prices will be between 914 EUR/kWp and 1,297 EUR/kWp according to the projections with a future capacity over the reference scenarios of the World Energy Outlook of the International Energy Agency (IEA). A drop under the 1,000 EUR/kWp mark is expected by 2025 (EPIA 2011, p.31). This trend suggests that the potential to continue reducing prices is high and confirms the high learning rates of the technology.



source: Greenpeace/EPIA
Solar generation VI 2010.

Figure 5-7 Forecast prices in EUR/kWp for large PV systems

Source: EPIA 2011, p.31.

The cost per kW is an important signal to determine the economic feasibility, however it does not properly reflect the advantages of capital intensive technologies like solar, wind and hydropower. The avoidance of volatile fuel fossil prices and lower maintenance costs in combination with the availability and quality of the solar resources determines the cost of a kWh generated by the technology and therefore its competitiveness. It is important at this stage to note that the aim of this dissertation is to include this aspect in the simulation for a "fair" comparison of the technologies.

By means of a levelized electricity cost approach taking into account the economic performance of the technology over its lifetime a cost per kWh is calculated to allow the comparison of this cost with other technologies. Figure 5-8 shows the expected levelized electricity cost for large ground mounted systems according to the operating hours (quality of the resource) and the investment cost in 2010 and in the future. In very good locations in a sunbelt country like Colombia (lower curve in the figure) and with reduced investment cost as shown for the year 2030, the price per kWh can be under 5 Eurocents per kWh.

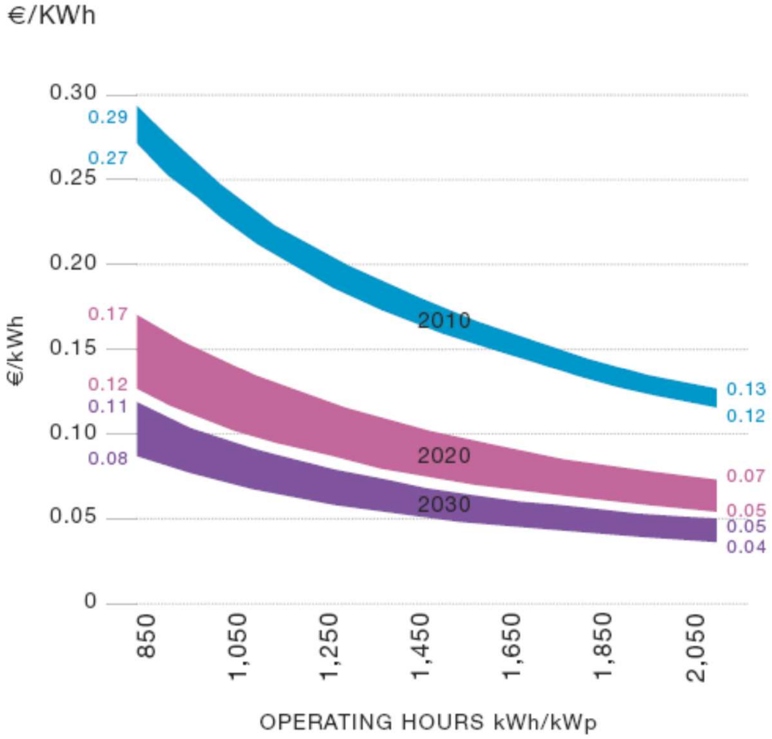


Figure 5-8 Levelized electricity cost for PV

Source: EPIA 2011, p.31.

5.2 WIND ENERGY

5.2.1 Physics

Wind energy is the product of a complex meteorological phenomenon involving the movement of the earth, pressure gradient forces, temperatures distribution over the globe. At a micro level the effect of topography and local climate. The main characteristic feature of wind is its intermittency. Therefore, the energy production of a wind energy converter is intermittent.

This movement of the air and its kinetic energy travels through the blades of a wind turbine, which turns this energy into a rotation of the rotor. As a result the kinetic energy of the wind is transformed in mechanical energy. The rotor is coupled to a generator which transforms the mechanical energy into electricity. In its simplest form the energy obtained can be described as follows (Johnson 2001, p.2-37):

$$E_W = \frac{1}{2} * \rho * A * \sum_{i=1}^{W} Cp_i \, p(U_i) U_i^3 * 8.760$$

where:

E_w = Turbine energy production [Wh]
W = number of intervals of wind speeds
A = Swept rotor area [m^2]
ρ = Air density [kg/m^3]
$p(U_i)$ = probability of a given wind speed interval *i* at hub height
U_i = wind speed
Cp_i = Power coefficient for a given wind speed interval *i*

The swept area and the power coefficient are variables dependant on the machine, whereas density and wind speed are site dependant. The wind speeds are grouped into intervals of 1 m/s to determine the number of hours in a year $p(U_i)$ that the machine will face a given speed interval. The third power of the speed makes the wind resource assessment a crucial aspect to estimate successfully the wind potential and thus the electricity production. A wind speed doubling increases the power eight times.

The machine makes use of a portion of the power in the wind. Modern machines are designed according to the lift force principle, which is a translation of the Bernoulli effect that explains the lift force resulting from different pressures, e.g. between the wing section of an aircraft into the rotor's blade to maximize the force driving the generator. Today wind energy converters can transform over 50% of the energy contained in the wind into electricity (IPCC 2011c, p.553). For every machine there is an optimum point at which this efficiency can be reached. For that reason the power coefficient Cp of the machine, which describes the portion of the wind that can be transformed, is not constant and manufacturers optimize the performance by the wind speeds with the highest probability to be seen per year. Therefore there are machines tailored for offshore, coastal, medium and low wind areas.

Wind speeds need to be measured in order to assess the wind resource at a given location. An annual wind speed frequency distribution has to be determined. The frequency distribution is estimated at the hub height of the wind turbine. A higher hub height automatically increases the wind speed. The frequency distribution is basically a histogram where all the set of measured wind speeds are distributed in intervals (1 m/s) and then plotted as the probability of the discrete wind speed. The independent variable is plotted along the horizontal axis (wind speeds), and the dependent variable, usually a percentage is plotted along the vertical axis (frequency). The independent variable can attain only a finite number of discrete values rather than a continuous range of values. The dependent variable can span a continuous range.

A histogram can be described by statistical methods. The most common density function is the Weibull distribution. The combination of the frequency distribution and the power curve of the turbine (resulting power at a given speed based on the Cp) determines the electricity generation at a specific location.

In a wind park configuration, wake losses occur due to shadowing effects between wind turbines placed close to each other. For that reason the main coming direction of the wind is of special relevance to design the wind park arrangement in order to have the greatest energy production. The wind rose of the set of data available illustrates the main coming directions of the wind.

The final layout arrangement is a result of a combination of several aspects such as area availability, wind resource behaviour, turbine size, environmental restrictions (visual and noise impacts) and economic aspects (investment, installation, access, connection point to the grid, etc). Figure 5-9 shows a wind park installation.

Figure 5-9 Wind park

Source: Nordex SE 2012.

5.2.2 Technical properties

A wind energy turbine comprises a tower, a nacelle which follows the wind direction and where main components are located and a rotor as shown in Figure 5-10. Manufacturers differentiate themselves by the way they drive the generator either via a gearbox or directly. A gearbox increases the revolutions per minute (rpm) of the rotor to be compatible with the generator. In a direct drive turbine the generator is directly coupled to the rotor. Gear boxes have dominated the market. (Navigating consulting 2011, p.99; EWEA 2009c, p.74)

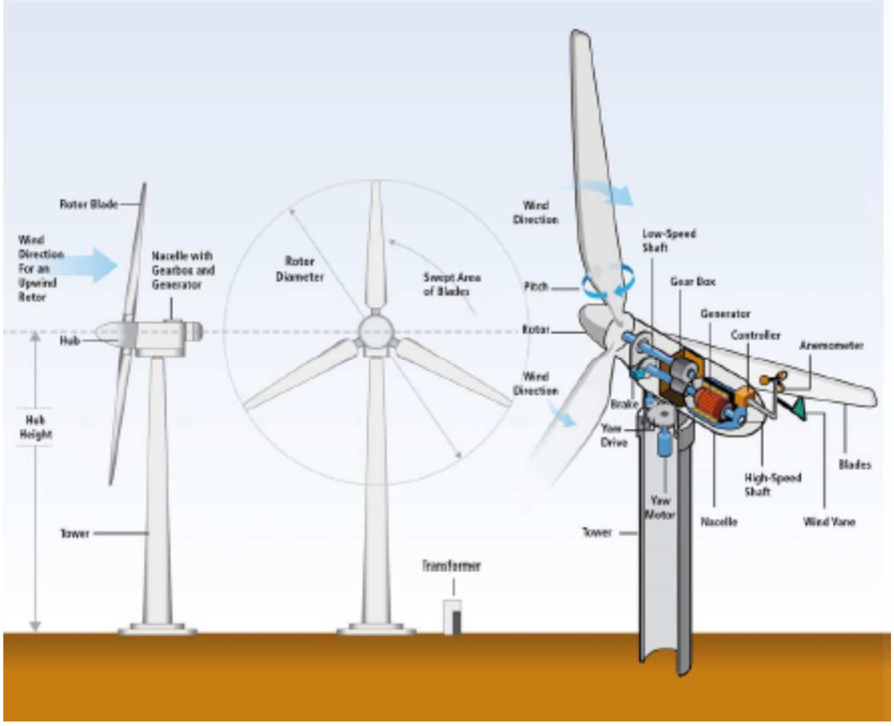


Figure 5-10 Wind turbine components

Source: IPCC 2011c, p. 21.

To limit the rotor power in high operational wind speeds, the machines use stall and pitch regulation. Modern turbines operate at variable speed which allows the rotor to maintain the best flow geometry for maximum efficiency and offers better output power quality to the grid, in contrast to old designs where the speed was held constant by the grid through the generator. The electrical energy is therefore generated at variable frequency and a converter, which is a power electronic device, matches the output to the frequency of the grid (EWEA 2009c, p.81).

Normally the turbine delivers a voltage output below 1,000 V, which has to be increased to a distribution voltage between 10 and 35 kV to be compatible with the grid. Therefore each turbine has a transformer to step up the voltage. The power is taken to a central point in a substation to step up the voltage again to the high voltage grid conditions above 100 to 150 kV. Small wind farms are mainly connected only to the distribution voltage without the need of a substation.

Commercial turbines for utility size applications range from 1,000 kW to 5,000 kW. Typical sizes between 1,500 kW and 2,500 kW account for 83.1% of all turbines supplied worldwide between 2008 and 2010 (Navigant consulting 2011, p.42). Larger capacities are typically for the offshore segment. The size development of the German wind market in recent years shows the majority of the turbines between 60 and 90 meters rotor diameter and more recently over 90 meters as shown in Figure 5-11. Around 50% of the new capacity installed in Germany in 2010 has hub heights higher than 101 meters (DEWI 2011, p. 44).

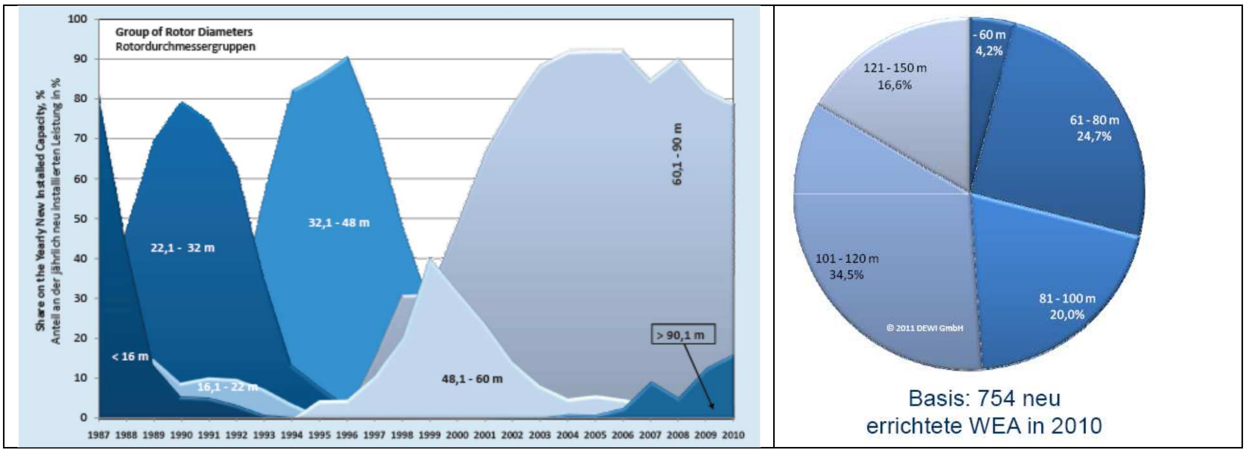


Figure 5-11 Size and hub height development

Source: DEWI 2011, p.44.

5.2.3 Market development

The total installed capacity worldwide amounted to almost 200,000 MW by 2010 with new installations in that year of 39,404 MW. 24,000 new wind turbines were erected in more than 50 countries. The expansion in the year 2010 was driven by South and East Asia, namely China which represented 53.6% of the installations (Navigant Consulting 2011, p.13). The cumulative capacity for installed wind power is shown in Figure 5-12.

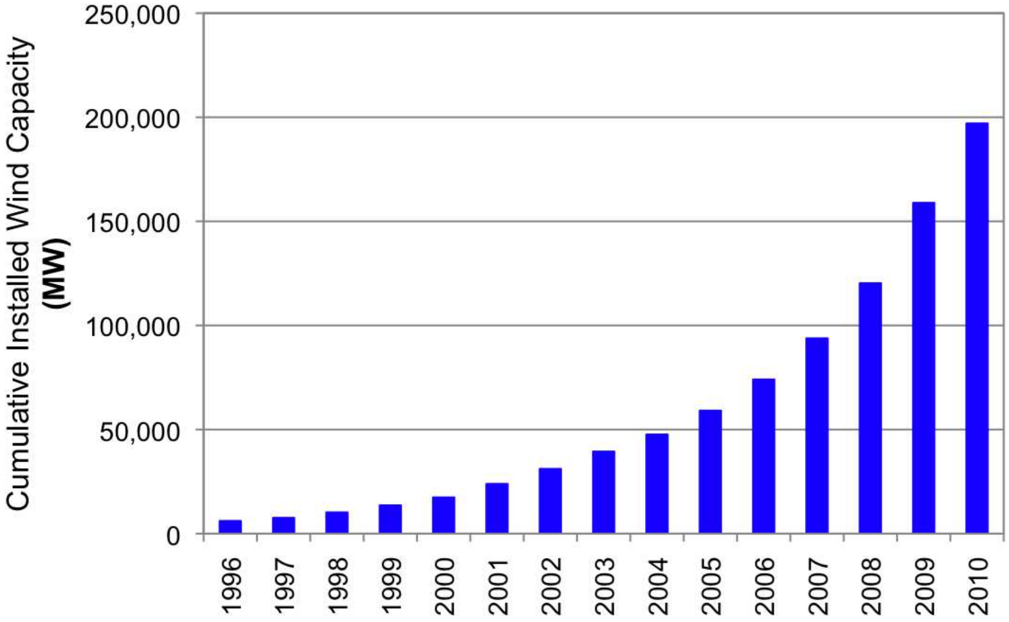


Figure 5-12 Cumulative global wind capacity

Source: Data from GWEC 2011, p.14.

Around 86,000 MW of the total installed capacity is found in Europe with a 43.8% share driven by Germany and Spain followed by Asia with 61,087 MW (31% driven by China and

India) and the Americas with 46,197 MW (23.4% driven by the USA). The top 10 markets in the world in the year 2010 are shown in Table 5-3.

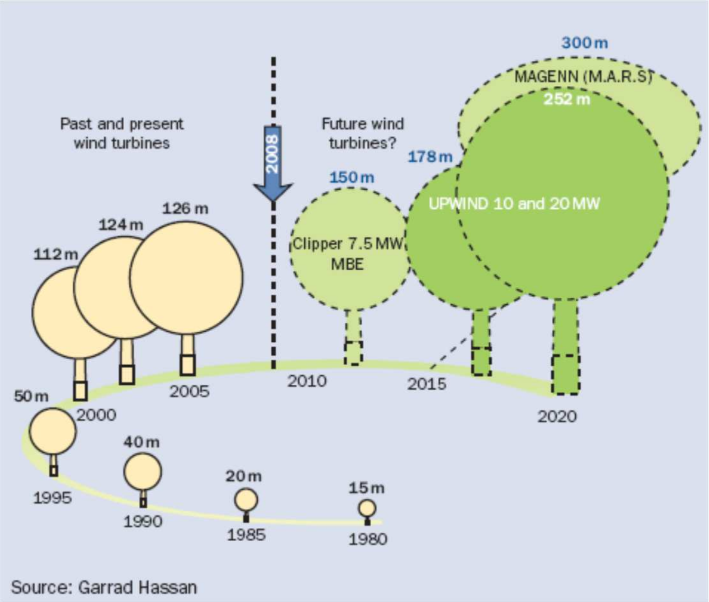
Table 5-3 The 10 largest markets in 2010 in MW

Country	2008	2009	2010	Share *(%)*	Cum. Share *(%)*
China	6,246	13,750	18,928	48.0%	48.0%
USA	8,358	9,922	5,115	13.0%	61.0%
India	1,810	1,172	2,139	5.4%	66.4%
Germany	1,665	1,917	1,551	3.9%	70.4%
UK	869	1,077	1,522	3.9%	74.2%
Spain	1,739	2,331	1,516	3.8%	78.1%
France	1,200	1,104	1,186	3.0%	81.1%
Italy	1,010	1,114	948	2.4%	83.5%
Canada	526	950	690	1.8%	85.3%
Sweden	236	512	604	1.5%	86.8%
Total	23,659	33,849	34,199		

Source: Data from Navigant Consulting 2011, p.29.

5.2.4 Road map

In the case of wind energy the technology trend is the up-scaling of wind turbine sizes along with turbine efficiency improvements and more recently the shift towards direct drive. The goal is to reduce the cost per kWh (EWEA 2009c, p.72). Up-scaling in the onshore segment has been seen over the years as shown in Figure 5-13 by the size of the rotor diameter.



Source: Garrad Hassan

Figure 5-13 Wind turbine size development

Source: EWEA 2009, p.6.

Gear boxes have dominated the market, where a direct drive wind turbine has been limited to only one manufacturer. Today manufacturers are now shifting to the direct drive concept, in which generators transform directly the torque from the rotor into electricity via its magnetic field. This brings the advantage of reduced maintenance and fewer components in the nacelle at the expense of a larger diameter of the generator and therefore with the resulting heavier weight and costs. A reduction of the extra cost is expected (Navigant Consulting 2011, p.99)

5.2.5 Current cost

Based on European wind installations, the European Wind Energy Association (EWEA) assessed the cost structure of a typical 2 MW installation as shown in the next table. Approximately 76% of the overall cost corresponds to the turbine.

Table 5-4 Cost structure of a 2MW turbine

	Investment *(1,000 EUR/MW)*	**Share of total costs** *(%)*
Turbine (ex works)	928	75.6
Grid connection	109	8.9
Foundation	80	6.5
Land rent	48	3.9
Electric installation	18	1.5
Consultancy	15	1.2
Financial costs	15	1.2
Road construction	11	0.9
Control systems	4	0.3
Total	**1227**	**100**

Source: EWEA 2009, p. 14.

The economic feasibility of a wind project certainly depends on its investment cost but more importantly on the wind resource available and therefore the capacity factor as shown in Figure 5-14 based on an investment of 1,225 EUR/MW (1,537 USD/MW in 2006 prices) and different discount rates. The price per kWh in coastal areas with a discount factor of 10% is over 6 Eurocents per kWh (7.53 USD cent/kWh).

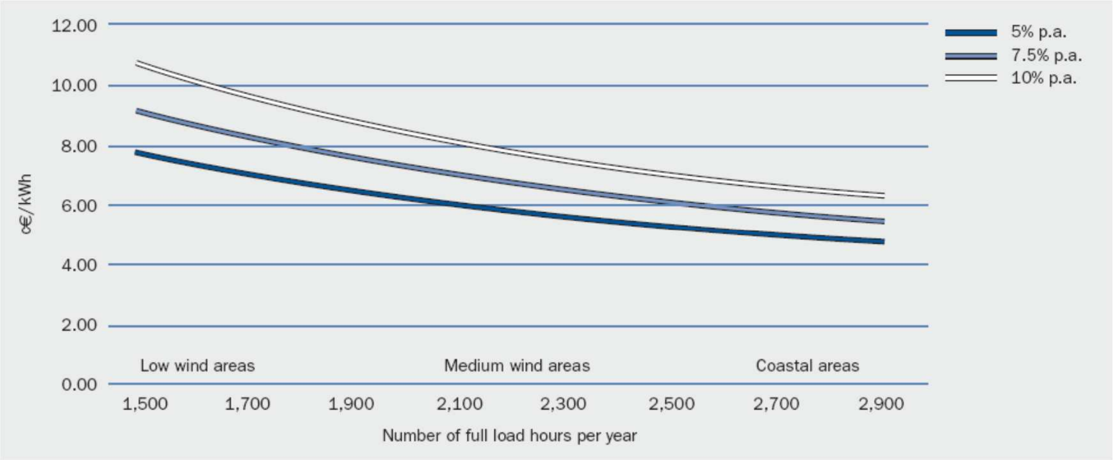


Figure 5-14 Wind energy generation cost

Source: EWEA 2009a, p.209.

5.3 GEOTHERMAL

5.3.1 Physics

Colombia possesses high volcanic activity with geothermal resources due to its location in the South American plate and presumably with the potential for the use of geothermal sources for power generation. However, a detailed assessment of the resource has not yet been achieved.

The quality of the geothermal resource defines the suitability and the type of technology for power generation. A geothermal reservoir is defined by its temperature, depth, amount of liquid available, etc. which are key parameters for the assessment of the quality. The resource, the geothermal fluid, is a steam, liquid or a mix of water/ steam at a given temperature and pressure according to the reservoir. Steam and water temperatures over 180°C are required for conventional electricity generation (Fridleifsson et al 2008, p.63).

The type of geothermal fluid and its temperature define the technology to be employed for power generation. The technologies for power generation use the resource water/steam in single or double flash generation plants and binary plants.

A more sophisticated technology, the Hot Dry Rock technology (HDR), for reservoirs without a liquid or gas as a medium but with high temperatures at depths over 5 km is currently being developed. The high temperatures can be used to transfer the heat energy to a liquid medium such as water. In this case water is injected at high pressure, which cracks the rocks to form a net of channels inside; the water is extracted at other point of the reservoir at a high temperature due to the thermal transfer between the rocks and the injected water.

Temperatures around 200 °C can be obtained to be transported to the surface. As in the case of conventional geothermal plants, a heat exchanger or a binary cycle will transfer the energy to a steam turbine generator cycle. For the Colombian case the direct use of geothermal reservoirs with water and/or steam will be considered.

5.3.2 Technical properties

The single and double flash power technologies are suitable for temperatures over 150°C of geothermal fluids. If steam is present in the geothermal fluid, it is directly piped to a turbine to drive the generator in a conventional Rankine cycle. In the case of water with high temperatures, steam is first obtained by reducing the water pressure to generate steam in a flash process. Thus, the flash cycle separates the steam from the fluid to be directed through the steam turbine. The condensed steam is re-injected to the reservoir together with remaining water in the flash process. Figure 5-15 shows a schematic representation of flash technologies.

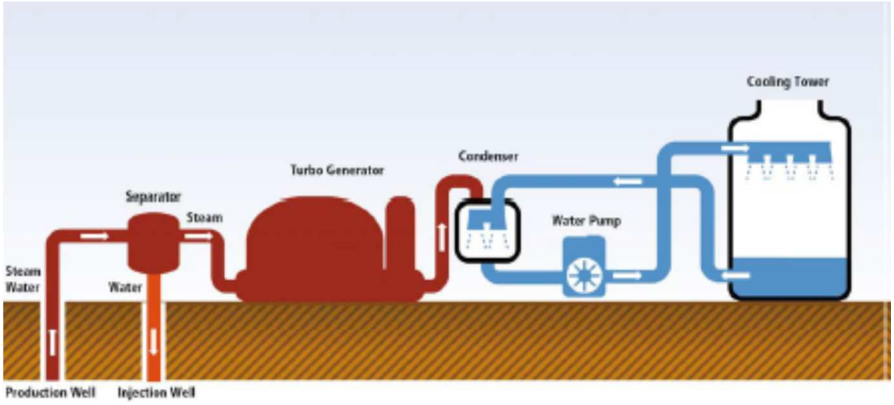


Figure 5-15 flash technologies for geothermal power

Source: IPCC 2011b, p. 15.

In the case of geothermal fluids with temperatures lower than 180 °C, a binary plant is the appropriate option, since the resource is not suitable to be used directly to generate electricity. A binary power plant is an Organic Rankine Cycle (ORC) which uses as a medium an organic fluid. The organic fluid has a low boiling point and high steam pressures at low temperatures. Fluids with these properties are, e.g. butane, isobutene o pentane (UPME 2003, p.37; IPCC 2011b, p.412). The geothermal fluid transfers (the primary working fluid) its heat energy to the organic fluid (the secondary working fluid) in a heat exchanger, which can drive a steam turbine. A typical size of these power plants is between 500 kW and 10 MW. As the flash system, the geothermal fluid is re-injected in the reservoir. Figure 5-17 shows a schematic representation of binary plant.

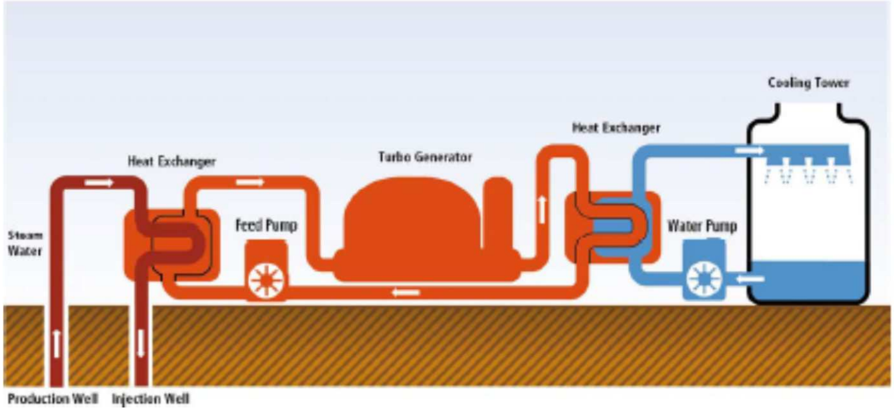


Figure 5-16 Binary plant

Source: IPCC 2011b, p.15.

5.3.3 Market development

The global installed geothermal capacity for electricity generation in the year 2010 amounted to 10,715 MW. In Latin America 1,468 MW have been installed in Central America which represents 13.7 % of the global capacity, where excellent geothermal resources are available for conventional geothermal technologies. 57 % of the global capacity is located in the USA, Indonesia and the Philippines (IGA 2010, p.2). Annual installations' development and global capacities are shown in Figure 5-17 and Table 5-5.

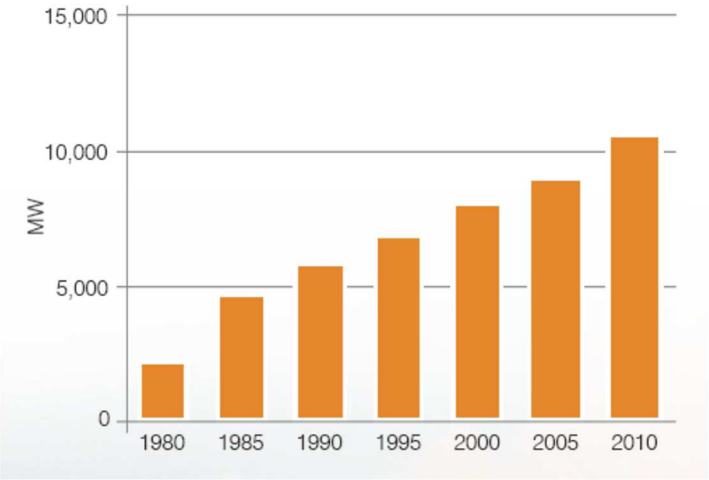


Figure 5-17 Geothermal capacities development

Source: IGA 2010, p.2.

Table 5-5 Global installed capacity in MW

Country	**Global Installed Capacity** *(MW)*
Australia	1.1
Austria	1.4
China	24
Costa Rica	166
El Salvador	204
Ethiopia	7.3
France	16
Germany	6.6
Guatemala	52
Iceland	573
Indonesia	1,197
Italy	843
Japan	536
Kenya	167
Mexico	958
New Zealand	628
Nicaragua	88
Papua-New Guinea	56
Philippines	1,904
Portugal	28
Russia	82
Thailand	0.3
Turkey	82.0
USA	3,093
Total	**10,715**

Source: IGA 2010, p.2.

5.3.4 Road map

Most of the components from conventional geothermal technologies related to the steam “side” or power block such as heat exchangers, turbines, cooling equipment, etc. are also used for other conventional technologies. Their development and improvement are more linked to those conventional energy technologies.

The main challenges of geothermal sources is the improvement of the resource assessment and extraction (high cost of drilling is a main barrier), the technological challenge of dealing with the corrosive nature of geothermal fluids and the production of materials for high temperatures and high pressure sources. Flash steam and binary plants should increase their efficiency (European Commission 2010, p. 2).

5.3.5 Current cost

According to the European Commission the cost of an average geothermal plant is around 2,000 EUR/kW (2,781 USD/kW in 2009 prices), where drilling accounts for 30% and 50% of total development cost accounts for drilling (European Commission 2010, p. 4).

5.4 CONCENTRATED SOLAR POWER (CSP)

5.4.1 Physics

Unlike the PV technology, where there is a direct transformation of the solar radiation into electricity, a concentrated solar power plant enhances and concentrates the radiation to generate heat to be transformed later in mechanical energy and electricity by means of conventional power technologies with steam turbines. This technology requires direct radiation (light) to be able to concentrate the radiation in one point to produce heat. The location of the power plant is therefore a key factor, where with limited cloud cover or shadows with a high exposure to direct radiation is required. The Guajira region in Colombia features these conditions.

For photovoltaic systems the addition of direct and diffuse radiation, measured by the global radiation, is important as a key parameter. By CSP technologies the key parameter is the Direct Normal Irradiance (DNI) measured by a pyrheliometer. DNI is the energy received by a surface perpendicular to the sun’s rays. Typically a DNI between 1,900 kWh/m^2/year and 2,100 kWh/m^2/year is required for a CSP application (IEA 2010, p.9).

To allow the concentration of the light, a receptor (in practice a mirror) which acts as a reflector concentrates the light at a given point. The mirrors include a tracking system to redirect and concentrate the light at one point as the sun changes its position during the day and the angle in which the light hits the mirrors. Depending on the tracking system, two main categories of CSP configurations can be found:

The first is the one axis tracking systems, which concentrate the radiation in a line (absorber pipe). The second, the two axis configuration, redirects the light to a given fixed point. The one axis configuration is typical of the parabolic trough technology. In a Fresnel collector type the concentrator is split in rows to direct the light to only one absorber tube. The solar tower and parabolic dish technology belong to the two axis configuration. Figure 5-18 illustrates the types of CSP technologies and Table 5-6 summarises the receiver and focus type of CSP technologies.

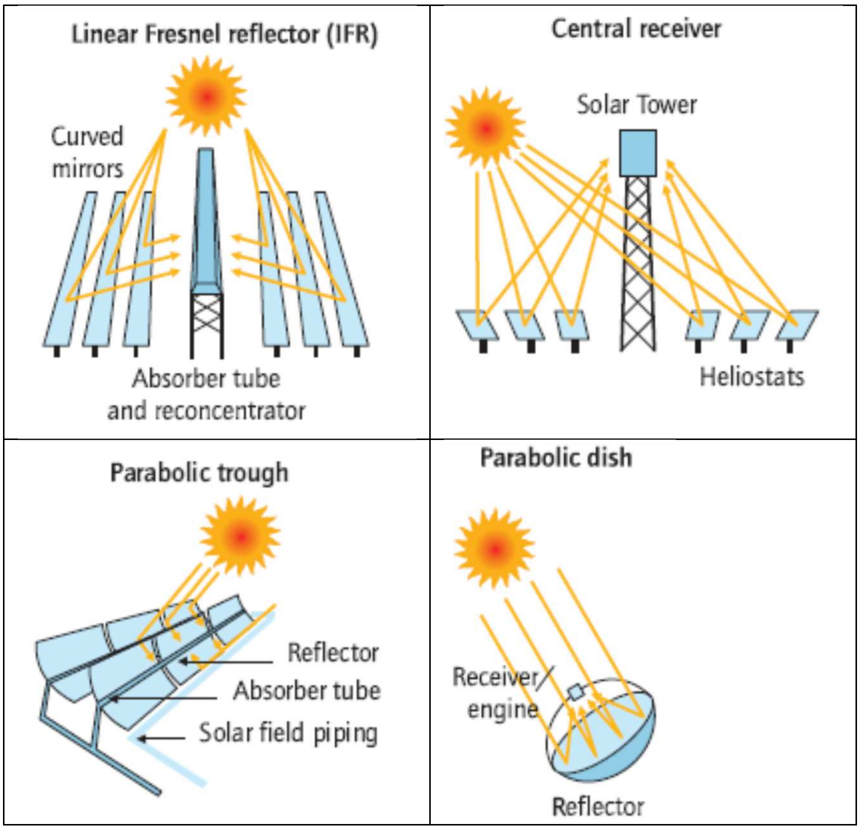
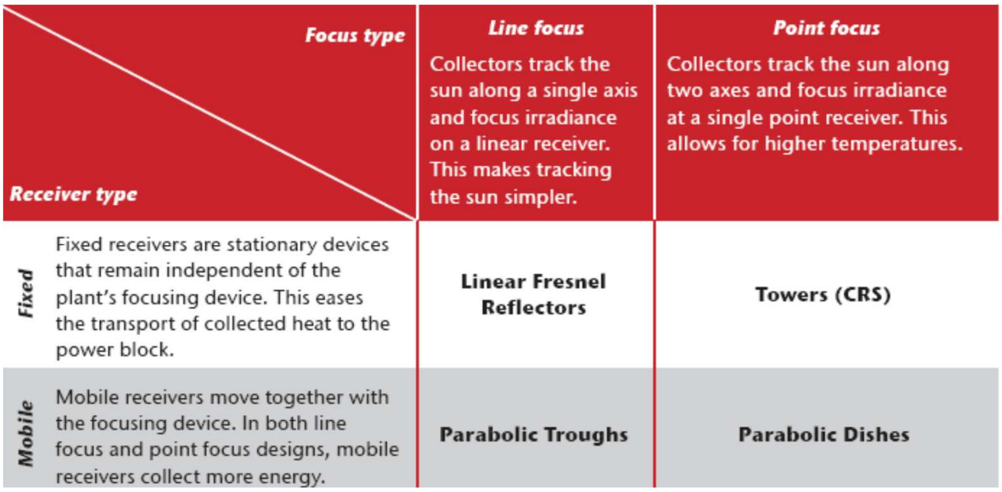


Figure 5-18 CSP technologies

Source: IEA 2010, p.11-12.

Table 5-6 CSP receiver and focus types



Focus type ***Receiver type***		***Line focus*** Collectors track the sun along a single axis and focus irradiance on a linear receiver. This makes tracking the sun simpler.	***Point focus*** Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows for higher temperatures.
Fixed	Fixed receivers are stationary devices that remain independent of the plant's focusing device. This eases the transport of collected heat to the power block.	**Linear Fresnel Reflectors**	**Towers (CRS)**
Mobile	Mobile receivers move together with the focusing device. In both line focus and point focus designs, mobile receivers collect more energy.	**Parabolic Troughs**	**Parabolic Dishes**

Source: IEA 2010, p. 11.

5.4.2 Technical properties

Parabolic trough solar collectors consist of linear parabolic shape collectors directing the sun’s direct beam radiation on a linear receiver (absorber tube) placed at the focus of the parabola (focal line). The mirrors are aligned in a north south horizontal axis and the tracking system follows the sun from east to west to keep the same focus during the day. The parabolic collector concentrates the radiation 80 times at the linear receiver. The solar field is a matrix of parallel aligned reflectors as shown in Figure 5-19.

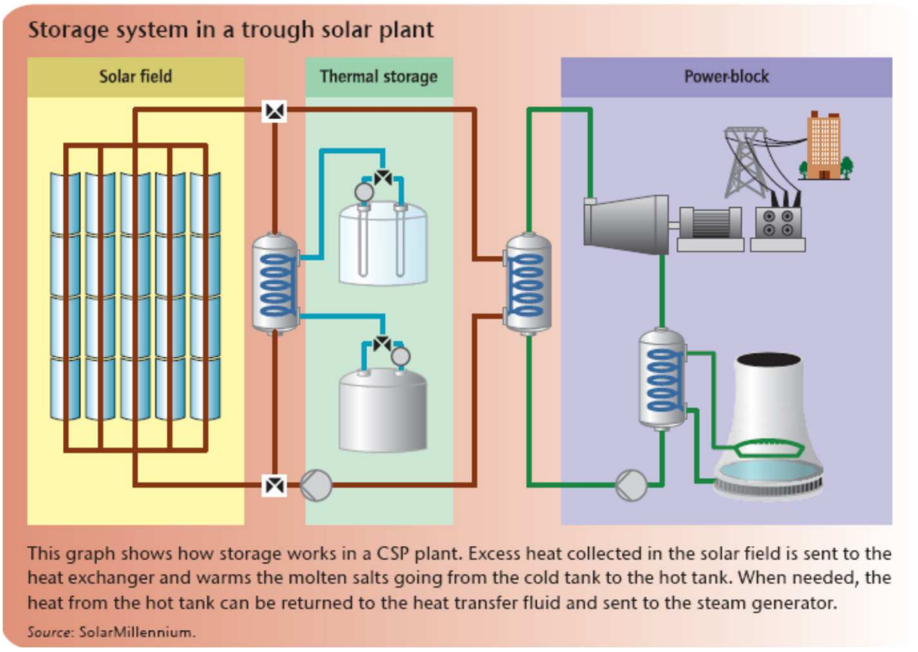
In the linear receiver circulates a heat transfer fluid in charge of delivering the heat gained (approximately 390°C) to the heat exchangers to generate high pressure steam (IPCC 2011a, p.355). The heat transfer fluid leaves the heat exchangers with a low temperature and returns again to the solar collectors. By means of a conventional steam cycle (Rankine – Cycle), the steam is directed through a steam turbine coupled to a generator to generate electricity. The steam travels through the condenser, which is re-circulated again to the heat exchanger as water with the feed water pumps.

Figure 5-19 Parabolic trough solar

Source: Solar Millennium 2010

A further improvement in the operation of the plant can be achieved by a parallel burner to produce additional steam allowing a controllable dispatch independent of the solar resource. It is possible to integrate a thermal storage in the system to avoid the use of burners. In this case the solar collectors transfer the extra heat to a storage system during the day. At night the storage delivers the heat to the exchangers to produce steam. The storage should be able to deliver temperatures over 400°C which is possible with a salt emulsion as storage media (IPCC 2011a, p.357).

The advantages of including thermal storage in the system are higher capacity factors, a reduction of part load operation of the turbine, reduction of the energy used for start-ups and the avoidance of losses due to minimum turbine load. Figure 5-20 exhibits the functioning of a storage system with two tanks:



Storage system in a trough solar plant

This graph shows how storage works in a CSP plant. Excess heat collected in the solar field is sent to the heat exchanger and warms the molten salts going from the cold tank to the hot tank. When needed, the heat from the hot tank can be returned to the heat transfer fluid and sent to the steam generator.

Source: SolarMillennium.

Figure 5-20 Storage system in a trough solar plant

Source: IEA 2010, p.13.

As shown in Table 5-7 below, most of the system losses take place in the power cycle. Improvements are expected in the optical and thermal properties of the receiver, higher temperature heat transfer fluids, direct storage system and balance of plant (BOP) equipment. According to an assessment from NREL a modern plant today should have efficiencies between 15 % and 17 % of the incoming energy from the sun until its transformation into electricity (NREL 2003, p 4-5). The technical features of a power plant are shown in Table 5-8.

Table 5-7 Projected efficiency of a trough CSP plant

Solar field optical efficiency	0.598
Receiver thermal losses	0.852
Piping thermal losses	0.967
Storage thermal losses	0.996
Power cycle efficiency	0.4
Electric parasitic load	0.922
Power plant availability	0.94
Annual solar-to-electric efficiency	**0.17**

Source: NREL 2003, p.4-6.

Table 5-8 Technical features of a trough CSP plant

Net power (MWe)	150
Capacity factor (%)	56%
Solar field (km^2)	1.47
Solar field operating temperature (°C)	500
Thermal storage (hrs)	12
Land area (km^2)	4.98

Source: NREL 2003, p.4-3.

Solar power tower technologies use hundreds to thousands of mirrors, which lead the solar radiation to a fixed point, a receiver located at the top of the tower. The receiver absorbs the energy and a heat exchanger located at the tower transforms the heat energy into power. The mirrors and their sun tracking system ensure that the concentrated solar radiation is directed to the tower tip. In the tower the receiver absorbs and transfers high temperatures over 1,000 °C. (IPCC 2011a, p. 356). This heat energy is then transferred to the medium, air or salt. The heat energy is transformed into electricity through a gas turbine or a Rankine steam cycle.

In a system with salt as a medium, cold salt from a storage tank is pumped to the receiver to be heated at a temperature around 600 °C (IPCC 2011a, p. 356). The salt is pumped to the hot storage tank and the heat exchanger coupled to the power block with a steam turbine to finally obtain electricity. The salt leaves the exchanger at a lower temperature and it is pumped to the cold salt storage tank. Figure 5-21 shows a solar power tower plant.

Figure 5-21 Solar power tower plant

Source: Scientific American 2008.

In the system with air as a medium in an open volumetric receiver, a compressor directs air through the receiver which is heated through the directed and concentrated solar radiation from the mirrors. The heated air circulating through the receiver reaches temperatures from 650 to 850 °C. In a heat exchanger the air transfers the heat to water to produce steam in conventional Rankine steam turbine/generator cycle with an efficiency of 35 %.

The use of a gas turbine in a combined cycle is another alternative. For that a tower system with a pressurized volumetric receiver is required. In a volumetric pressurised air receiver, the air is heated to 1,100 °C at a pressure of 15 bar which is redirected to the gas turbine. The remaining heat of the air at the exhaust of the turbine is recovered through the heat recovery steam generator (HRSG) coupled to a Rankine steam cycle. The higher efficiency of the combined cycle over 50 % increases the efficiency of the whole system. Thus an overall efficiency of the system from the energy contained in the solar radiation to electricity can be over 20 %. As with trough CSP plants, the major losses are due to the power cycle. Table 5-9 and Table 5-10 summarize the efficiencies and technical features.

Table 5-9 Projected efficiency tower CSP plant

Collector efficiency	0.563
Receiver efficiency	0.831
Power cycle efficiency	0.42
Electric parasitic load	0.9
Thermal storage	0.995
Piping	0.999
Power plant availability	0.94
Annual solar-to-electric efficiency	0.165

Source: NREL 2003, p. 5-4, 5-5.

Table 5-10 Technical features of a tower CSP plant

Net power (MWe)	100
Capacity factor (%)	73%
Solar field (km^2)	1.32
Receiver area (m^2)	1,110
Solar field operating temperature (°C)	565
Thermal storage (hrs)	13
Land area (km^2)	6.6

Source: NREL 2003, p. 5-1, 5-2.

5.4.3 Market development

The installed capacity of CSP power plants worldwide as of January 2010 was around 1,000 MW, where parabolic troughs have the largest share of the current CSP market. Projects under development and under construction are expected to reach a capacity of 15 GW (IEA 2010, p.9).

5.4.4 Road map

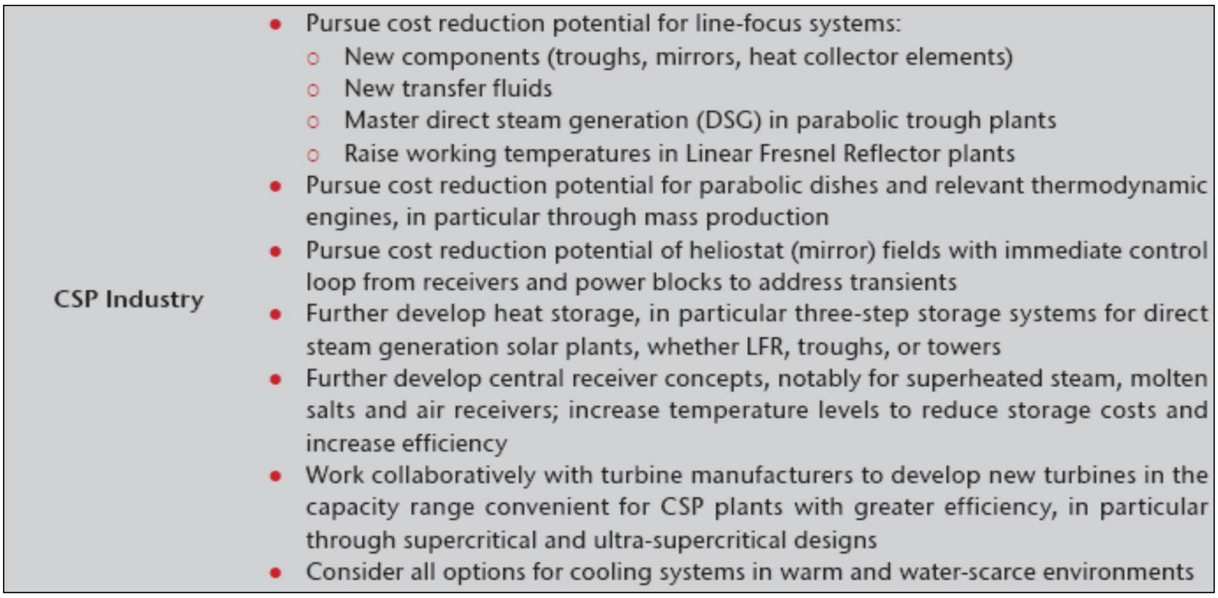
The aim is logically to improve the performance and reduce costs. Cost reductions should be achieved for the CSP by new solar components such as mirrors, heat fluids and collectors.

The mirror technology can be further improved by new techniques and materials for trough and fresnel technologies. The heat transfer fluids employed today can also be replaced by fluids able to reach higher temperatures. Advanced heat transfer fluids including pressurised gas, molten salts and nanofluids are a promising option. The possibility of improving the efficiency by direct steam generation (DSG) avoiding the use heat transfer fluids and heat exchangers offers a potential for reducing costs. Regarding the storage technologies, several options are promising by using inexpensive materials, such as increasing the heat capacity of molten salts with nanoparticles or the use of single tanks for cold and hot molten salts. The challenge of storage is by the direct steam generation which still has to be developed.

For the tower and dish technologies, higher temperatures can still be reached thereby improving overall efficiency. New receiver technologies could reach supercritical and ultra-critical temperatures and pressures as seen with modern coal fired power plants that reach efficiencies over 40 %. The use of pressured air as a fluid and its use in gas turbines can reach higher efficiencies, as high as 35 %.

Table 5-11 summarizes the main findings of the IEA road map in which this subchapter was based on:

Table 5-11 CSP Technology road map



CSP Industry	• Pursue cost reduction potential for line-focus systems: ○ New components (troughs, mirrors, heat collector elements) ○ New transfer fluids ○ Master direct steam generation (DSG) in parabolic trough plants ○ Raise working temperatures in Linear Fresnel Reflector plants • Pursue cost reduction potential for parabolic dishes and relevant thermodynamic engines, in particular through mass production • Pursue cost reduction potential of heliostat (mirror) fields with immediate control loop from receivers and power blocks to address transients • Further develop heat storage, in particular three-step storage systems for direct steam generation solar plants, whether LFR, troughs, or towers • Further develop central receiver concepts, notably for superheated steam, molten salts and air receivers; increase temperature levels to reduce storage costs and increase efficiency • Work collaboratively with turbine manufacturers to develop new turbines in the capacity range convenient for CSP plants with greater efficiency, in particular through supercritical and ultra-supercritical designs • Consider all options for cooling systems in warm and water-scarce environments

Source: IEA 2010, p. 41.

5.4.5 Current cost

The investment costs for CSP trough technologies in 2010 ranged from 4,200 USD/kW to 8,400 USD/kW depending on the technology, size, solar resource, labour and local costs and storage use (IEA 2010, p.27). The investment cost at the lower limit corresponds to trough technologies in excellent DNI locations without storage. The investment costs of tower technologies are higher than for trough plants. Experts expect strong reductions between 40% and 75% through improvements in the overall efficiency and mirrors fabrication (IEA 2010, p.27)

Regarding the generation costs and assuming a 10 % learning ratio, CSP cost are expected to fall 50 % in 10 years by the year 2020, in the case that capacities would double seven times. Accordingly, the electricity costs are expected to decrease faster through technological innovation, reaching competitiveness for peak and intermediate loads in those countries with highest sun exposure in that year. Figure 5-22 shows the levelized electricity cost under these assumptions.

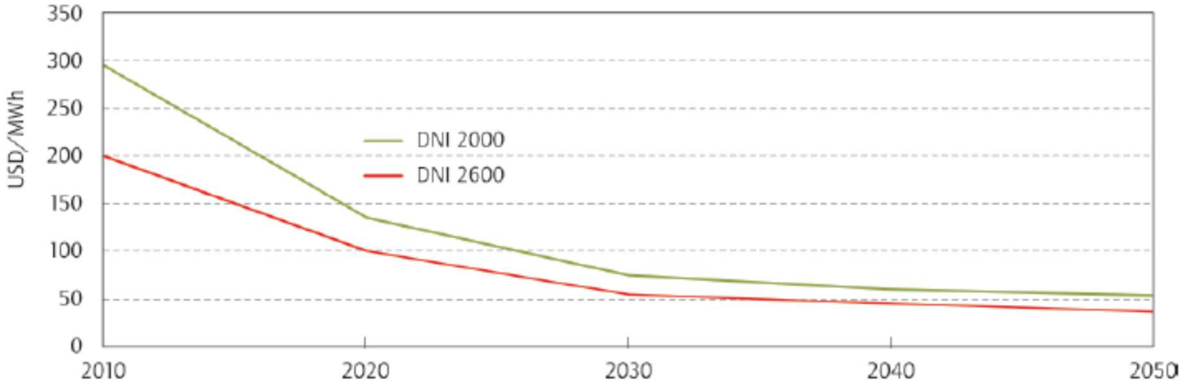


Figure 5-22 Projected evolution of the levelized electricity cost from CSP plants

Source: IEA 2010, p. 29.

5.5 BIOMASS

Biomass as a source of energy is an extensive research area due to the multiple choices available concerning the resources spectrum, the energy transformation and technologies and end use.

From the resource side, a vast variety of biomass sources are available suitable for energy purposes; both as a primary source to be used directly or as a sub-product from agro and forestry industries. In that context three main biomass source categories can be named: Forestry, Agriculture and Residues.

In the wood-based industries a variety of products are available such as wood logs, bark, wood chips, sawdust and pellets (European Biomass Association, 2008). Forest biomass is currently used mainly to produce heat and power (Smeets 2008, p. 13).

Dedicated energy crops are considered as an agricultural biomass resource. There are two types of energy crops that can be distinguished: conventional and lignocellulose. The conventional crops are used mainly to produce food such as maize, wheat, barley, sugar beet, sugarcane, rapeseed and soybeans. These types of crops are the most common biomass that is currently used to produce liquid biofuels for transportation (Smeets 2008, p. 12). On the other hand the lignocellulose is the type of biomass that is composed of cellulose, hemicelluloses and lignin such as eucalyptus and miscanthus. The main advantage of these sources is the less intensive management needed, the resulted higher yields of biomass per hectar, and great tolerance of relatively extreme soil and climate conditions. They are used for power and heat generation via combustion, though advanced conversion technologies such as gasification and fermentation are being developed (Smeets 2008, p. 12).

The residues can be classified by their origin in three main categories: Crop residues, agro-industrial residues and livestock residues. Crop residues are residues that are produced in agricultural fields such as straw and green agricultural waste. Agro-industrial residues include the residues from agro-industrial conversion of processing crops such as bagasse and oil palm pulp (Rosillo-Calle 2008, p. 44). Livestock residues are currently used to produce biogas, though manure has also a great potential value for non-energy purposes (fertilizers).

The key biomass resource for the Colombian case is the use of residues as a source of energy as discussed in detail in the renewable energy sources potential in Colombia (*see* Section 4.5), which shows that the residues, in particular those from the sugar industry, are an unexploited resource with the potential to contribute significantly to power generation.

Sugarcane residues are the solid waste of the sugar harvest, comprised mainly of tops and leaves of the sugarcane plant which may be gathered from a sugar cane field which is no longer in use (after harvest). Worldwide these sugarcane residues are largely wasted and in most cases, burned (Rosillo-Calle 2006, p.347). In contrast bagasse, which is the residue left at the mill after extracting the sugar juice from the cane stalk, is already used as fuel for the mill’s own thermal and electricity demand. In summary the use of the residues as a fuel source alone or in combination with bagasse might be an attractive option for the Colombian electricity power system.

The focus of this sub-chapter will be on the technologies for the use of solid biomass as residues. Suitable biomass conversion technologies are available for the different types of the resource as previously mentioned. Two conversion categories are in use for the conversion namely the thermochemical and biochemical processes (Faaij 2006, p. 345) and the technologies are classified within these categories such as combustion, gasification, pyrolisis, digestion and fermentation as shown in Figure 5-23.

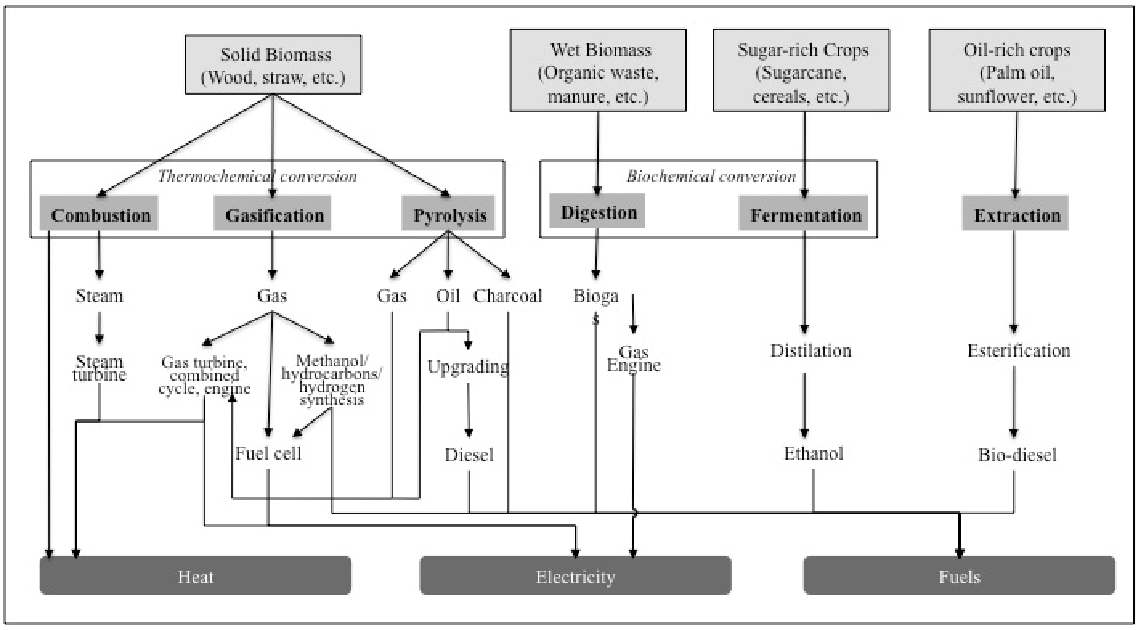


Figure 5-23 Biomass conversion routes

Source: Modified from Faaij 2006, p. 345.

The technologies for power generation using solid biomass, especially for sugar residues, which were selected for the modelling of the Colombian power system are direct combustion and gasification (IGCC), since these technologies have the potential to combine already well known and proved conventional technologies such as steam turbines and gas turbines. Solid biomass has the potential to be a substitute of conventional fossil sources to contribute to the energy sector (Briceño et al 2001, p.107).

5.5.1 Physics

Similar to conventional technologies making use of fossil sources such as coal, a combustion power plant using solid biomass uses a conventional Rankine steam turbine/generator cycle for the production of electricity and thermal energy (in a cogeneration configuration). The cycle consists basically of a boiler, steam turbine coupled to a generator, a condenser and water feeding pumps.

The boiler transfers the heat energy delivered by the combustion of the fuel into circulating water to produce steam at higher pressure and temperature with boiler efficiency normally over 90%. The boiler then directs the steam through a steam turbine coupled to a generator to generate electricity. The high pressure is then released and reduced as the steam travels through the turbine, which transforms the heat energy contained in the steam into mechanical energy by the rotation of the turbine. The generator coupled to the turbine transforms the mechanical energy into electricity. The overall efficiency of the system is normally over 30 %, if only electricity is produced. The low pressure steam leaving the turbine has to be cooled by means of a condenser to turn the steam into a fluid again. Thus it can be re-circulated to the boiler by feed water pumps and begin the cycle again to produce steam.

In a cogeneration configuration (combined heat and power -CHP-) the steam is extracted from a given section of the turbine to the required pressure or temperature depending on the process to be attended, which means that the demand for heat can be taken from any point of the cycle such as steam or hot water at the conditions desired. In addition, the overall efficiency is greatly enhanced, since the same fuel is used to produce electricity and heat energy at the same time, therefore operating economically more efficient instead of having two separate processes to produce electricity and heat.

The gasification of biomass to be used in conventional combined cycles (gas turbines and heat recovery steam generators), otherwise termed the biomass integrated-gasification combined cycle (BIGCC), is a promising option. Here the biomass is partially oxidized to form a gas mixture that can be burned out in conventional technologies such as gas turbines, engines and boilers. Gasifiers are a less developed technology in comparison to direct combustion technologies (IEA 2008, p 327), which is however considered as an option in the future especially as a BIGCC, since higher efficiencies can be reached in comparison to steam rankine cycles with this method.

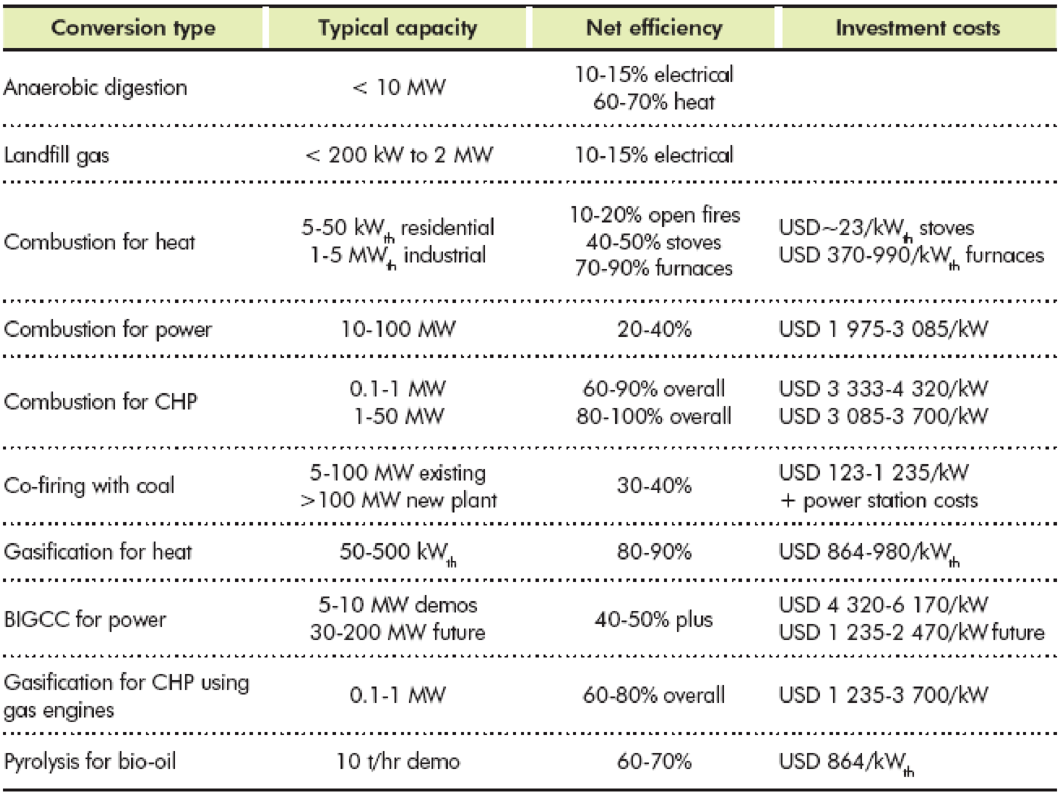
5.5.2 Technical properties

Table 5-12 shows an overview of the conversion technologies, their efficiencies and investment costs, which can be applied for the conversion of biomass.

Unlike a conventional power plant with sizes over 100 MW, a biomass power plant is normally between 10 and 20 MW due to the availability of the resource normally from surrounding areas and the area required for its storage due the lower calorific value per volume, which also limits the amounts to be transported.

For combustion technologies the biomass to be used defines the type of boiler between grate and fluidized bed firing. Grate boilers are suitable for capacities under 5 MW, whereas fluidized bed combustion have higher sizes up to 100 MW. Fluidized bed boilers allows for a more efficient production of electricity and are more suitable for agricultural residues, although they required specialized manufacturing materials and construction (Faaij 2006, p.350; IEA 2008, p.330).

Table 5-12 Biomass conversion technologies



Conversion type	Typical capacity	Net efficiency	Investment costs
Anaerobic digestion	< 10 MW	10-15% electrical 60-70% heat	
Landfill gas	< 200 kW to 2 MW	10-15% electrical	
Combustion for heat	5-50 kW$_{th}$ residential 1-5 MW$_{th}$ industrial	10-20% open fires 40-50% stoves 70-90% furnaces	USD~23/kW$_{th}$ stoves USD 370-990/kW$_{th}$ furnaces
Combustion for power	10-100 MW	20-40%	USD 1 975-3 085/kW
Combustion for CHP	0.1-1 MW 1-50 MW	60-90% overall 80-100% overall	USD 3 333-4 320/kW USD 3 085-3 700/kW
Co-firing with coal	5-100 MW existing >100 MW new plant	30-40%	USD 123-1 235/kW + power station costs
Gasification for heat	50-500 kW$_{th}$	80-90%	USD 864-980/kW$_{th}$
BIGCC for power	5-10 MW demos 30-200 MW future	40-50% plus	USD 4 320-6 170/kW USD 1 235-2 470/kW future
Gasification for CHP using gas engines	0.1-1 MW	60-80% overall	USD 1 235-3 700/kW
Pyrolysis for bio-oil	10 t/hr demo	60-70%	USD 864/kW$_{th}$

Source: IEA 2008, p.312.

Co-firing with conventional coal technologies is an option worth mentioning. Co-firing with biomass reduces CO_2 emissions. Agricultural and forest industries could be benefited, if their residues could be turned in to a market option and might provide a solution for not used or desired residues in the fields.

5.5.3 Market development

Global electricity generation and capacities for biomass and waste as of 2008 are reported by the International Energy Agency. The global capacity amounted to 52 GW with a total share of only 1 % by 2008, which delivered 267 TWh (IEA 2010a, p. 620). Figures for solid biomass are available for OECD countries. As of 2006 the power capacities amounted to 22.5 GW producing 160 TWh, where 59 % came from CHP plants. (IEA 2008, IEA 2008a, p. 35-36).

5.5.4 Road map

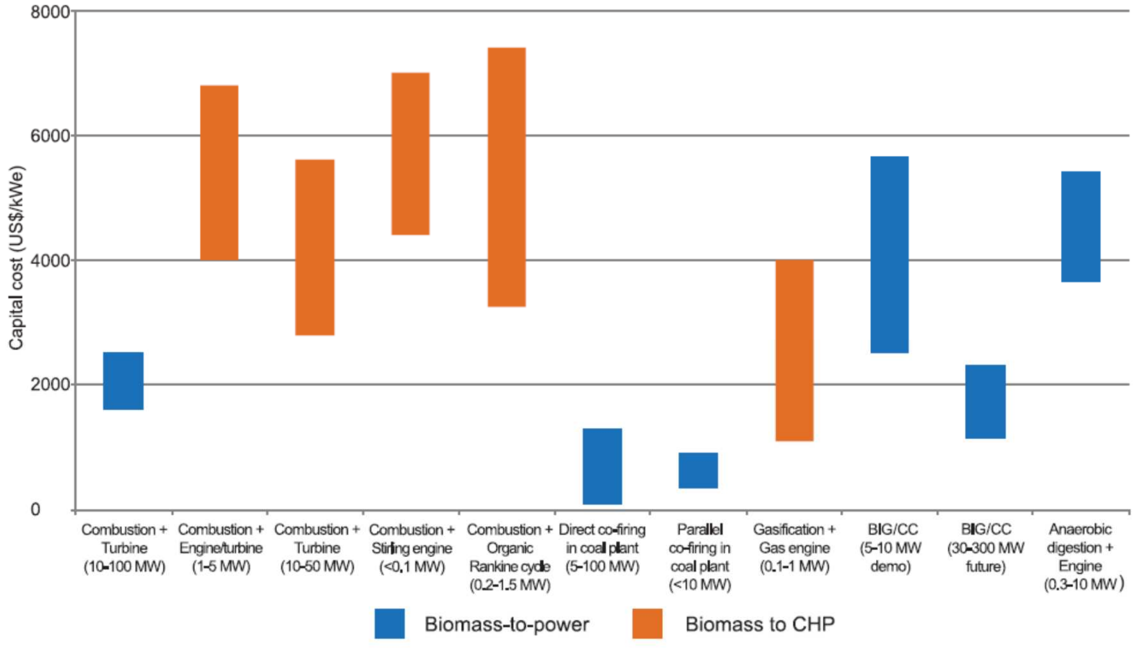
For direct combustion and gasification (IGCC) technologies, improvements are expected in the following areas (Rosillo-Calle 2006, p. 370; IEA 2008, Annex C):

- Improvement of integrated biomass gasifier/gas turbine (IBGT)
- Improved techniques for biomass harvesting, transportation and storage;
- Gasification of crop residues
- Increase use of forest and agricultural residue usage

The challenge is to make use of low cost waste and residues and reduce the high cost of conversion technologies. Improvements are also expected for conventional technologies for the conversion of biomass, namely gas turbine/steam turbine combined cycle (GTCC), circulating fluidized bed boilers (CFB), integrated gasification combine cycles (IGCC), cogeneration and co-firing.

5.5.5 Current cost

An overview of the investment costs and generation cost are shown in Figure 5-24 and Figure 5-25.

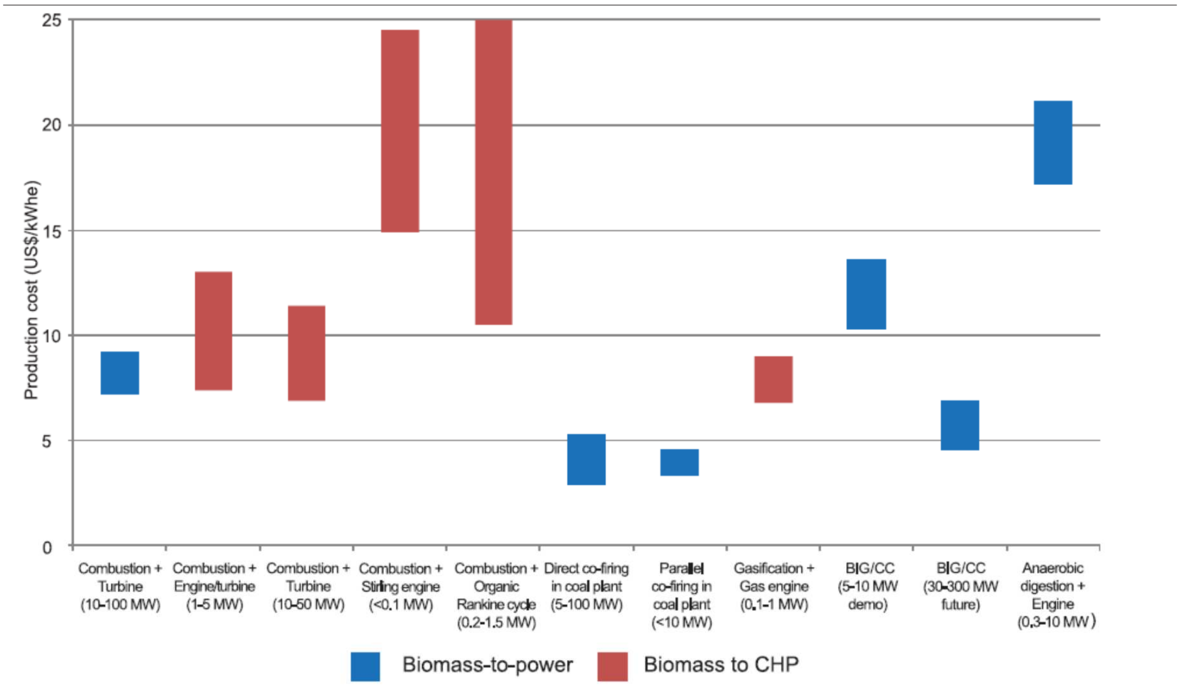


Note: Anaerobic digestion can also be run in CHP mode.

Figure 5-24 Investment costs biomass technologies

Source: IEA 2009, p.30.

Direct combustion technologies only for power offers the lowest costs, around 2,000 USD/kW in comparison to BIGCC technologies, which are expected to reduce the cost (still in the demonstration stage) in the future. In contrast CHP power plants are more expensive. Regarding the generation costs as shown in Figure 5-25, an improvement of the investment costs for BIGCC together with the higher efficiencies of the combined cycle could reach a lower cost per kWh, as in the case of direct combustion. Although biomass for CHP power plants has a higher cost per kWh the overall economic feasibility of such projects are easier to reach by the additional revenues provided by the sale of heat.



Note 1: Anaerobic digestion can also be operated in CHP mode.
Note 2: Production cost can be reduced by 60-80% (depending on technology and plant size) if free biomass feedstock is used, such as MSW, manure, waste water etc.

Figure 5-25 Generation costs biomass technologies

Source: IEA 2009, p.31.

The power technologies introduced in this chapter are proven technologies and are commercially available. These technologies have the potential to continue reducing their investment cost and improving their technical performance. These issues are further analyzed to determine in particular the evolution of the cost over the years in the prognosis analysis of the next chapter. In that way, a portfolio of technologies for power generation with conventional energy sources and new renewable energy sources will be obtained for the simulation of the Colombian power sector with the energy models.

6. PROGNOSIS ANALYSIS

The objective of this chapter is to conduct a prognosis analysis of all data required by the energy models to simulate the supply of electricity in Colombia in the long term. These energy models use the engineering approach for the simulation. Therefore a detailed description of electricity supply and demand is required.

First, the portfolio of power technologies including economic and technical aspects for Colombia is defined. A literature review of investment and operation and maintenance costs of power technologies is presented. Subsequently an analysis to project these costs for a time horizon from 2005 to 2050 is conducted. Based on experience curves, the costs for power technologies using new renewable energy sources are projected. A summary of all technical parameters of power technologies apart from their cost and including CO_2 emission factors is completed to be used for the energy models.

For technologies powered by fossil fuels, a projection of the fuel costs is also included. In addition fossil fuel reserves in Colombia and their demand is presented, which indicates the availability of these resources in coming decades. The models also require this information. As this is required for the supply side, the electricity demand of Colombia is also assessed for the time horizon of the analysis from 2005 to 2050. Thus, the supply and demand side of the energy models are covered.

The results of this prognosis analysis constitute the information basis required by the energy models to simulate the Colombian power sector.

6.1 PORTFOLIO OF TECHNOLOGIES

The Colombian power sector relies currently almost exclusively on conventional power generation technologies: large hydropower stations, coal power plants and gas turbine technologies. This reflects an energy policy tailored to energy resources that, at the moment of their implementation, were in abundance. Although Colombia is blessed with still plenty of hydropower and coal energy sources, Colombia’s high dependence on hydropower and natural gas has made the power generation expansion consider a broad spectrum of other alternatives.

As Chapter 4 and 5 show, Colombia has renewable energy sources that can be exploited to generate electricity with proven technologies. For that reason a portfolio of power generation technologies, conventional and non-conventional, for the Colombian case are defined here. To accomplish that task, two criteria to select technologies were defined as follows:

- Indigenous energy sources, conventional and non-conventional, are to be exploited.
- Proven technologies which are either competitive or close to being competitive.

A literature review was conducted with global technology and energy scenario studies to compile a set of technologies. First, current investment and operation and maintenance (O&M) were assessed in order to have a base to determine the cost development of technologies in the long run. The results for current renewable and conventional technology costs in 2005 US dollars are shown in Table 6-1 and Table 6-2.

Table 6-1 Investment costs of renewable energy technologies

Sources: Data from Greenpeace 2008, IEA (ETP) 2008, IEA 2009, ECN 2004, Blok 2007.

Technology		*Units*	**Greenpeace** (2005 USD)	**ETP** (2005 USD)	**IEA** (2005 USD)	**ECN** (2001 USD)	**Blok** (2001 USD)
Wind Onshore	Investment costs	$/kW	1,510	1,200	1,322	960 – 1,384	850 – 1,700
	O&M	$/kW/year	58		19.83	19,2 - 55,2	
		%	3.8		1.5	2 - 4	
Wind Offshore	Investment costs	$/kW	3,760	2,600	2,814	1,887 – 2,322	850 – 1,700
	O&M	$/kW/year	166		42.21	56.4 – 92.8	
		%	4.4		1.5	3 – 4	
PV	Investment costs	$/kW	6,600	5,500	4,245	6,029	5,000 – 18,000
	O&M	$/kW/year	66		14	60.2	
		%	1		0.3	1	
Concentrating Solar Power	Investment costs	$/kW	7,530	4,500	2,315		2,500 – 6,000
	O&M	$/kW/year	300		30		
		%	4		1.3		
Biomass combustion	Investment costs	$/kW	3,040	1,975 – 3,085		1,775 – 6,699	500 – 6,000
	O&M	$/kW/year	183			71 – 334.5	
		%	6			4 - 5	
Biomass IGCC	Investment costs	$/kW		4,320 - 6170	2,500	3,796	
	O&M	$/kW/year			50	189.8 – 246.7	
		%			2	5 – 6.5	
Co-firing with Coal	Investment costs	$/kW		123		212 - 245	
	O&M	$/kW/year					
		%					
Geothermal Hydrothermal	Investment costs	$/kW		1,700 – 5,700	946 – 2,838	1,898 – 2,791	800 – 3,000
	O&M	$/kW/year		33 - 97	18.92 – 56.76	37.8 – 55.8	
		%		1.9 – 5.7	2	2	
Geothermal Hot Dry Rock	Investment costs	$/kW	17,440	5,000 – 15,000	2,365 – 7,094		
	O&M	$/kW/year	404	150 – 300	47.3 – 141.8		
		%	2.3	3 – 2	2		

Wind and photovoltaic technologies are commercially available. Geothermal, hydrothermal and hydropower are mature technologies that are already in use. Concentrated solar power and biomass combustion and gasification are based on well known technologies with steam turbines and gas turbines with heat recovery steam generators respectively, where the innovation is the energy source and its transformation into heat energy. With these technologies the Colombian renewable energy sources can be exploited. Geothermal hard rock is still in its early stages of development. A description of the technical and market characteristics of these technologies are presented in Chapter 5.

Notably, differences are seen between technologies regarding their investment costs with wind technologies being, so far, the less expensive option. However a comparison based on the cost per kW does not reflect the cost of a kWh, which is ultimately the key decision factor. This issue will be addressed in the simulation with the energy models.

Investment and O&M cost estimations differ from the sources for the same technology. For instance Greenpeace costs are higher than cost estimates from the International Energy Agency. For concentrating solar power the costs between the sources do not show any similarity, this is explained by a selection of a given solar technology (e.g. parabolic trough, solar tower or dish system) in which the parabolic trough is the cheapest of its kind. Regarding conventional technologies, the literature review yielded the following results:

Table 6-2 Investment costs of conventional technologies

Sources: Data from Greenpeace 2008, IEA (ETP) 2008, UPME 2005, IER 2006, IEA 2008a.

Technology		***Units***	**Greenpeace** (2005 USD)	**ETP** (2005 USD)	**UPME** (2005 USD)	**IER** (2005 USD)	**IEA** (2005 USD)
Coal Power Plant	Investment costs	$/kW	1,320	1,400 – 2,000[1]	1,322	1,145	1,500 – 2,200
	O&M	$/kW/year			73	51	60 – 88
		%			5.5	4.4	4
Natural Gas Combined Cycle Power Plant	Investment costs	$/kW	690	600 - 750	683	548	660 – 750
	O&M	$/kW/year			36	28.6	26.4 – 30
		%			5.2	5.2	4
IGCC Power Plant	Investment costs	$/kW		1,800		1494 [2]	1,600 – 2,300[3]
	O&M	$/kW/year				66	64 – 92
		%				4.4	4
Hydropower	Investment costs	$/kW		2,500	1,055		
	O&M	$/kW/year			18.7		
		%			1.7		

[1] Cost range of a typical coal fired plant. The cost of ultra-supercritical is from 12% to 15% higher than the cost of a sub-critical

[2] Cost estimation by 2015

[3] Cost estimation by 2010.

Unlike the renewable sources, the sources for conventional technologies show similar costs. An exception is hydropower, where the Colombian source (UPME 2005) has a much lower cost, suggesting that the local component in the cost for hydropower plays a major role.

These are the portfolios of technologies to be considered in the simulation analysis for the Colombian power sector.

6.2 PROJECTION TECHNOLOGY COST – EXPERIENCE CURVES.

A key question of a simulation which simulates into the future is how cost and price will develop over time. In that sense, investment and operation and maintenance cost development are a central input into the energy models. These costs together with fuel prices are an essential component of the economic analysis. A suitable methodology therefore needs to be selected for the projection of these costs in the future to have a robust and credible analysis. Experience curves are a well known and applied methodology in energy scenario analysis to tackle the cost issue of power technologies. The reason why experience curves are employed and their pros and cons will be shortly discussed here in order to provide a sound argumentation for this selected approach.

Three methodologies can be named that address the assessment of future costs of technologies: experience curves, bottom up assessment and experts' opinion. (European Commission 2006, p.6). The first methodology is the observation of historical trends in cost reduction to derive a tendency in how costs may develop, which is the foundation of experience curves. The lower production costs are the result of the diffusion of the technology, gains by learning by doing and learning by using, up-scaling and mass production (Uyterlinde 2007, p. 4076).

An experience curve translates the experience observed into a rate of change in production costs as a fixed percentage with every cumulative doubling of production. It provides a trend or indication on how prices may develop. This approach differs from forecasting exercises, and thereby matches the concept of scenario analysis, in which case the goal is to measure the effect of lower prices by the diffusion of technologies. Thus, the integration of experience curves into energy models has made it easier to integrate technological change into energy system analysis and scenario planning (Neij 2008, p.2200). Experience curves are therefore an endogenous approach based on the amount of installed technology and they are time independent (Fischedick et al 2008, p.138).

It is argued that experience curves are loaded with uncertainties in cost development due to the aggregated approach. It is further argued that their use as a forecast tool in the long term is not appropriate because they are a “trend tool” and only suitable for short term analysis (Neij 2008, p. 2201).

A second methodology is then based on identifying the sources for cost reductions, expected development and innovations to come, main drivers of cost and development (bottom up assessment), which are the result of reports from industry, research groups and individuals giving an idea of the potential for cost reductions. Each source of cost reduction must be identified and analyzed separately (European Commission 2006, p.6 and Neij 2008, p.2201).
A third approach is based on experts’ opinions and judgments of experts, which use the experts’ deep understanding of the development dynamics of the technology. These approaches are exogenous, they are determined in advance and are independent of the actual diffusion rate of the technology (Uyterlinde 2007, p.4076).

In a study co-funded by the European Commission (cost development, an analysis based on experience curves), different technologies to generate electricity were analyzed within the NEEDS project (European Commission 2006). This study integrated the exogenous approach into the experience curve analysis in order to evaluate the cost reduction described by the experience curves. The study found that bottom up analysis together with judgmental expert assessments arrived at similar cost reductions as with the experience curve. Learning rates are subsequently suggested to be applied for the analysis of future cost development of new energy technologies

The experience curves describe how a unit cost declines with cumulative production. This relationship was first estimated by the Boston Consulting Group (BGC) in 1968, where the curve is expressed as:

$$C_{Unit} = C_0 Cum^b$$

$$PR = 2^b$$

$$PR = 1 - LR$$

Where:

C_{Unit} = Cost per unit
C_0 = Cost of first unit

C_{cum} = Cumulative production
b = Experience index learning coefficient
PR = Progress Ratio
LR = Learning Rate

The experience curve concept translated to the cost reduction of energy technologies starts by defining the learning rate of technologies, which will define the progress ratio. Thus a Learning Rate (*LR)* of 8% for wind energy, which describes the cost reduction in comparison to its previous level that can be achieved by each doubling of the capacity will yield a progress ratio (*PR)* of 92%. The experience index *b* measures the responsiveness of total cost to cumulative production (C_{cum}) based on the progress ratio. The cumulative production (C_{cum}) is the ratio between the capacities to determine the increase. Thus a projected capacity of wind onshore in 2020 of 348 GW in comparison to a 91 GW capacity by 2010 yields an increase of 3.8 times. Assuming a cost (C_0) of 1,139 USD/kW in 2010, the cost of the first unit, the new cost by 2020 can be calculated with the first equation. With an experience index b of 0.1203 the result is 970 USD/kW.

The results of the study of the European commission NEEDS, which recommended experience curves and their learning rates for selected energy technologies along with other results from the International Energy Agency are shown in Table 6-3. The NEEDS study detected large uncertainties for PV and CSP technologies where learning rates may vary between 0 and 5% in contrast to other technologies in which a range of 0 - 2% is suggested. The percent variations are supposed to cover the uncertainties of the experience curve approach.

The future development of investment cost for the Colombian power sector will be determined with experience curves for renewable technologies. For them a learning rate was selected to be applied in the analysis. A conservative learning rate was selected for wind as suggested by looking at the sources. For PV technologies a conservative figure of 18% was selected. Solar has not reach the same degree of diffusion as wind and it is believed that solar has a great potential to reduce cost drastically as have recently been shown in market figures. For CSP, Geothermal and BIGCC the same learning rates suggested by the sources were selected.

Table 6-3 Learning rates

Source: Data from European Commission 2006; IEA 2008 and 2009.

Technology	NEEDS	ETP	EIA	Selected
Onshore	10% ± 2%	7%	7%	**8%**
Offshore	10% ± 2%	9%	7%	**8%**
PV	20% ± 5%	18%	18%	**18%**
CSP	8% ± 5%	10%	10%	**10%**
PC	5% ± 2%			
IGCC	5% ± 2%	3%		
FBC	5% ± 2%			
CC	10% ± 2%			
GT	10% ± 2%			
Biomass fuel, logistics	15%			
Biomass conversion	5%			
BIGCC		5%	5%	**5%**
Geothermal			8%	**8%**

The experience curve approach for conventional technologies was not selected, since their cost projections are based on bottom-up approaches rather than experience curves. This issue will be further analysed in Section 6.5.

The introduction of new technologies into the Colombian power market at a large scale will depend on how these technologies further develop in international markets until reaching competitive prices. The Colombian power sector does not have any effect on, for instance, driving the prices (price taker). For that reason international prices are the reference point for the analysis and expected cost reductions will be based on how far these technologies continue penetrating international power markets, which is the topic of the next subchapter.

6.3 RENEWABLE ENERGY IN GLOBAL SCENARIOS

To make a projection of the investment cost of renewable energy sources, an estimation of the participation of these technologies in the power systems of the future is required. The cost will be driven by global development of the technology. For that reason energy global scenarios are assessed to see how far renewable energy sources may be part of energy power systems.

Global scenarios differ in their results, their assumptions, storyline of the scenario (business as usual scenario (BAU) among others considered) the modeling techniques, investment costs and technical parameters, portfolio of technologies considered, energy policies and technical innovations, as noted by comparison of scenarios performed by the Center of Research Solutions (Hamrit et al, 2007) and as pointed out by an IPCC scooping meeting on renewable energy sources (IPCC 2008, p.137).

Significant differences are observed between the scenarios regarding the share of renewable energies in the primary energy supply as shown in Figure 6-1. The share ranges from 10% to 50% for the year 2050 being the Energy Revolution from Greenpeace e(R) and the climate protection strategies for the 21st century: Kyoto and Beyond from the German Advisory Council of Climate Change (WBGU) the most optimistic (between 30% and 50% share in 2050) whereas the International Energy Agency (IEA) scenarios along with the IPCC are the most conservative (between 12% and 25% share in 2050).

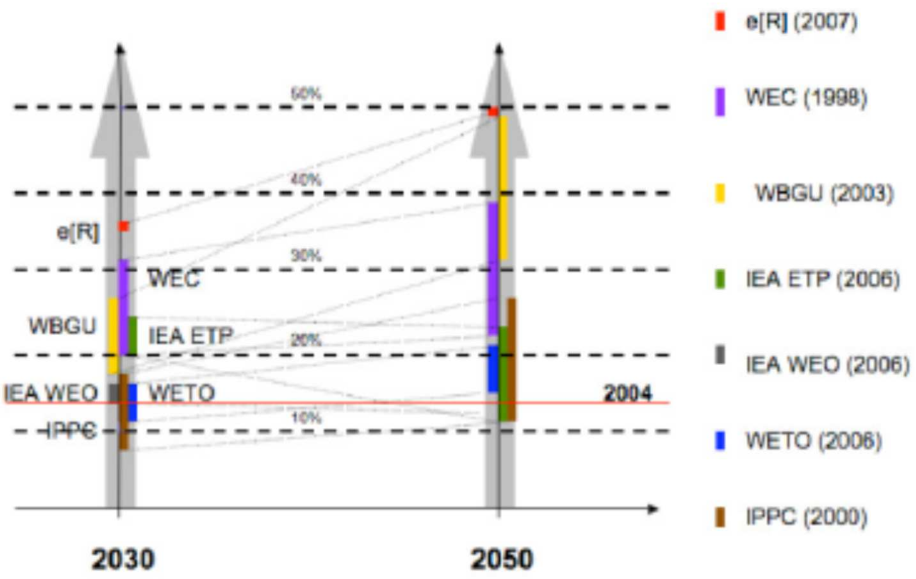


Figure 6-1 Share of renewable energies in the primary energy supply

Source IPCC 2008, p. 137.

In a recent analysis from the IPCC's authors in their Special Report on Renewable Energy Sources and Climate Change Mitigation, where 164 recent global energy scenarios were reviewed, the shares of renewable energy in primary energy supply reached 43% and 77% in 2030 and 2050 respectively for scenarios with the highest renewable energy shares (IPCC 2011a, p. 803).

The share of renewable energy sources in electricity generation follows the same trend as shown in Figure 6-2. The Greenpeace scenario reaches a 70% share whereas other scenarios range between 25% and 35%, the lowest being the IEA World Energy Outlook Baseline Scenarios.

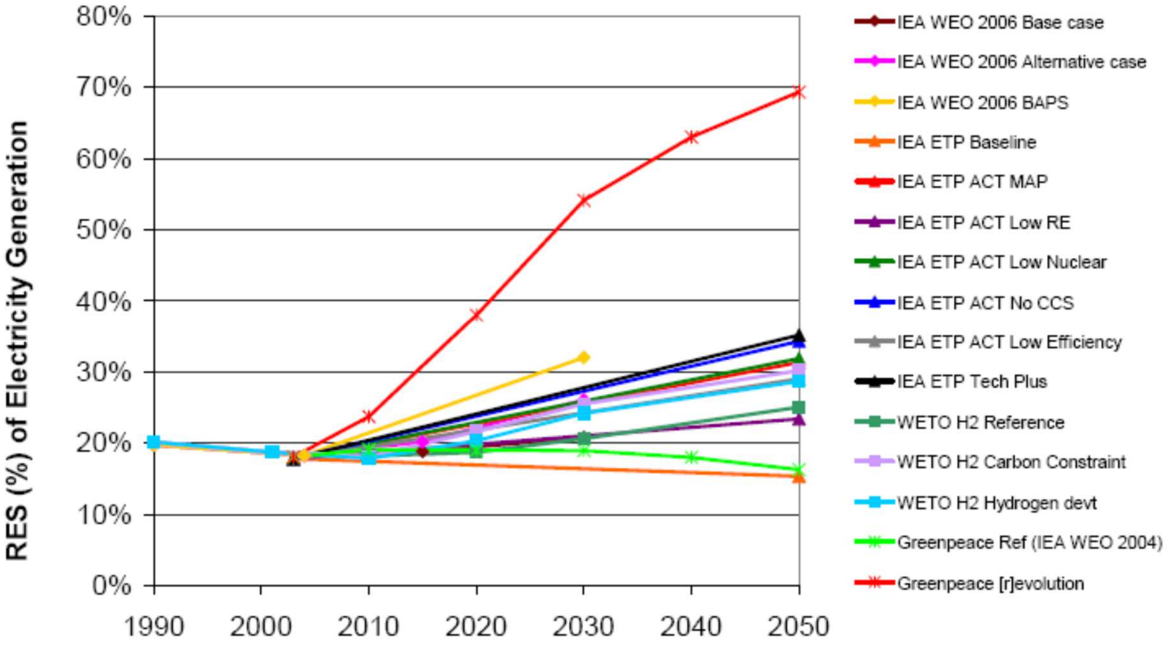


Figure 6-2 Share of renewables in electricity generation

Source: Hamrin et al 2007, p.7.

From four illustrative scenarios selected by the IPCC’s authors in their Special Report on Renewable Energy Sources and Climate Change Mitigation, it was found that shares of renewable energy sources range from 24% to 95% worldwide by 2050 (IPCC 2011, p. 818).

Since shares of renewable power of global scenarios differ substantially, the information required to estimate the capital cost of renewable energy sources in the future will be gathered from optimistic and conservative figures. Thus, the cost projection for the simulation of the Colombian power sector will consider both figures to make the analysis more robust. The Greenpeace and IEA scenarios (World Energy Outlook and Energy Technology Perspectives ETP) were selected.

These scenarios show not only the current cost of power technologies as already introduced in Section 6.1, but also the future capacity expected according to the scenarios’ storyline developed by the authors. In order to have more details about the costs estimation and the capacity in the long term obtained by their scenarios, the authors were contacted via e-mail and the objectives of this dissertation were explained. Only the IEA provided further information (IEA, 2009). The figures of the scenarios are presented in the next table:

Table 6-4 Global installed capacity of renewable technologies in GW

Source: Data from IEA 2007 and 2008, Greenpeace 2008.

Technology		2005	2010	2015	2020	2030	2040	2050
Wind onshore	Greenpeace	59	162		866	1,508	1,887	2,186
	ETP 2008				650	750		1,100 / 1,350
	EIA 2007[1]	33		140		708		1,299
Wind offshore	Greenpeace	0.3	1.6		27	114	333	547
	ETP 2008					150	250	350 /650
	EIA 2007	2		22		143		424
PV	Greenpeace	5.2	21		269	921	1,799	2,911
	ETP 2008	3				150 [2]		600 / 1,150 [2]
	EIA 2007	2		19		156		1,117
Concentrating Solar Power	Greenpeace	0.53	5		83	199	468	801
	ETP 2008					250		380 / 630 [3]
	EIA 2007	1		4		15		29
Biomass[5]	Greenpeace	21	35		56	65	81	99
	ETP 2008					0,5 [4](2025)		55 / 65 [4]
	EIA 2007			37		74		101
Geothermal[6]	Greenpeace	8,7	12		33	71	120	152
	ETP 2008							75
	EIA 2007	17		34	64			106

[1] ACT Map capacities IEA Scenarios

[2] 60 GW in the baseline scenario in 2030, 150 GW in 2035 and 600 GW by 2050 in ACT scenario. For BLUE scenario over 150 GW in 2030 and 1,150 GW by 2050

[3] World capacity below 10 GW in BASELINE Scenario, 250 GW in ACT and BLUE scenario. 380 GW and 630 GW for both scenarios by 2050

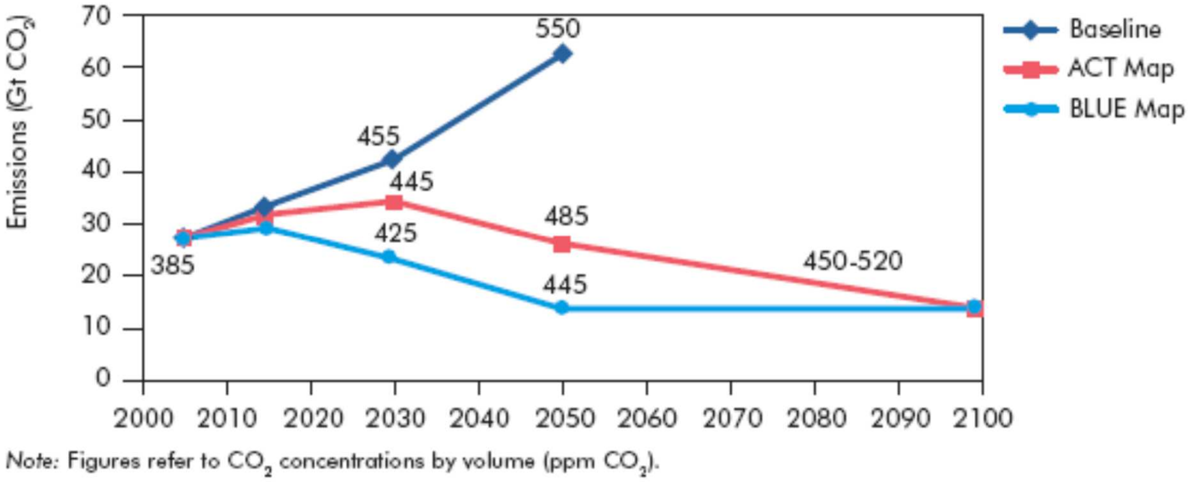
[4] The figures correspond mainly to BIGCC. 10 demoplants of 50 MW each between 2020 and 2050 for the baseline scenario, between 2015 and 2035 for ACT scenario and between 2010 and 2020 for BLUE scenario. Co-combustion technologies are also included, 5 GW for ACT scenario and 100 GW for BLUE scenario in 2040. 55 GW BIGCC between 2020-2050 for ACT and 65 GW in 2050 for BLUE.

[5] Biomass capacities include biogas, CHP and BIGCC in the Greenpeace scenario. The ETP and IEA figures correspond to BIGCC.

[6] The figures of ETP and IEA are for conventional geothermal capacities whereas the Greenpeace study probably refers to hard rock technologies

The scenario analysis of these studies differs in how the energy landscape should look like by the year 2050. For that reason their results are diverse.

The Energy Technology Perspectives (ETP) 2008 and the World Energy Outlook 2007 are the scenario studies of the International Energy Agency. The baseline scenario is found in the World Energy Outlook and serves as a reference point for the Act and Blue scenarios of the Energy Technology Perspectives. The Act scenarios reduce global CO_2 emissions to current levels (as of 2005) by 2050. In contrast the Blue scenarios target a 50% reduction by 2050 as shown in Figure 6-3 (approx. 14,000 Million tonnes). The combination of energy efficiency and the introduction of renewables (wind, PV, CSP, biomass), nuclear power and Carbon Capture Storage (CCS) shape the scenarios. By 2050, 35% of power generation comes from renewables in the Act map scenario and 46% in the Blue map scenario. The baseline scenario, by contrast, has only an 18% share (mostly Hydropower). CCS plays an important role to reduce CO_2 emissions, and from nuclear power, 32 GW per year until 2050 is required. Coal and natural gas will vary their share in the Act and Blue scenarios together with the amount of power units with CCS. Figure 6-3 and Figure 6-4 illustrate the scenarios' CO_2 concentrations and electricity production.



Note: Figures refer to CO_2 concentrations by volume (ppm CO_2).

Figure 6-3 Energy-related CO_2 emission and CO_2 concentration profiles for the Baseline, ACT Map and BLUE Map scenarios

Source: IEA 2008, p. 51.

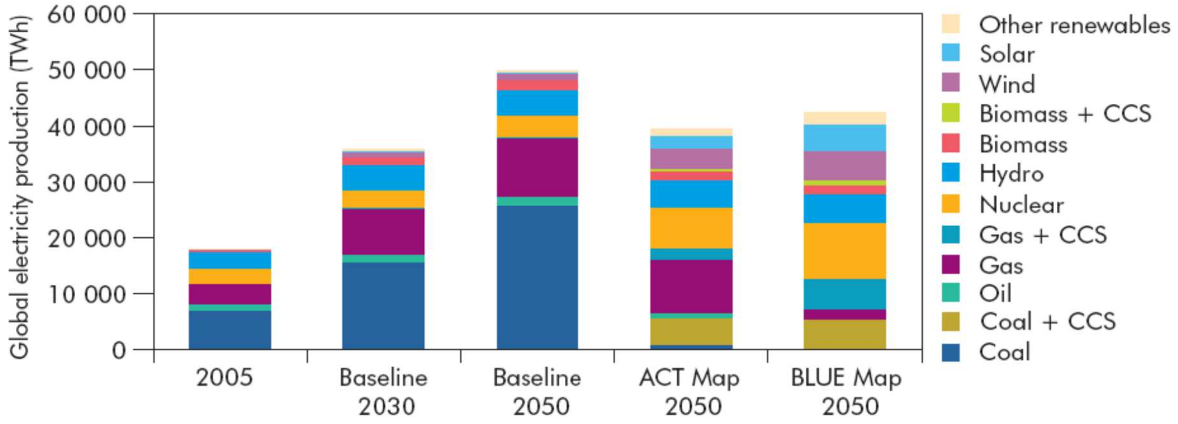


Figure 6-4 Global electricity production by fuel in the Baseline, ACT Map and BLUE Map scenarios, 2005, 2030 and 2050

Source: IEA 2008, p. 84.

The Greenpeace study takes as a reference scenario the baseline of the World Energy Outlook 2007 as a BAU and develops an energy revolution scenario with two objectives: the reduction of CO_2 emissions to assure a global temperature increase lower than 2°C and the phase out of nuclear power. Energy efficiency and renewables shape the power sector. Unlike the International Energy Agency scenarios, the energy revolution scenario reduces the use of conventional power to a minimum and wind and solar technologies are expected to contribute

46% in 2050. The total share of renewables amounts to 75%. The CO_2 emissions are reduced by 56% in comparison to 2005 figures (10,589 million tonnes in 2050). Figure 6-5 and Figure 6-6 illustrate the scenarios' CO_2 emissions and electricity production.

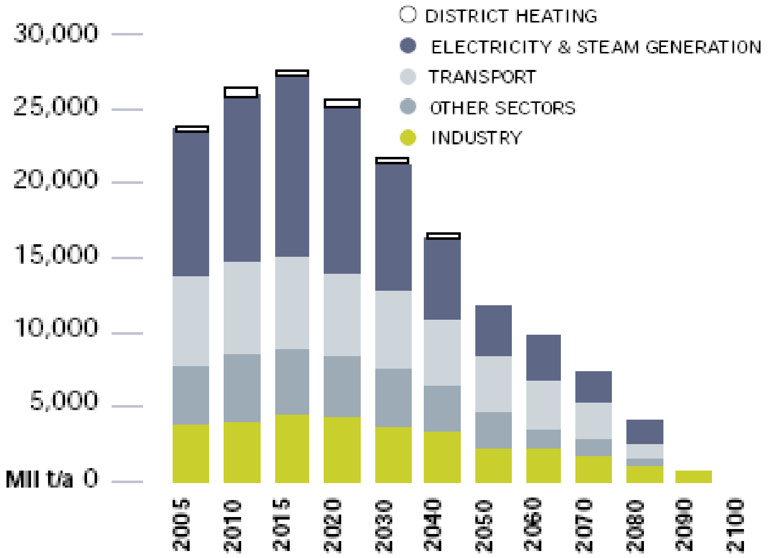


Figure 6-5 Global CO_2 emissions energy revolution scenario

Source: Greenpeace 2008; p. 14.

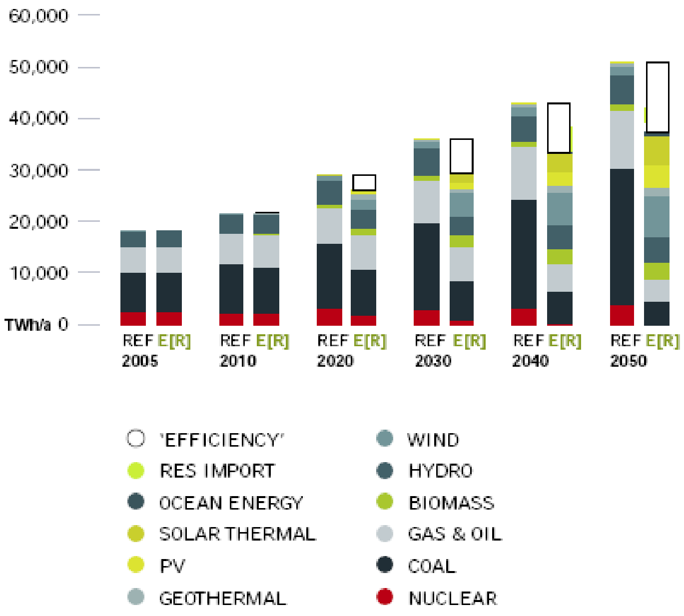


Figure 6-6 Global development of electricity supply structure under the reference and energy revolution scenario

Source: Greenpeace 2008, p. 56.

Both studies include an analysis with experience curves to determine the future cost of energy technologies. The Greenpeace study used the figures of the NEEDS study.

6.4 CAPITAL COST PROJECTIONS FOR COLOMBIAN ENERGY MODELING BASED ON EXPERIENCE CURVES

In order to apply the experience curve methodology to the Colombian case, current investment costs of renewable technologies and their global diffusion were assessed. A review of available sources shows that these costs vary and that diffusion depends on how new technologies are embraced in the future, where conservative and optimistic figures are found.

To minimize the uncertainties of the cost figures, a range per technology is derived according to the sources reviewed. In addition, the conservative diffusion of renewables of the ETP scenarios and the optimistic figures of Greenpeace are selected. As a result the experience curve analysis approach for the Colombian power sector will yield a low and high cost for a slow and fast penetration of renewable sources (their diffusion). The energy model will therefore be fed with this set of data. In that way a sensitivity analysis is included from the beginning.

Table 6-5 exhibits the range of investment costs selected from the literature review (*see* Table 6-1) along with O&M costs and the learning rate for the analysis.

Table 6-5 Cost and learning rates for the Colombian energy simulation

Technologies	**Investment Cost** (2005 USD/kW) *Low*	*High*	**O&M** (%)	**LR** (%)
Wind onshore	1,200	1,510	3%	8%
Wind offshore	2,600	3,760	4%	8%
PV	4,245	6,600	1%	18%
Concentrating Solar Power	4,500	7,530	4%	10%
Biomass IGCC	4,320	6,170	6%	5%
Biomass Combustion for power	1,975	3,085	5%	5%
Co-firing with coal	123	245	6%	
Geothermal Hydrothermal	1,700	5,700	2%	8%

Regarding the global installed capacity for renewables, an interpolation was necessary for the figures of the Energy Technology Perspective scenarios for the missing years 2010, 2020 and 2040 (*see* Table 6-4) based on the figures from the IEA (IEA 2007) in their Act map scenario, assuming that the penetration follows the same trend. This does not apply to CSP, where the projection was not realistic so a linear projection from the ETP was assumed. The biomass IGCC figures were taken only from IEA sources, since the Greenpeace report does not have a disaggregated figure for their biomass technologies. There is no data for biomass combustion. For geothermal, the figures taken correspond to conventional hydrothermal. The results are shown in Table 6-6.

Table 6-6 Global installed capacity in GW for experience curve analysis

Technology	2005	2010	2020	2030	2040	2050
Onshore	59	92	349	750	925	1,100
	59	162	866	1,508	1,887	2,186
Offshore	0.3	4	22	150	250	350
	0.3	1,6	27	114	333	547
PV	3	10	62	150	375	600
	5.2	21	269	921	1,799	2,911
CSP	0.5	6	104	250	315	380
	0.53	5	83	199	468	801
Biomass	0	13	27	40	48	55
	21	35	56	65	81	99
Geothermal	9	18	31	45	60	75
	8.7	12	33	71	120	152

The conservative capacity corresponds to the lowest figure from ETP scenarios (Act Map) and the higher capacities to the energy revolution scenario from Greenpeace. As an example of how the capacity of renewables differs from both scenarios, Figure 6-7 exhibits the global capacity for PV and wind in which the variations in the projections are more evident.

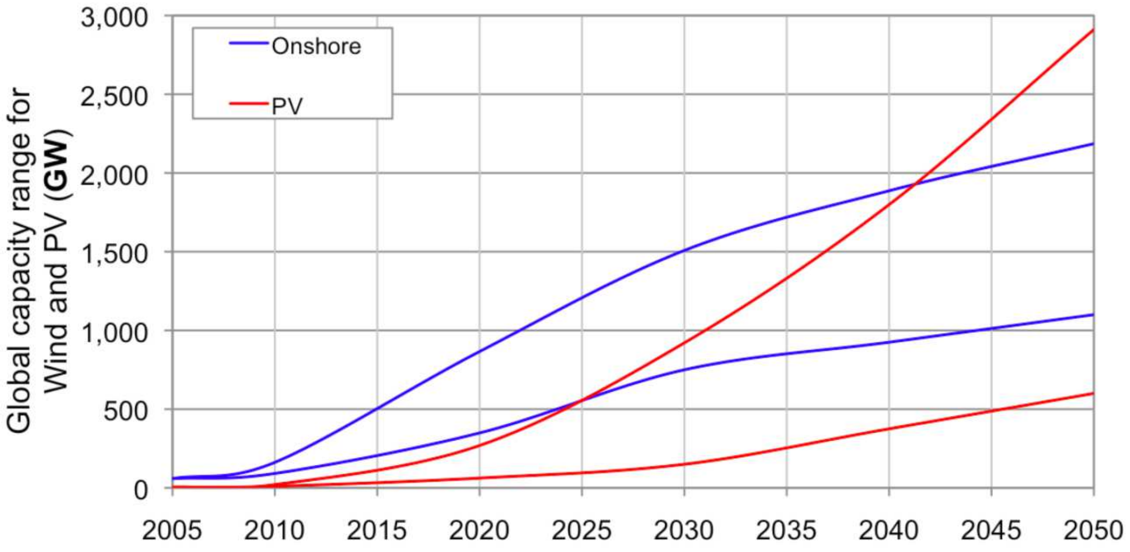


Figure 6-7 Global low and high cumulative capacity development of wind onshore and PV

By knowing the learning rates, investment costs and global capacities, the experience curve methodology yields the following results (*see* Section 6.2 for the mathematical formulation):

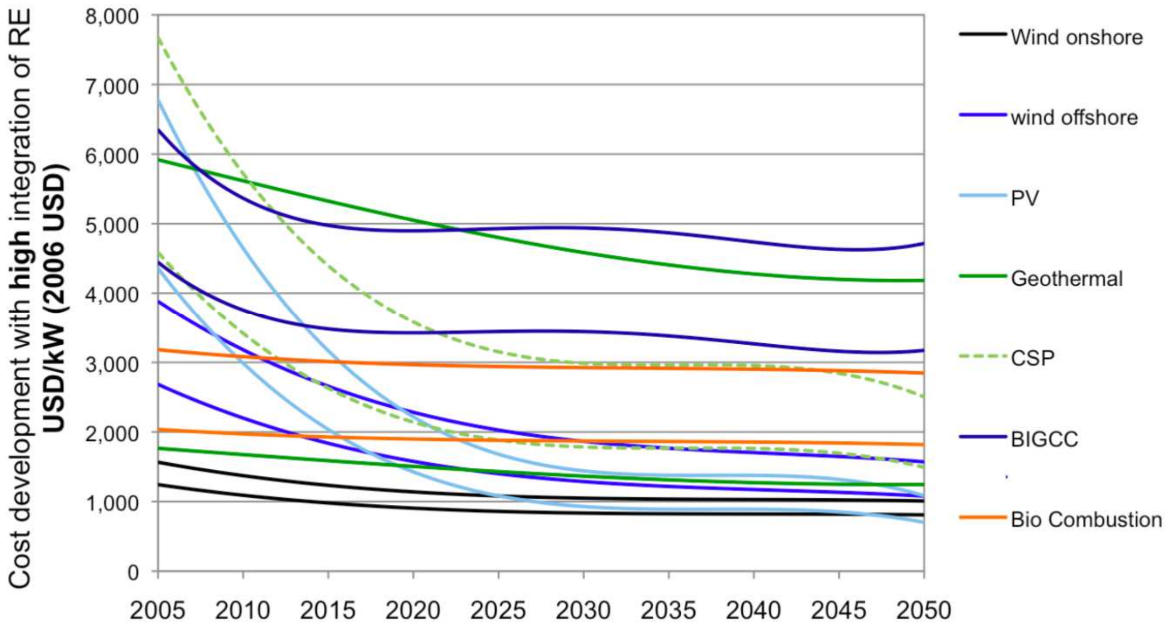


Figure 6-8 Investment cost with global high integration of renewables

Table 6-7 Investment cost with high diffusion of renewables

Technology	2005	2010	2020	2030	2040	2050
Wind onshore	1,200	1,062	868	813	793	783
	1,510	1,337	1,092	1,021	993	973
Wind offshore	2,600	2,126	1,513	1,272	1,117	1,052
	3,760	3,074	2,189	1,842	1,620	1,527
PV	4,245	2,846	1,372	965	797	693
	6,600	4,426	2,133	1,499	1,238	1,079
Geothermal	1,700	1,635	1,448	1,319	1,237	1,203
	5,700	5,484	4,856	4,429	4,158	4,042
Concentrating Solar Power	4,500	3,200	2,087	1,828	1,604	1,478
	7,530	5,353	3,492	3,058	2,687	2,475
Biomass IGCC	4,320	3,583	3,385	3,284	3,244	3,211
	6,170	5,118	4,836	4,693	4,635	4,585
Biomass Combustion for power	1,975	1,902	1,837	1,817	1,787	1,760
	3,085	2,972	2,871	2,841	2,795	2,754

The curves with the same color in Figure 6-8 represent the cost range of the technology (low and high investment cost development). A high learning rate as in PV and CSP (18% and 10% respectively) in combination with a strong diffusion bring the cost down in a short amount of time. In a period of 15 years the PV cost is reduced from 4,245 US/kW to 1,372 USD/kW (67% reduction) from its previous level in 2005 and hits the 1,000 US/kW mark around 2025 for the low investment cost curve. As soon as capacity growth per year stabilizes so do the investment costs. That is why the cost reductions are not as substantial as in previous years.

Biomass technologies have a low learning rate and do not have an aggressive diffusion, which cause relatively stable investment costs. Onshore wind will reach costs around 1,000 USD/kW, whereas offshore wind's investment costs are expected to be reduced, since important expansion rates are supposed to take place. Geothermal has a larger gap between the low and high investment cost (5,000 USD/kW), which must be better defined for the Colombian power sector modeling using another approach.

By a low penetration of renewables, the cost reductions are simply postponed as shown in Figure 6-9. Instead of a 15 year time span to push PV costs between 1,372 and 2,133 USD/kW by 2020, 10 more years are necessary to accomplish it. Nevertheless, PV and CSP experience an important reduction of cost over the years as offshore wind does to a lesser extent.

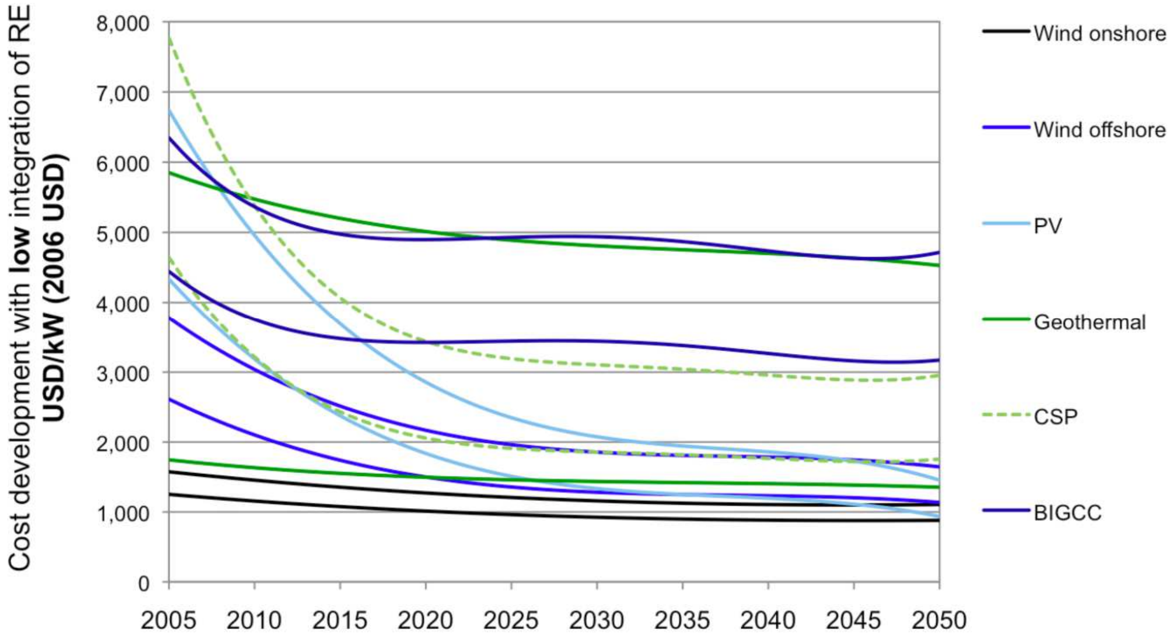


Figure 6-9 Investment cost with global low diffusion of renewables

Table 6-8 Investment cost with low integration of renewables

Technology	2005	2010	2020	2030	2040	2050
Wind onshore	1,200	1,139	970	885	865	845
	1,510	1,432	1,219	1,111	1,082	1,062
Wind offshore	2,600	1,891	1,551	1,231	1,157	1,112
	3,760	2,733	2,242	1,782	1,675	1,608
PV	4,245	2,999	1,781	1,386	1,065	932
	6,600	4,662	2,772	2,152	1,655	1,446
Geothermal	1,700	1,558	1,459	1,395	1,349	1,314
	5,700	5,221	4,889	4,672	4,516	4,397
Concentrating Solar Power	4,500	3,091	2,017	1,768	1,707	1,659
	7,530	5,171	3,373	2,954	2,851	2,771
Biomass IGCC	4,320	3,583	3,385	3,284	3,244	3,211
	6,170	5,118	4,836	4,693	4,635	4,585
Biomass Combustion for power	1,975	1,902	1,837	1,817	1,787	1,760
	3,085	2,972	2,871	2,841	2,795	2,754

The experience curve results do not lead to a straight forward conclusion about the competitiveness of the technology. Technical features and market characteristics have to be taken into account to see the convenience of their use, for example, based on their merit cost. However it is illustrated that the faster a technology is promoted, the sooner it may reach competitive levels by reducing cost and gaining experience.

6.5 CAPITAL COST OF PROJECTIONS FOR COLOMBIAN ENERGY MODELING FOR CONVENTIONAL TECHNOLOGIES

The experience curve methodology was applied to renewable energy technologies. Learning rates for these technologies are found in several sources. For conventional technologies, cost projections are based on bottom-up approaches rather than experience curves, which are limited for advanced fossil fuel technologies (European Commission 2006, p.24).

The sources reviewed for the cost estimation of those technologies (*see* Table 6-2) included projections of future cost. The analysis was complemented with a Colombian study for the assessment of power technologies cost, which gives an idea of the local cost in comparison to international estimations. It was found that investment costs for conventional technologies are very similar among the sources. The investment and O&M costs for the simulation in the energy models for the Colombian power system will be based on the bottom up approaches of the sources available.

The following tables (6-9 to 6-11) summarize the findings and explain the approach followed and sources taken. All costs are presented in 2005 US Dollars. The sources for the analysis are the NEEDS project, where a cost development of advanced fossil fuel technologies were derived (European Commission 2006, p.18) based on bottom up assessment from the Institut für Energiewirtschaft und Rationelle Energieanwendung (IER). In addition the estimations of the International Energy Agency studies were taken: the Energy Technology Perspectives (IEA 2008) and the Carbon Capture and Storage (CCS) A key carbon abatement option (IEA 2008a). The Colombian study, Costos Indicativos de Generación, is also included (UPME 2005).

In general, investment and O&M costs reductions are not very significant over the years, but improvements in the efficiency are expected. Typically a 40 year life span is used for conventional power plants for economic analysis.

Table 6-9 Pulverized coal fuel power plant

Item	*Units*	2005	2010	2020	2030	2040	2050
Investment	(USD/kW)	1,300	1,300	1,300	1,300	1,300	1,300
O&M	(USD/kW)	65	65	65	65	65	65
Efficiency LHV	(%)	40	45	50	52	53	53
Lifespan	(Years)	40	40	40	40	40	40

Notes:

- The sources consulted shows for conventional coal fired power plants investment costs between 1,000 USD/kW and 1,500 USD/kW. A price of 1,300 USD/KW is selected from the Colombian study as representative

- The reduction of investment costs of this technology over the years are expected to be between 10% and 16% (Greenpeace, IEA -CCS) while others sources (NEEDS, ETP) show an almost constant cost in the long run. This is understood as the price reduction of super critical and ultra-super critical PC power plants reaching the cost levels of today conventional PC power plants. Therefore, for the same cost a better efficiency by higher temperatures and pressures in the steam cycle are expected to be commercially available

- An investment cost of 1,300 USD/kW is therefore kept constant until 2050 with an increase of the efficiencies overtime

- NEEDS reports a 4% of investment cost to be O&M in average as well as the EIA-CCS Study. The Colombian Study reports a cost around 5.5%. A value of 5% is selected.

- Efficiencies are a representative average of the sources available (Greenpeace, ETP, IEA-CCS, NEEDS)

- Lifespan of this technologies ranges from 45 to 60 years. 40 years were selected. For the analysis until 2050 a replacement of a new installed unit will not be required

Table 6-10 Gas Turbine Combined Cycle

Item	*Units*	2005	2010	2020	2030	2040	2050
Investment	(USD/kW)	700	679	637	595	595	595
O&M	(USD/kW)	35	34	31,9	29,8	29,8	29,8
Efficiency LHV	(%)	57	58	61	63	63	64
Lifespan	(Years)	40	40	40	40	40	40

Notes:

- From Greenpeace and IEA sources a decrease in the investment between 12% and 17% is expected in 2030. A value of 15% is assumed. From 2030 onwards this value is kept constant. The decrease is assumed to be lineal

- Efficiencies being a representative average of the sources available (Greenpeace, ETP, IEA-CCS, NEEDS)

- Lifespan of a combined cycle is assumed to be 40 years. For the analysis until 2050 a replacement of a new installed unit will not be required

- NEEDS reports a 5.2% of investment costs to be O&M in average, EIA-CCS a 4%. The Colombian study reports a 5.3%. A value of 5% is selected

Table 6-11 Integrated gas combined cycle

Item	*Units*	2005	2010	2020	2030	2040	2050
Investment	(USD/kW)	1,800	1,720	1,560	1,400	1,400	1,400
O&M	(USD/kW)	75,6	72,2	65,5	58,8	58,8	58,8
Efficiency LHV	(%)	40	44	51	54	55	55
Lifespan	(Years)	40	40	40	40	40	40

Notes:

- The investment costs reported by ETP were selected, other studies show values for other years with same tendency (EIA_CCS, NEEDS)

- NEEDS reports a 4.4% of investment costs to be O&M in average, while the EIA-CCS study a 4%. A value of 4.2% is selected

- Lifespan assumed to be 40. For the analysis until 2050 a replacement of a new installed unit will not be required

- Efficiencies being a representative average of the sources available (ETP, IEA-CCS, NEEDS)

There are two technologies that show big differences regarding the investment costs. Hydropower investment costs from Colombian sources are significantly lower in comparison to international sources as well as geothermal whose cost has a variation of 5,000 USD/kW between the low and high cost estimates. For that reason, the Colombian source was selected to derive the investment cost as shown in Table 6-12. The future development of their investment cost is assumed to be constant. In addition, investment costs for a gas turbine are also included, which will be used as a peak technology in the energy models.

Table 6-12 Hydropower investment cost

Item	*Units*	**10 MW Run off the river**	**200 MW**	**600 MW**
Investment	(USD/kW)	2,000	1,125	1,055
O&M	(%)	2	2	2

Source: UPME 2005a, p.164.

Table 6-13 Gas Turbine

Item	*Units*	**150 MW**	**300 MW**
Investment	(USD/kW)	1,125	1,055
O&M	(%)	9,6	9,6
Efficiency	(%)	33	33

Source: UPME 2005a, p.164.

6.6 ELECTRICITY DEMAND

The Energy Planning Unit of the Colombian Energy and Mine Ministry (UPME) releases every year an indicative transmission and generation expansion plan with the objective to analyse how electricity demand can be supplied according to current and expected expansion in generation and transmission technologies in the middle term (15 year time horizon). A key analysis of the plan is the national electricity demand projections. This allows measuring the energy resources available and the transformation technologies to see how the power sector can reach expected demand goals. For the simulation of future power developments in Colombia in the accounting framework and optimization model, the demand growth until year 2050 will be based on the official electricity demand projections of the ministry.

The methodology for the projection of the UPME takes into account demand (sales) reported by the utilities, special demand loads (big industries) and transmission and distribution losses.

This recorded information is analyzed within the national economy and its sectors demanding electricity, in which energy prices, GDP growth among other parameters are put together by econometric models for the projection. The results are yearly and monthly projections which show the seasonality of the electricity consumption to determine the power required by means of the monthly capacity factor of the system with the latest two years data. The results of the demand projections are exhibited in Figure 6-10.

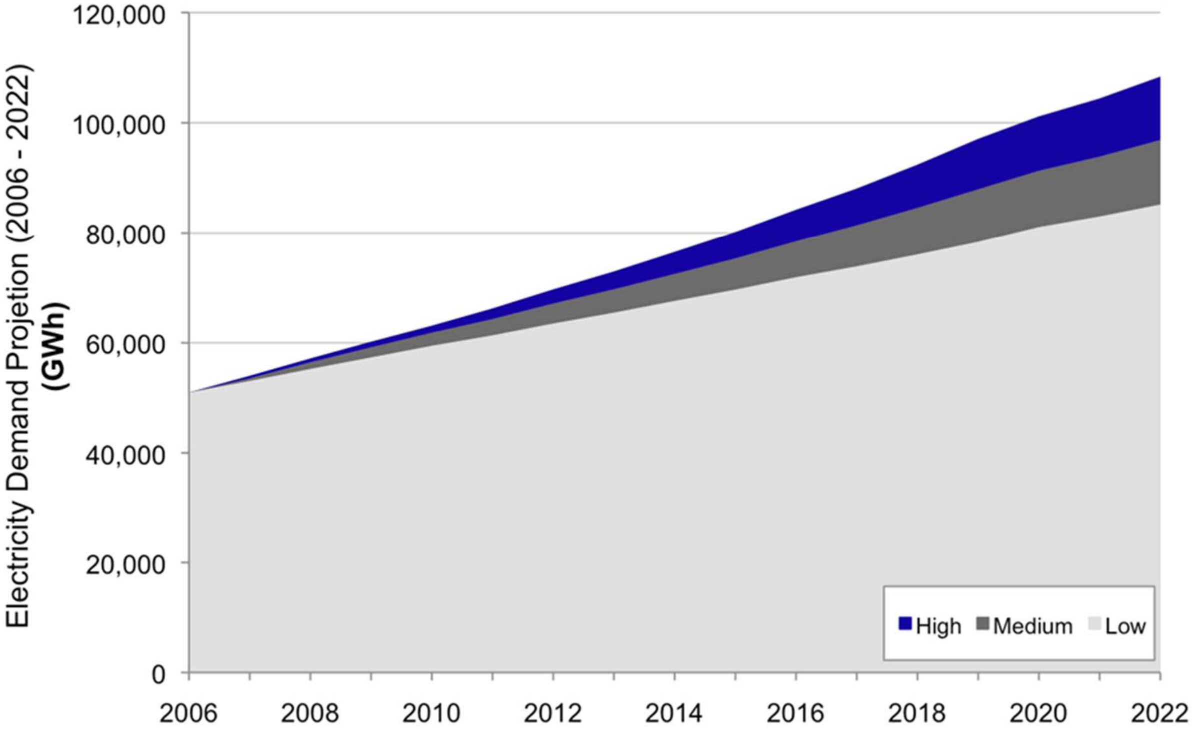


Figure 6-10 Domestic electricity demand from 2006 to 2022

Source: Data from UPME 2007. p.43

The projection corresponds to economic situation and expectations in 2006 and does not include international electricity transactions. The projection considers the losses of transmission and distribution which amount to 2.4% and 13% respectively.

As a result of a sensitivity analysis a projection tunnel is obtained showing a low, medium and high demand growth by year 2022. Table 6-14 summarizes the projection of electricity per year.

Table 6-14 Demand projection

Year	**Electricity demand** (GWh)			**Demand Growth** (%)		
	High	*Medium*	*Low*	*High*	*Medium*	*Low*
2006	50,815	50,815	50,815			
2007	53,850	53,400	52,900	5.97%	5.09%	4.10%
2008	57,002	56,317	55,087	5.85%	5.46%	4.13%
2009	60,040	59,019	57,180	5.33%	4.80%	3.80%
2010	62,950	61,678	59,292	4.85%	4.50%	3.69%
2011	66,085	64,155	61,193	4.98%	4.02%	3.21%
2012	69,544	66,980	63,340	5.23%	4.40%	3.51%
2013	72,808	69,562	65,303	4.69%	3.86%	3.10%
2014	76,372	72,351	67,442	4.89%	4.01%	3.28%
2015	80,009	75,189	69,490	4.76%	3.92%	3.04%
2016	84,072	78,320	71,753	5.08%	4.16%	3.26%
2017	87,925	81,238	73,736	4.58%	3.72%	2.76%
2018	92,251	84,418	75,917	4.92%	3.92%	2.96%
2019	96,937	87,787	78,214	5.08%	3.99%	3.03%
2020	101,012	91,157	80,920	4.20%	3.84%	3.46%
2021	104,263	93,722	82,845	3.22%	2.81%	2.38%
2022	108,224	96,750	85,029	3.80%	3.23%	2.64%

Source: Data from UPME 2007, p.43).

A newest demand projection version as of March 2009 shows different results (UPME 2009). First, the horizon was extended to 2030 and includes most recent economic development.

Figure 6-11 exhibits the two set of projections available until 2022 for the medium growth. The gap between years 2008 and 2011 varies from 4% to 10% showing the overestimation of the previous analysis.

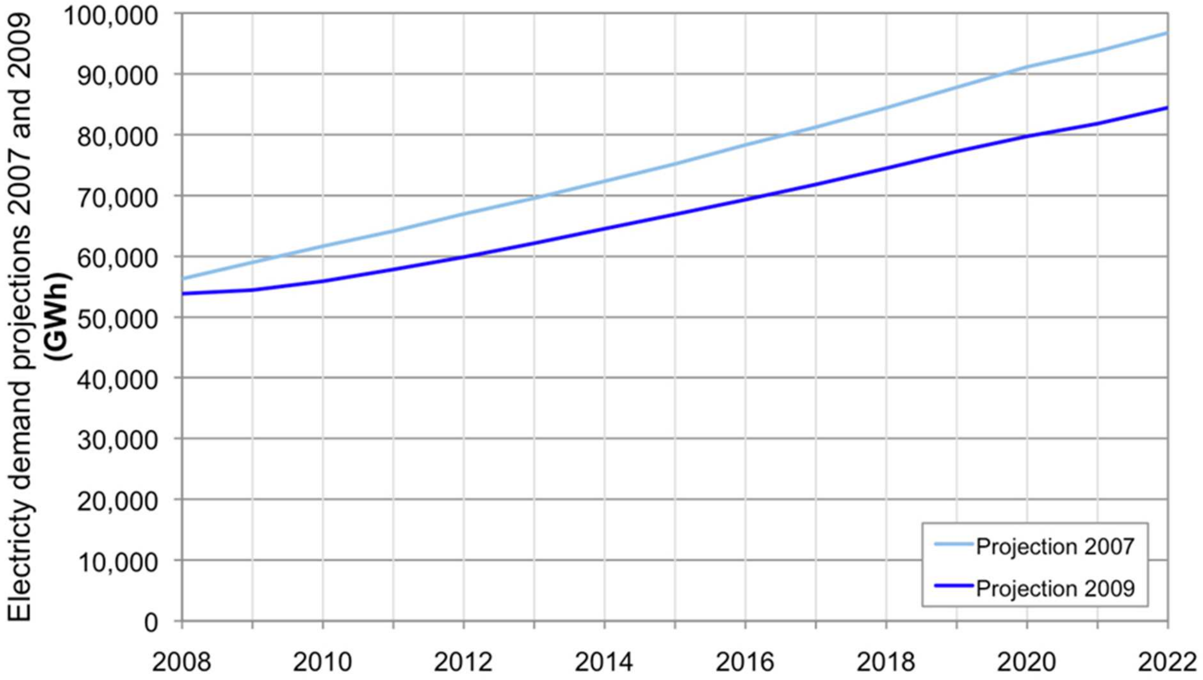


Figure 6-11 Domestic electricity demand projection 2007 vs. 2009

Source: Data from UPME 2009, p. 24.

From 2011 to 2022 the difference is approximately 11.6%. This is explained by the dramatic change in economic growth as seen by the demand growth in the second semester of 2007. The demand growth of 4% in 2007 shrunk to 1.6% in 2008 as a consequence of the slowdown of the economy with a GDP reduction from 7.5% to 3.5% for those years (UPME 2009, p.5). This contrasts to previous macroeconomic assumptions, which expected GDP's in 2008 and 2009 between 4% and 6% (UPME 2007, p.41). This GDP range was estimated to last until 2020. The projections have now shifted this GDP range to be from 2011 onwards after a recovery in 2009 and 2010. According to the new electricity demand projection the growth rates estimated for 2009 and 2010 should amount to 1.4% and 2.7% respectively and a 3.6% to 3.2% from 2010 to 2030 (UPME 2009, p.4).

Since the simulation in the energy models requires a projection beyond the last years available, 2022 and 2030, a set of data was extrapolated assuming growth rates of the last years available to be constant until 2050. The results are shown in Figure 6-12

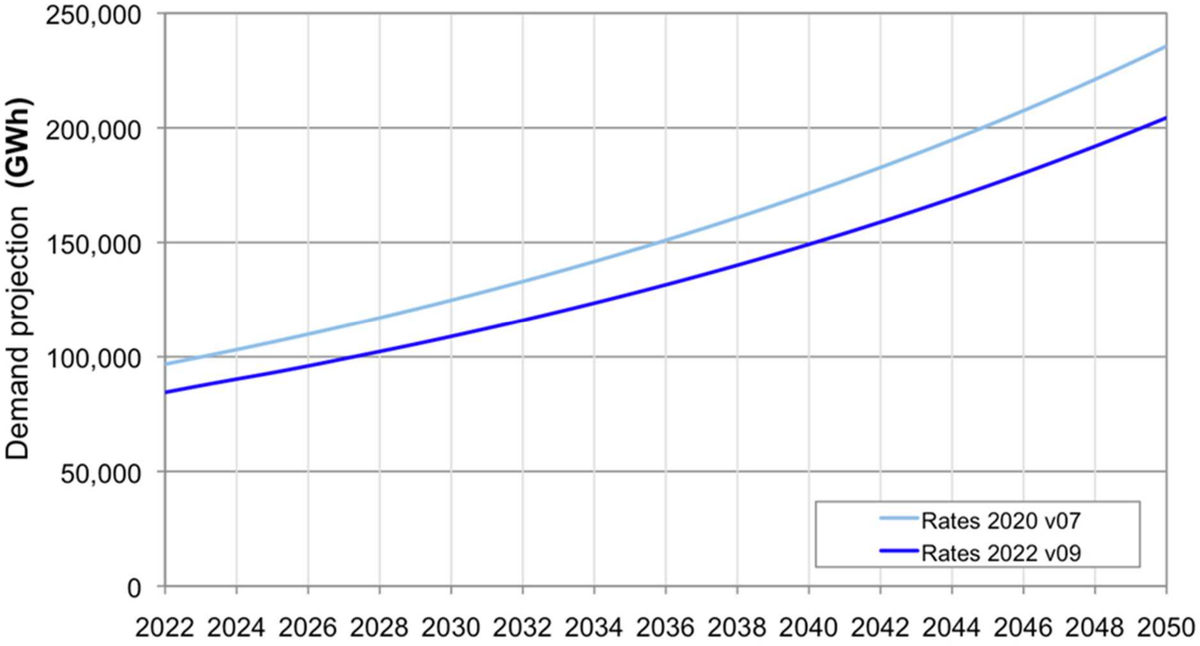


Figure 6-12 Domestic demand projection until 2050

Based on projections 2007 and 2009.

For the projection based on the 2007 figures, growth rates are 2.6 %, 3.2 % and 3.8 % for low, medium and high estimations by 2022. The growth rates of the demand projection in 2009 are of similar order 2.5%, 3.2% and 3.9 %. As the demand projection of 2009 goes until 2030 the growth rates by that year correspond to 2.3 %, 3.2 % and 4 %. The medium growth rate is almost equal in the projections available.

An average difference of 14.4% is observed from 2022 to 2030 and of 14.9% from 2031 to 2050 between the projections. The demand projection with the 2007 figures was projected from 2023 onwards whereas the 2009 version from 2031 onwards. The electricity demand projections for the energy models are based on the 2007 version.

An extrapolation of the electricity demand based on the last growth rate implies the loose assumption that growth is constant over those years. A comparison with countries which experience or are experiencing economic high growth and stabilize their electricity consumptions per inhabitant is included to guarantee that the assumption does not exceed reasonable limits as experienced by other countries, which already reached their industrialized phase. As electricity consumption per capita is used as an indicator to test those limits, the consumption per capita for the Colombian projection by the year 2050 is first calculated with current national and international Colombian population projections as shown in Figure 6-13.

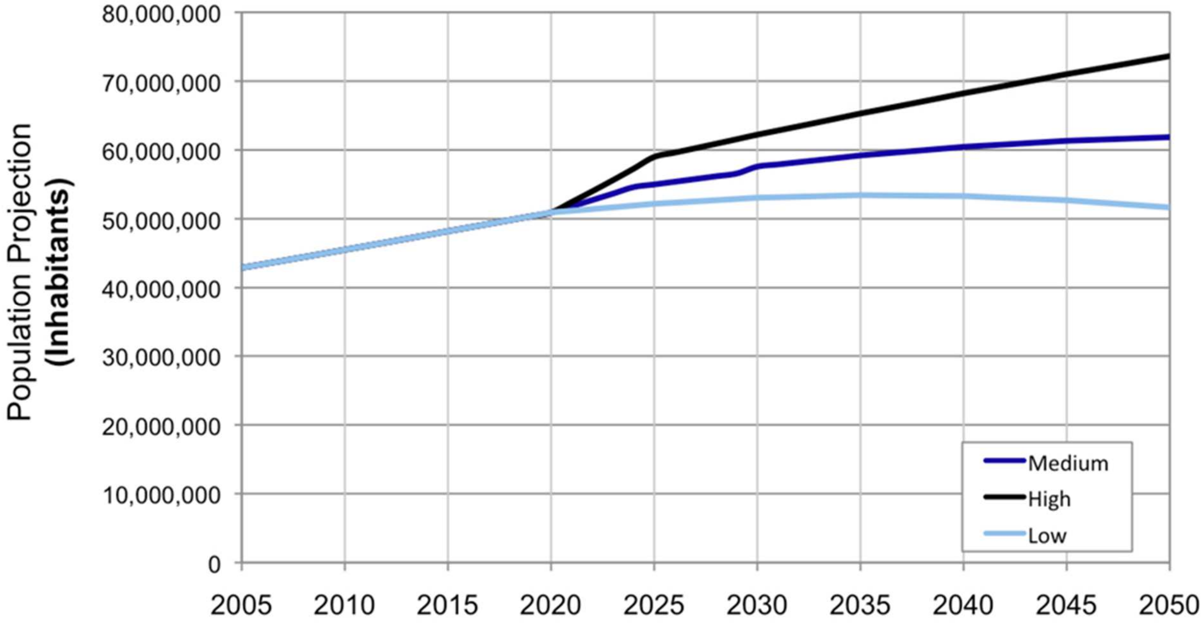


Figure 6-13 Population projection for Colombia

Source: Data from DANE 2009 and UNO 2008.

The above projection reflects the latest national statistics until 2022 (DANE 2009) and a further population growth based on UNO estimations from that year to 2050 (UNO 2008). The medium projection was selected to obtain the energy consumption per capita together with the demand projection figures of the 2007 version as shown in Figure 6-14

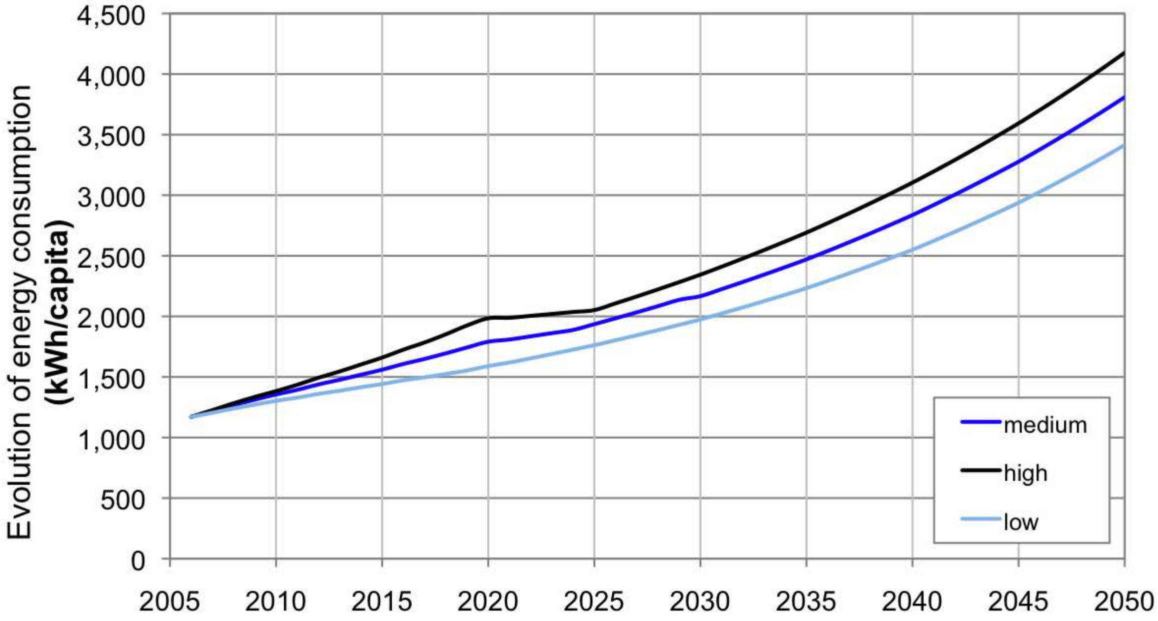


Figure 6-14 Estimated domestic electricity consumption per capita

A current consumption per capita of 1,170 kWh/head will increase over 300% to reach a consumption between 3,414 kWh/capita and 4,176 kWh/capita. Analogously the same procedure was applied for selected OECD countries as shown in Figure 6-15.

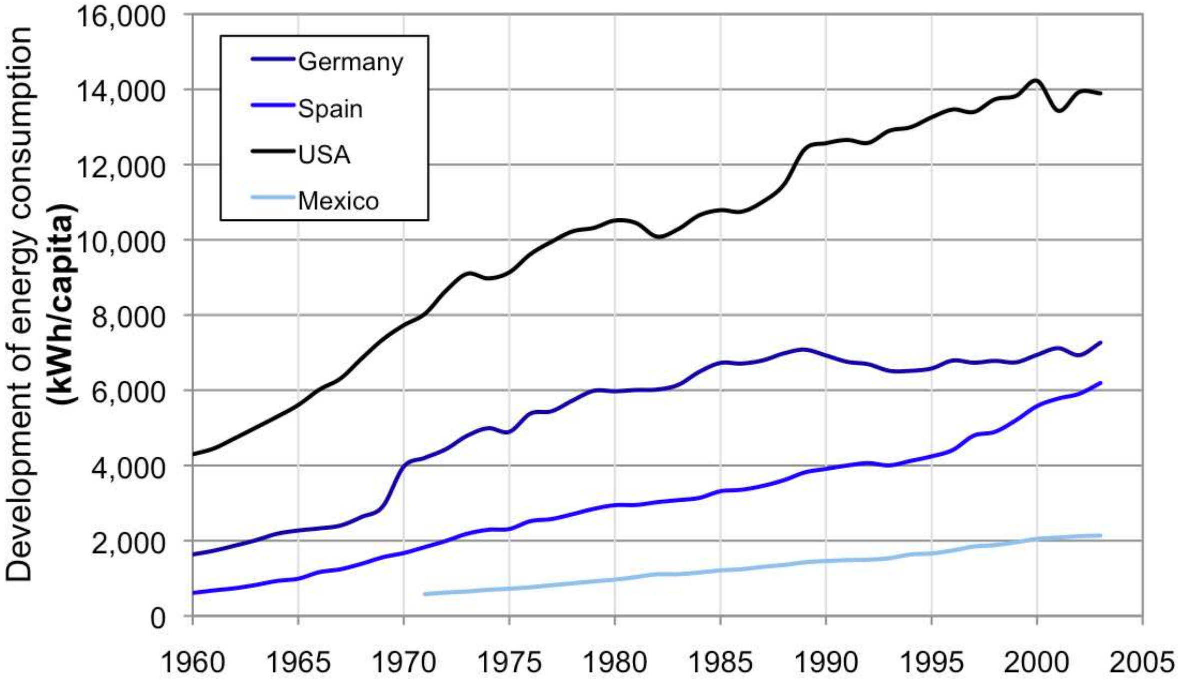


Figure 6-15 Electricity energy consumption per capita in countries: Germany, Spain, USA and Mexico

Source: Data from database energy statistics of OECD countries 1960 – 2003 (IEA, 2005).

By looking at the case of Spain in Figure 6-15, the consumption per capita has had a constant growth during the last 40 years; Spain was a country behind the development of industrialized countries in west Europe decades ago. Today Spain's economy is an industrialized nation and its energy consumption per capita has reached the levels of Germany of over 6,000 kWh/head, which also experienced an economic boom until stabilizing the consumption per capita in the nineties. Mexico has one of the biggest economies in Latin America and has a consumption per capita of around 2,000 kWh/head, whereas the United States of America reaches easily levels over 13,000 kWh. This demonstrates that the indicator cannot be taken as a definite cap to check the levels of consumption, which depends not only on the economy performance but also on society's consumption habits and preferences. However, it helps to illustrate that the electricity demand projection for Colombia beyond the years obtained by the econometric models should be around reasonable levels and do not lead to unrealistic results.

6.7 COLOMBIAN NATURAL GAS

6.7.1 Reserves and demand projections

Currently Colombia is self-sufficient to meet the national natural gas demand thanks to mainly two regions where 85% of the reserves are located. As shown in Figure 6-16 the first region is the north of the Colombian Caribbean coast in the fields of Ballena and Chuchupa. The second region is located in the eastern lowlands in the fields Apiay, Cusiana and Cupiagua (UPME 2007a, p.39).

Figure 6-16 Natural gas fields and relative infrastructure

Source: Ecopetrol 2012.

As of 2007 the country had 131.42 Gm^3 of commercial proved reserves including 25.52 Gm^3 for consumption in the operation of the fields (generation of electricity for the operation, operation of compressors, thermal treatment, operation of pumps among others uses). The reserves and supply from 2003 to 2008 are shown in Figure 6-17.

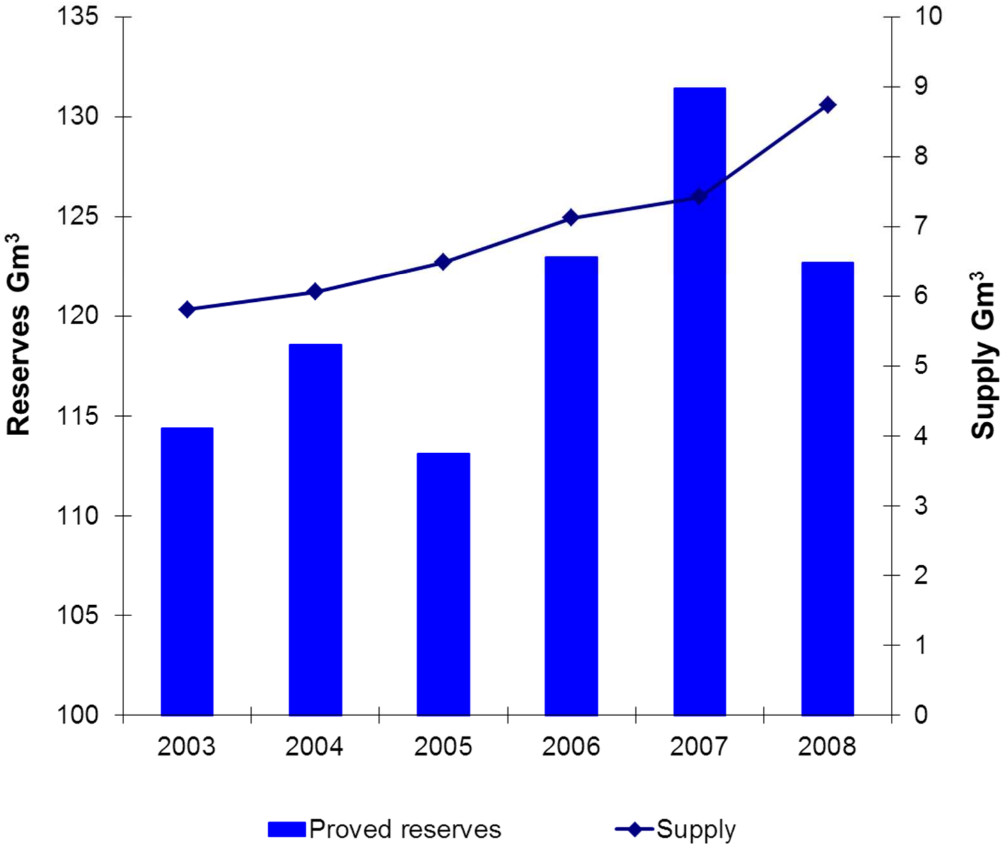


Figure 6-17 Natural Gas commercially proved reserves and supply

Source: Data from UPME 2009a, p.149-150, own calculations.

According to a projection conducted by the Energy Unit Planning (UPME), Colombian reserves are able to meet the demand until 2019 (UPME 2009b. p. 147). As of May 2008 the energy ministry reported reserves to last for 9.74 more years (MME 2008). A recent projection confirms the duration of these reserves (UPME 2010, p.144). Depending on the evolution of the demand the supply is predicted to be guaranteed with indigenous resources until between 2018 and 2020, further supporting the importance of finding alternative energy sources to meet the demand. In such a situation natural gas could be imported from Venezuela (pipeline capacity 14.15 million m^3 per day). Liquefied natural gas (LNG) is also an option to be imported from other markets. Figure 6-18 shows the projection for all sectors based on 2006 figures. It is worth noting that exports to Venezuela take place until 2012 (4.24 million m^3 per day). Afterwards 2.83 million m^3 per day of Venezuelan gas will be imported (UPME 2007a, p. 13; UPME 2009a, p13; Rigzone 2007).

The amount of gas required to meet the power sector ranges from 25% to 35% of the total natural gas demand. This range varies depending on periods of high electricity demand and availability of hydropower resources (wet and dry seasons), which results in a grade of uncertainty in the projections. 85% of natural gas demanded by the power sector is consumed by the power plants at the Caribbean coast (SSPD 2007, p. 43). In the modelling of the power sector, a scenario with a reduced availability of hydropower resources will therefore be included.

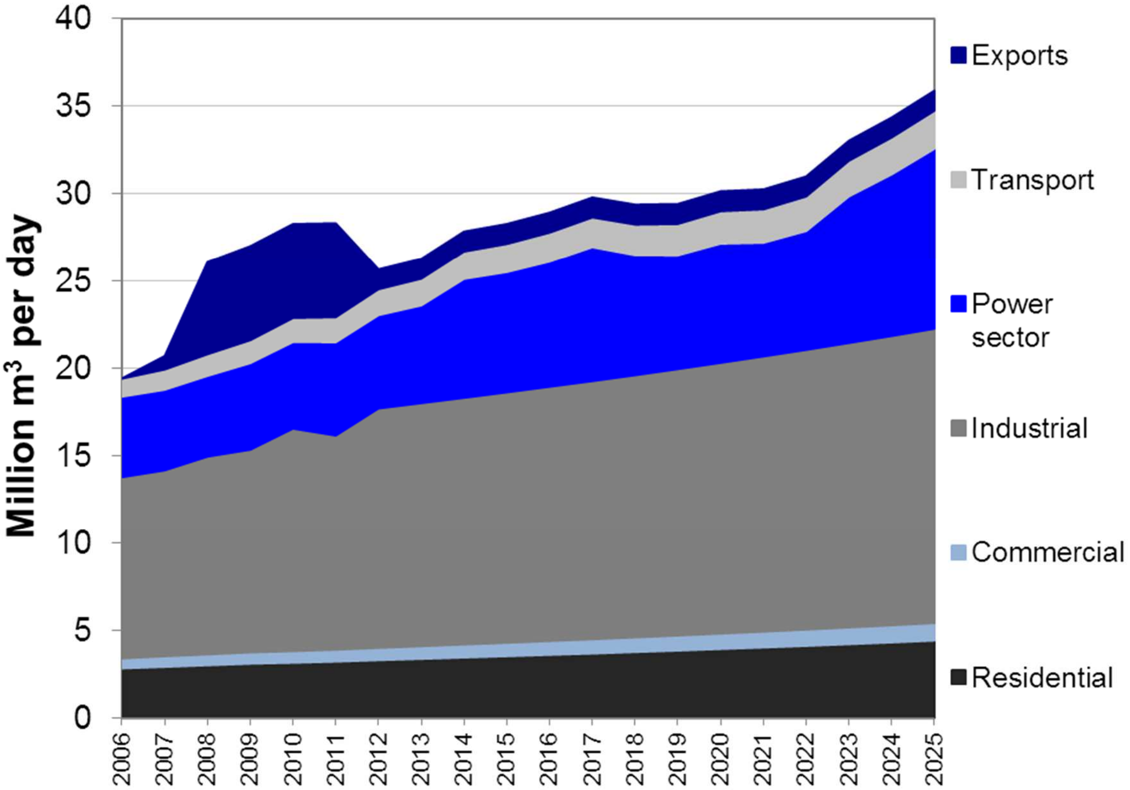


Figure 6-18 Projection of the of the natural gas demand

Source: Data from UPME, 2009b.

Most recent statistics show that commercially proven reserves have been kept over 113 Gm^3 for the last years. The Ministry of Mines and Energy reported reserves for 7 years by 2009. Residential, industrial and transport sector demand for natural gas continue growing and the power plants require much higher amounts during periods of periodical extreme weather conditions such as those associated with El Niño (UPME 2010, p.209).

As can be observed, the power sector is exposed to scarcity of natural gas resources in the midterm, making it mandatory to either depend on international natural gas markets and/or to search for new gas/oil fields or to find other energy sources and implement other technologies to back up current and future hydropower production.

6.7.2 Natural gas price projections

For a projection of the fuel cost for thermal power plants firing natural gas, the Energy Planning Unit UPME figures from its official analysis are used for the simulation in the energy models. The methodology of UPME for the projection is the result of an estimation of the gas prices at the production fields (wellhead price) and the transportation cost to the power plants via the gas pipeline infrastructure (UPME 2007a; UPME 2009b). For the natural gas production fields located at the Caribbean coast (Guajira and Opón) the maximum allowed gas prices are regulated by law according to CREG Resolution 119 of 2005, since price liberation can only take place if the Electricity and Gas Regulation Commission consider that a certain level of competition has been reached (UPME 2005b, p.75).

The methodology adjusts the price per semester, which is tied to international oil prices. The indexation is with New York Harbor Residual Fuel Oil index of the Energy Information Administration (IEA) of the United States as follows (CREG 2005, p.4):

$$PMR_t = PMR_{t-1} x \frac{\overline{INDEX_{t-1}}}{\overline{INDEX_{t-2}}}$$

Where:

PMR$_t$ = Maximum regulated price for the next period *t* (one semester) in US$/MBTU
PMR$_{t-1}$ = Maximum regulated price of previous semester *(t-1)*
INDEX$_{t-1}$ = Average of index from previous period *(t-1)*
INDEX$_{t-2}$ = Average of index from period preceding the previous semester *(t-2)*
INDEX = New York Harbor Residual Fuel Oil 1.0% Sulfur LP Spot Price from IEA

The Energy Information Administration provides a regular projection of oil prices from the present day to the year 2030. These projections are based on projections generated from the National Energy Modeling System (NEMS) that are used by the US governmental and federal agencies. The model has a market based approach for each fuel and consuming sector, accounting for economic competition between fuels and sources. It is an equilibrium model based on macroeconomic variables, fuel price per sector, demands and current legislation and regulations (EIA 2009c, p.1).

The energy models used for the quantitative analysis of this dissertation dispatch the power plants by merit order according to short term marginal cost determined by the fuel prices. To feed the model with that information, a data set with natural gas prices of existing power plants was obtained based on the 2007 projections of UPME available and the EIA Indexes in 2008, which were available at the moment of the calculation allowing an upgrading of the UPME projection applying the same methodology. For the gas production fields which do not have a regulated maximum price (Cusiana field), UPME determined the competitive prices by selecting those nodes in the pipelines, where those wells are competitive with the natural gas prices of the coast. In that way, the wellhead price was found after subtracting the cost of transportation (NETBACK methodology). Table 6-15 shows the wellhead prices for power plants with natural gas together with current transportation costs in 2006 dollars.

Table 6-15 Natural gas wellhead and transportation prices for power plants

Source: Data from UPME 2007a, p.9-12.

Power plant	**Transport** (US$/GJ)	**Wellhead price** (US$/GJ)	**Total** (US$/GJ)
Guajira	0.324	2.536	2.861
Mamonal	0.546	2.536	3.082
Barranquilla	0.419	2.536	2.955
Merielectrica	1.417	2.536	3.953
Centro	1.559	2.536	4.096
Palenque	1.936	3.630	5.567
Sierra	1.545	2.536	4.081
Dorada	1.802	2.536	4.338
Valle	2.658	2.536	5.194
Emcali	2.599	2.395	4.994

The indexes shown in Figure 6-19 are applied to the prices according to the methodology until 2020. Regarding the transportation costs, the cost of the pipeline sections from the gas fields, through the infrastructure up to supply nodes, were determined by UPME according to current contract and regulations including fees and taxes. The transportation costs are subsequently added to find the price for existing power plants as shown in Figure 6-20.

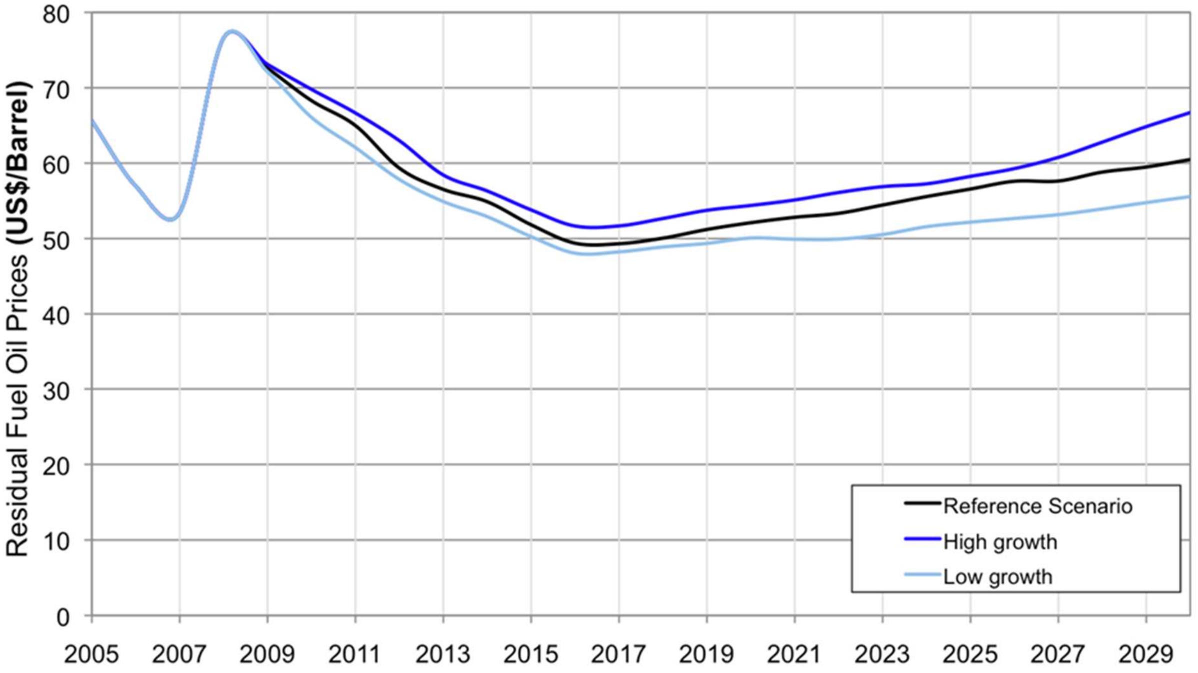


Figure 6-19 Residual Fuel Oil price projection from the EIA (2006 dollars)

Source: Data from Annual Energy Outlook (EIA 2008).

The power plants with low prices are mainly located at the coast, whereas those with higher prices are located in the interior of the country.

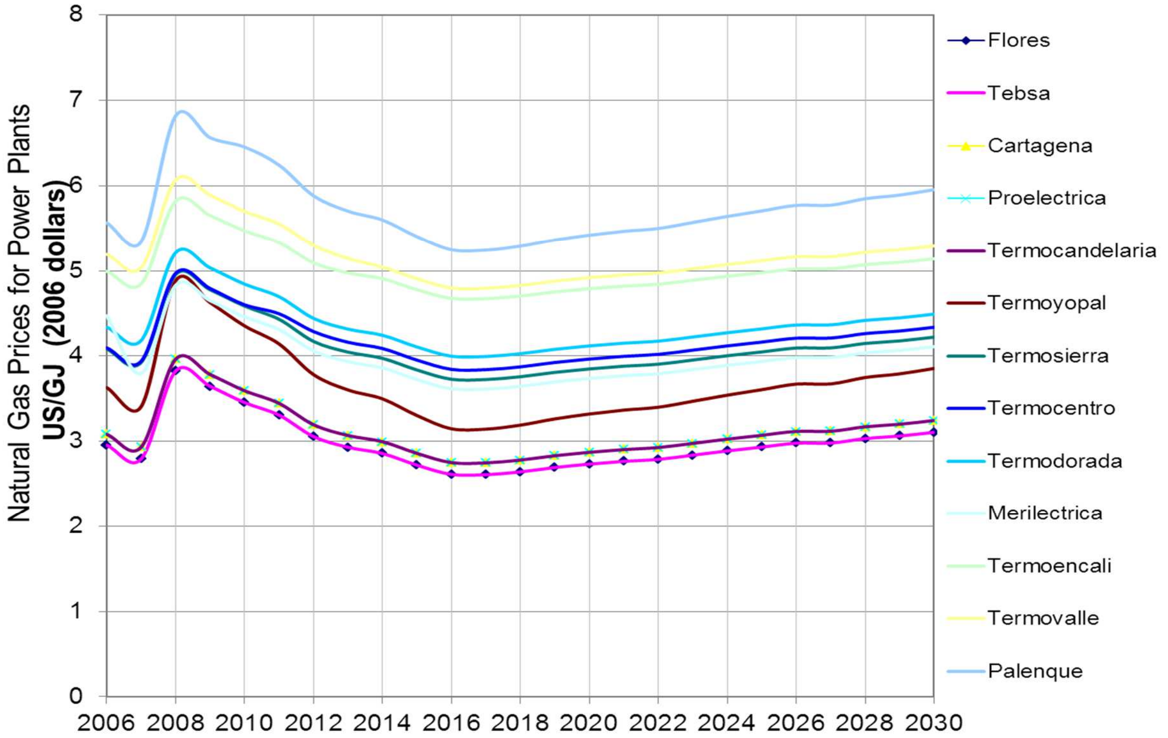


Figure 6-20 Natural gas price projections from 2005 - 2030 for Colombian power plants

For the overall economic valuation in the energy models LEAP and MESSAGE, only one generic natural gas price is allowed. Since most of the generation from natural gas power plants is concentrated at the Caribbean coast requiring more than 80% of the natural gas for the power sector (UPME 2010, p.214), the cost of the TEBSA power plant was selected as a representative price for the simulations. These prices are low in comparison to other power plants due to the proximity to gas production fields. In other words, the model will be tested with a set of “low prices” making the entrance of new technologies challenging.

The methodology for the projection of natural gas prices was updated with recent projections to take into account, not only the sharp drop of oil prices during the financial crisis, but also expected higher oil prices in the coming years. In addition, low and high natural gas prices are obtained to be used for sensitivity analysis in the energy models. For that a recent projection was selected (UPME and NATURGAS 2008, p.9-10). The low price scenario of this source reveals an underestimation of the projection already here introduced with 2007 data (*see* Figure 6-20).

This is due to a new projection from the EIA, which has been adjusted to account for the high prices in 2008 and the radical changes experienced by the energy costs due to the global economic crisis pushing the prices to a low and the rise of prices in 2010. Figure 6-21 illustrates how the fuel oil projections differ. As a result, the natural gas projections vary according to the fuel oil price trend as shown in Figure 6-22.

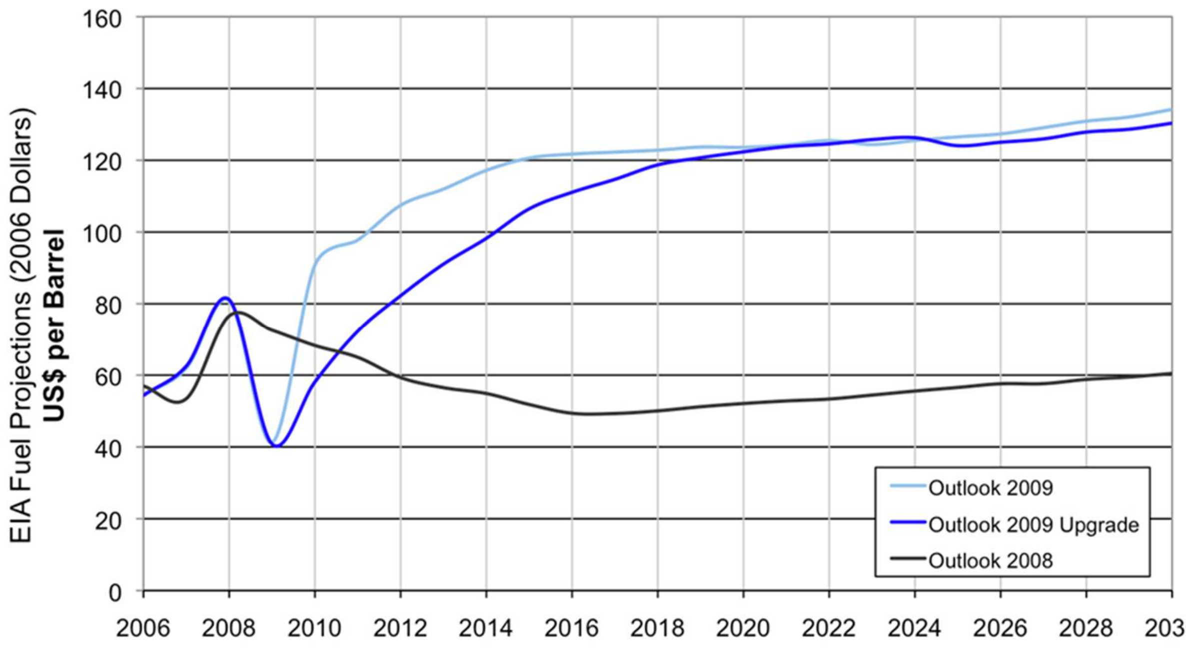


Figure 6-21 Oil price projections from 2008 to_2030 as predicted by the EIA

Source: Data from EIA 2008, Table 12; EIA 2009, Table 12; EIA 2009a, Table 12; own calculations.

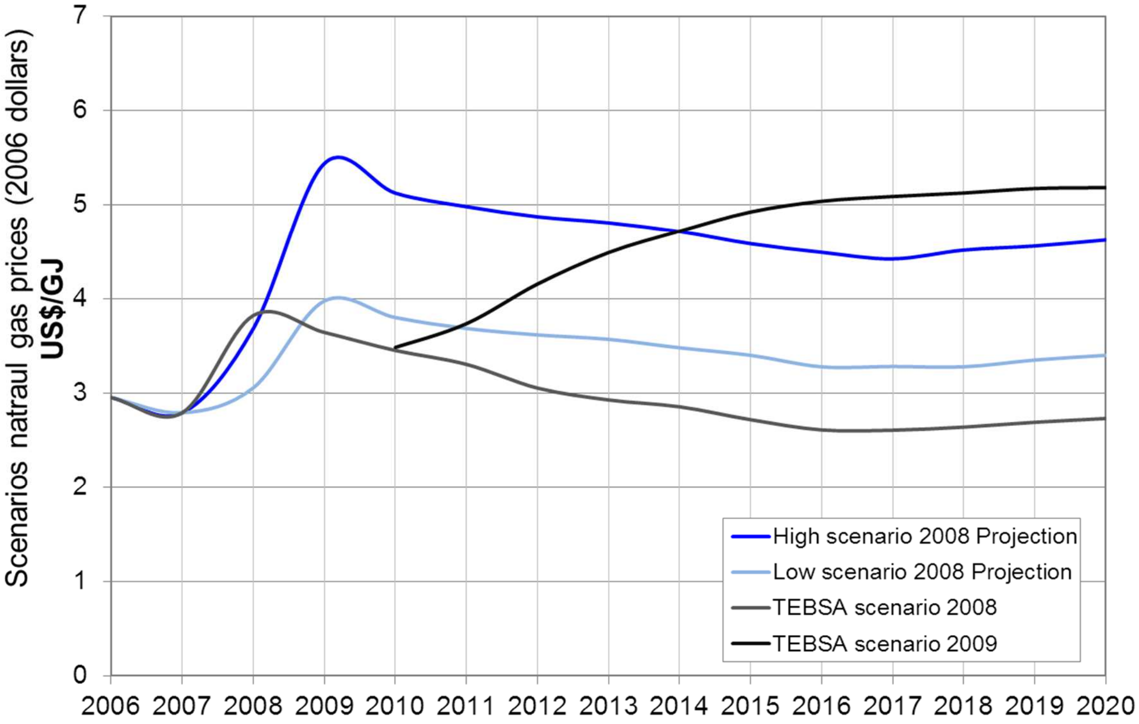


Figure 6-22 Projections available for natural gas prices

Source: Data from UPME 2007a, UPME and Naturgas 2008, UPME 2009a, own calculations.

In summary a sensitivity of the natural gas prices will be conducted in the energy models. The lowest price (TEBSA scenario 2008) and the latest projection (TEBSA scenario 2009) were selected to simulate a range of prices where prices will likely be.

6.7.3 Price of imported natural gas.

Current domestic natural gas reserves will be exhausted presumably before 2020. Therefore import of natural gas should be considered as an option to help meet the Colombian demand. An estimation of a price for natural gas imports is limited to imports from Venezuela or a world market for liquefied natural gas (LNG). Most Venezuelan gas is used for the exploitation of oil. Venezuela had the world’s eighth largest proven natural gas reserves (4.98 trillion m^3), which are still to be tapped, non-associated natural gas (not related to oil exploitation), for local and foreign markets (EIA 2011).

In order to have an indication of what price levels could be foreseen, an overview of international natural gas prices from the International Energy Agency, Greenpeace and the Energy Information Administration of the USA is shown in Table 6-16. For the energy models, a price for imported natural gas is assumed to be 5.69 USD/GJ (2006 USD) which would be 9% higher than the Colombian price in the high price scenario (5.21 USD/GJ).

Table 6-16 International natural gas prices

Source of imports	**2020** (US$/GJ)	**2030** (US$/GJ)
US Imports[1]		7.47
European Imports		6.95
Japanese Imports		7.43
US Imports[2]	13.81	15.29
European Imports	12.05	13.45
Japanese LNG	13.76	15.21
America[3]	5.60	
Europe	6.20	
Asia	7.80	
Reference[4]	7.78	
High oil price	8.06	
Low oil price	7.47	
Henry Hube Spot Price[5]	7.08	8.37
Average lower 48 Wellhead price	6.26	7.39

1 Price in 2006 USD. Source: IEA 2008, p. 573
2 Price in 2007 USD. Source: IEA 2008b, p.68
3 Price in 2000 USD. Source: Greenpeace 2007, p. 19
4 Price in 2007 USD. Source: EIA 2009, Table 12
5 Price in 2007 USD. Source: EIA 2009a Table A13.

6.8 COLOMBIAN COAL

6.8.1 Reserves and demand projections

As of 2009 Colombia had 6,668 Mt and 4.571 Mt of proved and indicative reserves respectively with a total potential of 16,669 Mt. With current exploitation rates and proved reserves, it is predicted that Colombia can supply international markets and the internal demand for 100 years (UPME 2010, p.68).

The exploitation of coal is mainly located at the Atlantic coast region. The mines in La Guajira and Cesar account for 90% of total Colombian coal production. The remaining 10% comes from mines in the Andean regions located in central Colombia (UPME 2010, p.75). Figure 6-23 shows the coal regions in Colombia.

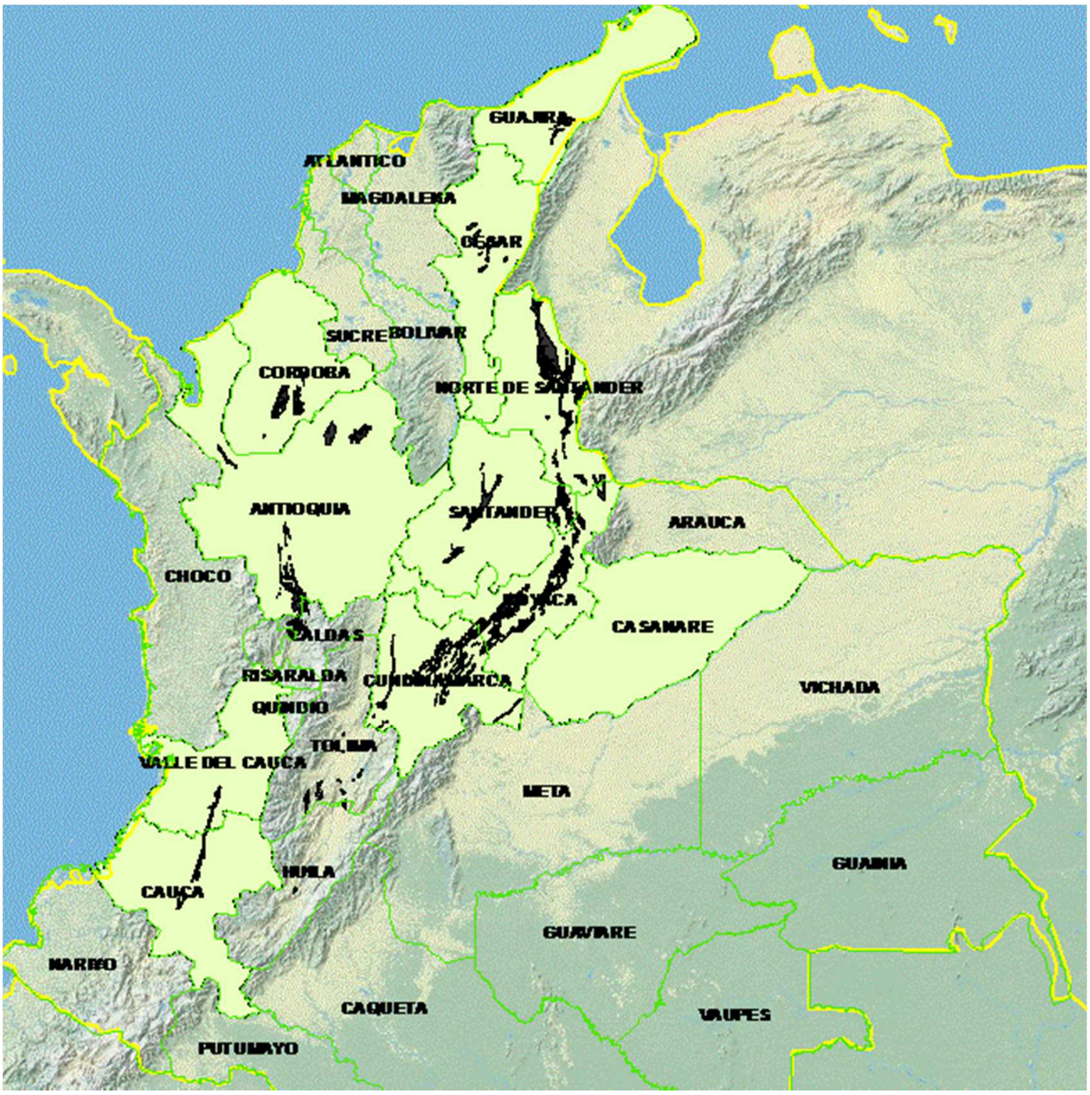


Figure 6-23 Colombian coal resources

Source: UPME 2012.

6.8.2 Coal price projection

Like the projections for natural gas, the projection of coal prices for thermal power is based on the official analysis of the Energy Planning Unit of the Ministry of Mines and Energy (UPME). Accordingly exploitation and transport costs are taken into account as well as the costs and projections of the EIA the United States' Department of Energy, to determine export prices (UPME 2007, p.78). The analysis was performed for the existing power plants. The results are shown in Figure 6-24.

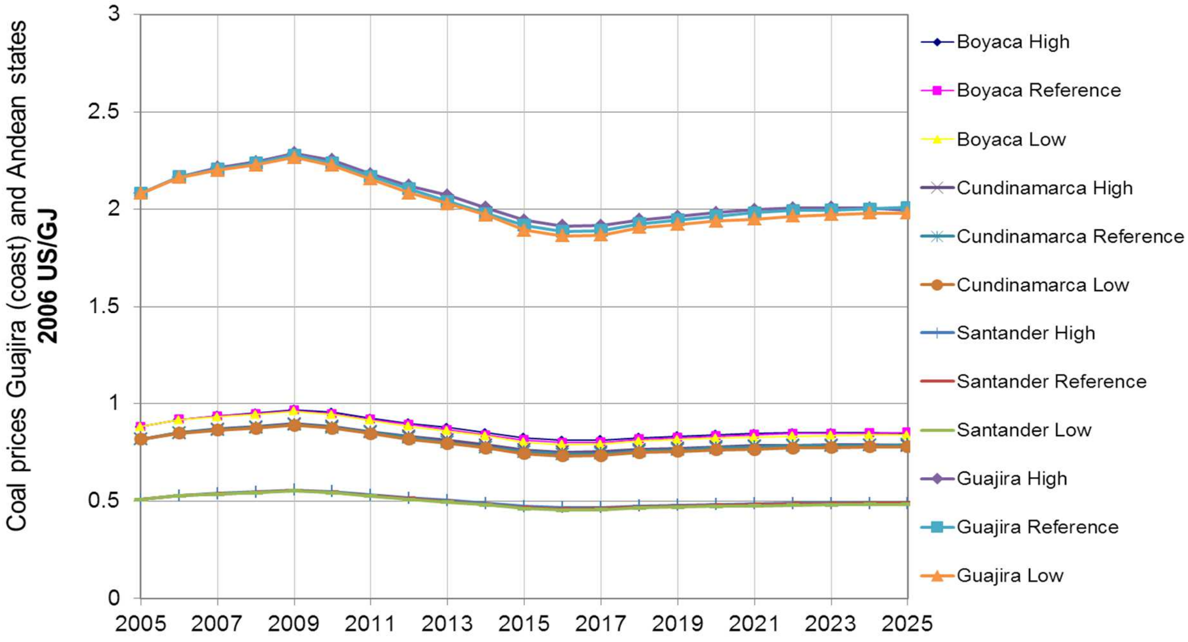


Figure 6-24 Coal price projections

Source: Data from UPME 2006, p.80, own calculations.

For the simulation in the energy models, the carbon price for power plants from the Guajira region is selected. Since most of the coal resources are located in this region, an expansion with coal power plants facing these prices driven by the international markets is expected. Latest coal prices reported by national statistics from 2008 to 2010 show prices levels of over 2.8 USD/GJ (after adjusting with inflation to be compared to 2006 USD prices), which suggest that the price projections should be seen as conservative in favor of technologies making use of coal (UPME 2010, p.90).

6.9 TECHNICAL PARAMETERS FOR RENEWABLE POWER AND CONVENTIONAL TECHNOLOGIES

The technical performance of the power technologies are simulated in the energy models. According to the literature review (*see* Chapter 5 for renewable energies technologies and Section 6.5 for conventional power technologies) a set of technical parameters were defined as shown in Table 6-18.

As hydropower drives the Colombian power system, the availability of water resources deserves special attention to be considered in the simulation. The contribution of hydropower is dependent on the availability of water resources, which is influenced by Colombia’s seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO). The ENSO is characterized by a variation in the temperatures of the surface waters of the tropical eastern Pacific Ocean which can cause extreme weather conditions (for example droughts caused by El Niño and floods by La Niña in Colombia) on a global scale, but in particular over South America. These extreme weather events can have a significant impact on Colombian hydropower generation.

In a cycle of El Niño and La Niña of around five years with differing intensities of droughts and floods, the availability of the water resources decreased causing thermal power plants to back up the lack of generation to cover the demand. This effect is shown in Figure 6-25.

In this case, a strong El Niño event reduced the share of hydropower to 40% of power generation. Under normal conditions the contribution of hydropower is over 70%. A more detailed analysis of the behaviour of hydropower plants in Colombia is provided in Chapter 10.

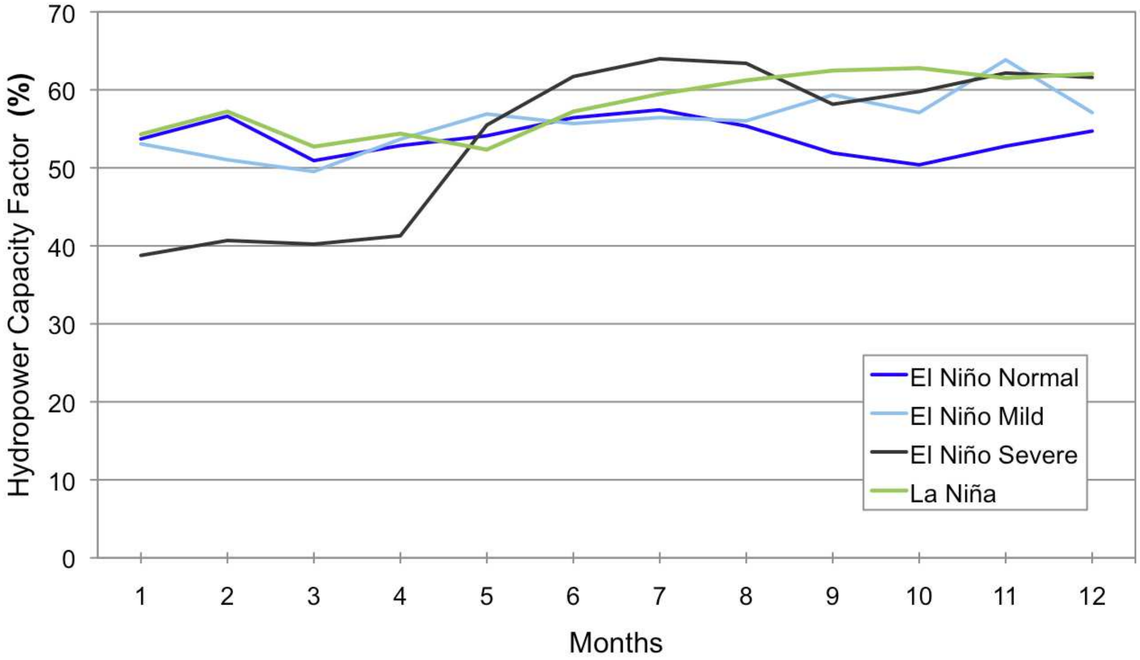


Figure 6-25 Capacity factor according to four climatology scenarios

Source: Data from XM 2011, own calculations.

The grade of accuracy of the energy models for the simulation of the technologies is not the same. In the case of hydropower, the capacity factor should be simulated per month. For the accounting framework model LEAP only three seasons per year can be modeled so the values of Figure 6-25 were averaged for seasons of 4 months. The particularities of the simulation in the energy models will be further described in the scenario analysis. The expansion of the system considers not only new power plants to be included by the energy model but also power plants under construction or approved to deliver electricity as listed in Table 6-17:

Table 6-17 Expected expansion of the Colombian power system

Sources: UPME 2008a, p.2; XM 2008, p.4; UPME 2007, p. 81.

Name	**Technology**	**Capacity** (MW)	**Year of operation**
Amoyá	Hydropower	78	2010
El Manso	Hydropower	27	2011
Bugalagrande	Hydropower	40.5	2010
Amaime	Hydropower	16.6	2010
Cucuana	Hydropower	60	2014
Miel II	Hydropower	135.2	2014
Porce III	Hydropower	660	2011
Porce IV	Hydropower	400	2015
Pescadero Itanguo	Hydropower	1.200	2018
Sogamoso	Hydropower	800	2014
Quimbo	Hydropower	396	2014
Termoflores IV	Combined cycle	160	2011

Finally, the reserve margin of the system which compares the maximum capacity of power plants and the peak of the system (normally in December) is set to be at least 20%, which is the minimum value required by the Colombian operation system (UPME 2005a, p. 92). This value is required to assure that the expansion considers this reserve.

Table 6-18 Technical parameters of power technologies

Power Technology[1]	*Existing Capacity [MW]*[2]	*New Size [MW]*[3]	*Lifetime [years]*[4]	*Decommissioning [year]*[5]	*Electrical Efficiency [%]*[6]						*Capacity Factor [%]*[7]	*Capacity Credit*[8]
					2006	*2010*	*2020*	*2030*	*2040*	*2050*		
Natural gas turbine	1,113	Existing	Existing	2034	33.9	33.9	33.9	33.9			70	
Natural gas combined cycle	1,919	Existing	Existing	2028	33.9	33.9	33.9	33.9			70	
Natural gas steam cycle	254	Existing	Existing	2010	33.9	33.9					70	
Coal power plant	976	Existing	Existing	2039	25	25	25	25			70	
Hydro reservoir >1.000 MW	2,636	Existing	Existing	> 2050							50 – 60	
Hydro reservoir < 100 MW	5,656	Existing	Existing	> 2050							50 – 60	
small hydro < 100 MW	658	Existing	Existing	> 2050							50 – 60	
Small thermal power plants	23	Existing	Existing	2015	30	30					70	
Cogeneration	25	Existing	Existing	> 2050	30	30	30	30	30	30	55	
Wind	18	Existing	Existing	2023							39	
New natural gas turbine	For expansion	150	40	-	35	35	35	35	35	35	90	100
New natural gas combined cycle	For expansion	500	40	-	57.2	58	61	63	63	64	80	100
New coal power plant	For expansion	300	40	-	41	45	50	52	53	53	80	100
New coal IGCC	For expansion	500	40	-	42	43.7	47.5	50	50	50	80	100

Power Technology[1]	*Existing Capacity [MW]*[2]	*New Size [MW]*[3]	*Lifetime [years]*[4]	*Decommissioning [year]*[5]	*Electrical Efficiency [%]*[6]						*Capacity Factor [%]*[7]	*Capacity Credit*[8]
					2006	*2010*	*2020*	*2030*	*2040*	*2050*		
New fluidised bed biomass	For expansion	100	40	-	40	40	40	40	40	40	80	100
New biomass IGCC	For expansion	200	40	-	42	43.7	47.5	50	50	50	80	100
New Wind	For expansion	Modular	20	-							33	20
New PV	For expansion	Modular	30	-							25.5	10
New solar CSP	For expansion	100	30	-							56	50
New geothermal	For expansion	50	40	-							80	100
New hydro reservoir	For expansion	600 - 1000	60	-							50 - 60	85
New hydro run-off	For expansion	100	60	-							50 - 60	85

Notes:

[1] Technologies for the simulation in the energy models for Colombia

[2] Existing power technologies in Colombian power sector as of 2006 (UPME 2007b, p.71). The power plants were grouped by technology

[3] Power plant sizes of new technologies. Wind and Solar are modular and their overall size (power park size) will be defined in the scenario analysis

[4] Lifetime of the technology which has to be replaced afterwards

[5] The commercial operation date of existing power plants was gathered to determine the year of decommissioning. The year shown corresponds to the last power plant

[6] The electrical efficiency of new technologies as reported by the literature review (*see* Section 6.5). Efficiencies of existing power plants with natural gas were calculated based on their actual production and consumption from 2003 to 2008 (data from XM 2009 and UPME 2008, p.151). Efficiency of existing coal is assumed to be 25%. Efficiencies for renewable energy power technologies are not required in the simulation since reserves from solar, wind and hydro energy sources do not need to be determined

[7] The maximum availability or capacity factor is the ratio of the maximum energy produced to what would have been produced if the process runs at full capacity for a given period (SEI 2006, p.24). For existing thermal power plants a lower availability of 70% was assumed. For hydropower resources the maximum availability under normal

conditions varies between 50 and 60 % as detailed in this subchapter. For renewable technologies the availability was set according to Chapter 4. The combination of the maximum availability and the rated power determines the energy contribution of the technology in the system

[8] Capacity credit is required for the expansion of the power system to consider the fraction of rated capacity that is firm in order to keep a minimum reserve margin of the entire system. A value of 100% is normally considered for thermal power, whereas intermittent energy sources have lower values (SEI 2006, p.113). Conservative capacity credits for wind and solar were assumed, which are lower than their capacity factor.

6.10 CO_2 EMISSION FACTORS AND PROPERTIES OF FOSSIL FUELS

For the simulation of CO_2 emissions in the energy models, the emission factors of fossil fuels were obtained from the program FECOC (Emissions factors for Colombian fuels) developed by the Colombian Science Academy for the Energy Planning Unit UPME (UPME 2005a, p.146). The program also delivers the heating values and chemical composition.

Table 6-19 Properties of fossil fuels

Source: Program FECOC (UPME-ACCEFYN 2003).

Fuel	Emission Factor	Higher Heating Value	Lower Heating Value
Coal Guajira	91,546 kg/TJ	29.06 MJ/kg	27.84 MJ/kg
Natural Gas Guajira	55,341 kg/TJ	39.40 MJ/Nm^3	35.51 MJ/Nm^3

7. SCENARIOS FOR THE COLOMBIAN POWER SECTOR

As per the methodology defined in Chapter 2, the scenario analysis of possible pathways that the power sector may take begins with the accounting framework model LEAP. LEAP will be used as a screening tool of possible scenarios to identify the cornerstones of the introduction of new technologies including renewable energy sources. Afterwards a simulation will be conducted in the optimization program MESSAGE.

This chapter introduces the scenarios created for the screening analysis. Each scenario is the result of an in-depth analysis of the functioning and features of the current power system along with the selection of future technologies that may be integrated into such a system depending on the resources and potential of both conventional and renewable energy sources in Colombia.

In general, scenarios fall into three categories: (1) more of the same; (2) more of the same but better or worse and (3) different but better (Schwartz 1991, p.20). A group of 10 scenarios were fashioned. They have been grouped in three families namely *business as usual scenario*, a *modest penetration of renewables* and a *renewable power system* with their respective variants. Substantial data was collected, analyzed, and determined to simulate the Colombian power system technically and economically in both models. During the description of scenarios the particularities of the energy model are introduced for a better understanding of the logic behind the simulation.

7.1 BUSINESS AS USUAL SCENARIOS

A business as usual scenario (BAU), or reference case, as it is also called is based on the assumption that the expansion of the power system will not experience transcendental changes in the way it develops as observed in the last years so the future power system will look similar to the current situation, more of the same. As shown in previous chapters, the electricity sector relies heavily on hydropower resources whereas thermal power plants, mostly run with natural gas, operate at sub-optimal efficiencies to cover the remaining demand. Hydropower amounts to 67% of the total generation capacity but delivers between 70% and 80% of the electricity generated. Regarding thermal power plants, around 5% run with coal and 27% with natural gas.

Table 7-1 and Figure 7-1 illustrate the capacity and generation of the power system from 2003 to 2009 respectively.

Table 7-1 Generation capacity in MW for the Colombian Power System, 2003 – 2007

	Hydropower		Coal		Gas		Wind		Others		Total
Year	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*	*(%)*	*(MW)*
2003	8839	67.0	692	5.2	3656	27.7	0	0.0	13	0.1	13200
2004	8923	66.5	692	5.2	3766	28.1	20	0.1	16	0.1	13417
2005	8948	67.0	694	5.2	3682	27.6	10	0.1	14	0.1	13348
2006	8956	67.4	700	5.3	3585	27.0	18	0.1	20	0.2	13279
2007	8997	67.1	700	5.2	3675	27.4	18	0.1	20	0.1	13410
2008	9002	66.8	700	5.2	3739	27.7	18	0.1	20	0.1	13479
2009	9036	66.7	700	5.2	3759	27.8	18	0.1	30	0.2	13543
2010	9026	66.5	700	5.2	3759	27.7	18	0.1	65	0.5	13568

Source: Data from XM (2011).

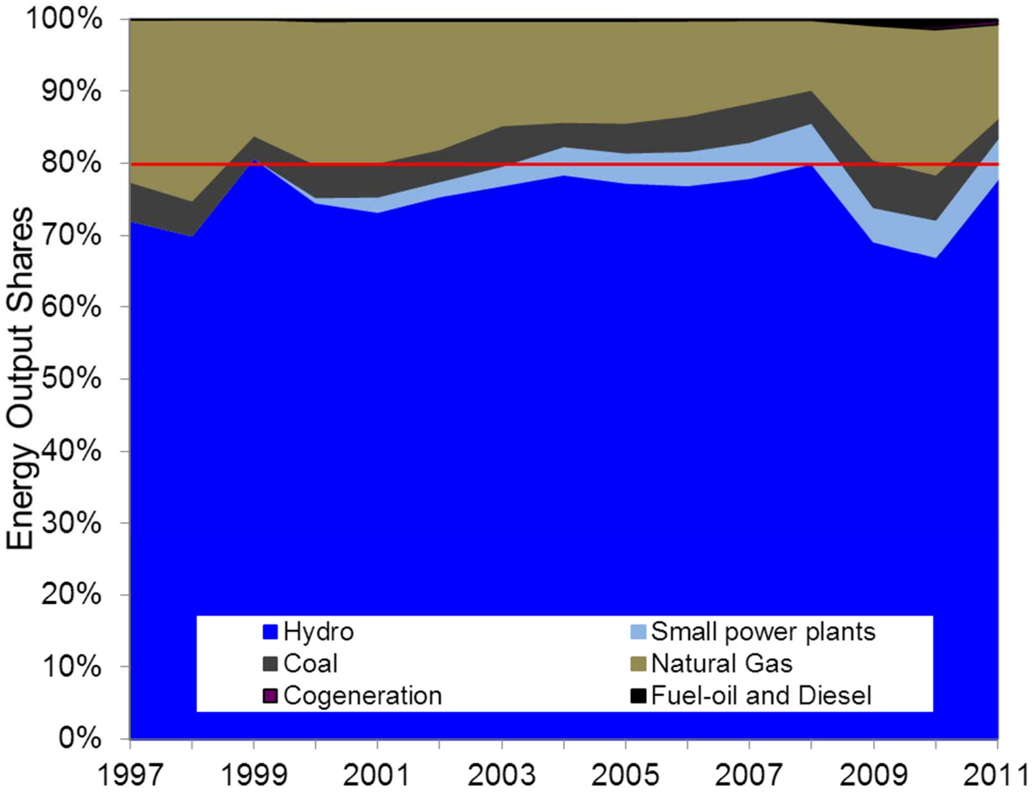


Figure 7-1 Energy output shares by energy source for the Colombian interconnected system (SIN)

Source: Data from XM 2011.

For the purpose of the screening methodology the BAU scenarios start from the premise that the expansion of the system is based on conventional energy sources such as hydropower, natural gas and coal and with state of the art technologies at the time the plant is added. The following subchapters introduce three variants that are plausible as future pathways for the expansion of the system:

7.1.1 Planned additions

In this scenario it is assumed that current capacities [MW] and generation [GWh] of the technologies with current energy sources will continue having the same shares. This means that large scale hydropower plants will continue playing a dominant role and there are no restrictions for the implementation for such large projects due to environmental, political, acceptance and conflicting local issues. The hydropower potential is still enormous, 84 GW, and will be exploited. Also, it is assumed that the availability of the water sources will not be changed over the years, so that any reduction of the ability to deliver firm power remains between the known margins, the capacity credit is kept constant, and the rain and dry seasons are within the known limits. To account for the seasonality of this resource, thermal power plants will continue to back up the system, as is done today.

Power plants fed with natural gas are further installed regardless of the availability of gas resources and any shortage is supplied by imported gas from Venezuela or LNG from the world market. Alternatively, new gas resources might be available. As new discoveries have not yet officially confirmed, the import of natural gas is assumed to take place. It is assumed that the required infrastructure for the transportation is at hand as other sectors also will rely on natural gas. Coal power plants will be also included, however playing a modest role in the production such as today’s current situation, despite the fact that coal resources are plenty in Colombia (coal resources are mostly exploited for foreign markets).

Accordingly, the expansion of the system in the accounting framework model LEAP is an input into the model instead of an endogenous output based on costs and/or environmental criteria. Thus, the following basket of technologies is added as shown in Table 7-2.

Table 7-2 Expansion in Planned Additions

Sequence	Technology	Unit Size	Efficiency *(%)*		Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
		(MW)	2006	2050	*(%)*	*(%)*	2006	2050	*(%)*	Rule
1	Gas turbine combined cycle	500	57	64	80	100	700	595	5	I.A.O.R.C*
2	Hydro-reservoir	1,000	-	-	40 - 62	85	1,055	1,055	2	I.A.O.R.C
3	Hydro run-off	100	-	-	40 - 62	85	2,500	2,500	2	I.A.O.R.C
4	Coal fired power plant	300	40	53	80	100	1,300	1,300	5	I.A.O.R.C
5	Gas turbine	150	35	35	90	100	495	495	5	I.A.O.R.C

* In ascending order of running cost

As shown in Table 7-2, cost and efficiency gains due to further development of the technology are entered into the simulation. Operation and maintenance costs are a percentage of the capital cost. The capacity credits listed are kept constant over the horizon of the analysis. The model adds new power plants according to the sequence listed on the table starting with the combined cycle as many times as required to ensure the reserve margin of the entire system. Typical unit sizes were selected for the expansion.

7.1.2 Planned with coal

Unlike the Planned Additions scenario, this scenario makes use of the abundance of coal resources available. Since proved reserves of natural gas will not last for the whole time horizon, coal resources will supply this shortage in the power sector. Current power plants will continue running with natural gas but new investments will shift to coal power plants. As the Planned Additions scenario hydropower plays a significant role and it is kept in that way. This situation may be the result of a system with the lowest cost possible and little regard for higher emission of pollutants and greenhouse gases (GHG).

Altogether, thermal power plants with natural gas continue having an important share in the first years and coal will increase its participation in the thermal power portfolio and will dominate the thermal power production in the long run. This scenario may also be seen as a BAU using more coal sources.

Accordingly, the expansion of the system in the accounting framework model LEAP is achieved with the following power generation technologies as shown in Table 7-3.

Table 7-3 Expansion in Planned with coal

Sequence	Technology	Unit Size	Efficiency *(%)*		Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
		(MW)	2006	2050	*(%)*	*(%)*	2006	2050	*(%)*	Rule
1	Integrated gas combined cycle	500	42	55	80	100	1800	1400	4,2	I.A.O.R.C*
2	Hydro-reservoir	1000	-	-	40 - 62	85	1055	1055	2	I.A.O.R.C
3	Hydro run-off	100	-	-	40 - 62	85	2500	2500	2	I.A.O.R.C
4	Coal fired power plant	300	40	53	80	100	1300	1300	5	I.A.O.R.C
5	Gas turbine	150	35	35	90	100	495	495	5	I.A.O.R.C

* In ascending order of running cost

The integrated gas combined cycle technology replaces the combined cycles. In that way, the system possesses the flexibility in the operation which gas turbines offer in comparison to conventional coal power plants with the classic steam cycle.

7.2 MODEST PENETRATION OF RENEWABLES

As the objective of this dissertation is to evaluate alternative pathways of the power generation expansion in Colombia, this scenario differs from the BAU by including new technologies based on renewable energy sources. The inclusion of these technologies in the system might be the result of market forces alone. In that case, price signals to attract investors and a level playing field for new technologies is in place.

However, knowing that the major bulk of power comes from hydropower resources with very low prices and coal and gas are currently the dominant fuels in the market, promotion mechanisms might be required to allow new technologies to enter the market.

It is worth noting that the inclusion of new technologies as an input into the model instead of an endogenous output based on costs and/or environmental criteria is performed here. As the philosophy of the screening analysis is to explore alternative scenarios to visualize the technical, economic and environmental repercussions, a modest and aggressive introduction of renewable energy sources is examined.

This demands an assessment of the renewable energy potential to determine conservative and optimistic figures with respect to a workable contribution of sources such as wind, solar, biomass and geothermal in the power system as conducted in Chapter 4.

In the following, the assumptions and selected contribution for a *modest penetration* of renewable for every source is introduced.

7.2.1 Wind

The best wind resource regime is found in the coastal Caribbean state of La Guajira. A potential of 22 GW were identified for this region (ESMAP 2007, p.27). As shown in Chapter 4, a potential between 5,000 and 10,000 MW is realistic for this region depending on the area availability for wind power development and without considering other good areas in other regions in Colombia.

For this scenario, with modest penetration of renewables, it is assumed that 5,000 MW of wind energy is feasible and easily reachable with only 2% of the area of La Guajira peninsula. As international experience shows, this can be achieved in a relatively short time period. In Germany, Denmark and Spain, where policies for the promotion of renewables are already in place, 5,000 MW were reached in 10 and 12 years in Germany and Spain respectively as shown in Figure 7-2. In Denmark, the 5,000 Benchmark has not been hit, but by being a relatively small country, the penetration of wind has been considerable.

As a possible development pathway for the wind energy development in Colombia, it is assumed that the installation of 5,000 MW is completed in a conservative period of time of 16 years. The wind energy growth rates from Spain, Figure 7-3, are taken to simulate the achievement of 5,000 MW in Colombia. For Germany, Denmark and Spain it has been observed that after 16 years the installation of more turbines begins to slow down, since the potential or maximum capacity and permitted areas allowed are close to being reached.

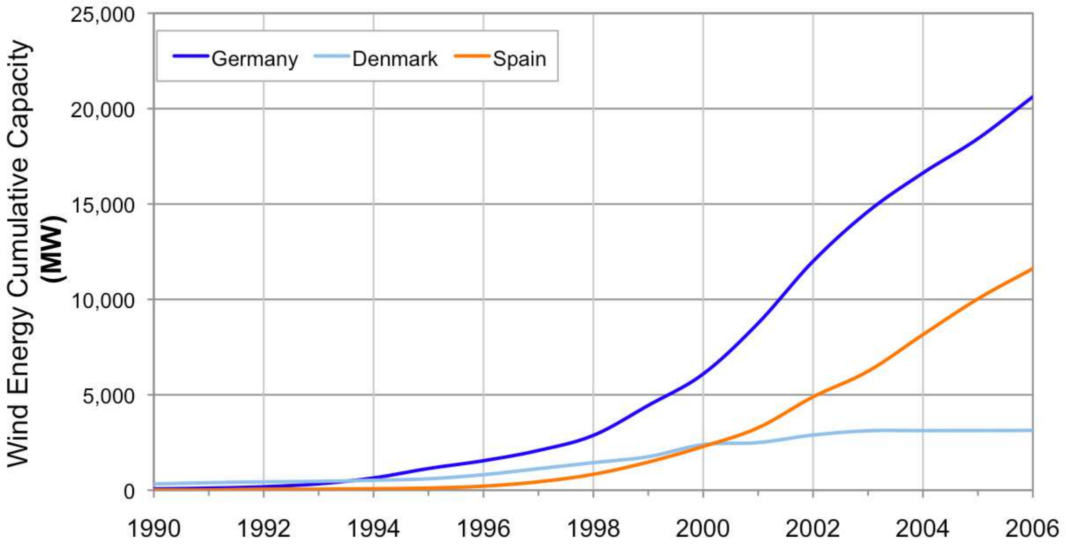


Figure 7-2 Cumulative wind energy capacity in Denmark, Germany and Spain

Source: Database Eurostat 2007, own calculations.

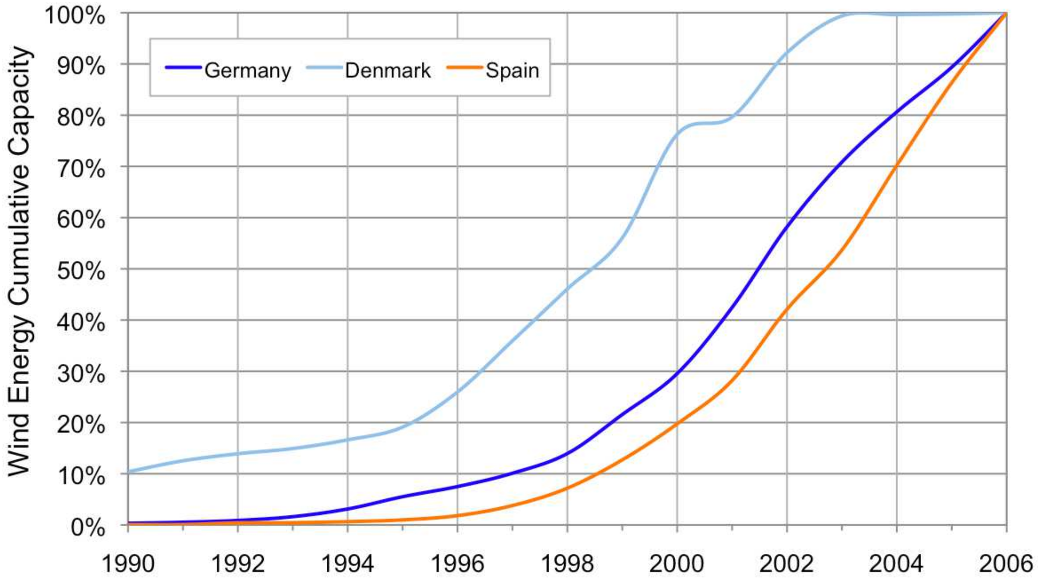


Figure 7-3 Relative wind capacity development in Denmark, Germany and Spain

Source: Database Eurostat 2007, own calculations.

The outcome to be simulated in the energy model is shown in Figure 7-4 for a period of 16 years starting in 2010. Afterwards, the 5,000 MW will remain constant until 2050. It means the replacement of old units after 20 years of operation takes place to maintain the capacity.

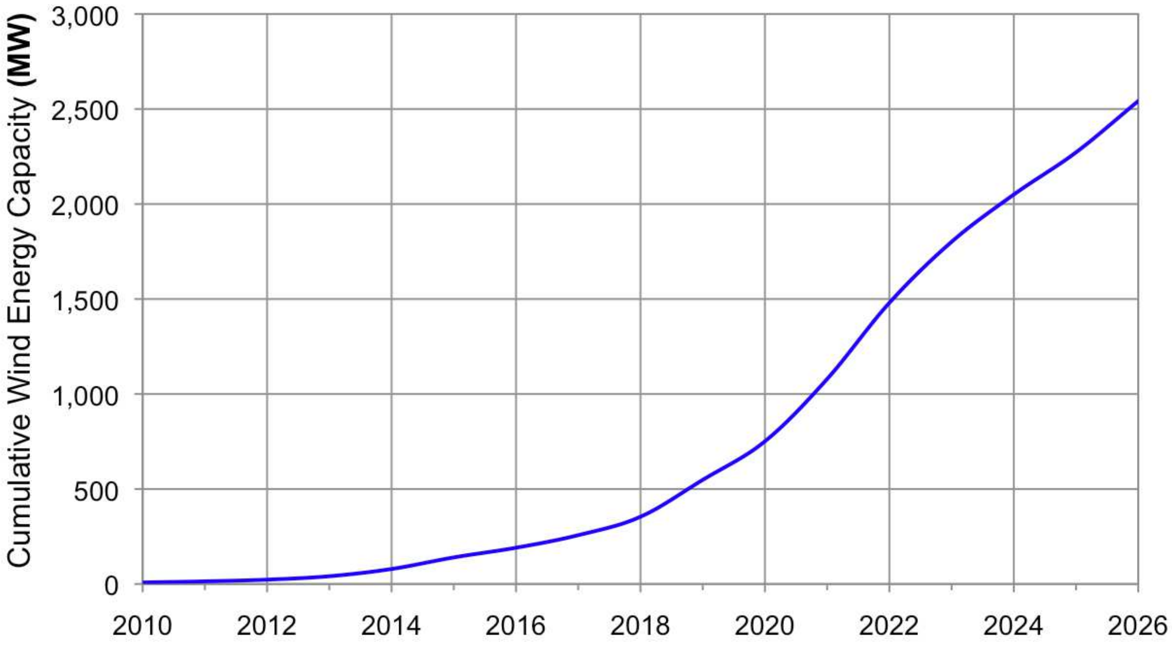


Figure 7-4 Cumulative wind capacity development

A summary of main technical and economical parameters of on-shore wind energy for the modeling is shown in Table 7-4.

Table 7-4 On-shore technical and economical parameters

Technology	Unit Size	Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
	(MW)	*(%)*	*(%)*	2006	2050	*(%)*	Rule
On-shore wind	2	30	20	1.200	783	3	R.F.C**

* For the modeling a value for every four-month period was entered.
** In the model all energy produced is taken (Run to full capacity)

As wind is an intermittent source of energy, the total wind energy production was simulated to be always dispatched.

7.2.2 Solar

Like the development of wind energy technology for large scale power generation, large solar power stations also contribute today to large scale power systems. Photovoltaic cells (PV) and concentrated solar power (CSP) are the two solar technologies being developed.

Similar as for wind, the Colombian Caribbean State of La Guajira is also proven to have the country's best solar resources along with other Caribbean coastal regions. The most promising technology for large scale solar applications may be CSP technologies, since CSP allows the thermal storage of energy and thereby improves the delivery of firm energy. Large scale solar power plants will be included in the simulation and it is assumed that PV and CSP plants will have a modest share of the Colombian system total capacity. For instance, with 1% of the area of La Guajira, 41 units of CSP power plants of 150 MW each can be installed amounting to 6,150 MW (*see* Chapter 4)

For a modest penetration of renewables in this scenario, only a share of the potential for 1% will be taken for both technologies. CSP power plants of 100 MW are to be installed every three years together with PV plants of 50 MW each. This yields 1,200 MW of CSP and 600 MW of PV in 2050 starting in 2015.

Alternatively, a scenario without PV plants will be simulated. Thus, the avoidance of additional investments on back-up technologies to keep the reserve margin of the system is included thanks to the higher capacity credit of CSP (thermal storage and operation flexibility) in comparison to PV. Therefore, 600 MW of PV will be replaced with CSP units for a total of 1,800 MW. Figure 7-5 exhibits the future capacity installation.

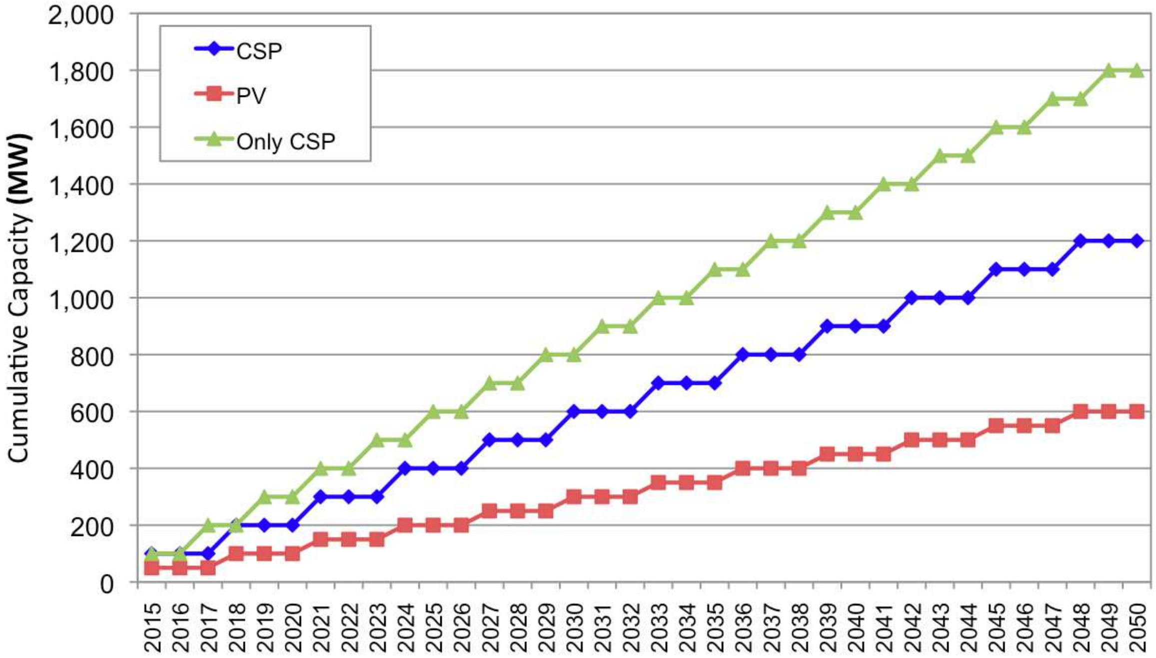


Figure 7-5 CSP and PV installation development

A summary of main technical and economical parameters of PV and CSP for the modeling is shown in Table 7-5.

Table 7-5 CSP and PV technical and economical parameters

Technology	Unit Size	Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
	(MW)	*(%)*	*(%)*	2006	2050	*(%)*	Rule
PV	50	25,5	10	3,705	693	1	R.F.C*
CSP	100 - 150	56	50	3,872	1,478	4	R.F.C

* In the model all energy produced is taken (Run to full capacity)

7.2.3 Geothermal

Colombia possesses the potential to produce power with geothermal resources. Unfortunately, the potential for geothermal power generation in Colombia has not yet been determined (*see* Chapter 4).

In other Latin American countries geothermal power plants for electricity production already exist as indicated in Table 7-6 , which shows that geothermal sources are successfully exploited and contribute to load base of power systems. Without having an idea of the potential, a conservative figure of the contribution of geothermal will consider the installation of 600 MW for this scenario assuming Colombia may reach at least 1 GW like Mexico.

Table 7-6 Geothermal capacity of Latin America

Country	Capacity *(MW)*
Mexico	953
Guatemala	53
El Salvador	204
Nicaragua	87
Costa Rica	163

Source: Fridleifsson 2008, p.60.

For the simulation, a power plant size of 50 MW is selected and installed every three years from 2015 to reach 600 MW in 2050 as shown in Figure 7-6.

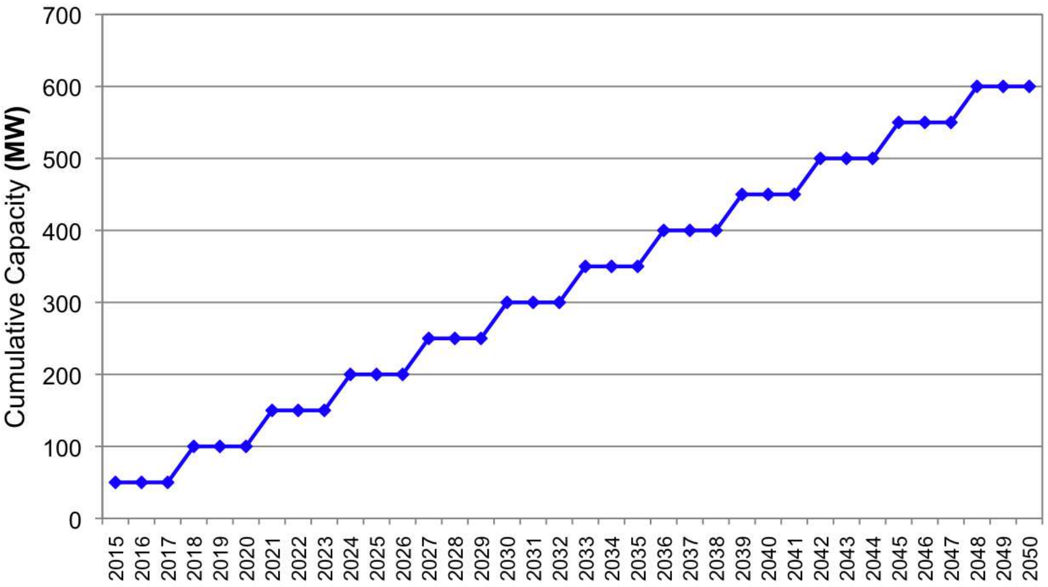


Figure 7-6 Geothermal installation development

A summary of main technical and economical parameters of the geothermal plants for the simulation is shown in Table 7-5.

Table 7-7 Geothermal technical and economical parameters

Technology	**Unit Size**	**Capacity Factor**	**Capacity Credit**	**Capital Cost** *(US 2005 Dollars/kW)*		**O&M**	**Dispatch**
	(MW)	*(%)*	*(%)*	2006	2050	*(%)*	Rule
Geothermal	50	80	100	1,685	1,203	2	R. F.C*

*In the model all energy produced is taken (Run to full capacity)

7.2.4 Biomass

The biomass potential of Colombia is vast. The assessment shows already as of 2006 a theoretical potential of 5,000 MW with crop residues that do not have a commercial use and therefore are accessible for power generation. The analysis also shows that the development of potential land use could yield over 59,000 MW from residues by optimizing the livestock areas so that more land is available for agriculture, forests and conservation. The expansion of agricultural areas of interest for power generation is from oil palm and sugar cane plantations. (*see* Chapter 4)

Unlike promising wind and solar resources located in specific areas, mainly in north Colombia, crop residues can be obtained practically all over the country where demand centers and the national grid are located. This offers technical and economic advantages by having the possibility of selecting from a wide range of suitable areas for their implementation.

Direct combustion of biomass and biomass integrated gas combined cycles (BIGCC) are the technological options selected for the modeling. Given the huge potential and flexibility in the plant location as conventional power technologies, biomass power plants will be included in the expansion cycle of the model. The expansion with biomass will be the result of the portfolio of technologies considered in the expansion cycle in LEAP as shown in Table 7-8. The main technical and economic parameters are shown in Table 7-8 as well.

7.2.5 Expansion cycle

This scenario, with a modest penetration of renewable sources of energy, can be seen as a future power system with a much more diversified mix of conventional and non-conventional technologies. Conventional technologies, including the combustion of biomass, belong to the expansion cycle endogenously modeled as shown in Table 7-8. In contrast, wind, solar and geothermal sources are forced to enter the system at the capacities and time schedules conceived as explained.

The intention is to continue running the system based on conventional technologies, in particular hydropower, and supported with the introduction of other renewable sources.

Table 7-8 Expansion in modest penetration of renewables

Sequence	Technology	Unit Size	Efficiency *(%)*		Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
		(MW)	2006	2050	*(%)*	*(%)*	2006	2050	*(%)*	Rule
1	Hydro-reservoir	1000	-	-	40 - 62	85	1055	1055	2	I.A.O.R.C*
2	Fluidised bed biomass	100	40	40	80	100	1975	1760	5	R.F.C**
3	Hydro-reservoir	600	-	-	40 - 62	85	1055	1055	2	I.A.O.R.C
4	Hydro run-off	100	-	-	40 - 62	85	2500	2500	2	I.A.O.R.C
5	Coal fired power plant	300	40	53	80	100	1300	1300	5	I.A.O.R.C
6	Gas turbine combined cycle	500	57	64	80	100	700	595	5	I.A.O.R.C
7	Biomass integrated gas combined cycle	200	42	50	80	100	4320	3211	6	R.F.C
8	Gas turbine	150	35	35	90	100	495	495	5	I.A.O.R.C

* In ascending order of running cost

** In the model all energy produced is taken (Run to full capacity)

7.3 RENEWABLE POWER SYSTEM

If the philosophy before was the combination of conventional and renewable energy technologies in the Colombian power system, in the present scenario renewable energy sources compose almost the entire system, so the contribution of fossil fuel power plants is pushed to a minimum. To achieve that, the contribution of wind, solar, biomass and geothermal sources is increased. Wind energy is greatly exploited together with the use of biomass. Instead, geothermal and solar are increased less intensively. As might be expected, hydropower will continue having a significant share both in the capacity and the production as it is the least cost technology with the best potential in Colombia.

This scenario is what might be called a sustainability scenario since it is being fed with sources that are likely to always be at disposal. This is converse to those systems reliant on fossil fuels as an energy source, which are depletable resources, and additionally bear heavy environmental costs, e.g. CO_2 emissions into the atmosphere.

This scenario assumes an effort to radically reshape the Colombian power system. Political will and energy policies tailored to the promotion of renewables are a must to accomplish such a change. The following section presents a description of how the renewable energy sources might enter into the system.

7.3.1 Wind

For this scenario the installation of 5,000 MW of on-shore wind energy from the modest penetration of renewables scenario is increased. By knowing that a capacity of 10,000 MW is feasible by increasing the dedicated area of the installation to around 4% of La Guajira peninsula, a further linear expansion of the existing 5,000 MW in 2026 takes place in a period of 16 years by 2042. The growth is assumed to be linear. Afterwards the capacity of 10,000 MW is maintained. After a 20 years life span, turbines are replaced with a same size unit from 2030 onwards. The main technical and economic parameters shown in Table 7-4 remain the same.

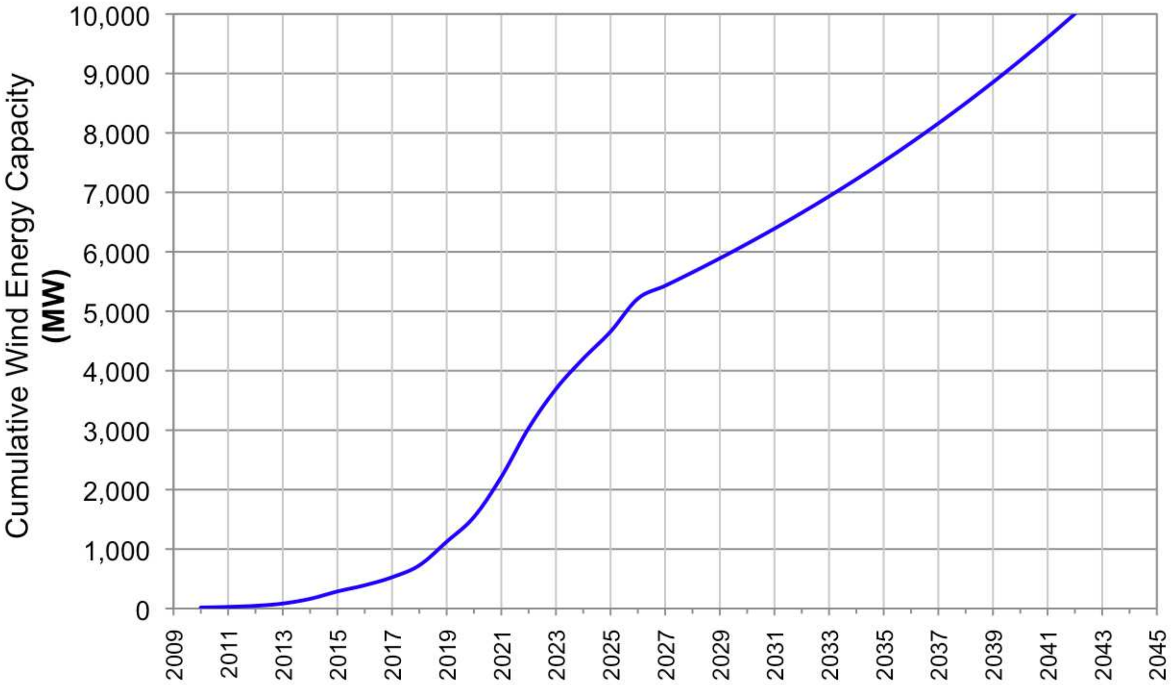


Figure 7-7 Cumulative wind energy capacity development

7.3.2 Solar

In contrast to the sizes and rates of installation of the solar technologies in the modest penetration of renewable scenario, the penetration rates are here modified to reach a higher capacity. For the CSP technology a power plant of 150 MW is selected and installed every three years to reach 2,700 MW. A goal for PV was set to 900 MW by installing units of 50 MW every two years. Accordingly, the introduction of exclusively CSP power plants are also modeled by installing two units of 100 MW every two years until completing 3,600 MW in the system by 2050. Figure 7-8 depicts the installation development for this scenario. The main technical and economic parameters remain the same as shown in Table 7-5.

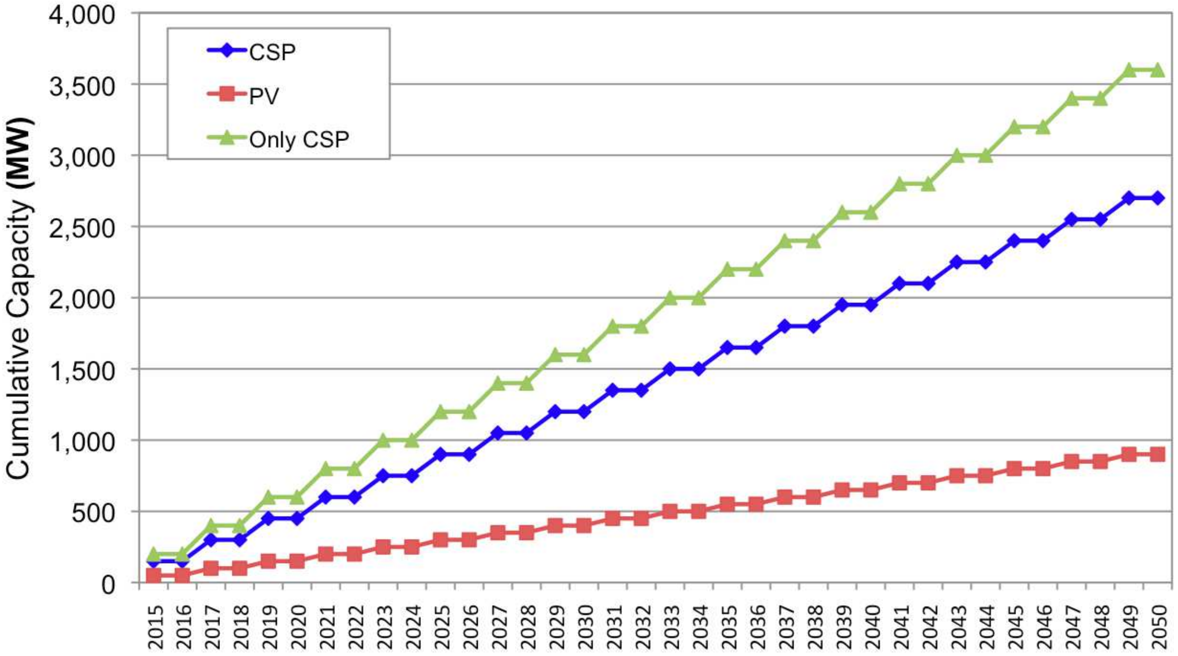


Figure 7-8 Cumulative CSP and PV installation development

7.3.3 Geothermal

The geothermal capacity is increased in this scenario to 900 MW in comparison to the modest penetration of renewables scenario. Thus, the goal of 1 GW is almost reached by installing 50 MW units every two years as shown in Figure 7-9. The technical parameters remain the same as shown in Table 7-7.

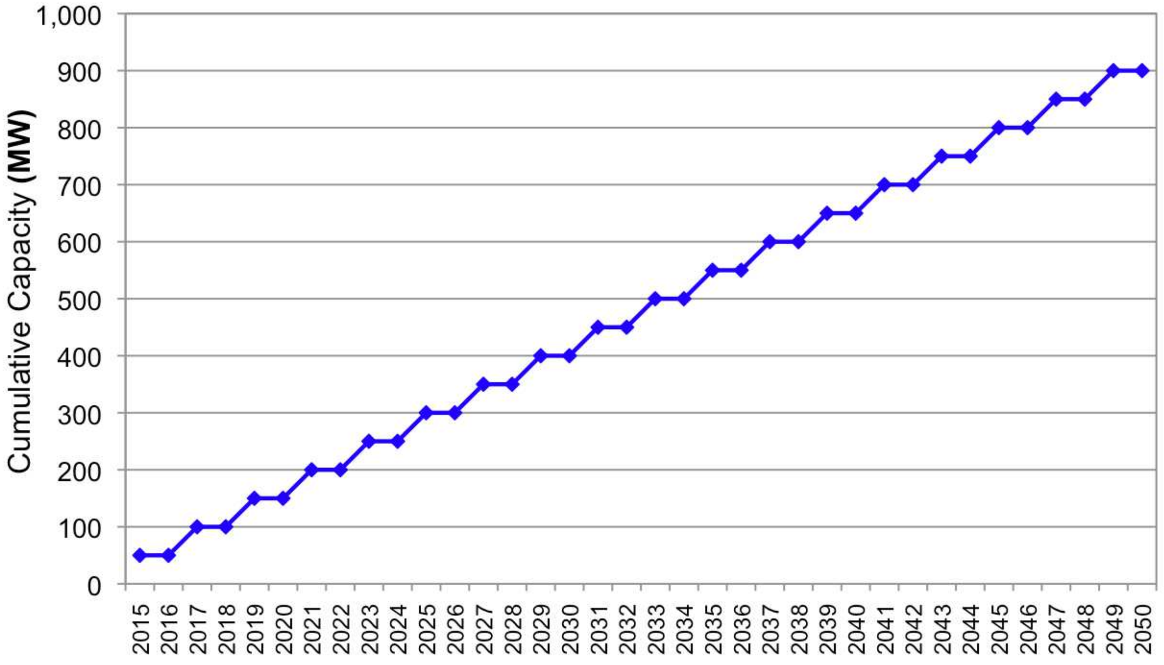


Figure 7-9 Cumulative geothermal installation development

7.3.4 Biomass

Direct combustion of biomass with fluidized bed combustion technologies and biomass integrated gas combined cycles (BIGCC) are engaged to contribute to the expansion of the system. This time, the sizes are doubled in the expansion cycle in order to increase their share in the system. Accordingly, the expansion will be modeled in the expansion cycle. The portfolio of technologies considered in the expansion cycle along with biomass is shown in Table 7-9.

7.3.5 Expansion cycle

Similar to the expansion cycle of the diversified system of the modest renewable penetration scenario, the portfolio of technologies are a mix of conventional and non-conventional technologies and sources. However, the gas turbine combined cycles were not included in order to continue pushing down the demand of natural gas. To cover for that loss, the capacity of biomass IGCC power plants shifts from 200 to 400 MW. Since coal resources are plenty, coal power plants are still in the expansion cycle together with gas turbines needed for backing up the system.

It is important to note that the contribution of wind and solar has been greatly increased which shrinks the penetration of conventional power plants. Thus, the system runs mostly based on renewable sources and the role of gas and coal are kept at minimum. Table 7-9 summarizes the main parameters of the expansion cycle for the modeling.

Table 7-9 Expansion in the renewable power system scenario

Sequence	Technology	Unit Size	Efficiency *(%)*		Capacity Factor	Capacity Credit	Capital Cost *(US 2005 Dollars/kW)*		O&M	Dispatch
		(MW)	2006	2050	*(%)*	*(%)*	2006	2050	*(%)*	Rule
1	Hydro-reservoir	1,000	-	-	40 - 62	85	1,055	1,055	2	I.A.O.R.C*
2	Fluidized bed biomass	200	40	40	80	100	1,975	1,760	5	R.F.C**
3	Hydro-reservoir	600	-	-	40 - 62	85	1,055	1,055	2	I.A.O.R.C
4	Coal fired power plant	300	40	53	80	100	1,300	1,300	5	I.A.O.R.C
5	Hydro run-off	100	-	-	40 - 62	85	2,500	2,500	2	I.A.O.R.C
6	Gas turbine	150	35	35	90	100	495	495	5	I.A.O.R.C
7	Biomass integrated gas combined cycle	400	42	50	80	100	4,320	3,211	6	R.F.C

* In ascending order of running cost

** ** In the model all energy produced is taken (Run to full capacity)

7.4 SENSITIVITY ANALYSIS

At this point, the scenarios' economic and technical parameters required by the screening methodology with LEAP have been defined. In order to make the simulation more robust and obtain more accurate results, a sensitivity analysis was conducted. Before introducing the variables to be tested in the sensitivity analysis, a summary of the three scenario families presented in the previous subchapters is first given to provide a better view of the screening procedure.

Table 7-10 Technologies for scenarios and given output [MW]

Technology	Planned Additions	Planned Coal	Modest Renewables	Renewable
Wind	-	-	5,000	10,000
Solar PV	-	-	600	900
Solar CSP	-	-	1,200 – 1,800	2,700 – 3,600
Geothermal	-	-	600	900
Fluidised bed biomass	-	-	Model Output	
Biomass integrated gas combined cycle	-	-	Model Output	
Co-firing with biomass	-	-	Model Output	
Hydro-reservoir	Model Output			
Hydro run-off	Model Output			
Gas turbine	Model Output			
Gas turbine combined cycle	Model Output	-	Model Output	-
Coal fired power plant	Model Output			
Integrated gas combined cycle	-	Model Output	-	-

The capacity and generation quantities are endogenously determined by the model according to the expansion cycle and technical and economic parameters introduced before for every scenario (*see* Table 7-8 and Table 7-9). An exception to that is wind energy, solar and geothermal sources, where the capacity is exogenously set and the full generation is delivered to the system.

For the model's sensitivity analysis, most of the technical parameters for all technologies are not changed. The technical parameters are the result of a literature review. Instead, a high uncertainty can be expected from economic variables. For that reason, the sensitivity analysis includes the following variables critical to the system:

- Investment costs of renewables due to a range of investment prices and the uncertainty on future penetration to decrease the cost.
- Cost of fossil fuels which depends on oil prices projections which vary.
- Discount factors which also may change according to investor expectations and financial conditions.

Regarding the investment costs of conventional technologies, the results of the literature (review) do not present drastic changes and thereby their cost projections are not altered (*see* Chapter 4).

From a technical point of view, issues such as the availability of water resources, public acceptance for large hydropower, planning issues, climate change, etc. are worth considering. Despite the fact that any effect on the contribution of hydropower due to this issues is not clearly foreseeable; the ability of hydropower plants to deliver energy and contribute greatly to the expansion of the system might be compromised. Thus, the capacity credit might be reduced and the expansion might be changed either by not including and/or reducing the unit size of a hydropower plant. As a consequence, less hydropower capacity will be in the system allowing other technologies to have a higher participation.

For the reasons above, the modeling with the accounting framework model LEAP for the screening analysis and subsequently with the optimization model MESSAGE must take into account, for the running of the scenarios, the uncertainty on both the technical and economic sensitive variables. Table 7-11 and Table 7-12 exhibit the parameters to be changed to test the influence from them on the results and ultimately test the power system.

Table 7-11 Economic variables for sensitivity analysis

Variable	Description
Natural gas price	Low prices: Natural gas prices from power plant TEBSA and projection with low price EIA data from year 2008 which corresponds to the lowest natural gas price projection High prices: According to latest analysis from UPME without gas price regulation
Coal price	Low and high prices from the Cerrejón open mine are taken.
Capital cost of renewables	Low cost: Lowest capital cost with a high penetration worldwide of renewables High cost: Highest cost of renewables with low penetration of renewables worldwide.
Discount factor	A standard value of 10% is applied. Values of 0%, 5% and 15% are also simulated

Table 7-12 Technical variables for sensitivity analysis

Variable	Description
Capacity credit hydropower	85% as a high value and a reduction from 85% to 70% from 2006 to 2020. Afterwards, it is kept at 70%.
Expansion with hydropower	Planned Additions: Unit size reduced from 1000 MW to 600 MW in expansion cycle (*see* Table 7-2) Planned with coal: Unit size reduced from 1000 MW to 600 MW in expansion cycle (*see* Table 7-3) Modest penetration: The unit of 600 MW is removed from expansion cycle (*see* Table 7-8) Renewable power system: The unit of 600 MW is removed from expansion cycle (*see* Table 7-9)

8. SCREENING ANALYSIS

The aim of the screening analysis with the accounting framework model LEAP is to obtain a first inside view of how the power system could be expanded according to the scenario families introduced and to evaluate technically, economically and environmentally the performance of the system. The model LEAP has expanded the system with the technologies assigned to every scenario following the predefined capacity development for renewable energy technologies and the expansion cycle for all other power technologies. Thus, the generation required to cover growing demand and the overall capacity required for the system are obtained. As soon as the system is defined technically, the bookkeeping of the economic parameters and emissions of greenhouse gases and pollutants is computed.

The main results to be introduced in this chapter are therefore the capacity (GW), the energy output (GWh), the net present value of the overall power system (capital, O&M, and fuel costs in 2006 Million USD), CO_2 emissions (Million tonnes). With this information for every scenario an assessment of the scenarios is conducted. This assessment is the purpose of this chapter. To facilitate the interpretation of the results, they are presented per scenario. An overall analysis is later introduced and a summary of the main findings closes the chapter.

8.1 PLANNED ADDITIONS

The Colombian power system is expanded with today’s conventional energy sources. The same shares in the capacity and the production are maintained. In other words, the current portfolio of technologies and energy sources are scaled for the future (more of the same scenario).

Consequently, the system delivers 50.8 TWh in 2006 and produces 230.4 TWh by 2050 which is around 4.5 times the existing demand. The share of hydropower over the time horizon is mostly between 70% and 80% and the fossil fuels cover what remains with still more natural gas than coal as shown in Figure 8-1.

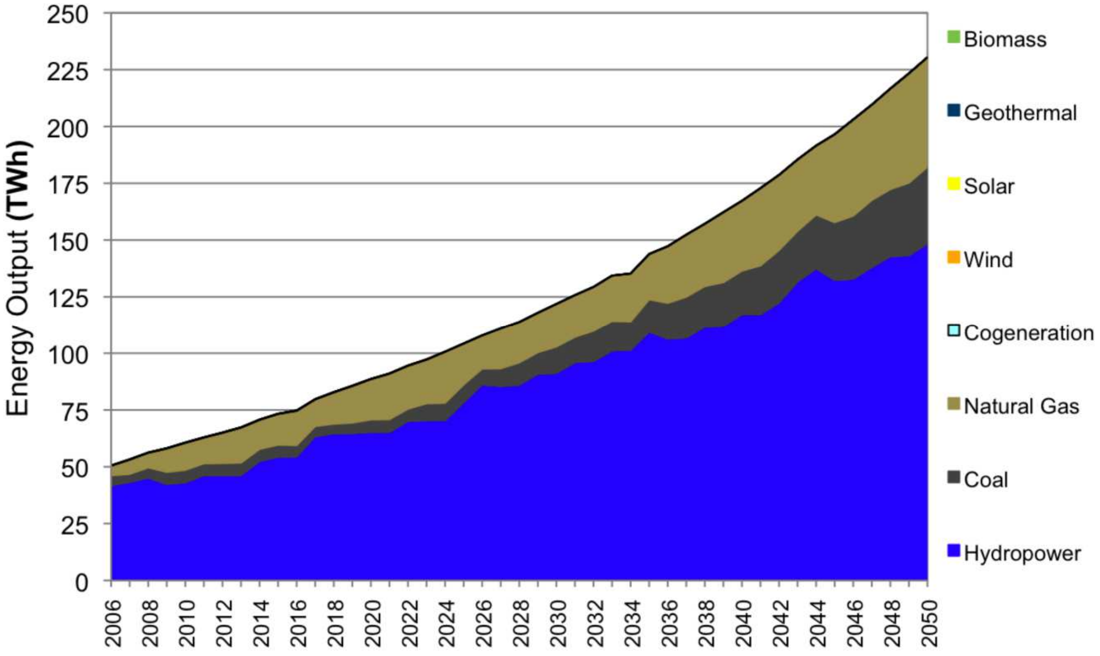


Figure 8-1 Energy output planned additions

The fluctuating delivery of power from hydropower plants is due to the availability of the resource in given years as entered into the model.

Regarding the capacity of the system, Figure 8-2 exhibits the results. The system is expanded from 13.3 GW in 2006 to 47.6 GW by 2050, almost four times the current power capacity. The capacity shares of every energy source are similar to the base year, 2006, all over the time horizon. Hydropower continues to be the major electricity source in the system.

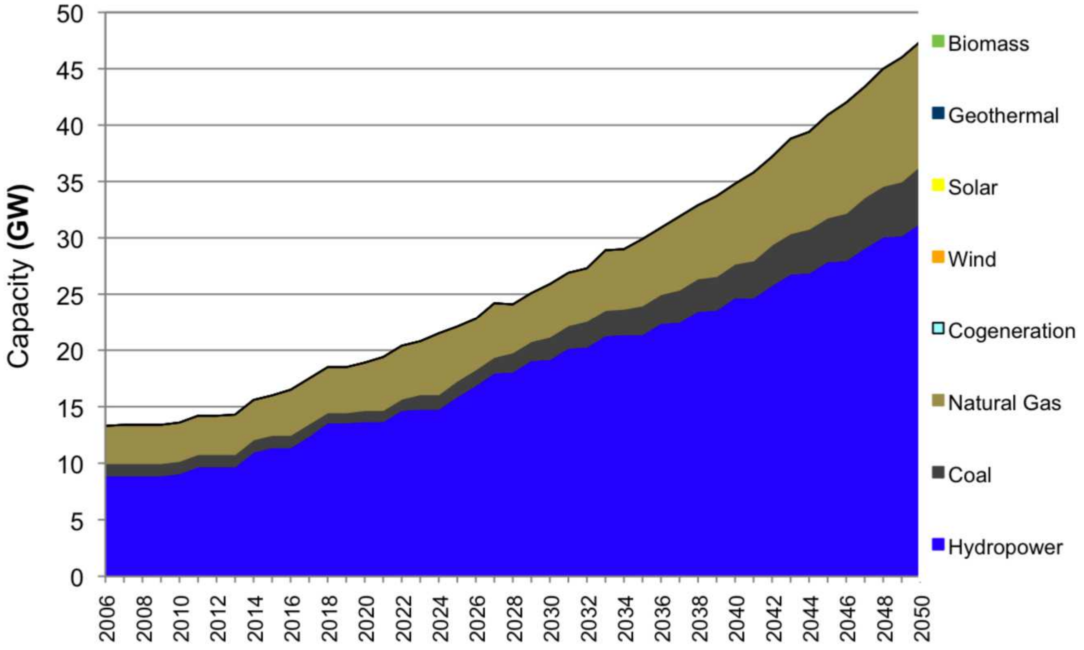


Figure 8-2 Capacity planned additions

By generating electricity with natural gas and coal, the system releases 833 million tonnes of CO_2 into the atmosphere in total over a period of 40 years as shown Figure 8-3.

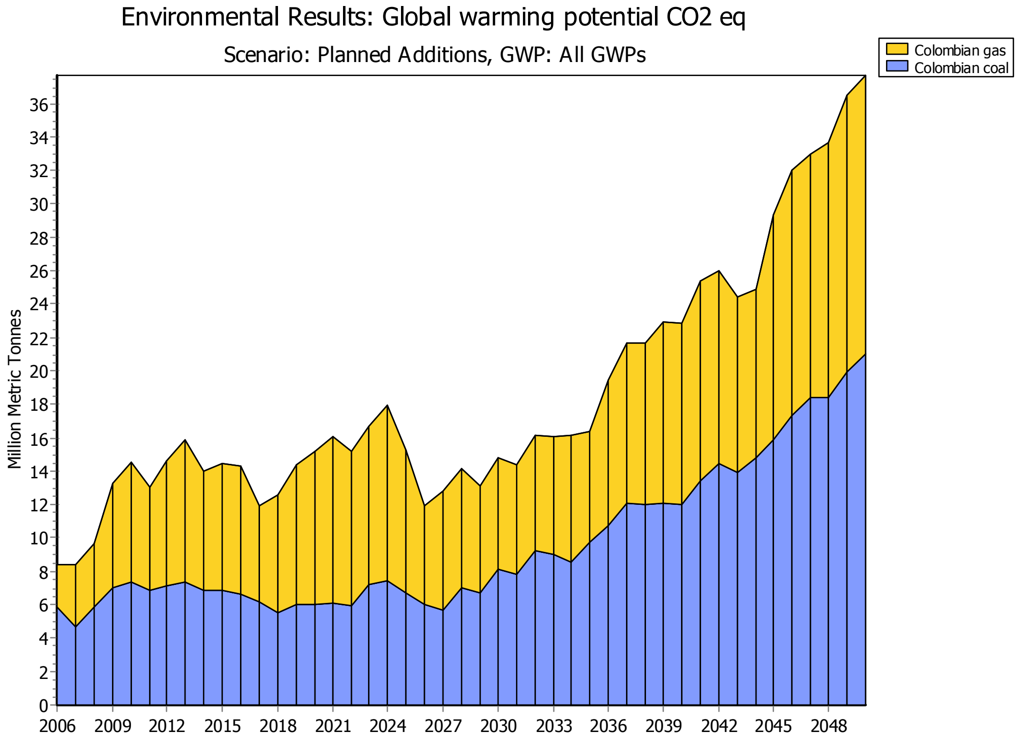


Figure 8-3 CO_2 emissions with planned additions scenario

8.2 PLANNED WITH COAL

The results show the effect of shifting the future thermal power investments towards coal power technologies and over time relying less on scarce natural gas resources as shown in Figure 8-4. The system runs on existing natural gas turbines and gradually the energy production is based on coal resources. As usual, hydropower dominates the system. A total of 230.4 TWh are generated by 2050, where coal has a share of 33% of the total energy production which is an increase from the 8% in the base year. Hydropower has a share of 64% by 2050. In contrast the participation of gas decreases from a high of 20% in 2010 to less than 3% in the energy production.

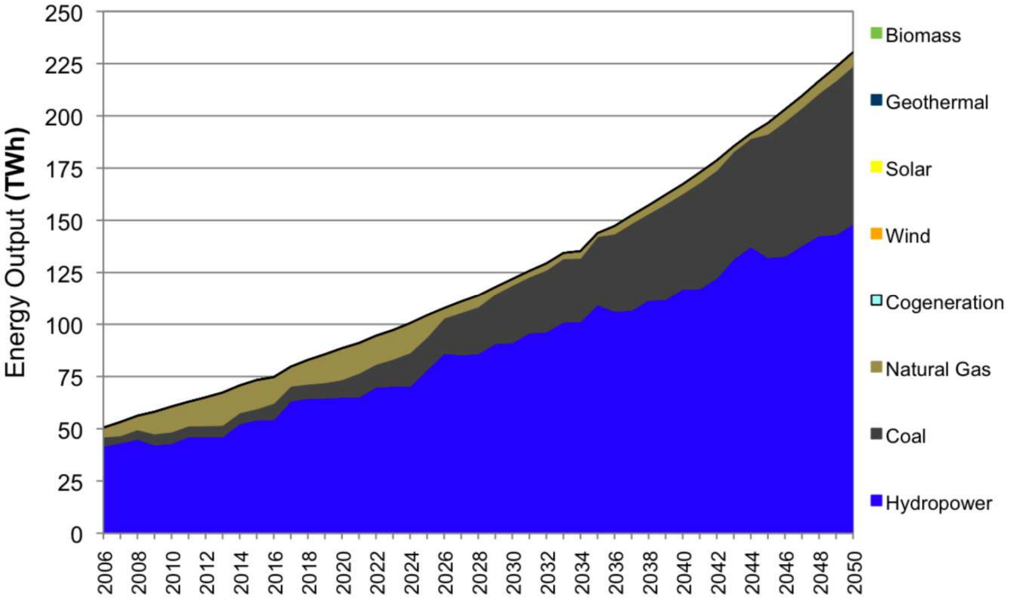


Figure 8-4 Energy output planned coal

The capacity expansion of the system is not altered by introducing direct combustion coal technologies and coal gasification combined cycles. Since coal power and the natural gas technologies have similar technical features in the model, namely the capacity credit, the reserve margin is still kept regardless of the introduction either of gas or coal technologies. Therefore, the same power of 47.6 GW by 2050 is also obtained. From the 7% coal share in the first 15 years, in which current natural gas power plants are replaced, coal technologies reach a share of 29% at the end of the period. In total 8,500 MW of IGCC power plants are installed together with 5,100 MW of direct combustion coal power plants. 66% of the overall capacity is based on hydropower by 2050. The results are shown in Figure 8-5.

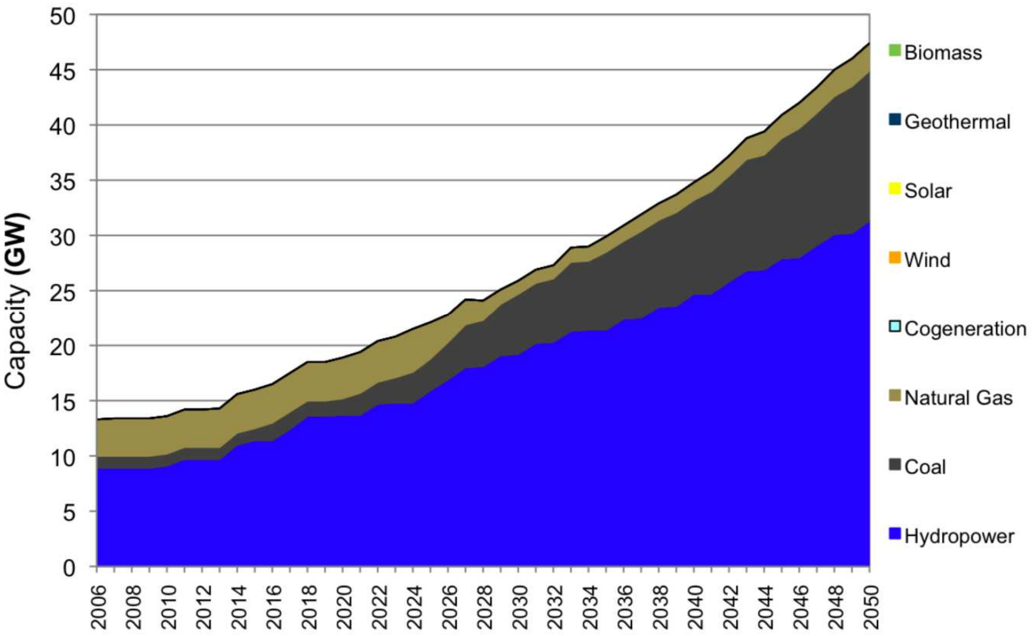


Figure 8-5 Capacity planned coal

An immediate effect of burning more coal sources is the increase of CO_2 emissions in comparison to cleaner natural gas. 1,061 million tonnes of CO_2 (*see* Figure 8-6) are released over a period of 40 years.

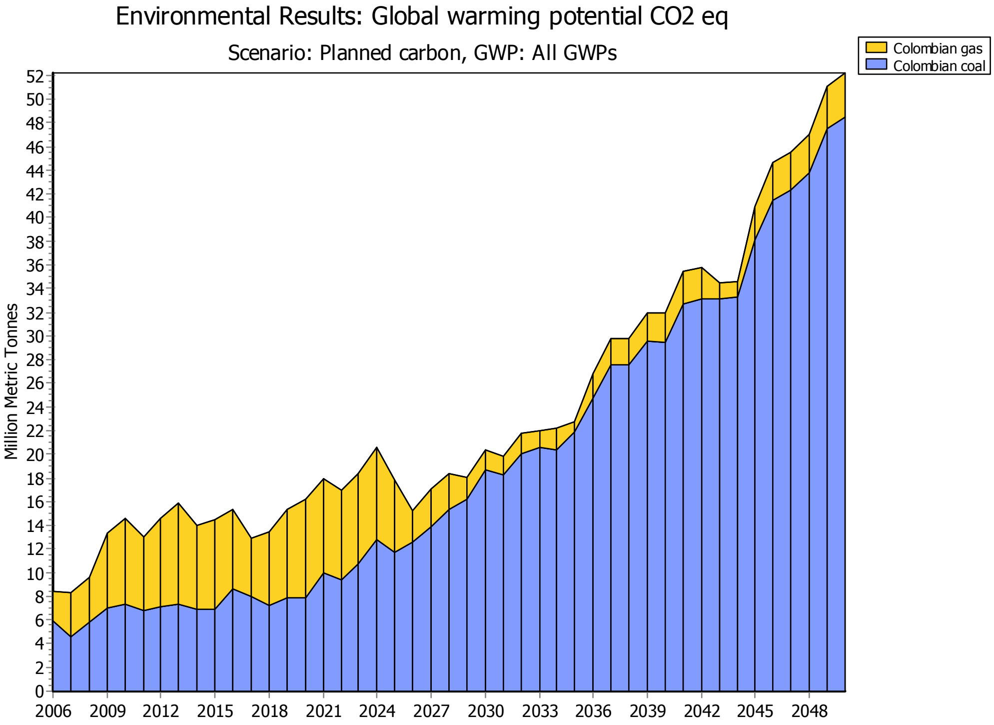


Figure 8-6 CO_2 emissions with coal expansion scenario

8.3 MODEST INTRODUCTION OF RENEWABLES

This scenario is the combination of conventional and non-conventional energy sources in the power system, where a full range of technologies make a contribution to the system. Thus, the energy sources are enhanced as can be seen in Figure 8-7.

The effect of forcing the model to include renewable sources, which is analogous to a policy for the promotion of new technologies, shows the displacement of generation from conventional sources, especially natural gas and coal energy sources. Hydropower supports the system but the current generation from thermal power plants decreases as solar, wind, geothermal, and biomass sources enter the system. This trend is notably visible by the year 2030. As soon as the contribution of wind, solar, and geothermal reach the capacity set in the scenario and it is not increased, other sources engage to expand the system. That is why coal and natural sources start to increase their share in the system from 8,400 GWh in 2030 to 37,800 GWh by 2050. In this case biomass contribute to not allowing the thermal sources to have a bigger share, since there is no a given capacity of biomass technologies in the system like the other new renewables and the share increases over the years.

As in other scenarios, hydropower continues to be the major electricity source in the system. However the share of hydropower and thermal power plants is reduced due to the inclusion of renewable energy sources.

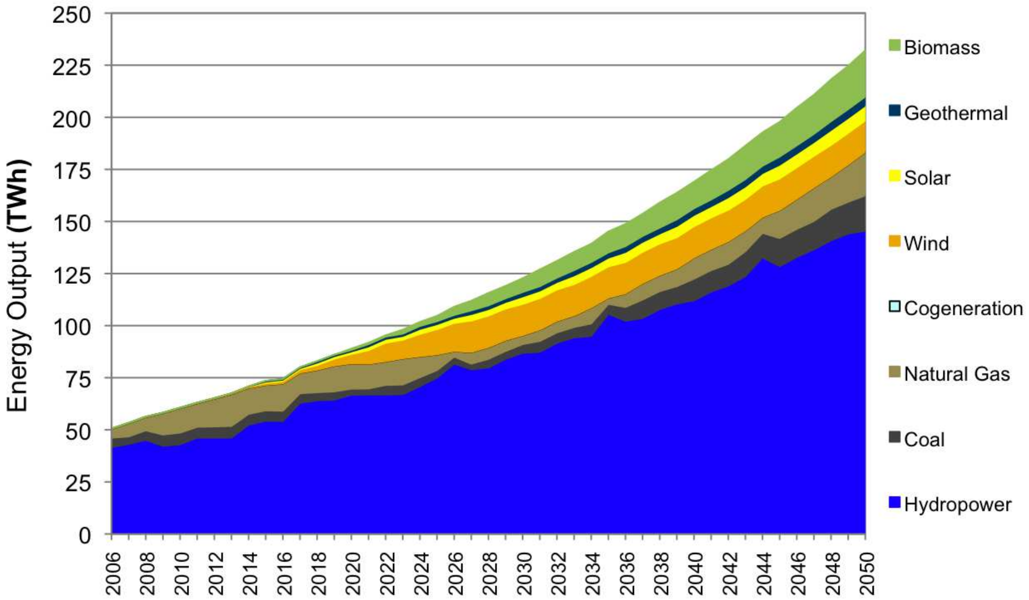


Figure 8-7 Energy output: Modest introduction of renewables

Regarding the capacity, a similar situation is observed as shown in Figure 8-8. Wind energy has the largest share of new renewables in GW but after completing the expansion of 5,000

MW of wind, coal and gas technologies must enter the system again to help the expansion. By including intermittent sources of energy like wind and solar, reserve capacity is required to back up the system as soon as those sources are not available. This aspect is considered by including the capacity credit of every source and its power generation technology. The results show that the system grows from the 13.3 GW from the base year 2006 to 52.9 GW by 2050 which is a larger capacity in comparison to business as usual family scenarios (47.6 GW from planned additions and planned with coal) due to the nature of the wind and solar resources.

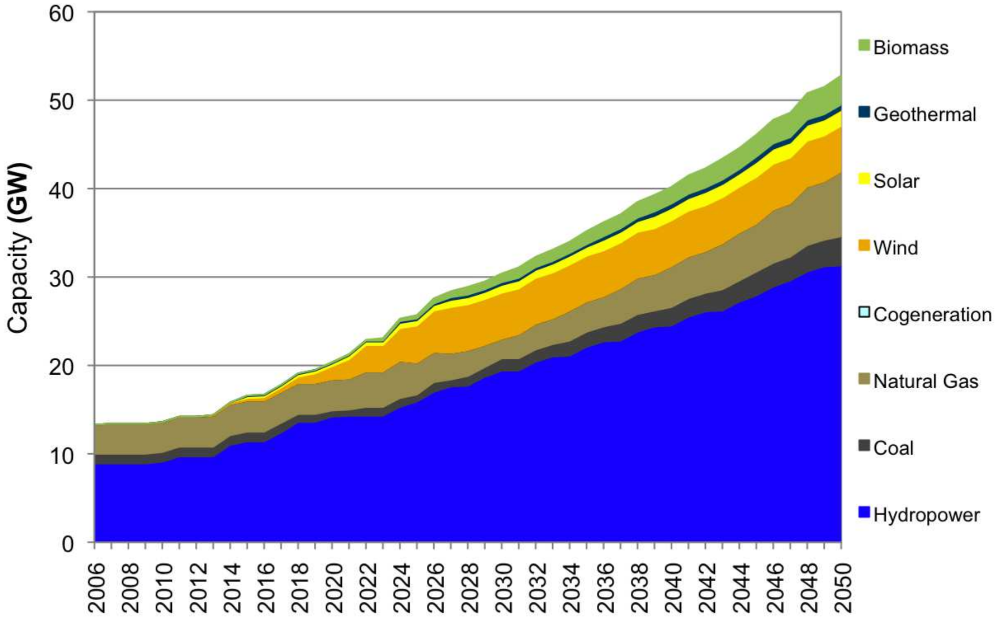


Figure 8-8 Capacity: Modest introduction of renewables

Unlike business as usual scenarios, the inclusion of new energy sources different from natural gas, coal and hydropower diversifies the portfolio of sources and technologies in the system. To illustrate this, Figure 8-9 shows the percentage contribution of renewables during the time horizon of the analysis.

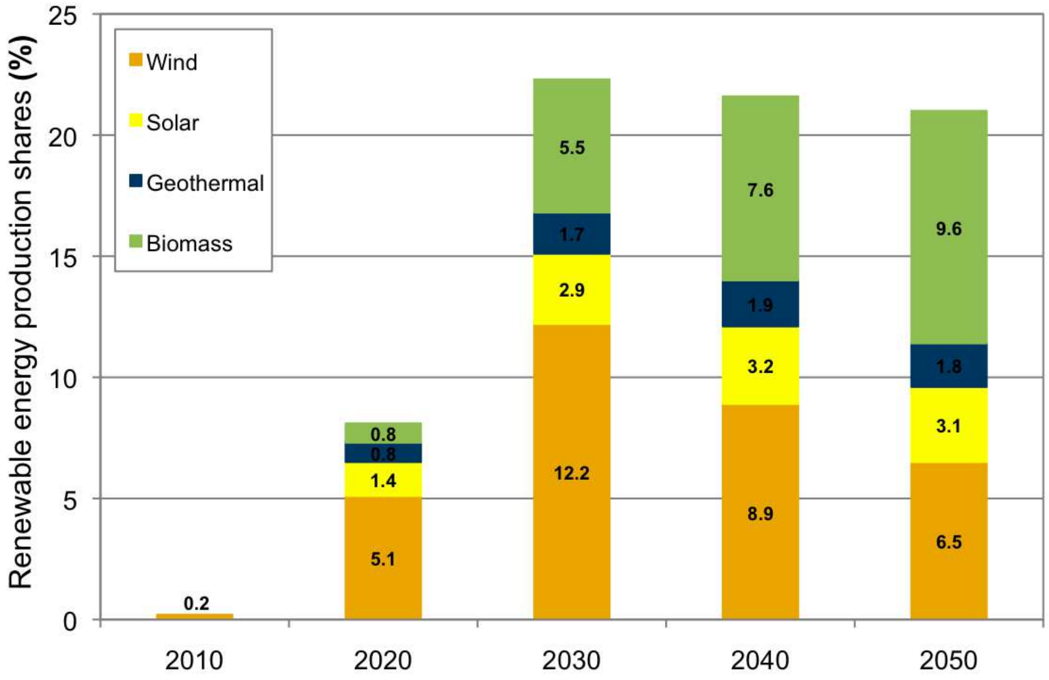


Figure 8-9 Energy production shares of new renewables in the modest introduction of renewables

Wind energy is the main source of new renewable energy. As soon as the expansion with wind energy is over, 5,000 MW in the system by 2027 (13.5 % of total capacity), biomass increases its share in the system gradually from 2030. Renewable energy sources different from hydropower then reach a share over 20% by 2027. This share is maintained until 2050.

In contrast, the share of fossil fuel sources is exceeded in the production by new renewables as shown in Figure 8-10. From a share of up to 30% in 2013 of fossil sources, the new energy sources make the energy from fossil sources shrink to a low of 5.6 % in 2026. Afterwards, fossil fuels increase their share to 16.3% by 2050. Those values are already lower than the new renewable shares so the mix of conventional and non-conventional is achieved for the system with an introduction especially of wind energy from 2010 for a period of 16 years and the constant growth of biomass over the whole period.

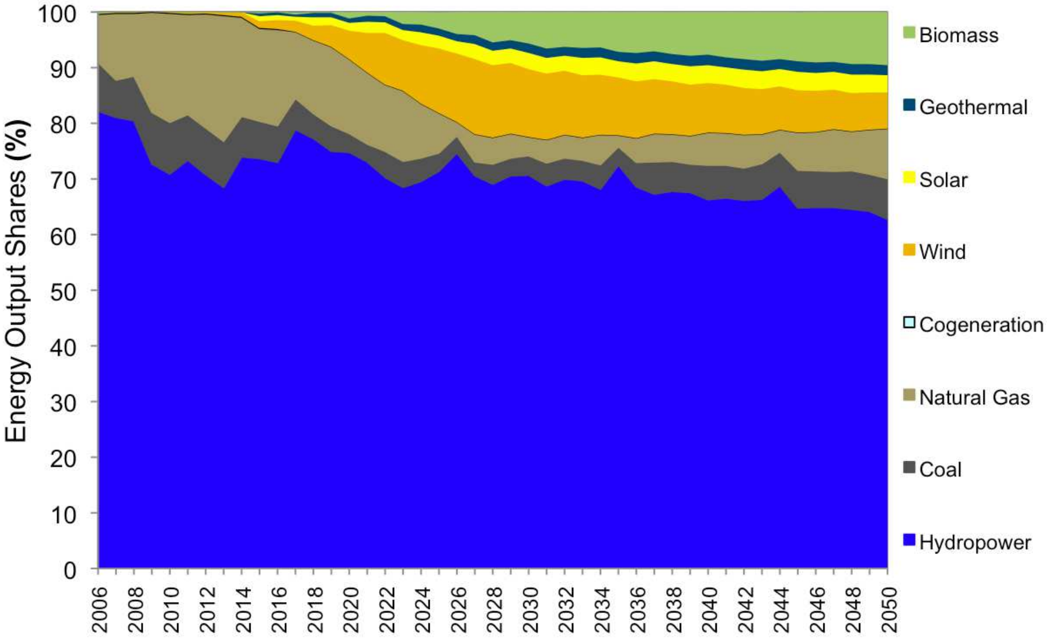


Figure 8-10 Energy output shares in the modest introduction of renewables

An issue worth mentioning is the emission of greenhouse gases by fossil fuel sources in this scenario as illustrated in Figure 8-11. As it was seen in the business as usual scenarios, planned additions and planned with coal, emission levels grow in accordance with the constant inclusion of more fossil fuel power technologies in the system. Although this scenario includes fossil fuels, a clear reduction of emissions per year take place as new renewable sources start displacing conventional fossil fuel sources and therefore decreasing the installations and use of fossil fuels. As soon as the maximum capacity for wind, solar and geothermal is reached; fossil fuels are consequently again in demand, resulting in an increase of emissions in the last 20 years.

However this scenario is already a contribution to tackle the growing emission from business as usual scenarios, in which a total amount of 445 million tonnes are released in comparison to 833 and 1,061 million tonnes from the business as usual scenarios. In other words, a reduction of 50% and 58% respectively is achieved.

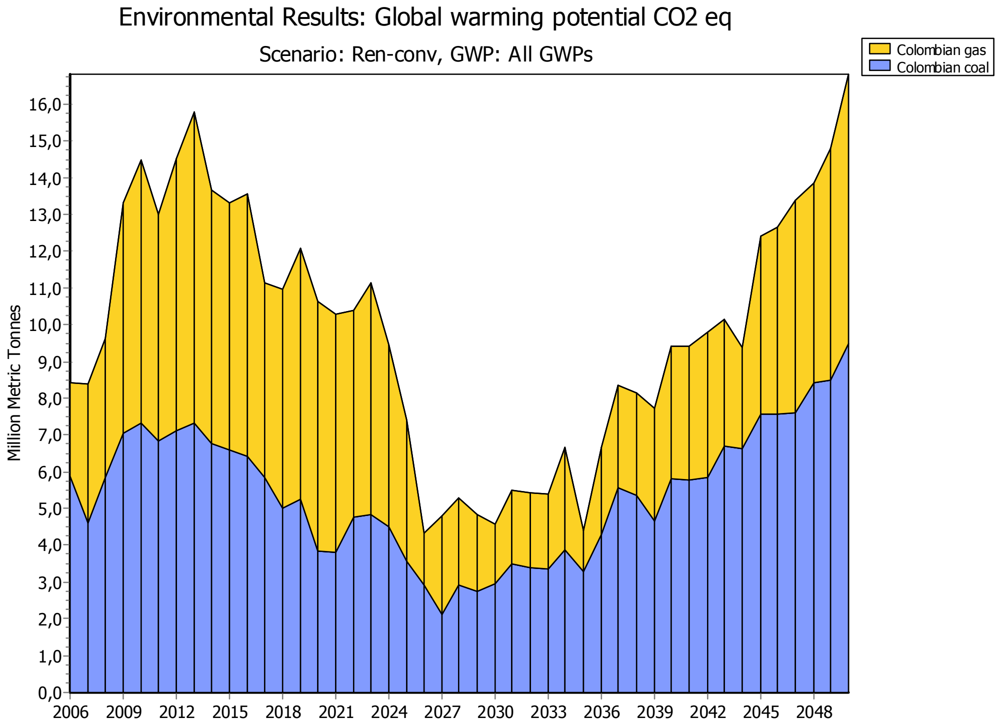


Figure 8-11 CO_2 emissions with modest penetration of renewables

8.4 RENEWABLE POWER SYSTEM

This scenario relies more on new renewable energy sources. Thus, the contribution of fossil fuel sources are pushed to a minimum and the dependence on hydropower is also reduced. The results are illustrated in Figure 8-12 and Figure 8-13.

The result of having a continual expansion with renewables instead of a cap on the capacity of wind, solar and geothermal sources guarantees that these sources are always on the rise so the system receives a larger delivery of electricity from these sources every time. 10,000 MW of wind energy is to be completed in a period of 32 years, from 2010 to 2042, and a greater contribution of biomass account for the biggest share in the system after hydropower. A transition from a system having fossil fuel power plants to supplement hydropower to a system relying almost exclusively on renewable sources is achieved. Coal is still present with a small share while natural gas is still burned in gas turbines for the peak loads. Existing combined cycles running with natural gas operate until they are replaced completely by renewable technologies.

From an upper-most generation of 20,900 GWh from fossil power plants by 2013 corresponding to a share of 31% of total electricity generation, these power plants deliver less than 4% of total electricity generation from 2027 onwards. The opposite is experienced by the new renewables from a negligible participation in the system in the first years until progressively reaching around 40% in 2035 in the production as it is shown in Figure 8-14.

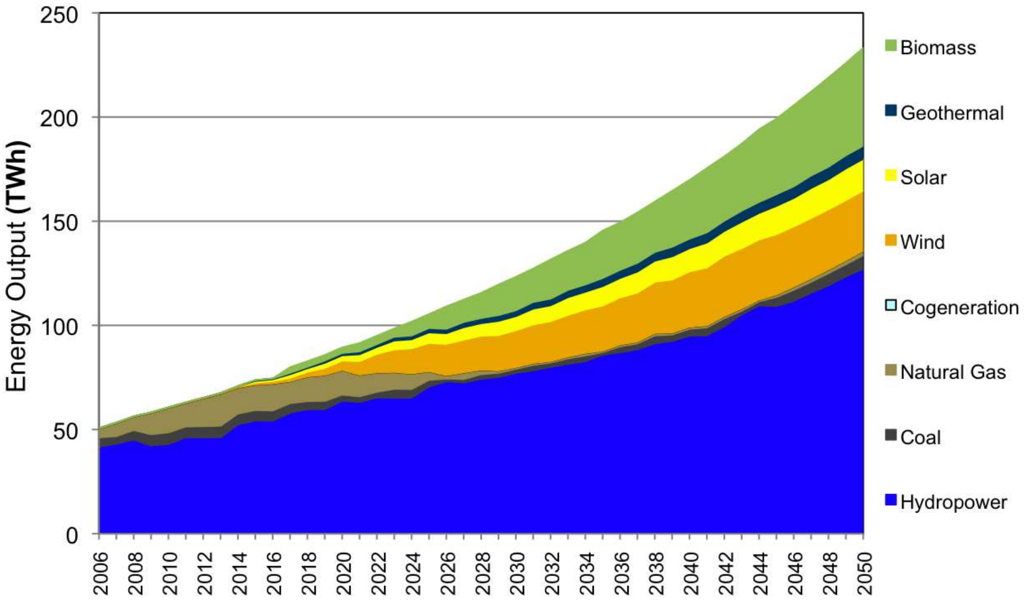


Figure 8-12 Energy output: Renewable power system

By relying more on renewable sources, in particular, intermittent sources such as wind energy, the need of firm energy required for the system in this scenario is higher. The capacity required in this case for the system amounts to 58 GW by 2050, which override other scenarios in terms of capacity. Similar to the generation figures, new renewables have higher shares than their fossil fuel source counterparts in the system after 2022 when the capacity share of fossil fuels is 17% in comparison to 20% from renewables. After that year new renewables increase their share in the system until climbing to 37% starting in 2037. Biomass and wind energy are the sources that supply the most power to the system capacity.

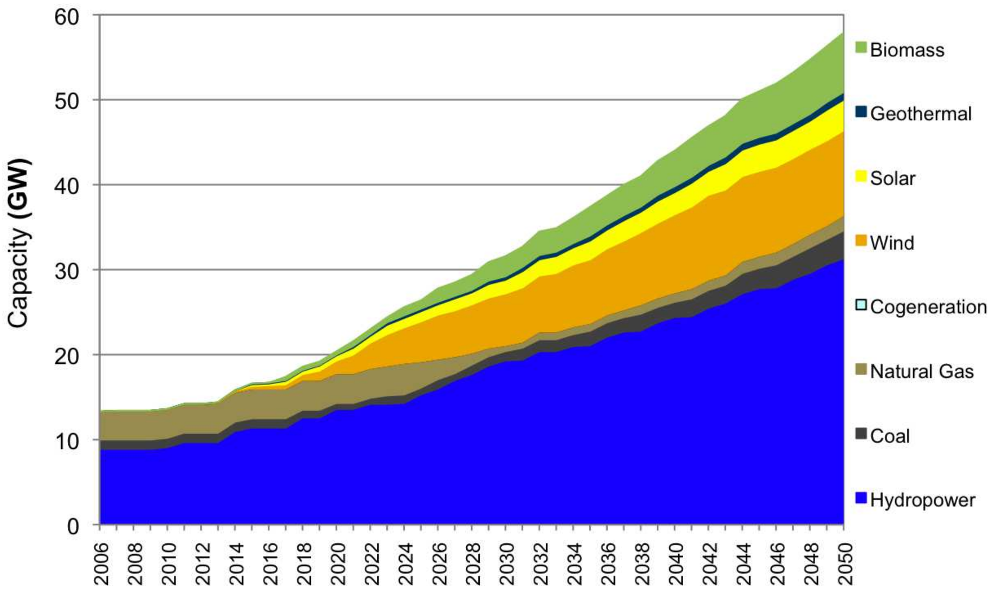


Figure 8-13 Capacity: Renewable power system

To highlight the contribution of new renewables in this renewable power scenario, Figure 8-14 exhibits the shares of every source and the overall contribution to electricity generation in the system. Unlike the modest introduction of renewables scenario, the participation of the new renewables is higher and most importantly without stopping the expansion. Wind reaches its cap of 10,000 MW in 2042, and solar and geothermal in 2050 whereas biomass always increases its share. Thus, a share of over 40% is obtained and maintained, so a call for fossil fuel power plants is avoided.

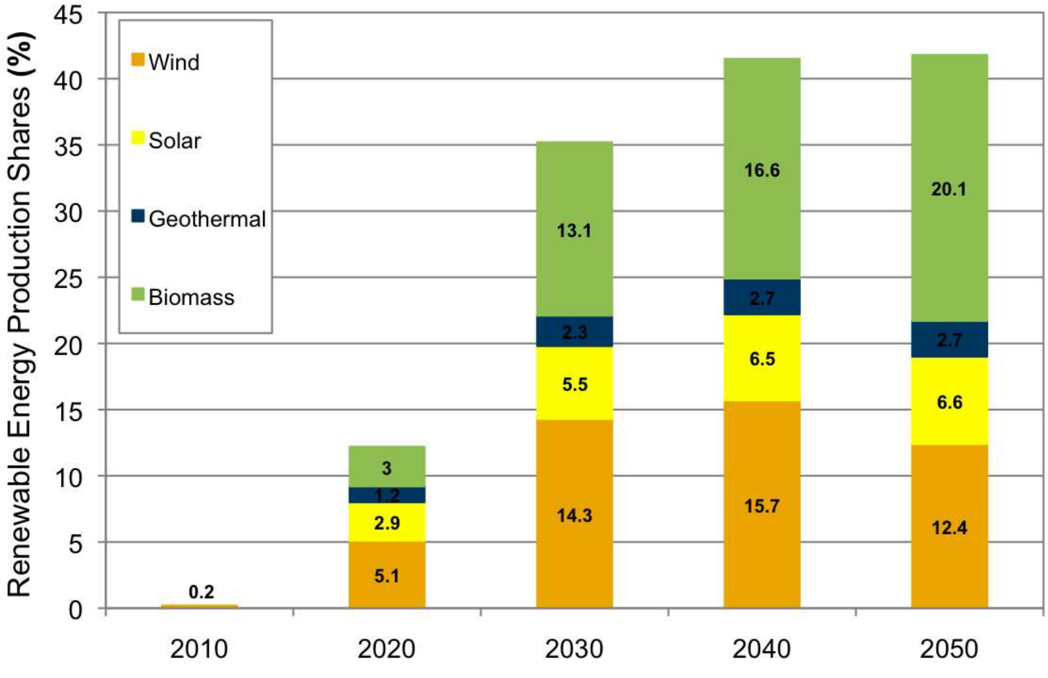


Figure 8-14 Energy production shares in the renewable power system

The overall development of the system with all energy sources in the production is shown in Figure 8-15. The penetration of renewables displaces generation from fossil fuels and the share of hydropower in the system is decreased from 80% to values slightly under 60%. This means that hydropower continues playing a major role in power generation but the dependence of the system on hydropower is spread over the new sources. Fossil fuel is still present with a minimum of participation. This results from giving priority to renewable power in the dispatch.

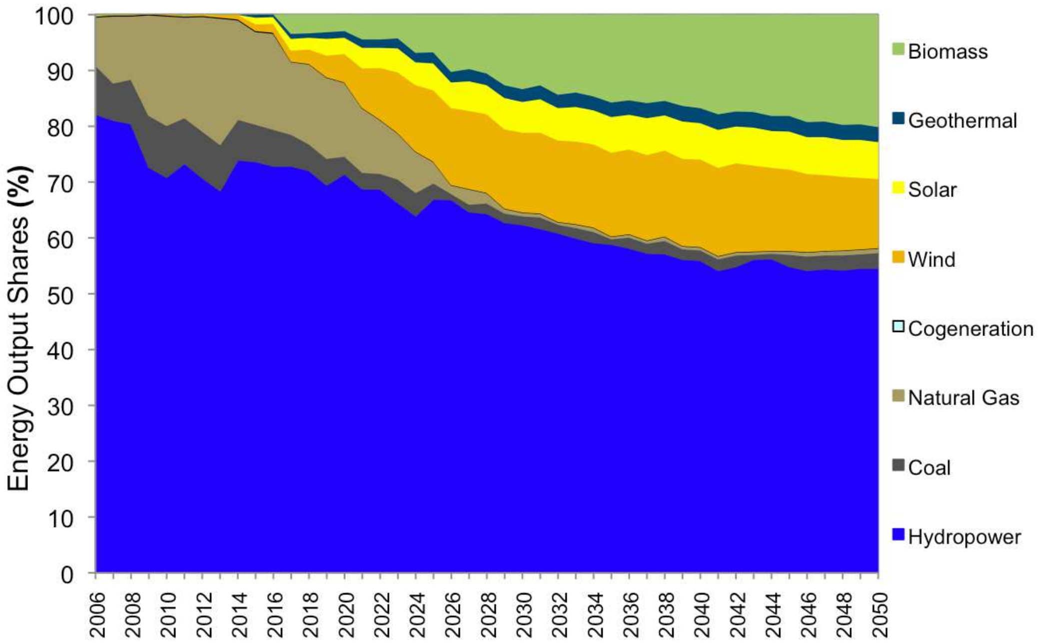


Figure 8-15 Energy output shares in the renewable power system

As more generation from fossil fuel sources is replaced, a drastic reduction of CO_2 emissions takes place in a renewable power system scenario. In contrast to the scenario with a modest introduction of renewables, an increase of emissions does not take place after reductions are accomplished from 2027 to 2044. A light increase occurs afterwards.

A total amount of 283 million tonnes of CO_2 are released in comparison to 445 million tonnes from the modest penetration scenario. In comparison to the business as usual scenarios planned additions and planned with coal, the reduction is very significant, 66% and 73% reduction of CO_2 emissions is achieved. As it can be seen in Figure 8-16, the yearly CO_2 emissions from the base year 2006 are reduced by 50% on average from year 2026 to 2050.

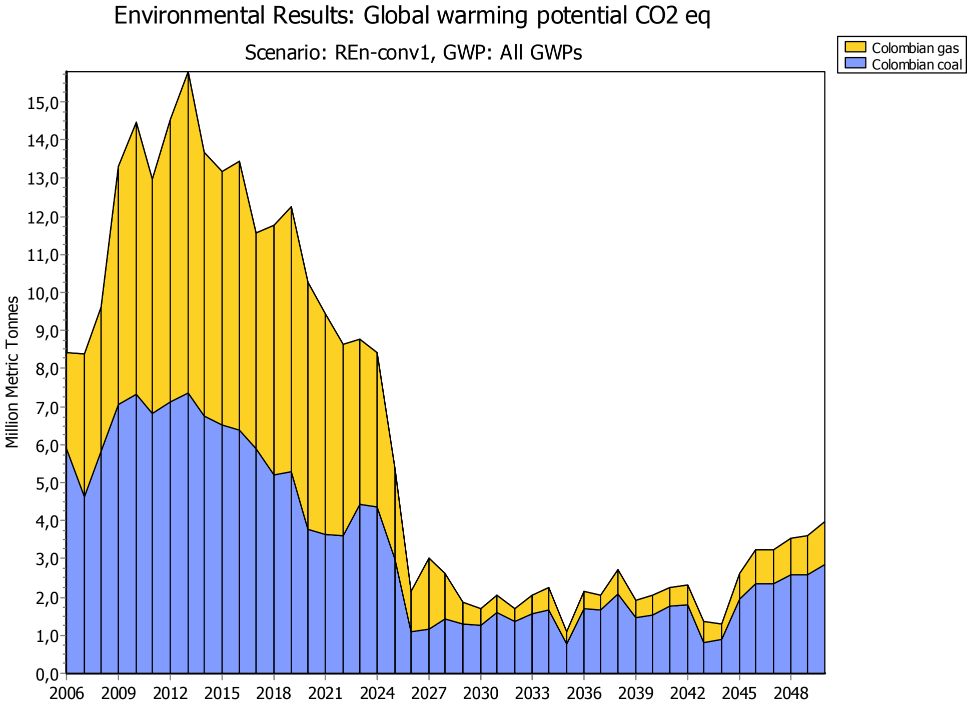


Figure 8-16 CO$_2$ emissions with renewable power system

8.5 SCREENING RESULTS

The different pathways of the power sector that have been described show how diverse the shaping of the Colombian power sector can be as exemplified by the scenarios families here introduced. As the objective of this dissertation is to quantify not only the technical outcomes but also economic and environmental issues, this summary will focus on a comparison of these aspects between the scenarios.

The scenario families possess a set of technologies with distinctive economic and technical features. The amount and kind of power plants in the system and their contribution to electricity supply determine the overall cost.

All of this has been accounted for by means of cash flow analysis to determine the Net Present Value (NPV) of all scenarios so to allow for a comparison about the economic merit of every alternative. The NPV of all scenarios, including the sensitivity analysis with natural gas prices and renewable energy investment and O&M costs, are shown in Table 8-1 and Figure 8-17. All economic results shown in this chapter were calculated with a discount factor of 10% and are expressed in 2006 US Dollars.

Table 8-1 Economic valuation of scenarios in million dollars

	BAU Planned	**BAU Coal**	**RET Modest**	**RET Renewable**
Low cost renewable technology				
Capital	5,301	6,018	7,200	8,482
O&M	6,617	6,859	7,167	7,820
(1) Total	*11,918*	*12,877*	*14,367*	*16,302*
High cost renewable technology				
Capital	5,301	6,018	8,611	10,871
O&M	6,617	6,859	7,590	8,655
(2) Total	*11,918*	*12,877*	*16,201*	*19,525*
Fuel costs				
Low price NG	5,319	4,076	3,857	3,486
High price NG	6,011	4,739	4,514	4,146
Coal	1,691	2,254	1,431	1,338
Biomass	0	0	53	125
(3) Total fuels low price	*7,011*	*6,329*	*5,340*	*4,949*
(4) Total fuels high price	*7,703*	*6,992*	*5,997*	*5,608*
Low price NG + low cost RET (1+3)				
NPV [Millions 2006 Dollars]	**18,929**	**19,206**	**19,707**	**21,251**
High price NG + low cost RET (1+4)				
NPV [Millions 2006 Dollars]	**19,621**	**19,869**	**20,364**	**21,910**
Low price NG + high cost RET (2+3)				
NPV [Millions 2006 Dollars]	**18,929**	**19,206**	**21,542**	**24,474**
High price NG + high cost RET (2+4)				
NPV [Millions 2006 Dollars]	**19,621**	**19,869**	**22,198**	**25,134**
Emission of pollutants				
CO_2 [Million Tonnes]	833	1,061	445	283
CO_2 NPV	145	159	119	111

An immediate conclusion by looking at the total NPV (in bold numbers) is that scenarios with new renewables in the system, modest penetration and renewable power, are the more expensive alternative in comparison to BAU scenarios in economic terms. This means that fossil fuel cost savings by using renewable energy sources are not enough to recover both the extra capital, O&M costs and the extra power required to guarantee the minimum reserve margin as shown in the Table 8-1 with the rows marked with (1), (2), (3), and (4). The investment and O&M costs constitute together the larger shares in the total NPV.

However a closer look at the relative extra cost, measured with the NPV between the scenarios, provides a better idea of the gap between them:

- Modest penetration of renewables versus BAU scenarios with low investment cost of renewables between 2.5% and 4.1%

- Modest penetration of renewables versus BAU scenarios with high investment cost of renewables between 11.7% and 13.8%

- Renewable power scenario versus BAU scenarios with low investment cost of renewables between 10.3% and 12.3%
- Renewable power scenario versus BAU scenarios with high investment cost of renewables between 26.5% and 29.3%

The inclusion of renewable energy technologies will represent extra economic expenses ranging from 2.5% to 29.3%. This depends on the development of investment costs and fuel prices, and the energy mix of the power system. Table 8-2 shows the additional expenses in detail.

Table 8-2 Additional expenses from renewables

Sensitivity Parameters	Modest		Renewable	
	Carbon	*Planned*	*Carbon*	*Planned*
Low price NG + low cost RET	2.6%	4.1%	10.6%	12.3%
High price NG + low cost RET	2.5%	3.8%	10.3%	11.7%
Low price NG + high cost RET	12.2%	13.8%	27.4%	29.3%
High price NG + high cost RET	11.7%	13.1%	26.5%	28.1%

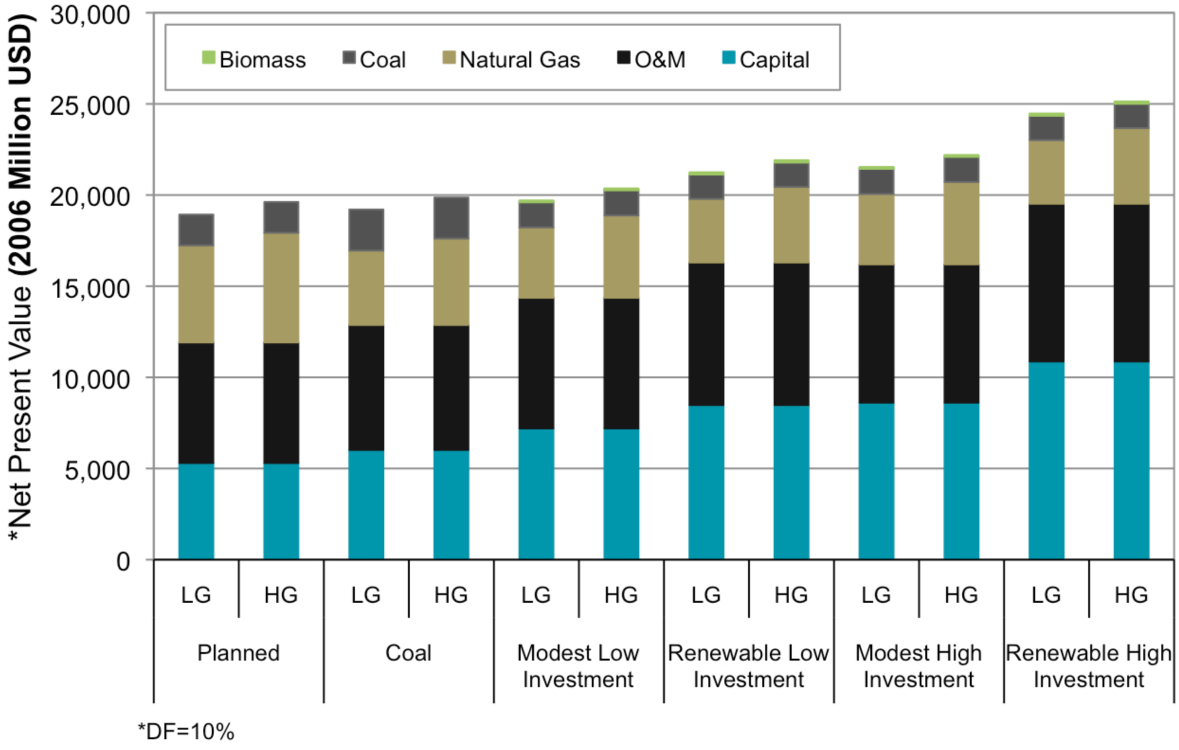


Figure 8-17 Additional expenses from renewables

LG: Low price natural gas; HG: High price natural gas.

8.5.1 Sensitivity analysis of the results

The sensitivity to natural gas prices does not have a major influence in the economic valuation of renewable scenarios versus BAU scenarios. This happens because the increase in the natural gas price affects all scenarios and the use of fossil sources are intensive in the first years for all of them until new renewables start gradually becoming part of the system. Those first years have a larger influence in the cash flow evaluation than savings taking place after 2015.

Very high prices of fossil fuels would speed up the implementation of other energy sources, where new renewable technologies could be competitive at some point by their own merits. It is important to point out that the results are not the outcome of a competitive model selecting the best suitable technologies according to market forces. Instead, the mix of technologies has been previously determined and renewables were forced to dispatch all their production. So a change in the fuel prices in the accounting framework model does not affect the mix of technologies and their production between scenarios.

An issue that was also tested in the modeling is the possibility that hydropower can no longer provide the same levels of capacity and production as observed in recent years. For this case the capacity credit and the capacity expansion with hydropower was reduced. The results with this variation are exhibited in Figure 8-18 and Figure 8-19. These figures show the results in the capacity and production with and without this hydropower adaptation for a better understanding of the economic valuation, which can be seen in Table 8-3.

In general, the model adds more units of other technologies to cover for the reduction in the capacity credit of hydropower to guarantee the minimum reserve margin. Thus, the total capacity is increased over 50 GW for BAU scenarios by 2050 in comparison to a lower capacity in the BAU scenarios without the hydropower sensitivity. In all cases the installation of coal power plants increases. This is necessary to back up the lesser generation from hydropower, therefore the expansion cycle is forced to add them. By having more coal fired power plants, the model dispatches them more to cover the demand. The dispatch by merit order of running cost contributes to a higher volume of electricity from coal source by being consequently first dispatched. This explains why the NPV of natural gas under this hydro reduction is lower than the scenarios without this ingredient in the analysis.

In the case of the renewable scenarios, hydropower does not decrease its share in the system as much as the BAU scenarios due to the backup available from renewables so the expansion cycle is not forced to add new conventional power plants. However, more coal and gas fired power plants are installed along with biomass units which are integrated in the expansion cycle. The system relies on the expansion of these technologies to account for the reduction of capacity from hydropower. The contribution of biomass is higher which impedes more output coming from fossil sources.

What this hydropower sensitivity shows in the renewable scenarios is that an increase of capacity and generation of biomass is the main effect in the modeling unlike the engagement from fossil fuel sources in the BAU.

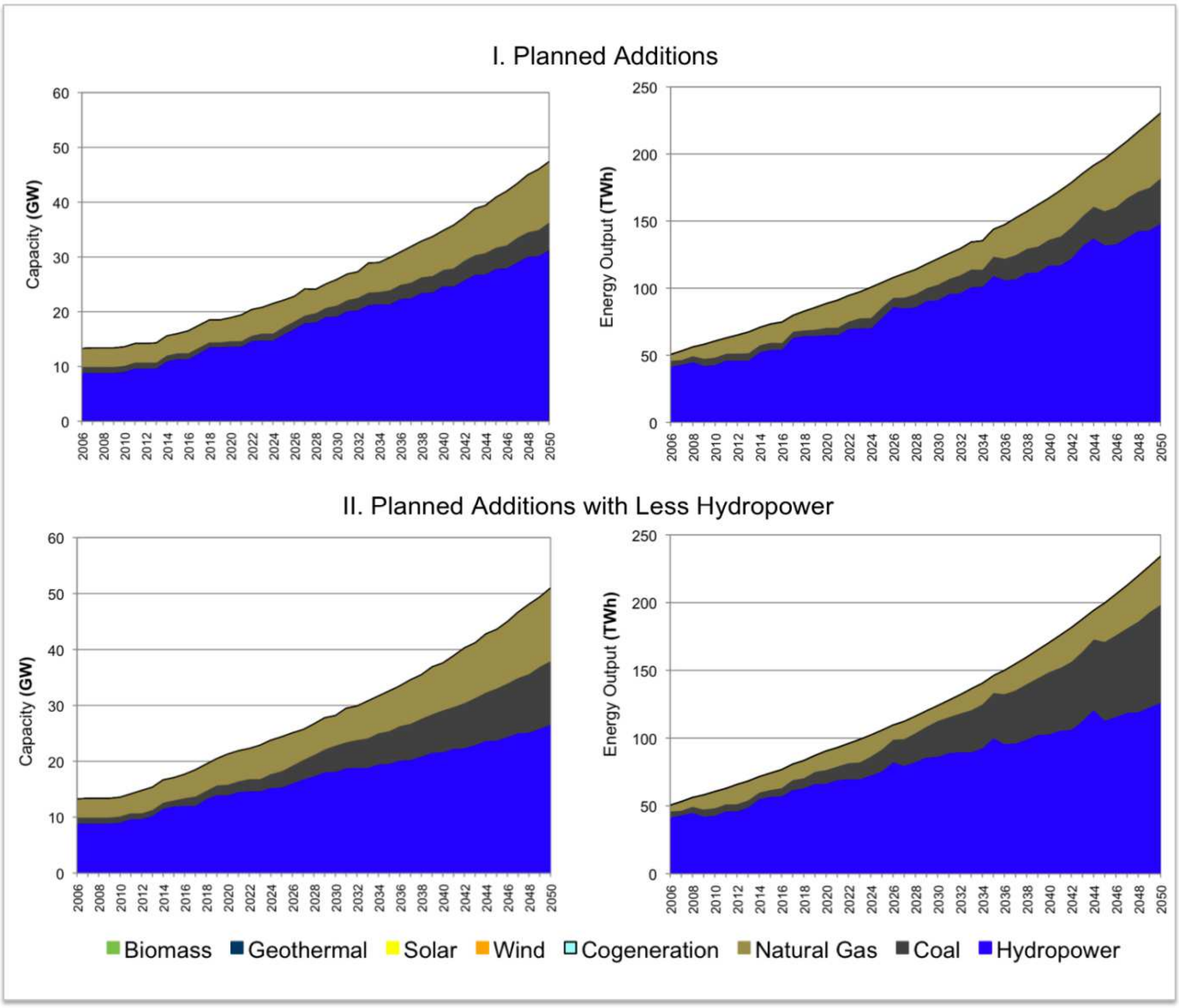


Figure 8-18 Sensitivity to hydropower in planned Additions

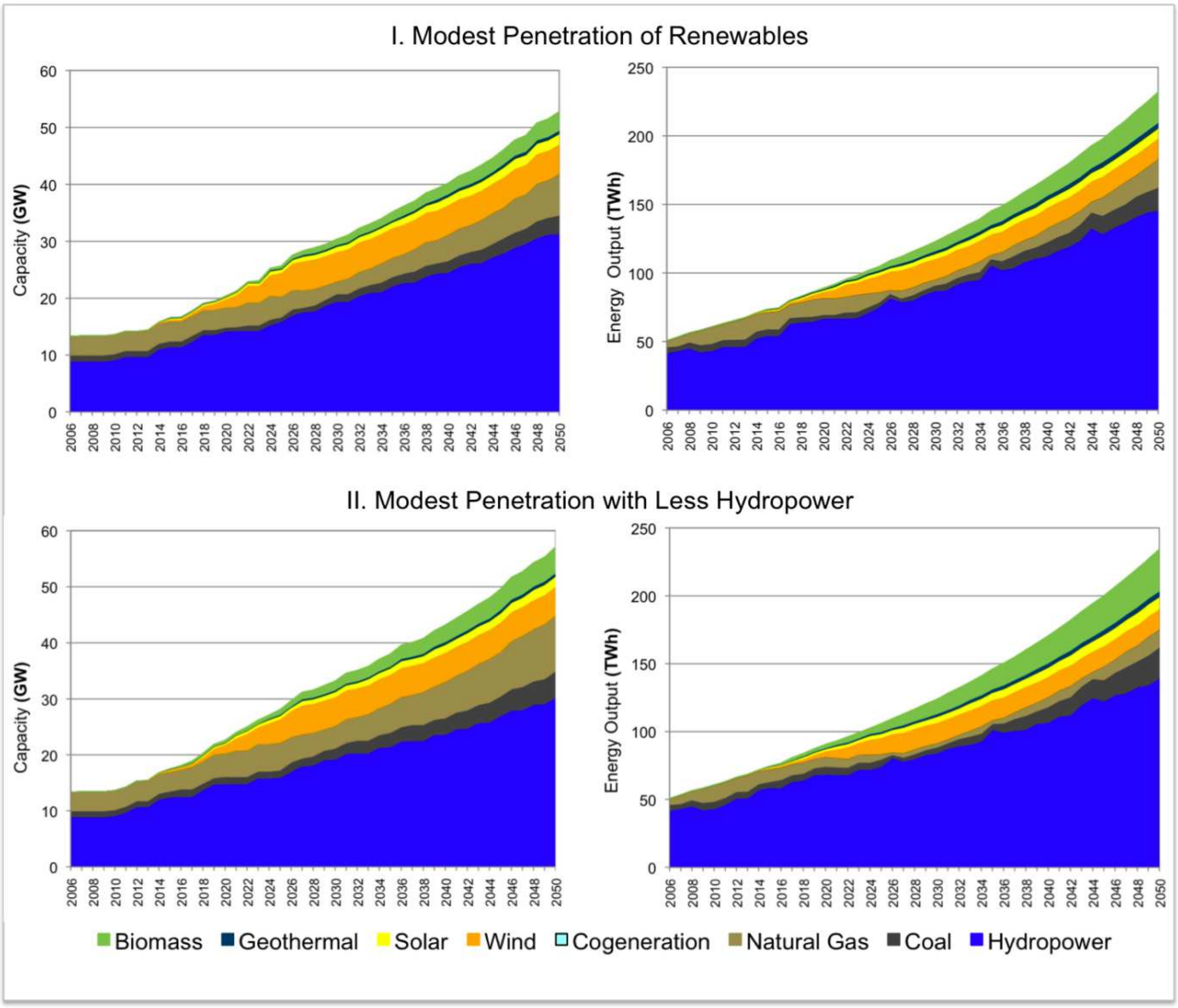


Figure 8-19 Sensitivity to hydropower in the modest penetration of renewables

As the previous economic results for the scenarios without the hydropower sensitivity show, the NPV of scenarios with renewables are costly in comparison to BAU scenarios as shown in Table 8-3 and Table 8-4. However, the relative extra cost has increased between the scenarios renewable versus BAU scenarios. Less hydropower units in the expansion automatically represent a higher cost for the system as other technologies have higher costs. Secondly, the NPV of renewable scenarios increases more pronounced than the increase in the BAU scenarios because more fossil and biomass units are required. Again, it is important to point out that this effect does not correspond to an optimization of the system; it is rather an output of the predefined expansion cycle. For instance the share of gas and coal should be better adjusted to decrease overall investment and production costs. In summary, the extra economic expenses range from 3.7% to 44%.

Table 8-3 Economic valuation of scenarios with less hydropower

	BAU		RET	
	Planned	*Coal*	*Modest*	*Renewable*
Low cost renewable technology				
Capital	6,469	7,619	8,782	10,814
O&M	7,177	7,473	7,865	8,926
(1) Total	*13,646*	*15,092*	*16,647*	*19,740*
High cost renewable technology				
Capital	6,469	7,619	10,431	13,818
O&M	7,177	7,473	8,454	10,149
(2) Total	*13,646*	*15,092*	*18,886*	*23,968*
Fuel costs				
Low price NG	4,148	2,907	2,890	2,484
High price NG	4,730	3,390	3,375	2,918
Coal	2,198	2,645	1,437	1,252
Biomass	0	0	95	224
(3) Total fuels low price	*6,346*	*5,552*	*4,422*	*3,960*
(4) Total fuels high price	*6,929*	*6,035*	*4,907*	*4,395*
Low price NG + low cost RET (1+3)				
NPV [Millions 2006 Dollars]	**19,992**	**20,644**	**21,070**	**23,700**
High price NG + low cost RET (1+4)				
NPV [Millions 2006 Dollars]	**20,575**	**21,127**	**21,554**	**24,135**
Low price NG + high cost RET (2+3)				
NPV [Millions 2006 Dollars]	**19,992**	**20,644**	**23,308**	**27,928**
High price NG + high cost RET (2+4)				
NPV [Millions 2006 Dollars]	**20,575**	**21,127**	**23,793**	**28,362**
Emission of pollutants				
CO_2 [Million Tonnes]	1,119	1,176	404	202
CO_2 NPV	155	162	107	94

Table 8-4 Additional expenses from renewables with less hydropower

Sensitivity Parameters	Modest		Renewable	
	Carbon	*Planned*	*Carbon*	*Planned*
Low price NG + low cost RET	2.1%	5.4%	14.8%	18.5%
High price NG + low cost RET	2.0%	4.8%	14.2%	17.3%
Low price NG + high cost RET	12.9%	16.6%	35.3%	39.7%
High price NG + high cost RET	12.6%	15.6%	34.2%	37.8%

8.5.2 Capacity credit analysis

Another aspect that was worth analyzing is the effect of the capacity factor and capacity credit of technologies in the system. This has been analyzed by means of shifting PV – CSP solar technologies to only CSP and by increasing the share of wind energy from 5,000 MW to 10,000 MW.

Regarding the solar technologies, the higher capacity factor of CSP plants in comparison to a PV solar plant makes it possible to generate more electricity and avoid the installation of other plants in the system in order to maintain the reserve margin. In the modest penetration of renewables scenario the overall total NPV of the system with only CSP power plants is higher than a combination of PV and CSP units (*see* Table 8-5). Despite the fact that a larger production of CSP avoids more generation from conventional power plants, in this case hydropower and fossil sources, the savings does not recover the extra cost of the investments (their dispatch is by merit order while the dispatch of renewables has been set to maximum delivery).

Table 8-5 Economic analysis PV-CSP vs. CSP

	RET		**RET**	
	Modest PV-CSP	*Modest CSP*	*Renewable PV-CSP*	*Renewable CSP*
Low cost renewable technology				
Capital	7,200	7,208	8,482	8,462
O&M	7,167	7,201	7,820	7,840
(1) Total	*14,367*	*14,409*	*16,302*	*16,302*
(2) Total	*16,201*	*16,258*	*19,525*	*19,506*
Fuel costs				
Low price NG	3,857	3,843	3,486	3,488
High price NG	4,514	4,498	4,146	4,145
Coal	1,431	1,433	1,338	1,333
Biomass	53	52	125	119
(3) Total fuels low price	*5,340*	*5,328*	*4,949*	*4,941*
(4) Total fuels high price	*5,997*	*5,982*	*5,608*	*5,597*
Low price NG + low cost RET (1+3)				
NPV [Millions 2006 Dollars]	**19,707**	**19,736**	**21,251**	**21,243**
High price NG + low cost RET (1+4)				
NPV [Millions 2006 Dollars]	**20,364**	**20,391**	**21,910**	**21,899**
Low price NG + high cost RET (2+3)				
NPV [Millions 2006 Dollars]	**21,542**	**21,586**	**24,474**	**24,446**
High price NG + high cost RET (2+4)				
NPV [Millions 2006 Dollars]	**22,198**	**22,240**	**25,134**	**25,103**
Emission of pollutants				
CO_2 [Million Tonnes]	445	444	283	282
CO_2 NPV	119	119	111	111

This avoidance of generation from conventional power plants including biomass technologies (they are included in the expansion cycle) varies depending on the portfolio of technologies, their share and their capacity credit in the system. Thus, a small share of CSP plants in the system, 1,800 MW or 3.4% of the total capacity in 2050, does not help to reduce the size of the overall system just by having a better capacity credit. For instance in the modest penetration of renewables with only CSP plants, only a 150 MW Gas turbine unit could be postponed, which is insignificant. Nevertheless, the increase of the capacity credit affected the year in which a power plant should be added to the system and therefore the mix in the system as shown in Figure 8-20 from 2021.

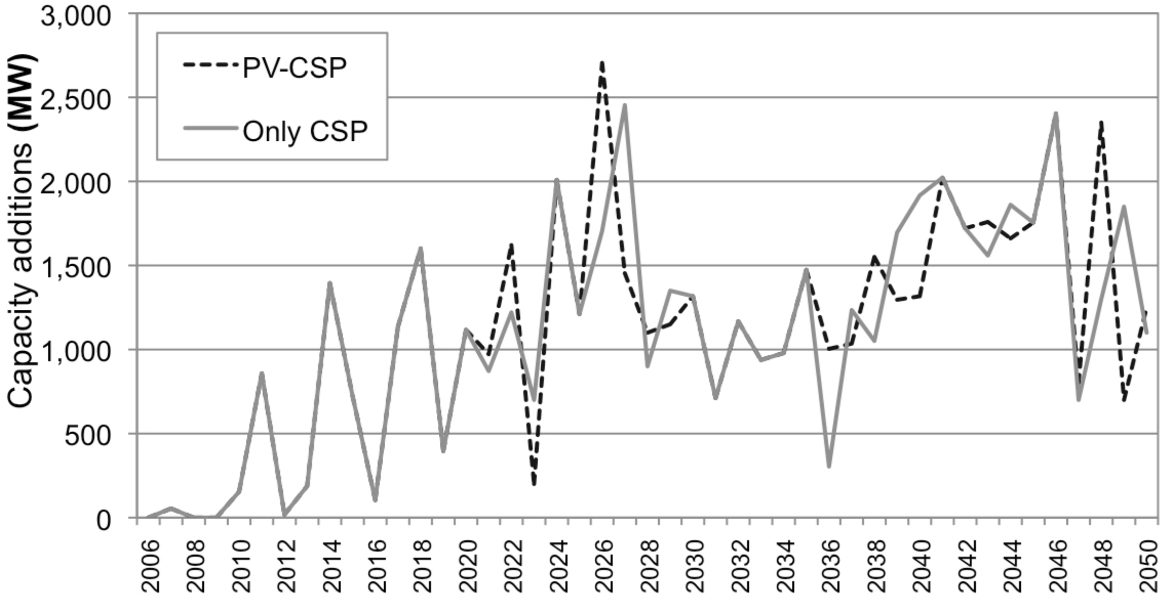


Figure 8-20 Capacity additions PV-CSP vs. CSP in the modest penetration of renewables

The expansion of the system is naturally unaltered for the first years until the expansion with solar sources begins in 2015. The effect of the capacity credit on the units added for the expansion takes place in 2021. It results in changes in the dispatch of power plants as exhibited in Figure 8-21, where gas consumption is altered, at times the gas consumption being higher with only CSP plants. This explains why the economic analysis from Table 8-5 shows NPV for fuels with higher or lower values and that the small share of solar technologies in the system do not allow for a straightforward conclusion in this case.

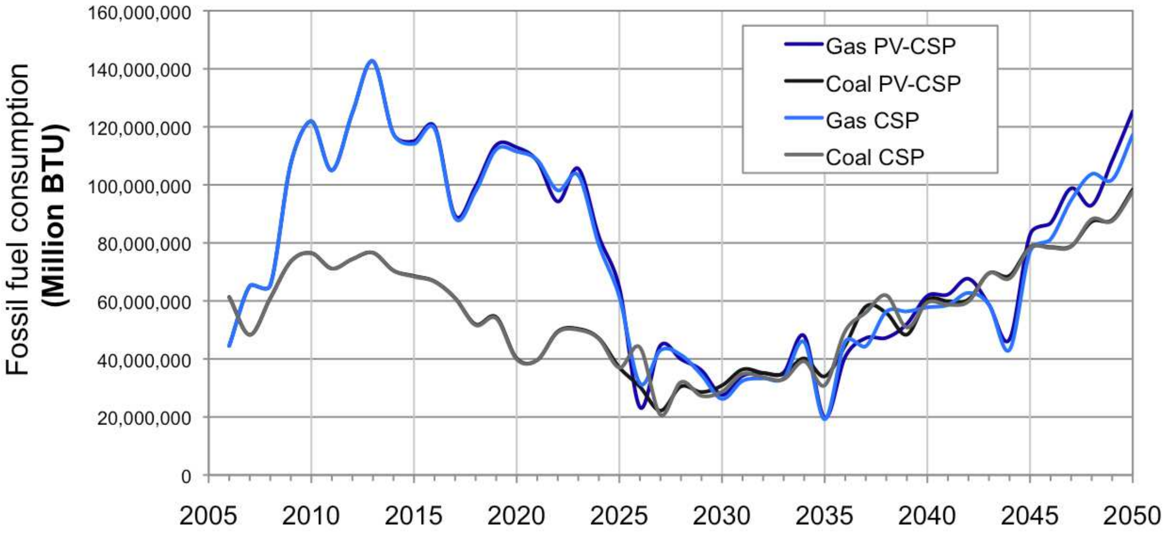


Figure 8-21 Fossil fuel consumption PV-CSP vs. CSP in modest penetration of renewables

A different result can be seen in the renewable power scenario as shown in Figure 8-22, where the effect of the capacity credit of CSP is greater due to its higher share in the system. By the year 2050, the introduction of only CSP power plants for solar technologies, shows a decrease of 650 MW in the total capacity of the system, where the solar share is 6.3 %. Figure 8-23 shows the minor effect in fossil fuel consumption.

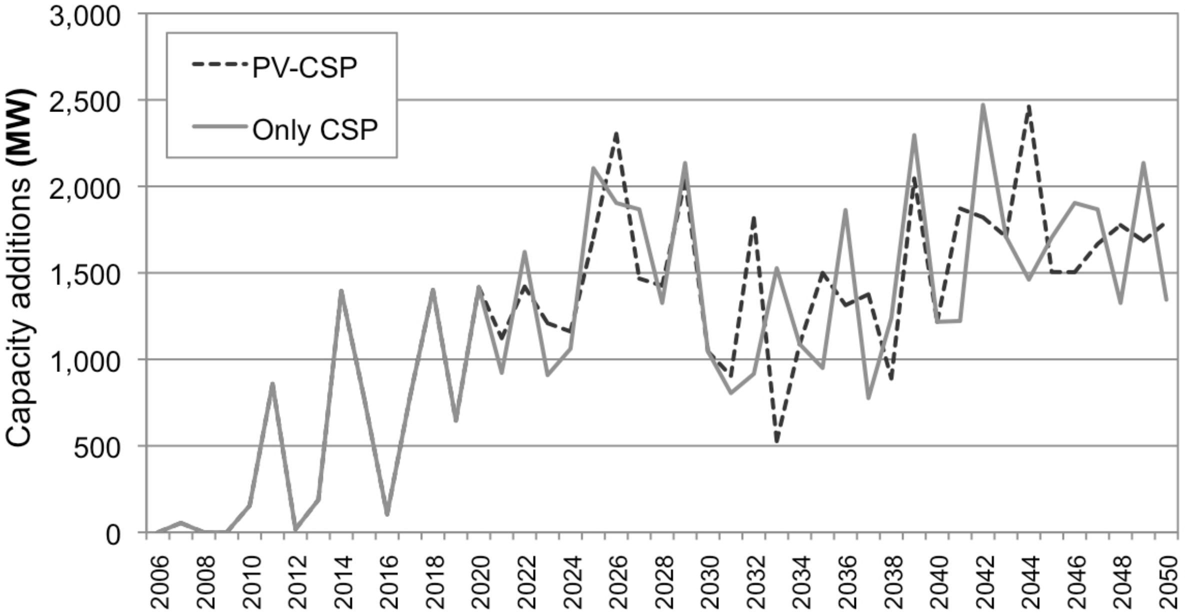


Figure 8-22 Capacity additions PV-CSP vs. CSP in renewable power scenario

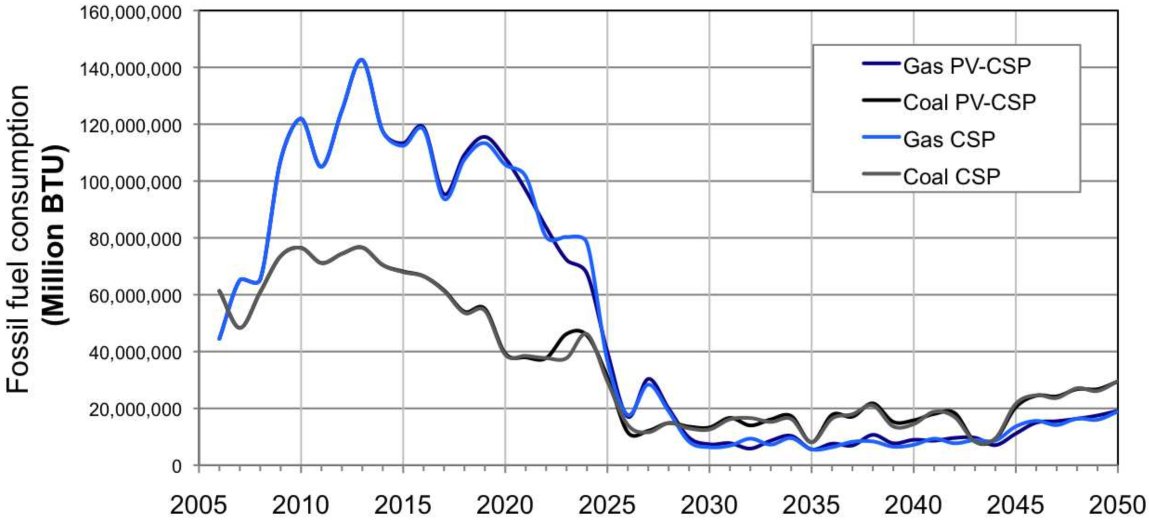


Figure 8-23 Fossil fuel consumption PV-CSP vs. CSP in renewable power scenario

In general, the shift to only CSP power plants does not show a significant effect in the economic valuation. The share of solar power is very small to have an influence on the system by the better capacity credit of solar thermal. However, it can be observed that the capacity factor and capacity credit then are crucial parameters that influence the size and generation of the system. The role of the capacity credit can be further illustrated by comparing the two scenarios with new renewables. As more wind and solar resources are exploited, the capacity credit of those technologies demands from the system more back-up as shown in Figure 8-24. The renewable power scenario requires 4,600 MW of additional power in comparison to the modest introduction of renewables. This is a 9% increase from 52.8 GW to 57.4 GW by 2050, which is needed to back up the system due to higher shares of wind and solar sources.

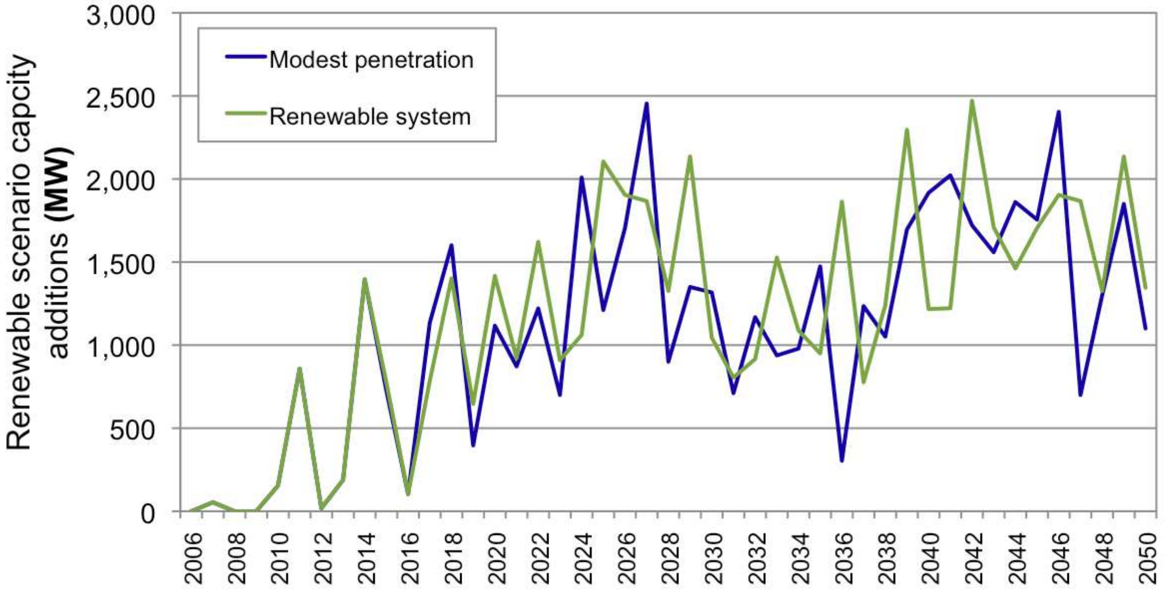


Figure 8-24 Capacity additions in scenarios with renewables

This is a crucial aspect for the introduction of renewable energy sources which are intermittent as solar, wind and hydropower. Hydropower reservoirs allow storage and therefore flexibility in the operation. With regards to solar sources, the use of CSP power plants with thermal storage make it also possible to tackle firm energy issues. Regarding wind energy, storage is possible by means of direct applications such as hydrogen production and compressed air energy storage (CAES), otherwise backup from other power generation technologies in the system needs to be available, in other words additional capacity in the system is required.

What makes the Colombian system interesting for a high share of new intermittent energy sources such as wind energy is the large number of hydropower reservoirs at hand. Thus, hydropower plants can have an important contribution in improving the operation of the system with a high share of wind power. Whenever wind resources are not available, a hydropower plant covers the gap. This may also be seen as a business opportunity for hydropower, not only to feed the load base of system but also to back up the system. The simulation has been run with a typical capacity credit of wind of 20% from power systems that rely more on fossil fuel sources. A committed hydropower production to backup wind could shift the capacity credit to higher values. It depends on the availability of hydro resources, number of hydro power plants and its seasonality.

A closer look at this topic is presented in Chapter 10 but a quantitative analysis in that regard is beyond the scope of this dissertation. However it should be conducted at a future time so to gain a better understanding of the integration of wind energy in the system. The simulation has maintained the value of 20% capacity credit of wind as a conservative parameter to test the scenarios with renewables.

8.5.3 CO_2 emissions

Regarding CO_2 emissions the contribution of renewable energy sources to reduce millions of tonnes over the time horizon is indisputable as shown in Figure 8-25 from data in Table 8-1. BAU scenarios are the least cost alternatives but they will increase the emissions significantly above today’s current levels, coal being the main source.

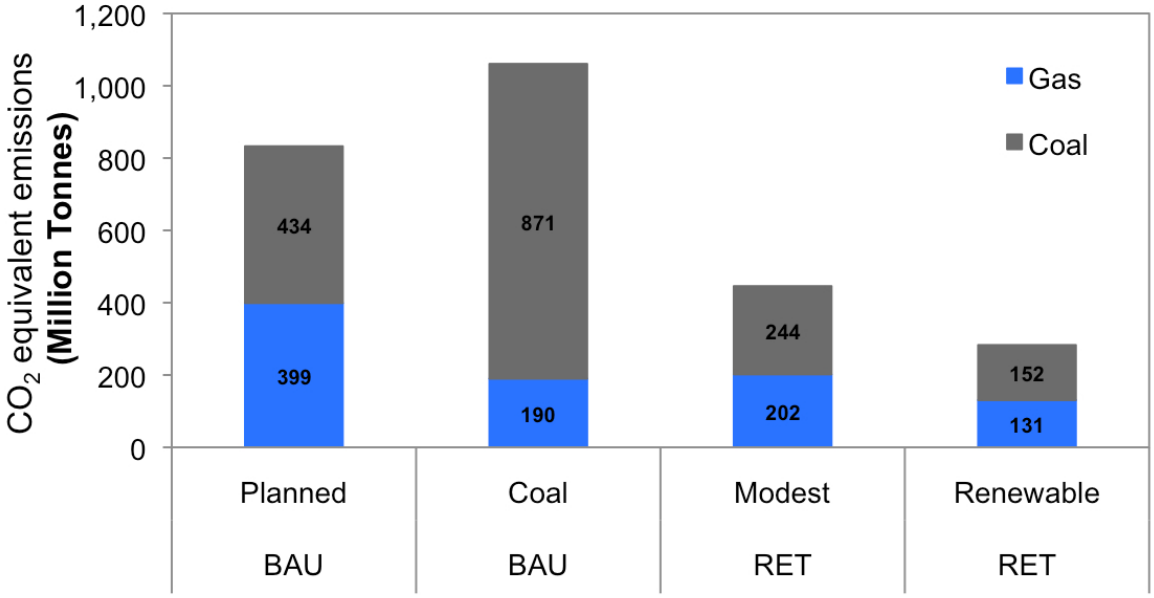


Figure 8-25 CO_2 equivalent cumulated emissions in all scenarios

To illustrate the relationship between the CO_2 savings and the cost of scenarios with new renewable technologies, the cost of the avoidance of CO_2 emissions is calculated. This is done in order to identify the least cost alternatives to reduce a tonne of CO_2 which is the cost to be charged per tonne to match the cost of the BAU. The results are shown in Table 8-6.

Table 8-6 CO_2 savings cost per tonne for all scenarios and sensitivites

Scenarios \ CO_2 Cost	Low NG-LowRET		HighNG-LowRET		LowNG-HighRET		HighNG-HighRET	
(USD/Tonne)	M	R	M	R	M	R	M	R
- Planned vs. Renewables	30.1	66.5	28.7	65.5	99.1	158.6	97.7	157.5
- Planned coal vs. Renewables	13.2	42.4	13.0	42.2	59.3	109.0	59.1	108.8
- Planned vs. Renewables [H2O]	22.2	60.3	20.2	57.9	68.4	129.1	66.4	126.7
- Planned Coal vs. Renewables [H2O]	7.7	44.7	7.7	44.0	48.1	106.4	48.1	105.7

M: Modest, R: Renewables, [H2O]: less hydropower

In general the cost per tonne is very sensitive to the capital cost of renewables, whereas the natural gas prices do not have a major influence.

An expansion based on coal sources in comparison with the modest penetration of renewables scenario shows the lowest prices per tonne since these BAU scenarios release the largest amount of CO_2 so the avoidance is consequently greater. The cost ranges from 7.7 USD/tonne to 59.3 USD/tonne depending on hydropower availability, natural gas prices and capital cost of renewables. Similarly for planned BAU scenarios the cost ranges from 20.2 USD/tonne to 99.1 USD/tonne.

The same analysis with the renewable power scenario shows higher costs per tonne of CO_2 avoided. For BAU scenarios with coal from 42.2 USD/tonne to 106.4 USD/tonne and with planned additions from 57.9 USD/tonne to 158.6 USD/tonne.

CO_2 costs per tonne are overestimated since the efficiency of the new fossil fuel power plants added to the system was set at their highest value which assumes always a load factor of the plant that reaches the highest efficiency. That is arguable since thermal power plants do not operate always in the base or intermediate load at maximum capacity and their dispatch is therefore variable. CO_2 emission savings are therefore underestimated.

8.6 SUMMARY

The integration of new renewable technologies in power systems at a moderate or great scale has implications for costs, the portfolio of technologies, the portfolio of energy sources and the environment on a local and global scale.

The screening methodology with the accounting framework model LEAP produced the expected results, the modeling of the power sector as a big picture, and has shown the effect of the inclusion of new technologies on the system under different developments in the power expansion by means of scenarios. Thus, the key issues for the Colombian case that shape the power sector were identified and quantified.

Large hydropower plants will continue playing a major role. As being the least cost alternative and still having great potential, hydropower will always be the main driver for the expansion and electricity production. Even in the event of decreased availability of water resources and new hydropower installations, the contribution of hydropower will influence the amount of new technologies based on fossil or renewable energy sources.

The results show that BAU scenarios are the least cost alternative even with a major expansion with coal. Hydropower and coal are abundant resources. Natural gas is currently the favoured option over coal. Natural gas for electricity generation in the future will depend on its availability in Colombia. Imports of natural gas might be costly resulting in a dependence on foreign energy sources.

A power system with the inclusion of new renewable technologies is strongly driven by their investment costs. The renewable scenarios were in all cases more costly than BAU scenarios. Gas prices were not determinant to reduce the gap between the BAU scenarios as all scenarios make use of it in existing power plants and important future gas savings take place after today's existing gas turbines and combined cycles reached their lifespan. The relative extra cost of renewable scenarios with low investment costs in comparison to BAU scenarios in a horizon until 2050 is between 2.5% and 4.1% for a steady 20% share of new renewable energy sources from 2030 (*see* Figure 8-9). This is a very motivating signal, which suggests that in the long term, and only based on economic merits, investment in renewable energy technologies may not represent a burden for the energy sector, if the cost of renewables are kept at a minimum in the future.

Since investment costs of new technologies are one of the main drivers to reach competitiveness and Colombia would have to import these technologies, the competitiveness depends on the development of international prices. This makes the Colombian power sector a price taker. In a global effort to lessen the reliance on fossil fuel energy sources to halt GHG emissions globally and to assure the 2°C maximum tolerable increase of global temperatures in coming decades will further the chances to increase the share of renewable energy sources for power generation globally. Such a situation may further decrease the cost of renewable energy technologies as they will boost the installation of more capacity.

Dependence on international prices can be avoided with a set of right policies in Colombia to push investment costs down by promoting, for instance, the local content for the introduction of new technologies, by incentivising joint ventures with local industries and attracting foreign investment to manufacture the goods locally.

The results also show the effect of intermittency of renewable energy sources such as wind and solar. Low capacity credits of these energy sources can be overcome with indirect or direct storage. The joint operation of hydropower plants with wind and PV power plants can lower the required backup power, thus, improving the economics of a system with renewable energy sources. This could boost the penetration of these technologies. The model did not include that improvement, so results are conservative in that regard.

A better optimized system may yield other results by choosing a portfolio of technologies that reach the least costs, or that minimize GHG emissions or that find an optimal combination of both based on market forces instead of the iterative procedure with scenarios in which the accounting framework model LEAP is based on. For that reason a second step in this quantitative analysis is to simulate under ideal market conditions the portfolio of technologies, letting market forces alone to define the portfolio and production of power technologies. This will greatly enhance the results that have been produced up to now. The optimization model will better define the maximum share of renewable energy sources that the system may have based on economic merits measured as the least cost of the system. The results with optimization approach are presented in the next chapter.

9. OPTIMIZATION OF THE POWER SYSTEM

Unlike the scenario analysis with the accounting framework model LEAP, the energy mix of the power system will now be determined by economic merits. The optimization model MESSAGE here applied, will find the least cost power system through the optimization process (*see* Chapter 2 for more details). The parameters for the simulation are the same as those introduced previously in the prognosis analysis in Chapter 6. Instead of defining scenarios by determining in advance how the expansion should be done as it was created in LEAP, the optimization model selects from all technologies available, the least cost option over the horizon of the analysis according to the framework set for the expansion such as the availability and seasonality of energy sources and renewable energy potential.

Since the optimization model approach is based on market forces and allows a more detailed description of the demand and seasonality in the electricity production, an additional analysis of the Colombian power system is necessary for the simulation. Similar to the screening methodology, a sensitivity analysis is also conducted. In the following subchapters a brief description of these additional inputs required for MESSAGE is introduced. The results of the simulation with MESSAGE are presented later. A summary of the key findings with MESSAGE concludes the chapter.

9.1 ADDITIONAL INPUTS ANALYSIS FOR MESSAGE

9.1.1 Electricity demand

Since the electricity demand module of MESSAGE allows for a more detailed description of its behaviour, a further analysis of the Colombian electricity demand shape was conducted for the simulation.

The pattern of the demand for every month of the year was defined based on the Colombian electricity demand for the year 2007, and it is assumed that this pattern is similar over the years. Figure 9-1 shows the shape of the electricity demand in January grouped per hour in order to determine the shape of a typical day (the area under the curve corresponds to the total demand in January in kWh). As can be seen, a pattern of this demand can be distinguished: Part 1 corresponds to the morning hours, part 2 corresponds to daylight hours, part 3 describes the night peak hours where electricity demand per hour is the highest and part 4 the night hours.

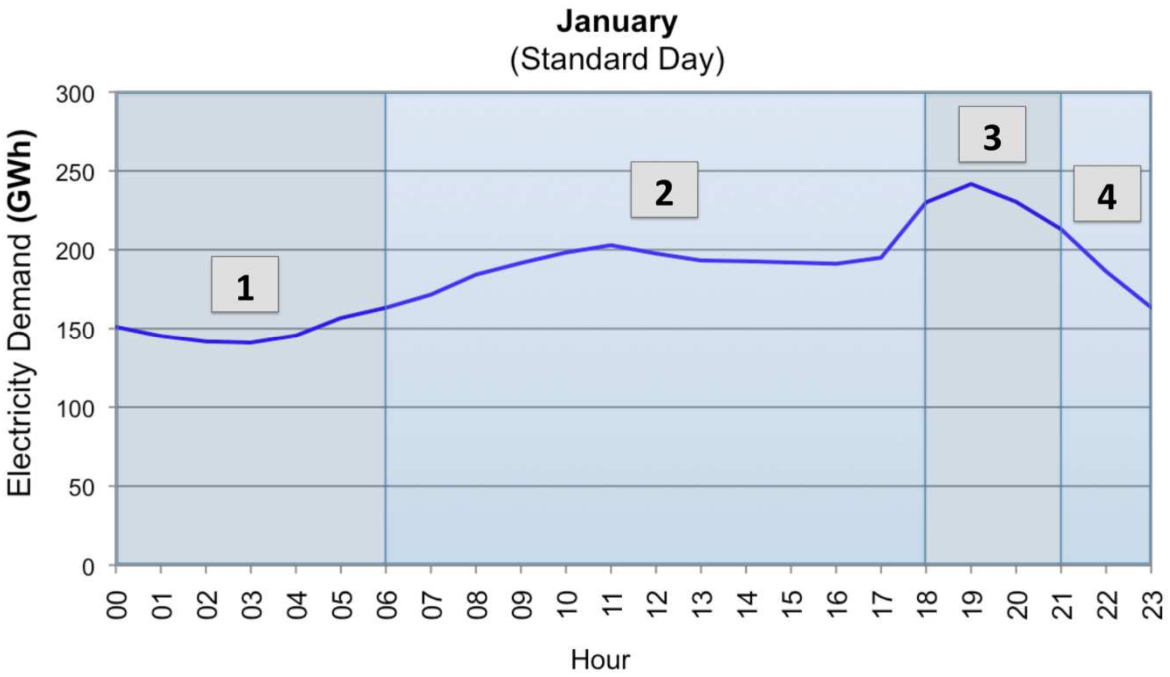
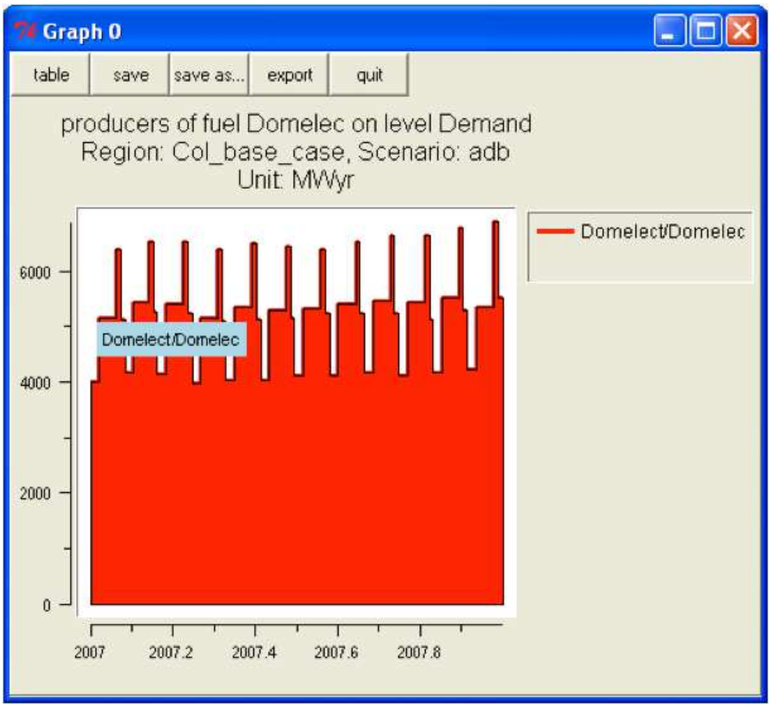


Figure 9-1 Electricity demand of one standard day in January

Source: Data from NEON, own calculations.

This analysis performed for the other months of the year also exhibited the same pattern. In that way MESSAGE dispatches the power plants to attend to these sections of the demand per month. Every year the demand is higher and additional power plants will be added to the power system as soon as existing power plants cannot cope with the demand. A load curve is internally calculated by MESSAGE as the combination of the 4 part of the days per month and the electricity demand share of a given month in a year as shown in Figure 9-2.



producers of fuel Domelec on level Demand
Region: Col_base_case, Scenario: adb
Unit: MWyr

Figure 9-2 Demand load curve for MESSAGE

9.1.2 Hydropower

Since MESSAGE can simulate the dispatch of hydropower in the load curve of the system, a further analysis of its behaviour was conducted. Figure 9-3 shows the generation of hydropower per month over the last 15 years. During the period from January to April (the dry season), the share of hydropower in the system is lower than in other months. To simulate the contribution of hydropower according to this seasonality, a load curve of the hydropower production was determined as shown in Figure 9-4 , which was entered into MESSAGE.

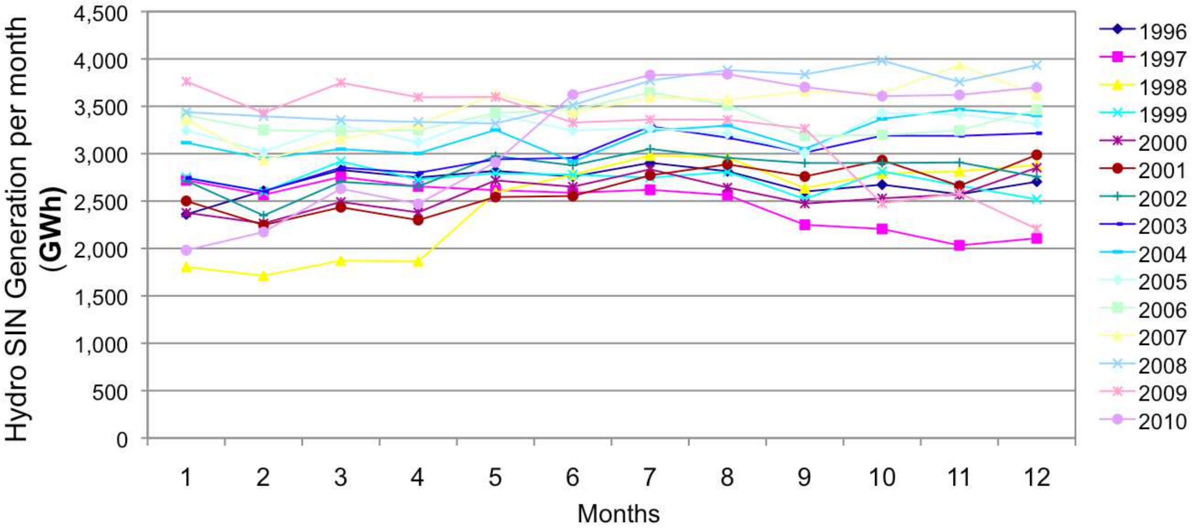


Figure 9-3 Hydropower generation per month

Source: Data taken from XM 2011, own calculations.

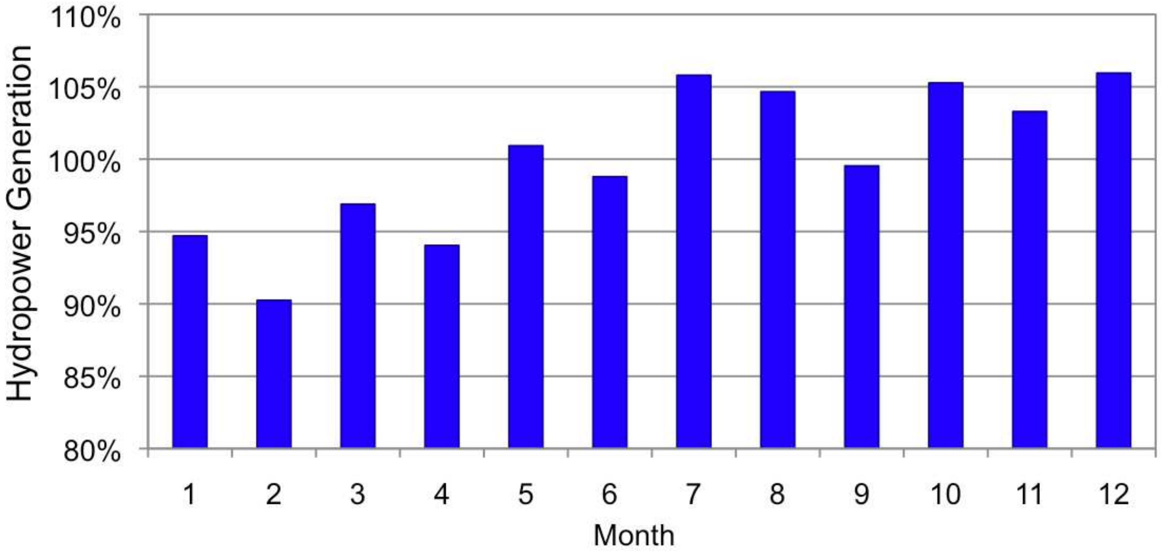


Figure 9-4 Load curve for hydropower in MESSAGE

The load curve for hydropower in MESSAGE, which is presented in Figure 9-4, describes the changes of average capacity factors. The load curve is calculated as the ratio between the energy produced per month and the maximum capacity of the system. The average was determined as shown in Figure 9-5. The load curve describes the changes of the capacity factor over the month of the year. A maximum capacity factor for MESSAGE was set at 60%.

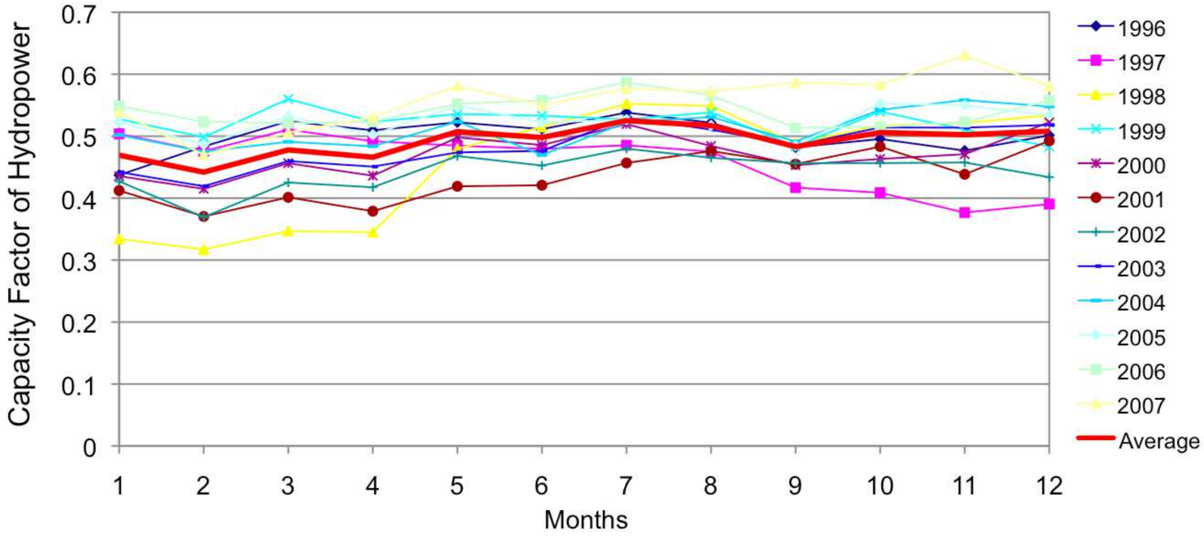


Figure 9-5 Capacity factor of hydropower

Source: Data from XM 2008, own calculations.

9.2 SENSITIVITY ANALYSIS FOR MESSAGE

Like the accounting framework model, LEAP, a sensitivity analysis was also conducted in MESSAGE. The economic parameters used for the sensitivity analysis in LEAP were also used for the sensitivity analysis in MESSAGE and included: fossil fuel prices, investment costs and discount factors, which are described in Table 7-11. Technical parameters of power technologies are provided in Table 6-18.

The main difference between the two energy models is that in MESSAGE there is no set of scenarios to control the expansion of the power system. The scenario is a result of the simulation in MESSAGE. The expansion is then controlled by the economic and technical parameters. The technical parameters were adjusted for hydropower and the electricity demand as shown in the previous subchapter. Unlike LEAP, only a cap for the expansion of renewable energy technologies was defined and their dispatch was not forced. This is done to allow the model to select the optimal power system with a high degree of flexibility. A sensitivity analysis tailored to MESSAGE for the contribution of hydropower is included. A summary of these technical parameters for the expansion is shown in Table 9-1.

Table 9-1 Technical variables for sensitivity analysis

Variable	Description
Expansion	Wind power: Maximum 10,000 MW Solar power: Maximum 5,000 MW CSP: Maximum 5,000 MW Hydropower: Maximum 84,000 MW Geothermal: Maximum 900 MW Conventional fossil fuel power plants: No - limits
Dispatch	Renewables were not forced to be dispatched
Contribution of hydropower	Reference case: The maximal contribution for the analysis from 2010 onwards was set at 80% Hydropower Sensitivity: The maximal contribution for the analysis from 2010 onwards was set at 70%

Analog to the simulation with LEAP, in MESSAGE the possibility that hydropower can no longer provide the same levels of capacity and production was simulated. The hydropower sensitivity in MESSAGE set at 70% the maximal contribution of electricity into the system.

9.3 TECHNICAL RESULTS

The results of the optimization model MESSAGE are assessed according to the energy mix obtained, the least cost value of the whole power system and the CO_2 emissions. A reference case for the simulation was defined, which corresponds to the combination of low cost of renewable energy technologies and low cost of natural gas and coal. The reference case is then compared with the sensitivity analysis for costs and hydropower production.

The simulation was performed from 2006 to 2050. To facilitate the control of the variables in MESSAGE the first years in which actual data are available were simulated from 2007 to 2010. Afterwards the expansion was simulated in intervals of 5 years. The outputs of the simulation as shown in the following figures in this chapter display the year 2045 as the final year. However this year corresponds to the interval 2045 – 2050.

9.3.1 Reference case

The results are shown in Figure 9-6 and Figure 9-7. The system continues generating electricity with current conventional technologies with hydropower, coal and natural gas, until 2020, when natural gas resources for the power sector become scarce and imports are necessary. For that reason more electricity will be provided by new coal technologies (bed fluidized combustion and IGCC) and the consumption of natural gas is reduced.

At the same time, and driven by high natural gas prices (import price) and competitive investment costs, wind energy enters the system based on its own economic merits after 2020 becomes an important share of the system over the years until reaching the capacity of 10,000 MW from 2045. As well as wind, geothermal along with fluidized bed combustion and IGCC with biomass enter the system. CSP will manage to have a small share, which is seen from 2020 onwards. In contrast, PV enters the system very late from 2045 on despite its very low cost but lowest capacity factor of all of the technologies available.

The share of renewable energy electricity apart from hydropower amounts to 0% in 2020 and reaches 29% in 2050. This helps to lessen the high dependence on hydropower resources which is pushed below the 80% cap maximum contribution.

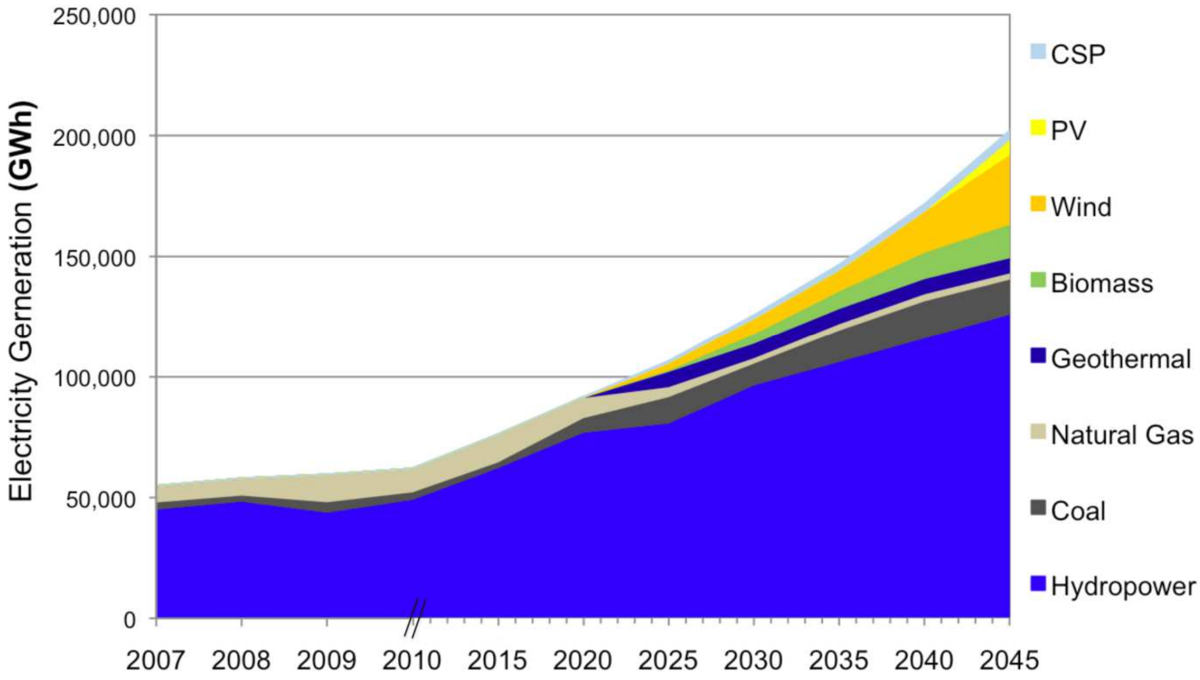


Figure 9-6 Electricity generation for the reference case

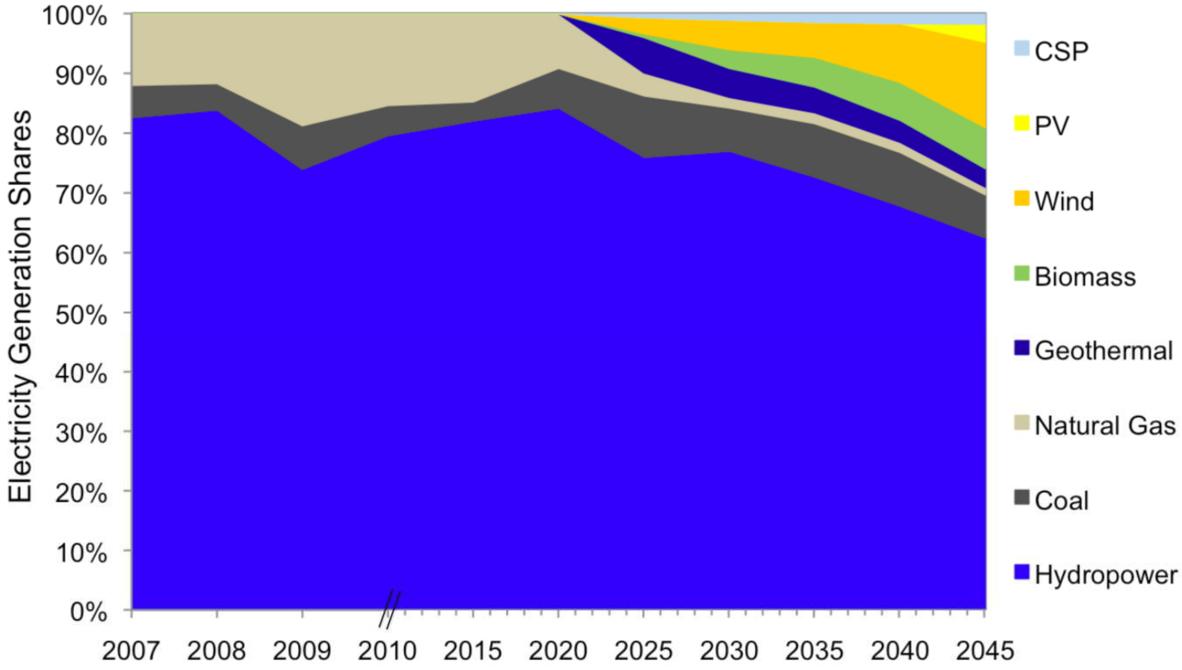


Figure 9-7 Shares of technologies in electricity generation

Regarding CO_2 emissions, the combination of hydropower and a more efficient production utilizing new coal power plants and renewable energy technologies in the power system makes CO_2 emissions remain below the maximum level calculated in 2009 as shown in Figure 9-8. Thus the system is able to reduce emissions further and maintained current levels.

Since electricity demand continues growing and coal power technologies increase their production over the years, emissions increase slightly after 2030.

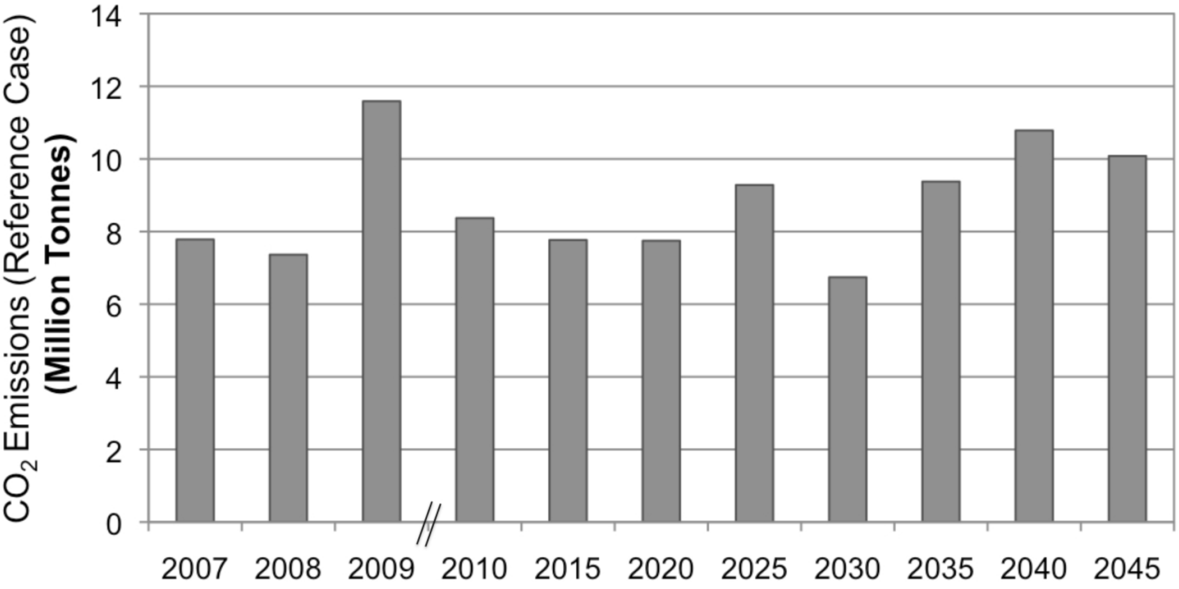


Figure 9-8 CO_2 emissions in the Reference case

9.3.2 Sensitivity with high fossil fuel costs

The results with high prices for natural gas and coal are shown in Figure 9-9 and Figure 9-10. By having higher natural gas prices, coal technologies are dispatched with higher shares at the expense of natural gas, which will nevertheless continue supplying the system together with coal technologies until 2020. Hydropower keeps its share in the energy mix around 80% until 2020 and will be reduced by the higher share of coal and the entrance of fluidized bed combustion with biomass and geothermal.

It is worth noting the delay of wind energy to enter the power system in comparison to the reference case. This is explained by a higher price of natural gas allowing existing coal plants to be preferentially dispatched and therefore accelerating new investments in coal power plants. As soon as their share in the system is increased, an expansion with new technologies is postponed. This proves that a preference today for a given technology affects the future mix of the system as is shown by the logic of the least cost optimization in the simulation.

The installation and dispatch of new renewable energy technologies because of higher fossil fuel prices is not accelerated before 2020, which coincides very closely to the reference case scenario. This is the result of the new balance between coal and natural gas from 2010 to 2020 and higher shares of coal afterwards. Wind power enters the system between 2025 and 2030. Once more CSP and PV technologies enter the system with small shares, they generate slightly more electricity than the reference case. Biomass becomes the main contributor of electricity after wind power.

The share of renewable energy electricity apart from hydropower amounts to 0.7 % in 2020 and reaches 29% in 2050 by its own economic merits helping to lessen the high dependence of hydropower resources which is pushed below the 80% cap maximum contribution.

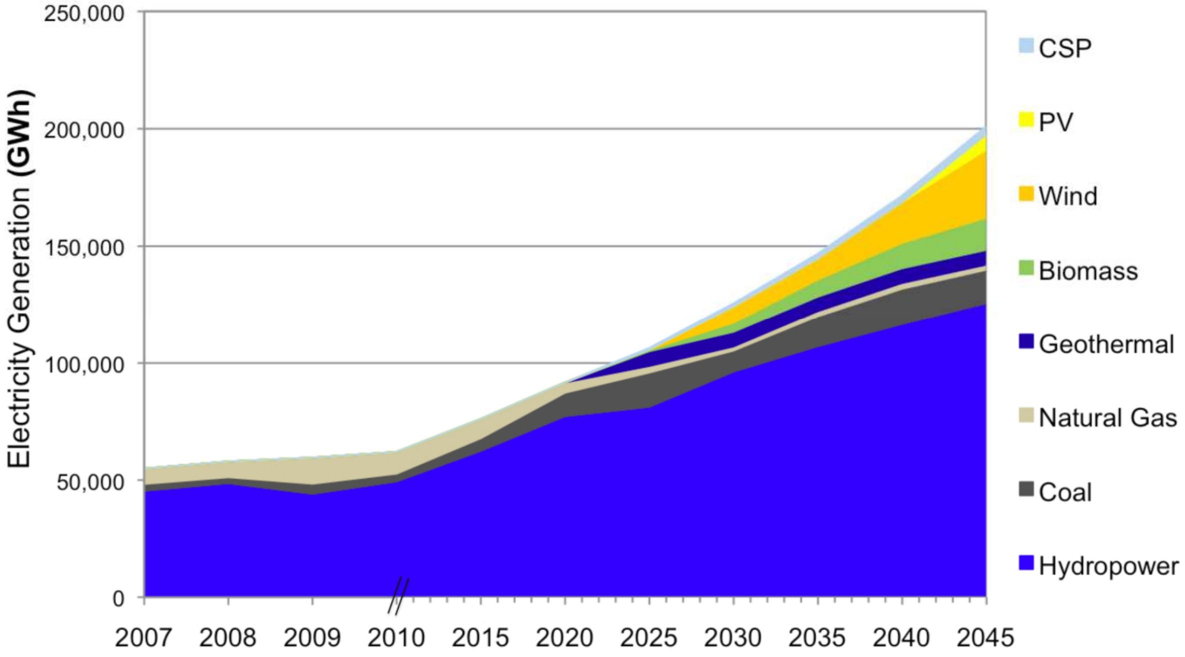


Figure 9-9 Electricity generation with high fossil fuel prices

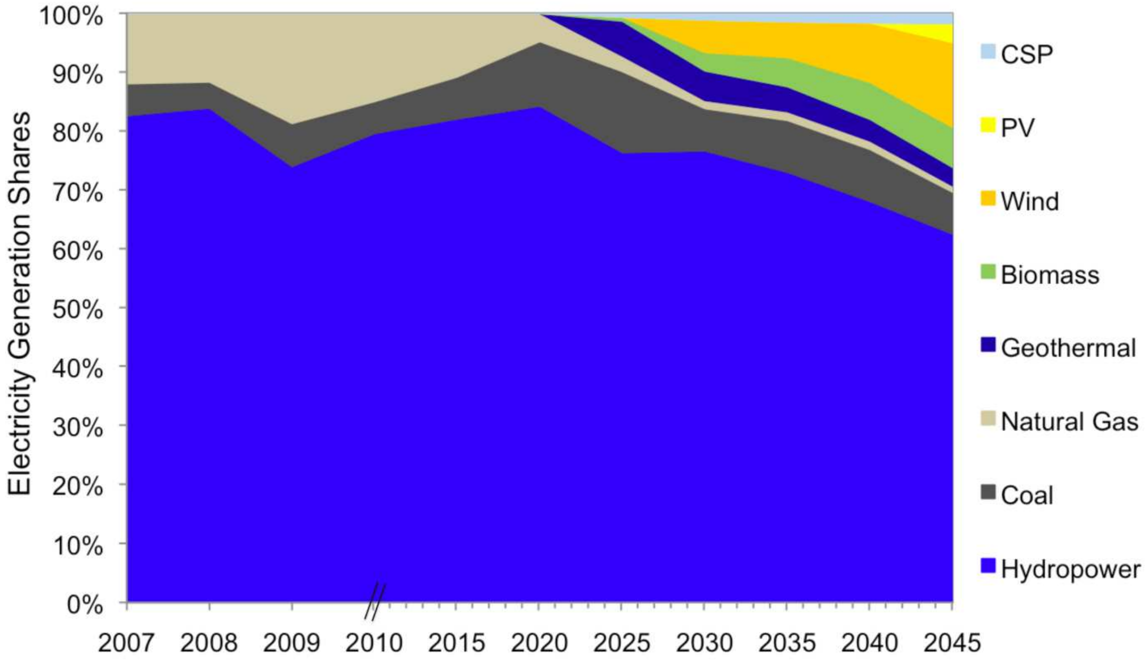


Figure 9-10 Shares of technologies in electricity generation with high fossil fuel prices

By reducing the shares of natural gas technologies and dispatching more coal power plants, CO_2 emissions increase from 2010 to 2025 as shown in Figure 9-11. Analog to the reference case, the introduction of wind and renewable energy technologies reduces the emissions afterwards. Emissions are kept around 10 million metric tonnes per year.

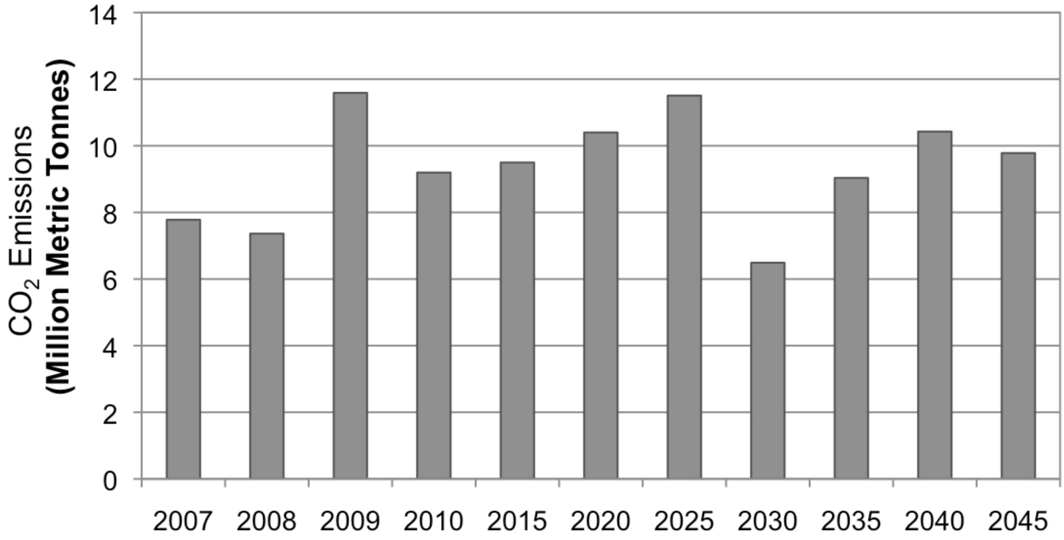


Figure 9-11 CO_2 emissions with high fossil fuel prices

9.3.3 Sensitivity with high costs for renewable energy technologies

The results of sensitivity for investment costs of renewable energy technologies are summarized in Figure 9-12 together with a sensitivity for the cost of fossil fuels. A high reliance on natural gas and coal takes place from 2010 to 2020. Unlike the low investment cost in the reference case, the introduction of wind power and biomass technologies is postponed for the period 2025 to 2030; a delay of five years. Despite the increases in investment costs, new renewable energy technologies manage to enter the system by their own economic and technical merits and reach slightly reduced shares in comparison to the low investment scenario for the last 20 years of the analysis (approximately 1.6% on average for low fuel prices and 1.9% on average for high fuel prices).

The optimization model shows that the introduction of new renewable technologies takes place during a period of 10 years between 2020 and 2030. This is the period where renewable technologies are competitive with conventional technologies. The scale of their introduction depends on how cost and prices will develop until then as shown be the sensitivity analysis.

Regarding fossil fuel costs, a higher cost for natural gas increases the share of coal in the system. The expansion with wind energy will reach its full potential after 2045 anyway. The share of new renewable energy electricity without hydropower amounts to 0% in 2020 and reaches 27% in 2050 by its own economic and technical merits and so the high dependence of hydropower resources is pushed below the 80% cap maximum contribution.

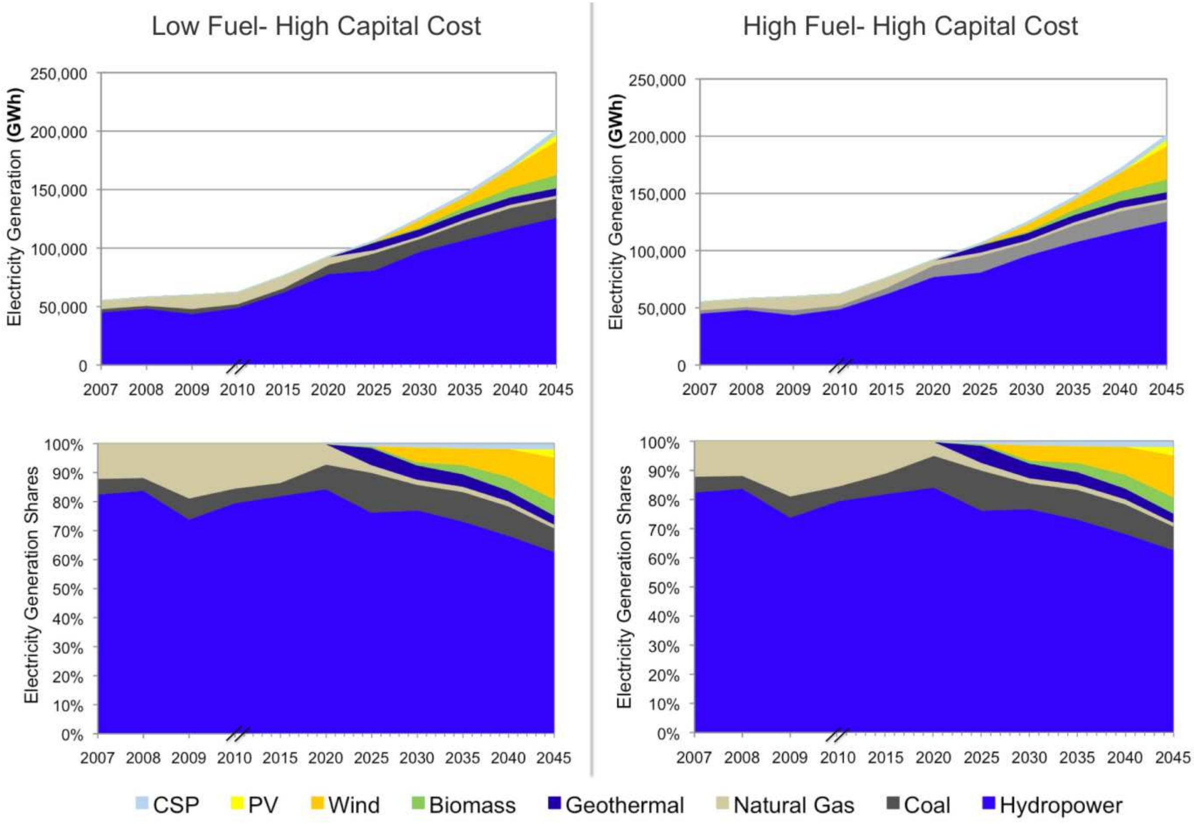


Figure 9-12 Electricity generation and share of technologies in electricity generation for high investment costs

CO_2 emissions increase slightly due to a higher share of coal as shown in Figure 9-13. However they do not surpass the 12 million tonnes.

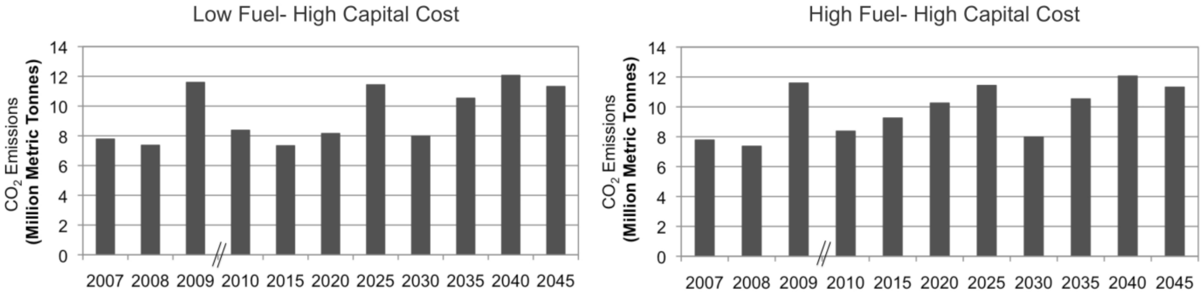


Figure 9-13 CO_2 emissions with high investment costs

9.3.4 Sensitivity for hydropower

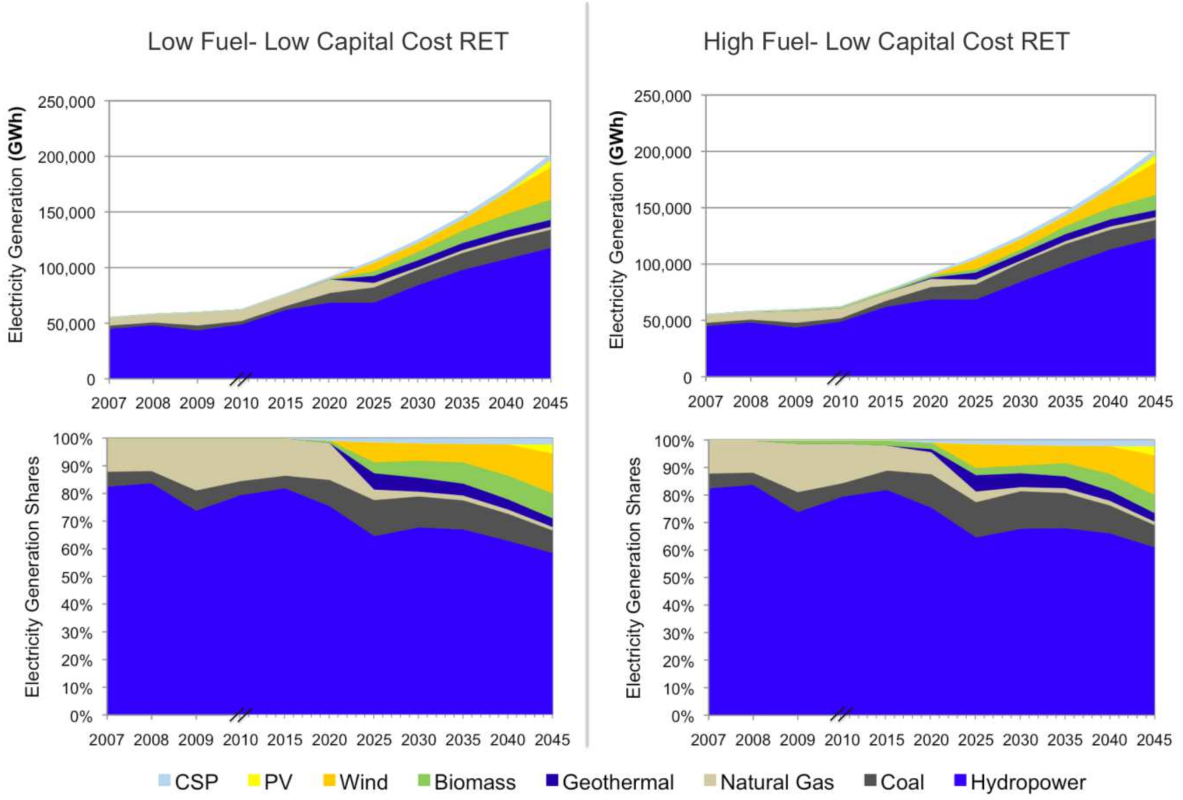
With a sensitivity simulating a lesser contribution of hydropower in the system, the chances to introduce other technologies are naturally enhanced. The results are shown in Figure 9-14 for low cost of renewable energy technologies. In this case coal power technologies profit from a maximal contribution of 70% of generation from hydropower in the coming years.

The dependence on natural gas and coal begins to increase in 2010. The share of natural gas is reduced after 2020 to a minimum due to scarcity and high prices of imported natural gas. In contrast, coal increases its share in the system over the years to be later reduced again as renewables reach higher shares in the system after 2035.

The introduction of fluidized combustion biomass, geothermal and CSP is brought forward between 2015 and 2020, and their share in the system is increased. Noticeable biomass and geothermal technologies play a more important role in the system under the low investment scenario. Wind enters the system after 2020 with higher penetration rates so the share of wind in the system reaches a constant portion over the years.

The shares of renewable energy electricity apart from hydropower amount to 1.54% and 4.22% in 2020 for the low and high fuel scenario respectively. The shares are 31.8% and 29.4% in 2050 by its own economic and technical merits. The shares of renewable energy sources help to decrease the high dependence on hydropower resources which is pushed below the 70% cap maximum contribution.

As previously stated in the sensitivity analysis, a higher fuel cost for natural gas affects only the shares of coal and natural gas in the coming future. However, the combination of higher fuel costs, less hydropower resource availability and low cost of renewable energy technologies is the most favourable scenario for renewable energy sources. In that case the contribution of renewable energy sources is already around 18% in 2025.

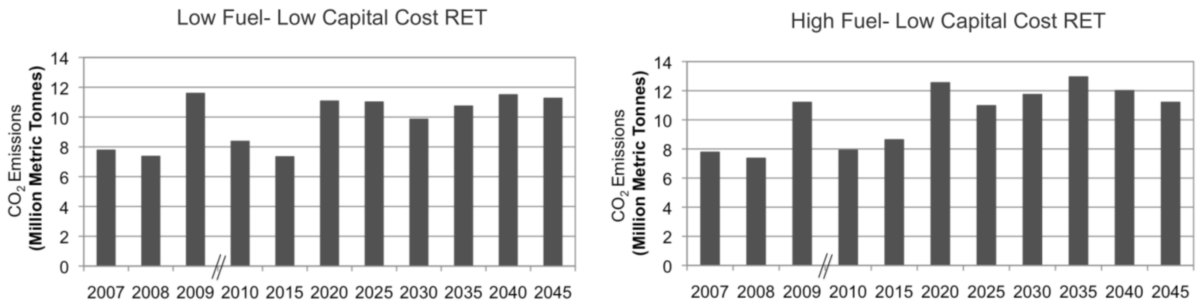


Low Fuel- Low Capital Cost RET

High Fuel- Low Capital Cost RET

Figure 9-14 Electricity generation and shares of technologies in electricity generation with less contribution of hydropower (low cost for renewables)

As a consequence of the reduction of hydropower generation in the system, the emissions of CO_2 increase due to the higher contribution of natural gas and coal in the system. They exceed 10 million tonnes of CO_2 beginning in 2020 as shown in Figure 9-15.



Low Fuel- Low Capital Cost RET

High Fuel- Low Capital Cost RET

Figure 9-15 CO_2 emissions with a lower contribution of hydropower

In a scenario with a lower contribution of hydropower combined with higher investment costs for renewables, as shown in the results exhibited in Figure 9-16, the dependence on coal and natural gas sources increases. Soon after 2010 the share of coal increases in the system over the years. This is in particular noticeable by high fuel costs of natural gas. The expansion of the power system relies on important shares of coal. The higher cost of renewable technologies postpone a high penetration of renewable energy sources after 2025 allowing coal power plants to enter the system to support the reduction of hydropower.

However, a higher contribution of renewables is observed after 2040. Unlike the low investment costs sensitivity, the introduction of renewables occurs after 2020. A higher cost of renewable energy technologies postpones their introduction for 5 years. Again biomass and geothermal achieve important shares and wind power reaches its maximum capacity after 2045.

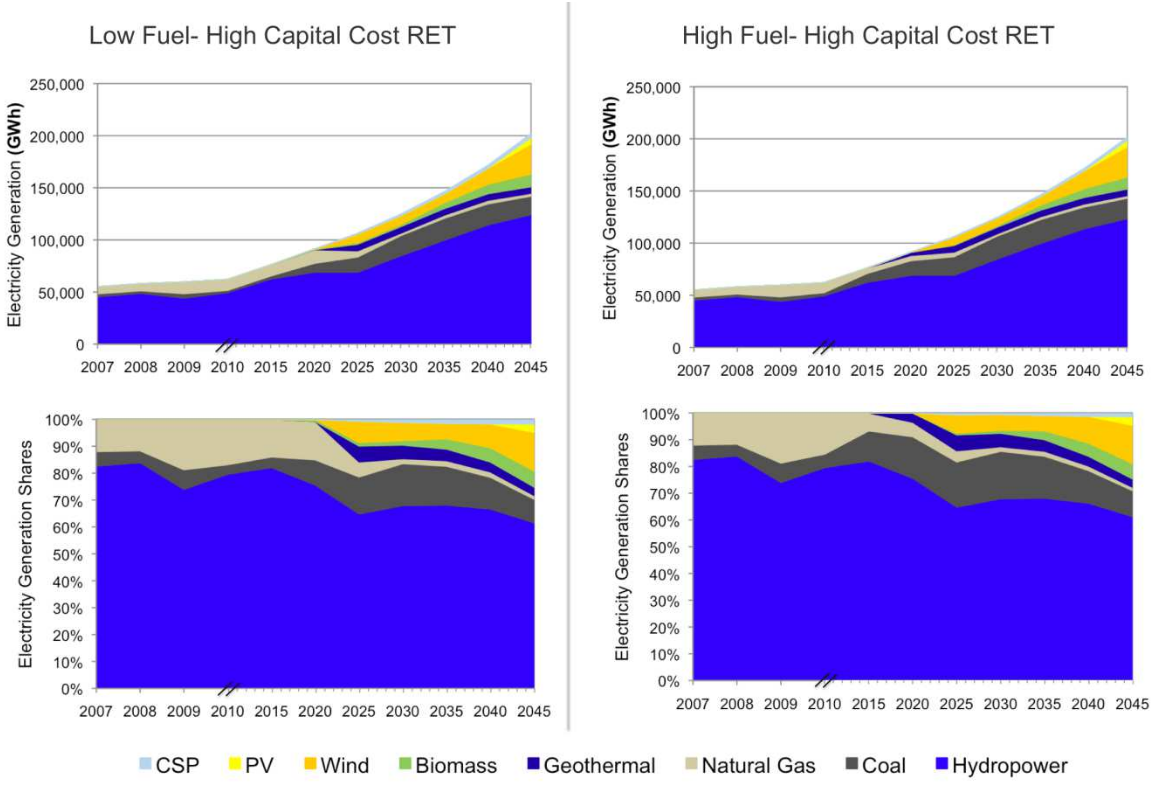


Figure 9-16 Electricity generation and shares of technologies in electricity generation with less contribution of hydropower (high cost for renewables)

As expected, this sensitivity tops the CO_2 emissions of all simulations introduced until now. The emissions reach a new maximum of almost 16 million tonnes for the period between 2035 and 2040 as shown in Figure 9-17.

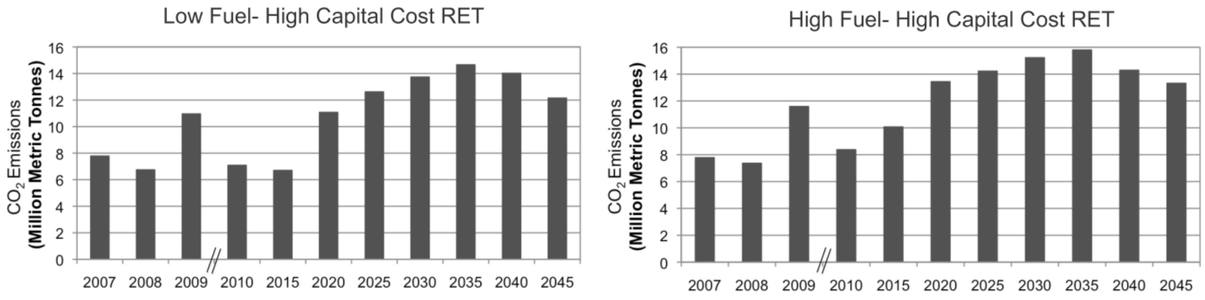


Figure 9-17 CO_2 emissions with a less contribution of hydropower

Unlike the accounting framework model LEAP where the scenarios were predetermined, the optimization model result suggests that new renewable energy technologies will be part of the system under all sensitivity analysis. Unfavourable economic conditions for renewable energy technologies with high investment costs, low fossil fuel prices and high shares of hydropower, did not inhibit the expansion with these technologies. However the speed of this penetration and its magnitude depends on them.

9.4 LEAST COST RESULTS

The objective of the optimization model is to find a system with the overall least cost. The optimal solution then is the net present value of all costs and investments of expanding and operating the power system under the parameters set in the model such as electricity demand, investments and O&M costs, fuel prices, availability of resources, etc. Table 9-2 shows the results for the reference case and the sensitivity analyses.

Table 9-2 Least cost optimisation results

	Sensitivity Parameters	Reference Case Sensitivities		Hydro Sensitivity	
		(Million 2006 USD)	*(%)*	*(Million 2006 USD)*	*(%)*
1	Low price fuels + low cost RET Reference case	13,105	-	13,856	-
2	High price fuels + low cost RET	13,419	2.4	14,369	3.7
3	Low price fuels + high cost RET	13,622	3.9	14,666	5.8
4	High price fuels + high cost RET	14,036	7.1	15,131	9.2

RET: Renewable energy technologies

A higher share of hydropower is always the least alternative option for the system over the years. A reduction of hydropower implies automatically higher costs for the system as shown in Table 9-2 for the scenarios with the hydropower sensitivity.

The relative maximum extra cost of having high cost for renewable energy technologies in the power system by comparing the net present values with the reference case (low fuel prices, low cost RET) is between 7.1% and 9.2 %.

A reduction of hydropower contribution is more costly in comparison to an increase in fuel costs indicating that the value of the system expressed as the net present value is more sensitive to hydropower (13,856 vs. 13,419 and 14,666 vs. 14,036 Million in 2006 USD).

9.5 CO_2 EMISSION COSTS

Combining renewable energy policies and carbon prices for climate change mitigation accelerates the deployment of renewables (IPCC 2011 p.75). Based on the results of the accounting framework model LEAP, the price of CO_2 per tonne was determined by comparing the renewable scenarios with the BAU scenario results. Thus a price to be charged per tonne to match the cost of the BAU was found. Prices per tonne are between 7.7 USD/tonne and 158.6 USD/tonne of CO_2 –Eq. (2000 USD).

In the optimization model, the result suggests that a price for CO_2 is not required to guarantee the entrance of renewables into the system. The least cost system is achieved with renewables by their own economic and technical merits. However, a carbon price would accelerate the competitiveness of renewable energy projects and therefore their entrance into the system. This would reduce the share of coal power plants in the power generation sector in the future.

A carbon price would be the result of a global policy to reduce CO_2 emissions to combat climate change. Therefore an additional analysis conducted with MESSAGE includes a carbon price to determine the effect on the energy mix. According to the IPCC, carbon prices between 20 and 50 USD/tonne of CO_2 (2000 USD) implemented globally between 2020 and 2030 would deliver deep emission reductions by mid-century consistent with the stabilization of CO_2 at around 550 ppm CO_2-eq (IPCC 2007, p.621). These results were reported by the IPCC with a high level of confidence which would help decarbonize the world’s electricity system (IPCC 2007, p.660).

Assuming the introduction of a global carbon tax from 2020 with a sustained price of 20 USD/tonne of CO_2 until 2050, results were obtained for the reference case including the sensitivity for hydropower as shown in Figure 9-18 and Figure 9-19.

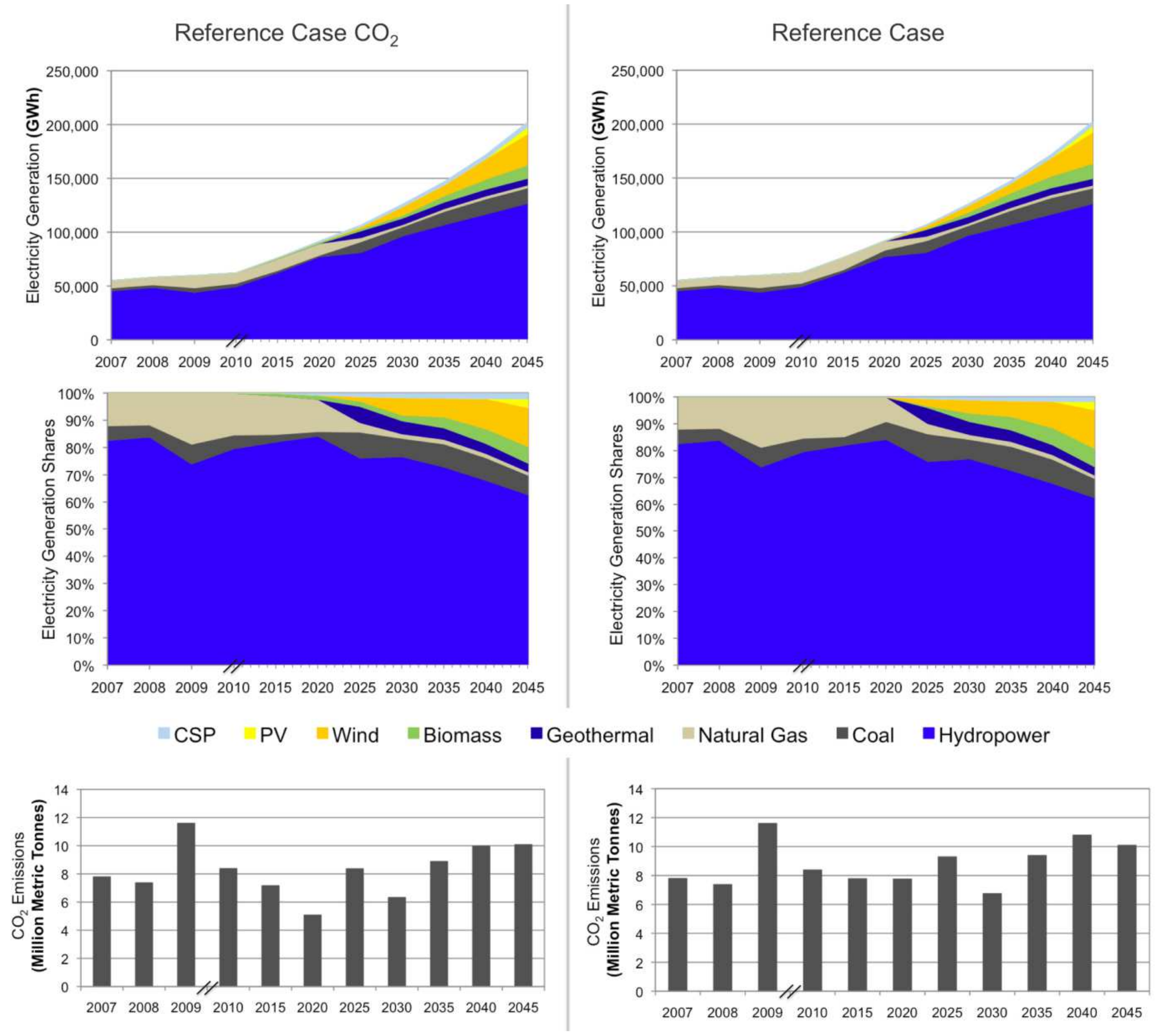


Figure 9-18 Reference case with prices for CO_2 vs. Reference Case

It was found that the contribution of coal sources to the system was further decreased in comparison with the results without a charge for CO_2 emissions. The overall CO_2 emissions of the power system are reduced and maintained under the 10 million tonnes of CO_2 mark.

The introduction of wind energy into the system was not brought forward, but more units were installed. This increases the share of wind in electricity generation. The introduction of CSP and biomass was accelerated as well as their share of electricity in total generation. Accordingly the share of coal in electricity generation is reduced. The results prove that the competitiveness and emissions from conventional plants are reduced by imposing a price per tonne of CO_2. This price increases the variable cost of production for these power plants.

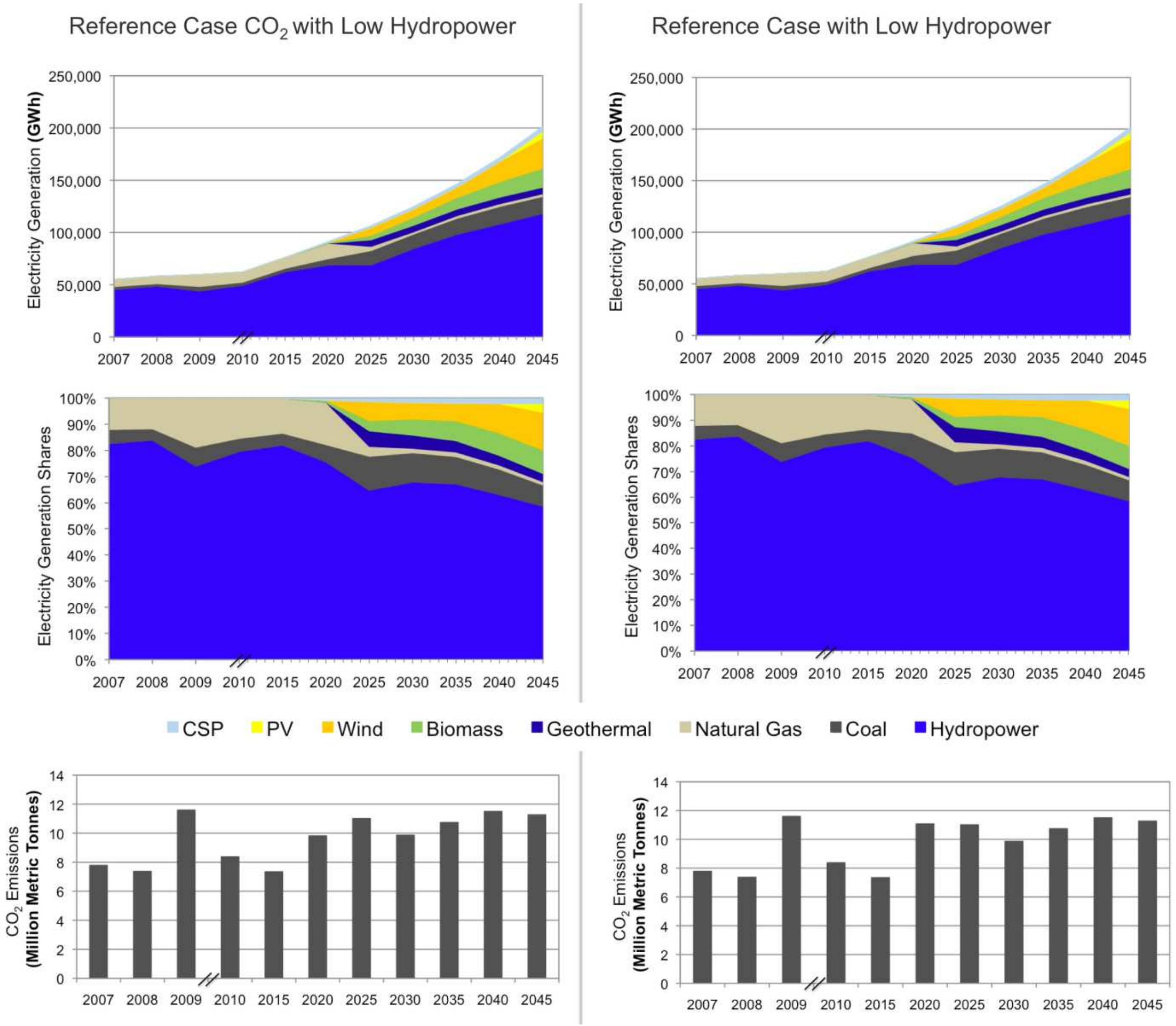


Figure 9-19 Reference case with less hydropower and prices for CO_2 vs. Reference case with less hydropower

Figure 9-19 compares the results of the sensitivity of hydropower with and without the introduction of a carbon tax. The results suggest that the carbon tax did not have the same impact suggesting that more coal power plants are indeed needed together with more new renewable sources to cover for less hydropower. A reduction of the share of coal takes place only from 2020 to 2025 which is compensated by more natural gas. The reduction of CO_2 emissions is found only during this period of time. CO_2 emissions increase afterwards as the share of coal increases. The overall CO_2 emissions of the power system are maintained under the 12 million tonnes of CO_2 mark from 2020 onwards.

9.6 SUMMARY

Overview

Unlike the accounting framework model LEAP, the optimization model MESSSAGE determined the least cost power system based on economic and technical merits of the individual technologies. A BAU scenario was used as a point of reference for the scenario analysis defined in LEAP. This is converse to MESSAGE, in which the continuation of energy policies and the current conventional energy sources technologies hydropower, coal and natural gas were not an output.

In all scenarios simulated with MESSAGE, new renewable energy technologies were introduced to the power system regardless of fuel prices, investment and operation and maintenance costs sensitivities according to the potential defined for every source. The result suggests that, sooner or later, the introduction of new renewable energy technologies will take place in Colombia by its own economic and technical merits.

With the help of sensitivity analyses it was however shown that the entrance and electricity generation of new technologies will be accelerated or postponed according to economic conditions of fossil fuel prices, investment cost of renewable energy technologies and contribution of hydropower to the system. Therefore the results of the optimization model gives an indication to when and how much new renewable energy technologies can be expected in the system as illustrated in Figure 9-20 and Figure 9-21.

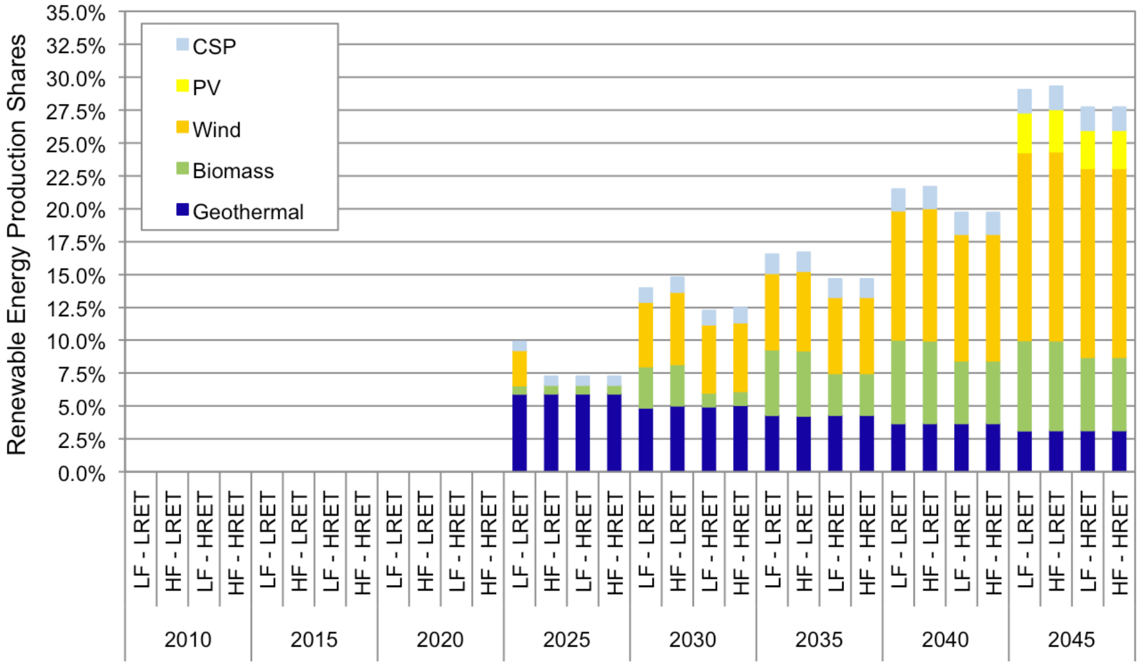


Figure 9-20 Renewable energy shares in electricity generation

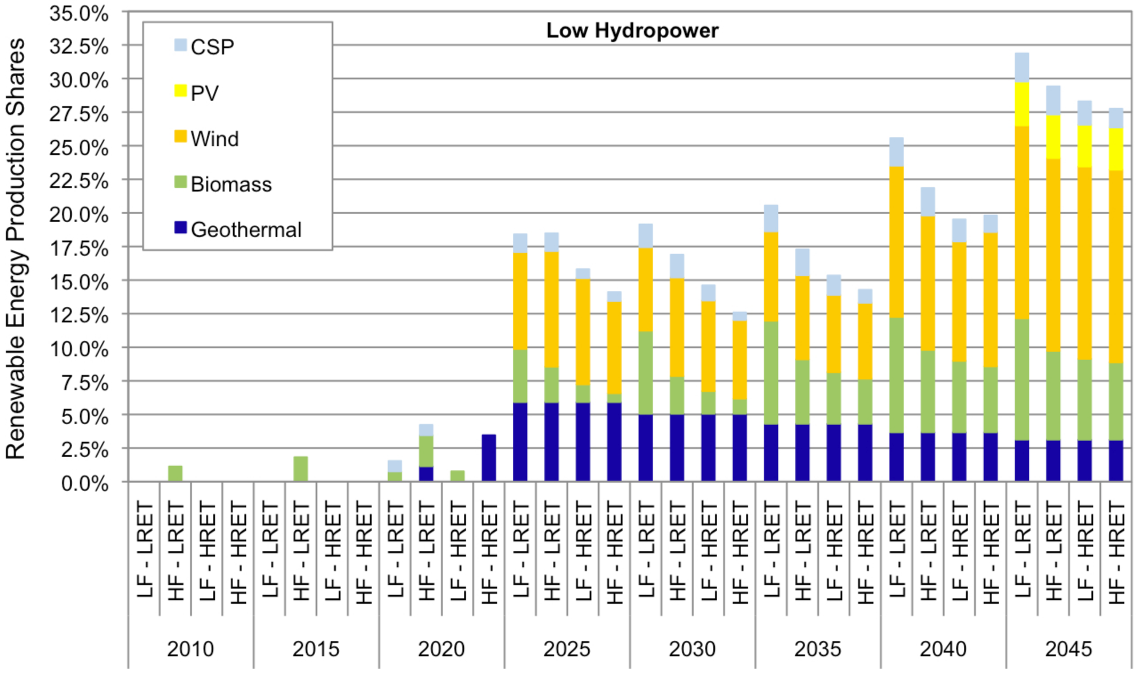


Figure 9-21 Renewable energy shares in electricity generation with less hydropower

Figure 9-20 and Figure 9-21 exhibit the key years where the reshaping of the power sector can take place, which is between 2020 and 2030. In an interval of ten years the power system will experience a transition to a more diverse system. This new system will have hydropower playing a key role and also include a variety of renewable energy sources such as wind, solar, geothermal and biomass. Despite the abundance of hydropower and coal, the entrance of new renewable energy technologies in the system is a powerful message especially for power sectors dominated by hydropower.

In summary fuel prices alone are not the key driver for the introduction of renewable energy technologies. Hydropower contribution to the system and the competitiveness of new technologies in the future drives the introduction of renewables. Under a scenario of a lower contribution of hydropower and low investment costs for renewables, the entrance of these technologies can be expected after 2015. Regardless of prices for fossil fuels and investment costs for renewable energy technologies, a share of new renewable energy sources between 7.5% and 17% can be achieved by 2025.

Technologies

According to the findings, the most promising new renewable energy technology is wind energy, which delivers most of the electricity from new renewable energy sources despite of a capacity factor of 33%. The potential of 10 GW is reached after 2040.

In all scenarios conventional geothermal technologies were introduced. The analysis does not take into account the costs to determine the availability and quality of the resource. This is a condition precedent to make sure that geothermal power plants can be installed. A potential of geothermal resources for power generation in Colombia has not yet been determined. The advantage of utilizing geothermal technologies is their dispatchability for base load as conventional technologies with coal and natural gas with capacity factors over 80%.

The use of biomass sources with fluidized bio combustion and biomass IGCC is present in the system notably in the scenarios with a lesser hydropower contribution and low investment and operation costs. The key challenge here is the use of solid residues especially from sugar plantations and their collection, disposal, and transport to power plants. Biomass has also high capacity factors around 80%.

In contrast, solar technologies as concentrated solar power and PV have a very modest contribution in the system. Concentrated solar power offers an interesting alternative with higher capacity factors with energy storage, however the high investment and operation and maintenance costs make them prohibitive for higher shares. A photovoltaic system has very competitive prices per kW, but its lower capacity factor is seen as a disadvantage for the system in the simulation by MESSAGE.

CO_2 emissions

The CO_2 emissions in all scenarios do not show noteworthy fluctuations and are kept, on average, between 10 and 12 million metric tonnes per year. Scenarios with a low contribution of hydropower and high investment cost for renewable energy technologies reach 14 million metric tonnes of CO_2. The CO_2 emissions are approximately 12 million metric tonnes in 2009, when the contribution of hydropower was not under normal conditions due to El Niño, and natural gas and coal were greatly dispatched. The introduction of renewable energy technologies and more efficient coal and natural gas technologies therefore keep the emissions at a constant level. The results with LEAP differed greatly with MESSAGE, since the scenarios were predefined to include renewable energy technologies and the magnitude of their contribution. CO_2 emissions in the accounting framework model LEAP showed, for instance in the BAU scenario with coal, over 50 million tonnes of CO_2 in 2050.

In addition a carbon price was included in the analysis under the assumption that a global policy is in place to combat climate change. The results prove that the competitiveness and emissions from conventional plants are reduced by imposing a price per tonne of CO_2. This helps to decarbonize the power system and further increase the share of renewable energy sources in the system, if carbon prices really increases the operation costs of conventional power plants to decrease their competitiveness.

The results presented here with MESSAGE along with the predefined scenarios of LEAP will be dependent on Colombia’s energy and market environment, where energy policy will dictate in which direction the power system should be developed. As the current policy of the country is the use of most competitive sources in the system, the renewable energy sources should enter the system by their own economic and technical merits at some point in time between 2015 and 2030 as shown in the results.

It does not mean that the market by itself will allow these technologies to become part of the system as soon as they are economically and technically viable. A policy framework that does not promote the long term will continue promoting presumably conventional and known sources and technologies. The market actors require information of the potential for the exploitation of renewable energy sources and the market signals in order to make the investment decisions of the future. By knowing that the transition might begin around 2020, a period of ten years should be used to pave the way to make possible this reshaping of the Colombian power sector with new energy sources.

The implementation of new technologies is possible with a set of right policies allowing a smooth transition to the power system of the future. The next chapter introduces in more detail these issues for the Colombian case.

10. RENEWABLE ENERGY IN THE CONTEXT OF THE COLOMBIAN POWER SECTOR

The introduction of new power technologies, including renewable energy technologies, into the Colombian power sector was simulated with energy models. The theoretical results suggest that renewable energy technologies will become a part of the Colombian power sector by their own economic and technical merits. Why these technologies should be introduced into the Colombian power sector is the topic of this chapter. In this chapter, the results of the simulation will be put into the context of Colombia's power sector so to better understand the importance of having these technologies.

Colombia's picture regarding global GHG emissions is analysed as well as the impacts of climate change in Colombia, which may affect the power sector, in particular hydropower. The current contribution of the Colombian power sector to GHG emissions is presented. Given the importance of hydropower in Colombia, the essential attributes of this resource, which essentially drive Colombia's power sector are also examined.

The results of the simulation of the Colombian power sector together with the analysis of hydropower and climate change in the Colombian context make possible a comprehensive analysis of the Colombian power sector and address the research questions of this dissertation. A summary of the reasons that could drive the promotion of technologies powered by renewable energy sources in Colombia is detailed. A summary of the facts and uncertainties facing the Colombian power sector is conducted to understand why renewable energy sources should be promoted in Colombia.

The entry of new technologies brings new challenges. The integration of renewable energy technologies is analysed with particular focus on the issue of intermittency in electricity production. The advantage of having wind energy combined with hydropower for the Colombian power sector is examined.

As the transformation in the power sector may not be only driven by market forces alone, an electricity market allowing a level playing field for new technologies to come via tailored energy policies is also necessary. This topic closes the chapter and the content of this dissertation.

10.1 RENEWABLE ENERGIES AND CLIMATE CHANGE

The latest report by the IPCC, the Fourth Assessment Report (AR4), comprises the most up to date policy which includes relevant scientific, technical and socio-economic information on climate change. The IPCC was established by the World Meteorological Organization and the United Nations Environment Programme in 1988 and their author teams consist of the world's leading climate change scientists and experts.

The synthesis report, which summarizes the findings of the AR4, confirms that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average see level" (IPCC 2007, p. 30).

The assessment also concluded that "there is high confidence that recent regional changes in temperature have had discernible impacts on physical and biological systems" (IPCC 2007, p. 30) and that the cause of change are due to "changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols, land cover and solar radiation alter the energy balance of the climate system and are drivers of climate change" and that "human activities result in emissions of four long-lived GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O) and halocarbons" (IPCC 2007, p. 37).

"Global atmospheric concentrations of carbon dioxide (CO_2) methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture"(IPCC 2007a, p.2).

Figure 10-1 illustrates the amounts and shares of GHG gases in the period from 1970 to 2004, the source and the sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2- eq.

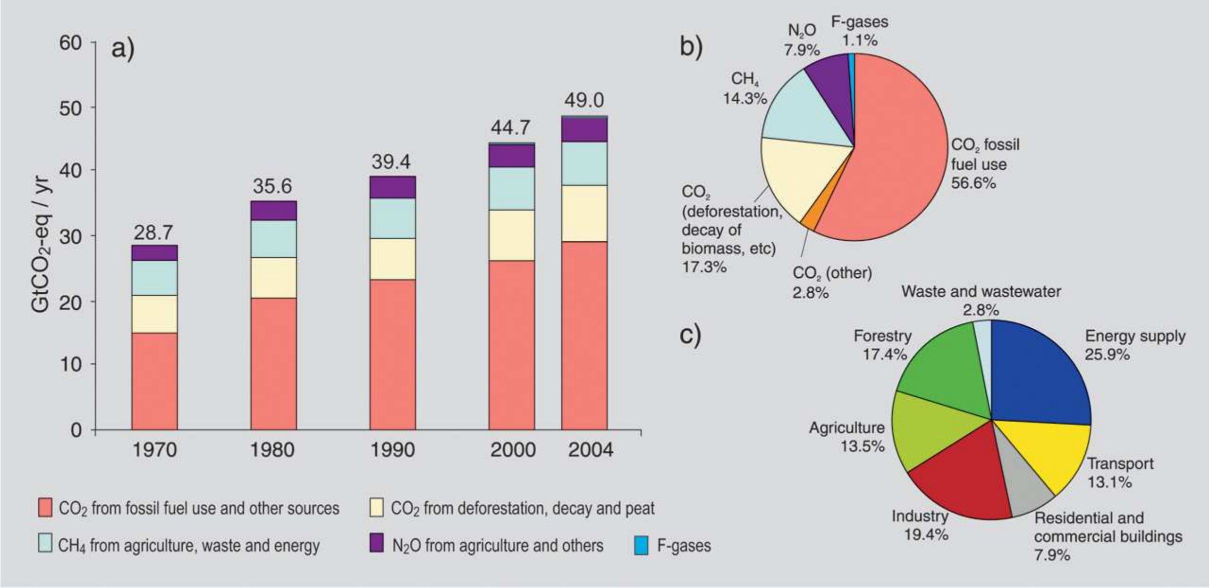


Figure 10-1 Global Anthropogenic GHG emissions

Source: IPCC 2007, p.36.

CO_2 is the most important GHG in terms of global warming. CO_2 concentrations in the atmosphere have increased by 80 % between 1970 and 2004. They represented 77% of the total GHG emissions in 2004 (IPCC 2007, p. 30). The energy supply sector is the sector that has contributed the most to GHG emissions as shown in Figure 10-1.

The report also notes the notable differences among regions in the world regarding their share in GHG emissions according to their income and population. The Annex I countries, which include all OECD countries as of 1990 and countries with economies in transition, account for 57% of the world's Gross Domestic Product based on their Purchasing Power Parity (GDPppp). These countries account for 46% of global GHG emissions as illustrated in Figure 10-2 (IPCC 2007, p. 37).

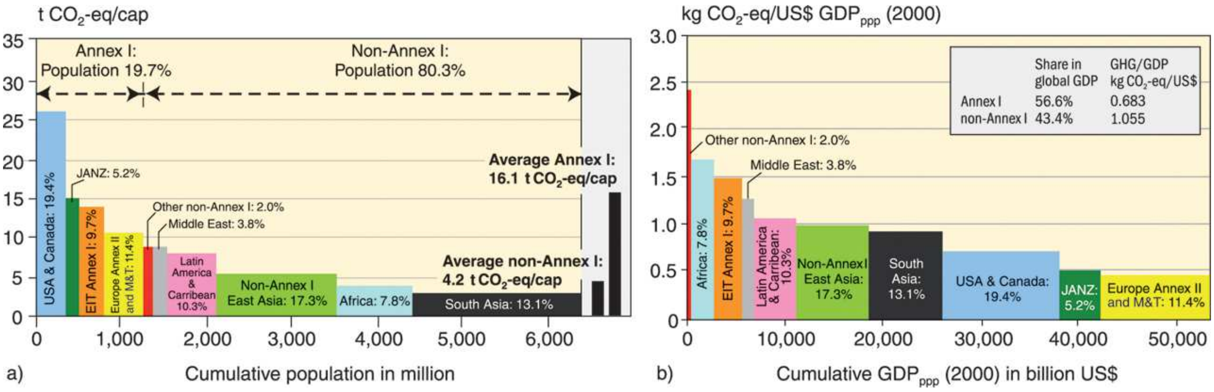


Figure 10-2 Regional Distribution of GHG emissions by population and GDPppp

Source: IPCC 2007, p.37.

Latin America and the Caribbean accounted for 10.3% of global GHG emissions as of 2004, the equivalent emissions per capita correspond to 30% of that of North America and emissions per USD of GDPppp are over 1.0 kg CO_2-eq/USD GDPppp (2000).

The impacts of climate change are dependent on the change in concentration of GHG's in the atmosphere over the next decades, and thus on GHG emissions, in particular anthropogenic emissions. Anthropogenic GHG emissions are characterised by demographic, economic and technological factors. Any combination of the expected development of these parameters results in a series of alternative scenarios and GHG emissions. Continued GHG emissions and therefore further warming will induce many changes in the global climate system that are likely to be greater than those observed in the last century (IPCC 2007, p.45).

Figure 10-3 shows the projected emissions in the absence of additional climate policies and the projected global average temperature for a set of scenarios showing how global warming might develop and thereby the expected range of global warming according to the GHG emissions predicted to be released in the 21st century.

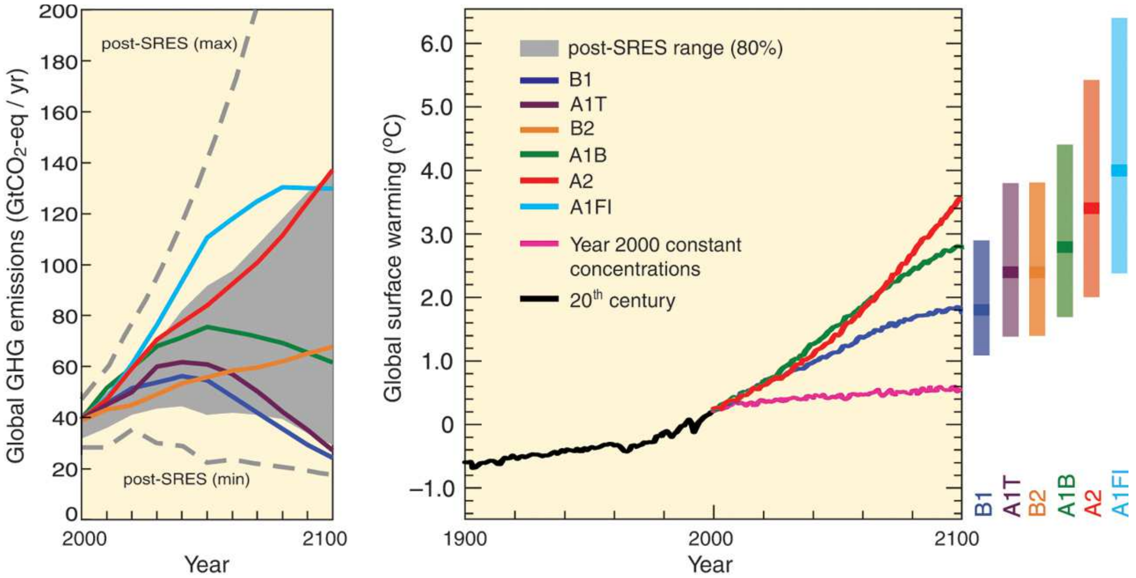


Figure 10-3 GHG emissions and global surface warming until 2100

Source: IPCC 2007, p.7.

Predicted impacts of global warming in Latin American as reported by the IPCC (IPCC 2007, p.50):

- Decrease in soil water that lead to gradual replacement of tropical forest by savanna in eastern Amazonia. Semi-arid vegetation will tend to be replaced by arid-land vegetation
- Risk of significant biodiversity loss through species extinction in many areas of tropical Latin America

- Productivity of some important crops is projected to decrease and livestock productivity to decline
- Changes in precipitation patterns and the disappearance of glaciers affecting water availability for human consumption, agriculture and energy generation

The above listed impacts have a confidence level of 'high' (*see* IPCC 2007, p.50).

The UN Framework Convention on Climate Change calls for a stabilization of GHG in the atmosphere and the Cancun Agreements in 2010 call for the avoidance of global warming of more than 2°C above pre-industrial values and agreed to consider a value of 1.5°C (IPCC 2011, p.11). In order to reach that value, the concentration of GHGs should be in the range of 445 to 490 ppm CO_2-eq, which would mean a peaking year for CO_2 emissions between 2000 and 2015 and a reduction of CO_2 emissions by 50 - 85% in comparison to the 2000 level, by the year 2050.

Such stabilisation levels "can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialised in coming decades, assuming appropriate and effective incentives are in place for development, acquisition, deployment and diffusion of technologies and addressing related barriers" (IPCC 2007, p.68).

Such a portfolio of technologies is mainly related to energy supply and energy efficiency. The combination of these technologies achieves an important stabilisation level. Renewable energy technologies in this context can contribute greatly to the stabilization as shown in Figure 10-4.

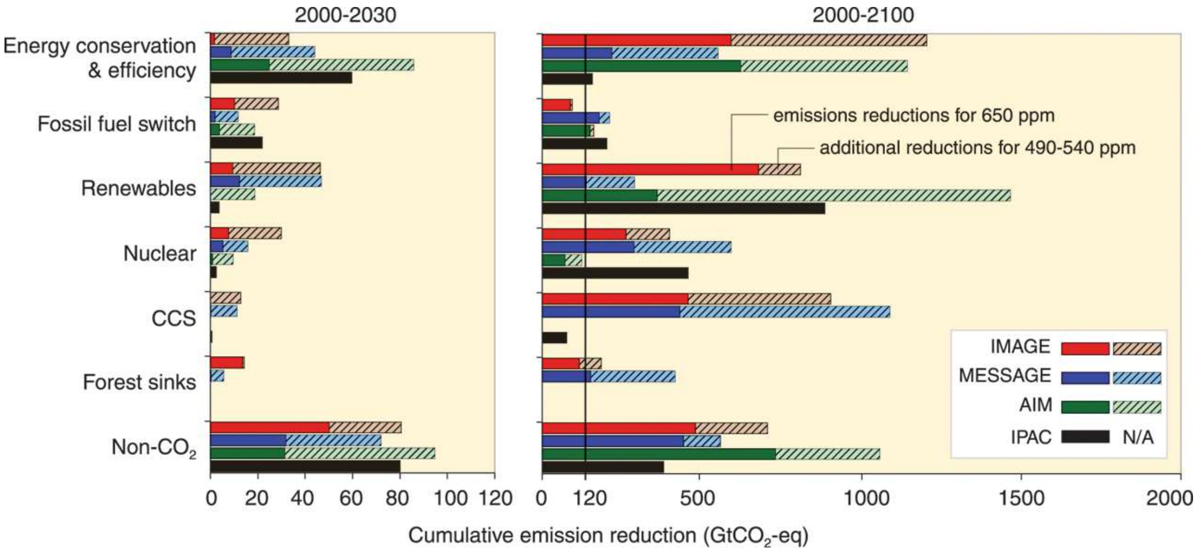


Figure 10-4 Portfolio of technologies for achieving stabilization of GHG concentrations

Source: IPCC 2007, p.68.

Coal, gas and oil represent 85 % of the global energy supply which amounted to 492 EJ by 2008 as shown in Figure 10-5 (IPCC 2011, p.15). Global energy supply relies heavily on these fossil fuel resources, which makes energy production the main contributor of CO_2 emissions in the atmosphere. Renewable energy resources present an attractive alternative to fossil fuel resources in light of global warming. Of the overall global primary energy supply in 2008, renewable energy sources had a share of 12.9% in which bioenergy represented 10.2%. 60% of the bioenergy share is biomass used in traditional cooking and heating applications in developing countries (IPCC 2011, p.15).

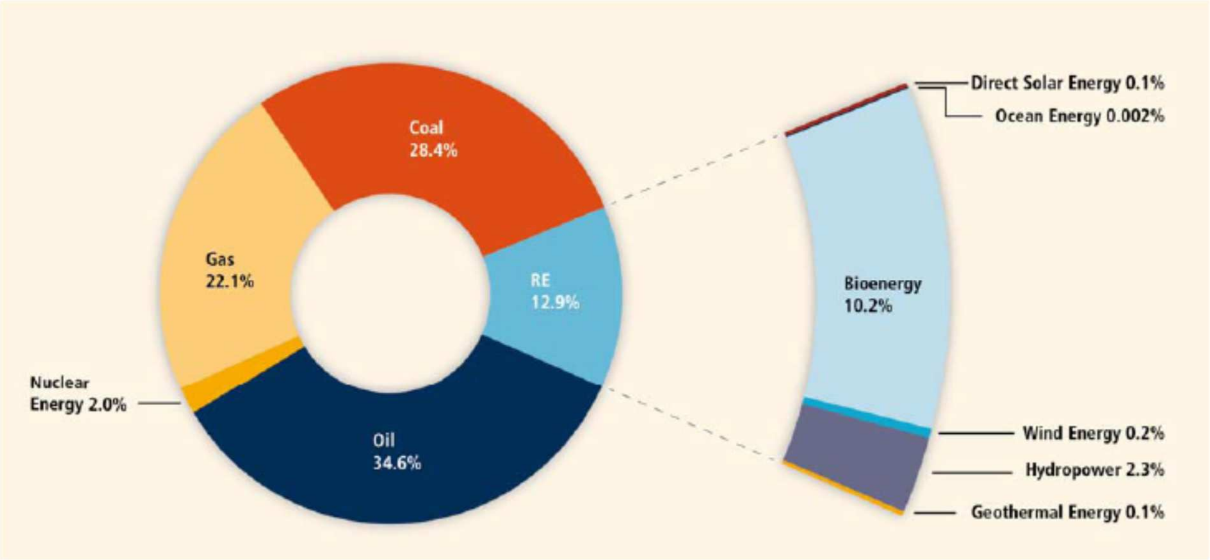


Figure 10-5 Shares of energy sources in total global primary energy supply in 2008

Source: IPCC 2011, p.15.

With respect to power generation renewable energy sources contributed 19% of global electricity supply, hydropower being the major contributor with 16%. The global electricity supply amounted to 72.65 EJ (20,181 TWh; 14.7% of total global primary energy supply). Figure 10-6 summarizes the energy sources of the word electricity generation (IPCC 2011, p.16).

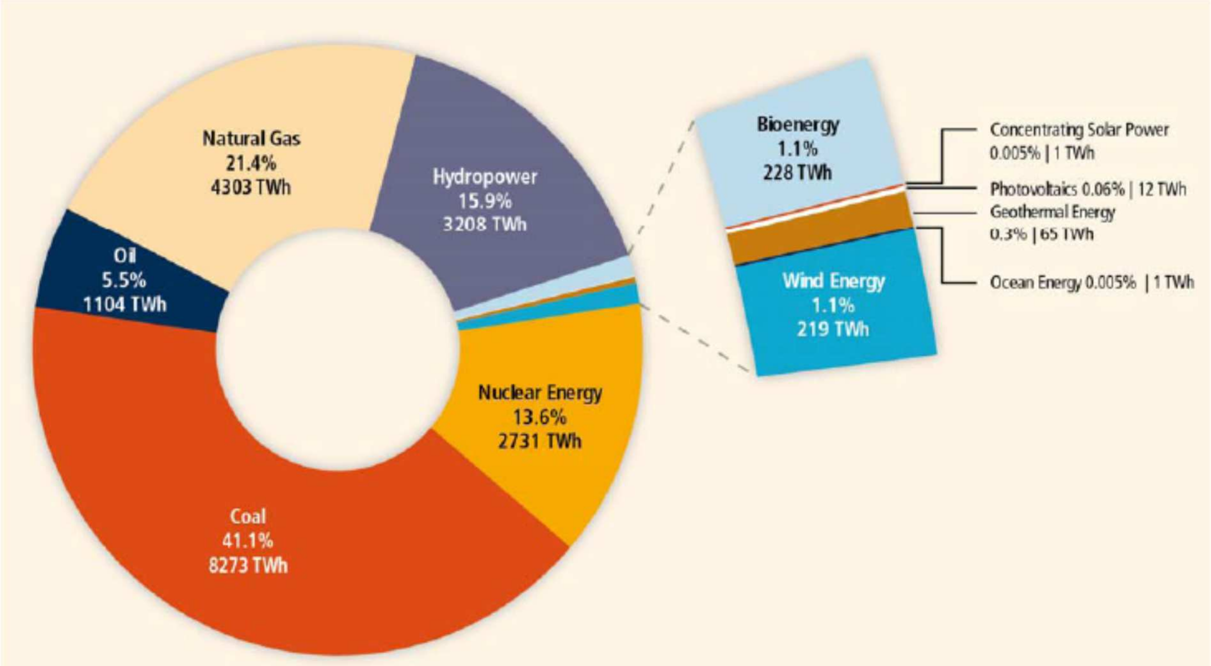


Figure 10-6 Share of primary energy sources in world electricity generation in 2008

Source: IPCC 2011, p.16.

As the global primary energy supply, electricity generation is dominated by fossil fuels representing 68% of total production. Including hydropower the share of renewable energy sources is 32%. The contribution of renewable energy sources apart from hydropower continues to be very small despite high penetration rates especially those of solar and wind technologies, which are already proven technologies and part of the global market.

In the global context renewable energy sources are a key option for reducing emissions in the power sector due to their low specific emissions relative to fossil fuels as shown in Figure 10-7. A successful implementation of these technologies together with other technical solutions such as improvements in supply and demand efficiency, shift to cleaner fuels, nuclear energy, carbon capture and sequestration (CCS) among other solutions are necessary to reach reduction targets.

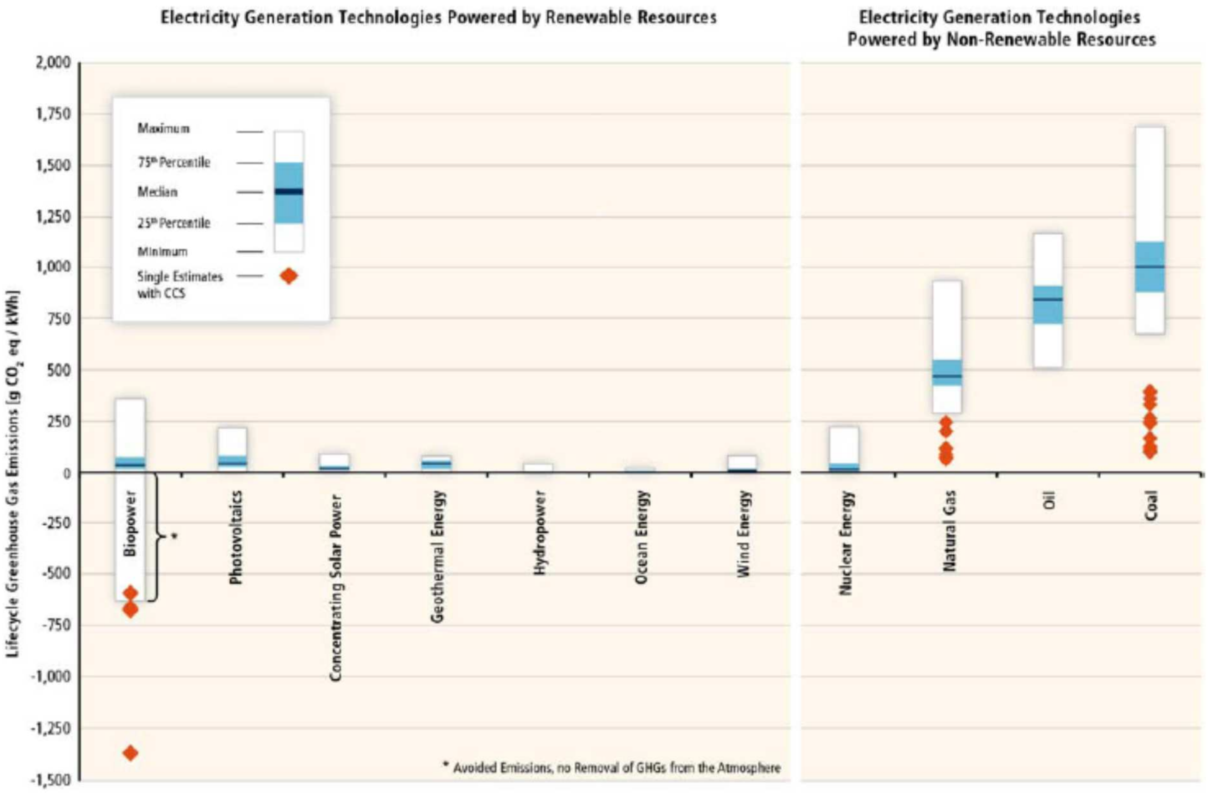


Figure 10-7 Lifecycle GHG emissions of power technologies

Source: IPCC 2011a, p.36.

10.2 CLIMATE CHANGE IN THE CONTEXT OF THE COLOMBIAN POWER SECTOR

Colombia approved the United Nations Framework Convention on Climate Change (UNFCCC) in Law 164 in 1994 and approved the Kyoto Protocol in Law 629 in 2000. Because of the commitments of those treaties, Colombian institutions have adopted a number of policies and strategies to address climate change. For example a national strategy for the implementation of the Clean Development Mechanism was developed by the Ministry of Environment in 2000. The first national communication was issued in 2001, which provided the national inventory of greenhouse gases for the years 1990 and 1994. The national strategy for the sale of environmental services for the mitigation of climate change was developed in 2003, and represents one among many other programs in Colombian institutions. Recently the second national communication for the years 2000 and 2004 was issued which is analogous to the global analysis of the IPCC by 2007 as introduced in the subchapter above.

Colombia's picture regarding its GHG emissions in comparison to global GHG emissions is very modest. The total emissions amounted to 180 million tonnes of CO_2 equivalent per year by 2004 (World: 49 Giga tonnes of CO_2 equivalent by 2004). In that context, Colombia contributes 0.37% of the total global GHG emissions. Figure 10-8 shows the emissions of the period 1990 – 2004 according to the national communications inventory of GHG per sector. Energy and agriculture sectors (including livestock) are the main "suppliers" of GHG accounting for more than 74%. Agriculture and land use, land-use change and forestry (LULUCF) together account for more than 50% of GHG (Ideam 2010, p.128).

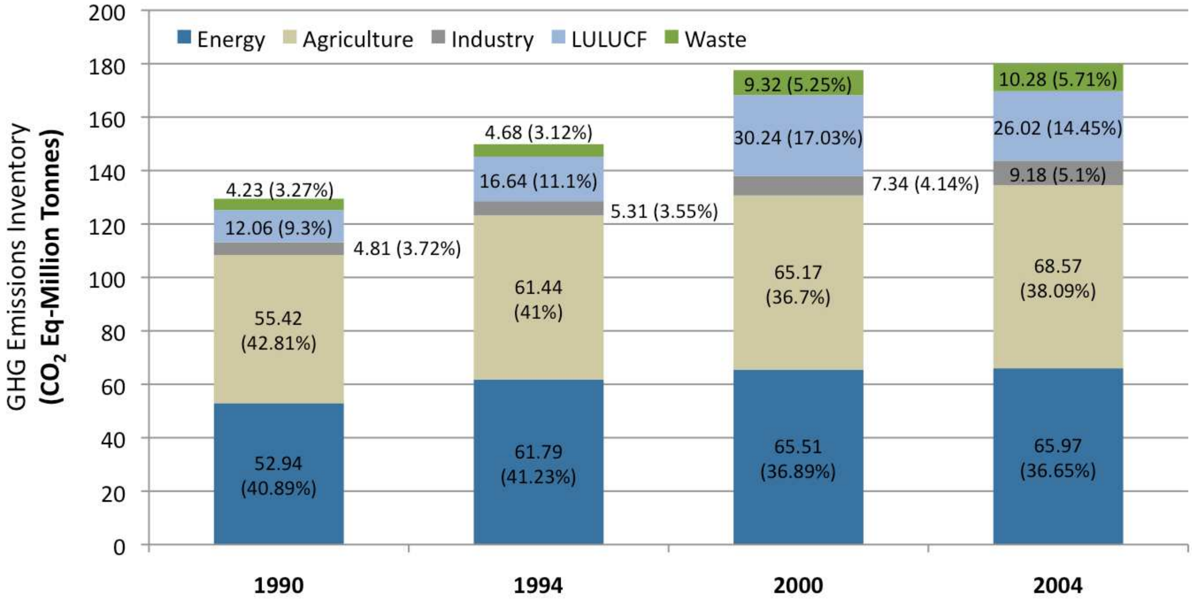


Figure 10-8 Colombian total emissions 1990 – 2004

Source: Data from Ideam 2010, p. 128.

In comparison to the regional distribution of GHG emissions (*see* Figure 10-2), Colombia's GHG emissions fall well below the Latin American GHG emissions per capita (Latin America emits approximately 8.0 CO_2 Eq. tonnes/cap) as shown in Figure 10-9. Regarding GHG per unit of gross domestic product (GDP), Colombia remains also lower than the Latin America average of around 1.0 kg CO_2/USD GDP_{ppp} (year 2000 value) as illustrated in Figure 10-9.

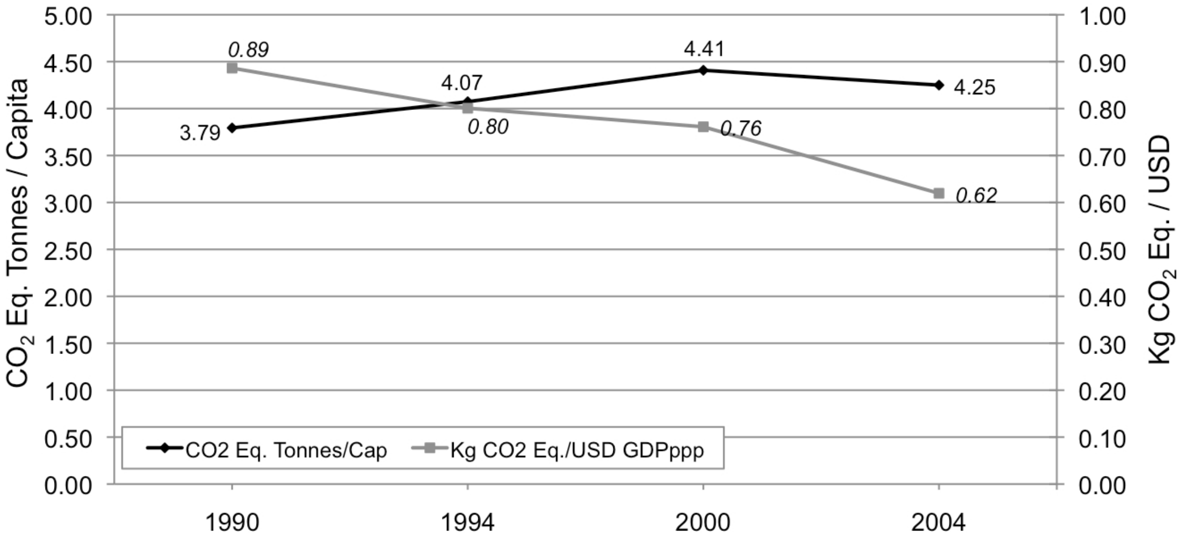


Figure 10-9 Colombian emissions per capita and GDP

Source: Data from Worldbank 2011 and DANE 2007, own calculations.

With respect to the energy sector (36.65% contribution of CO_2 emissions by 2004, *see* Figure 10-8), the GHG emissions have shown a steady level in the period from 2000 to 2004 due to the shift to cleaner fuel sources such as natural gas, the conversion of public transportation to natural gas and the high share of hydropower in the power sector in those years (Ideam 2010, p.148). The GHG emissions attributable to power generation amount to 8.49% (15.3 Million tonnes of CO_2 Eq) by 2004 in contrast to world figures of 23.16% (Ideam 2010, p.127).

Colombia had begun since 2000 to implement the necessary institutional mechanisms to define responsibilities, objectives, programs and measures to address climate change. The national energy plan, which provides a strategy to cope with the energy future needs of the country, includes the concept of sustainable development, the rational use of energy and use of non-conventional energy sources to diversify the basket of power generation technologies. These plans are still in the early stages of implementation and current barriers such as lack of information diffusion and high costs of technologies (Ideam 2010, p.163) have so far prevented the implementation of these technologies.

10.3 POTENTIAL IMPACTS AND VULNERABILITY OF COLOMBIA DUE TO CLIMATE CHANGE

The national communications have assessed the impacts and vulnerability of Colombia due to climate change. Based on the simulations conducted by Ideam, mean temperatures would increase by 1.4 °C for the period from 2011 to 2040, by 2.4°C for the period from 2041 to 2070 and by 3.2 °C for the period from 2071 to 2100. These findings are based on the results from the period 1971 to 2000 as a base case for the projections by climate models (Ideam 2010, p.54). Figure 10-10 illustrates the mean temperature differences and percentage change in rainfall over the Colombian region. It is noticeable that the Andean region is affected by the reduction of rainfall, where all hydropower plants are located.

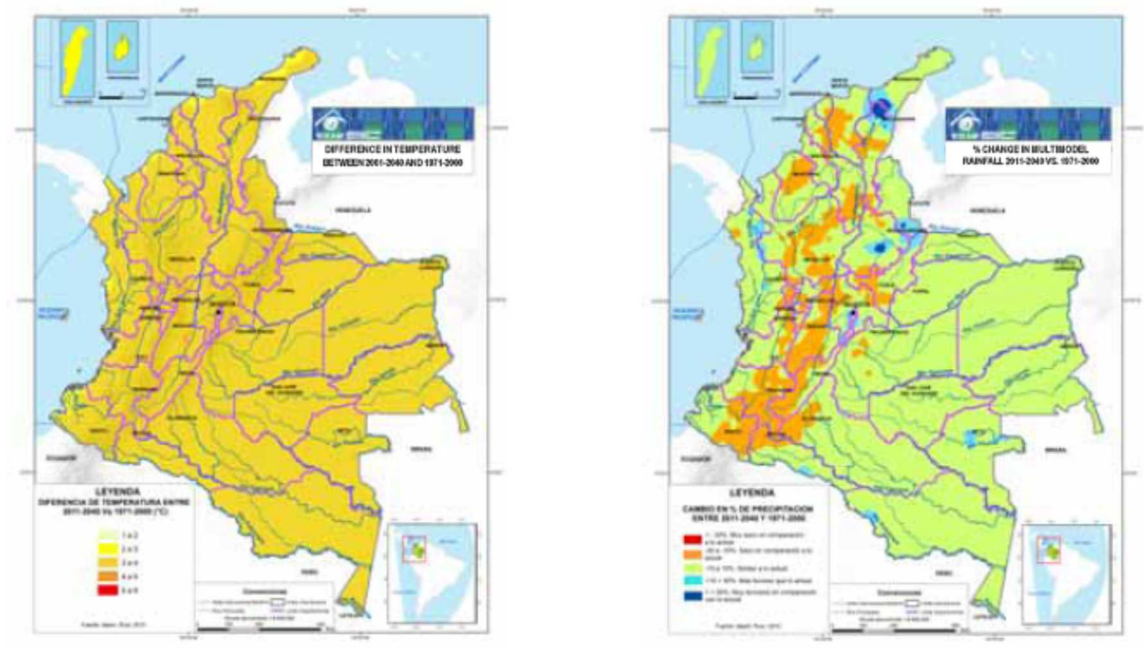


Figure 4.1 Map of the mean temperature difference from the multimodel for the period 2011-2040, compared to 1971-2000.

Figure 4.2 Map with the percentage change in rainfall from the multimodel in the period 2011-2040 vs 1971-2000.

Figure 10-10 temperature and rainfall change in the period 2011 - 2040

Source: Ideam 2010, p.54.

Climate change scenarios for the geographic region of Colombia due to climate change as predicted from simulations performed by Ideam (Ideam 2010; p. 59 – 62):

- Reductions in rainfall will occur over most of the country, in particular over the Caribbean region and some regions of central Colombia, whereas increases are expected in remote areas, where high demand centers are not located.
- Ecosystems of the Andean region with high concentration of population and production systems will be affected by pressure caused by the advance of the agricultural frontier due to over-utilisation and conversion of natural ecosystems into crop and pasture areas.
- In the period from 2011 to 2040 50% of the Colombian pasturelands may be affected by a deficit in rainfall
- 47% of the total peasant economy might suffer a very high impact due to reductions in rainfall.

- With respect to hydropower generation, high and very high impacts might be caused to 43% of the existing total capacity due to reduction of rainfall

The second national communication, therefore recommends research to be conducted on the vulnerability and availability of water resources in different scenarios of climate change, giving priority to sectors such as farming, electricity generation and public services (Ideam 2010, p.63).

In contradiction to the very modest CO_2 emissions emitted by Colombia in the global context, the evidence suggests that Colombia will be affected by climate change. As the second communication has pointed out, Colombia is highly vulnerable to the effects of climate change (Ideam 2010, p.62).

In a simulation of the energy sector with the model Markal in order to assess the options to reduce GHG emission in the Colombian energy sector from 2010 until 2040 (Cadena et al 2009), it was found that the contribution of the energy sector in the GHG emissions is expected to keep a share between 35% and 40% (Cadena et al 2009, p. 31).

Under the assumption that the country experiences high economic growth (Base Case 1), the simulation included a set of measures to reduce GHG emissions such as shifting to cleaner fuels (gas vs. coal), increasing number of passengers per vehicle use, the inclusion of a mix of renewable energies in the power system, the implementation of energy efficiency measure in the industrial and commercial sectors and the addition of electric powered small vehicles. The results are shown in Figure 10-11.

The measures that lead to the greatest reduction in CO_2 emissions are in the industrial and transport sector; remarkably in the shift from coal to gas in boilers, improvement of boilers' efficiency and improvement in the passengers per vehicle and use of biofuels. With respect to renewable energies in the power sector, they rank as the fifth measure (excluding large hydropower) with reductions of 38 Million tonnes of CO_2 eq.

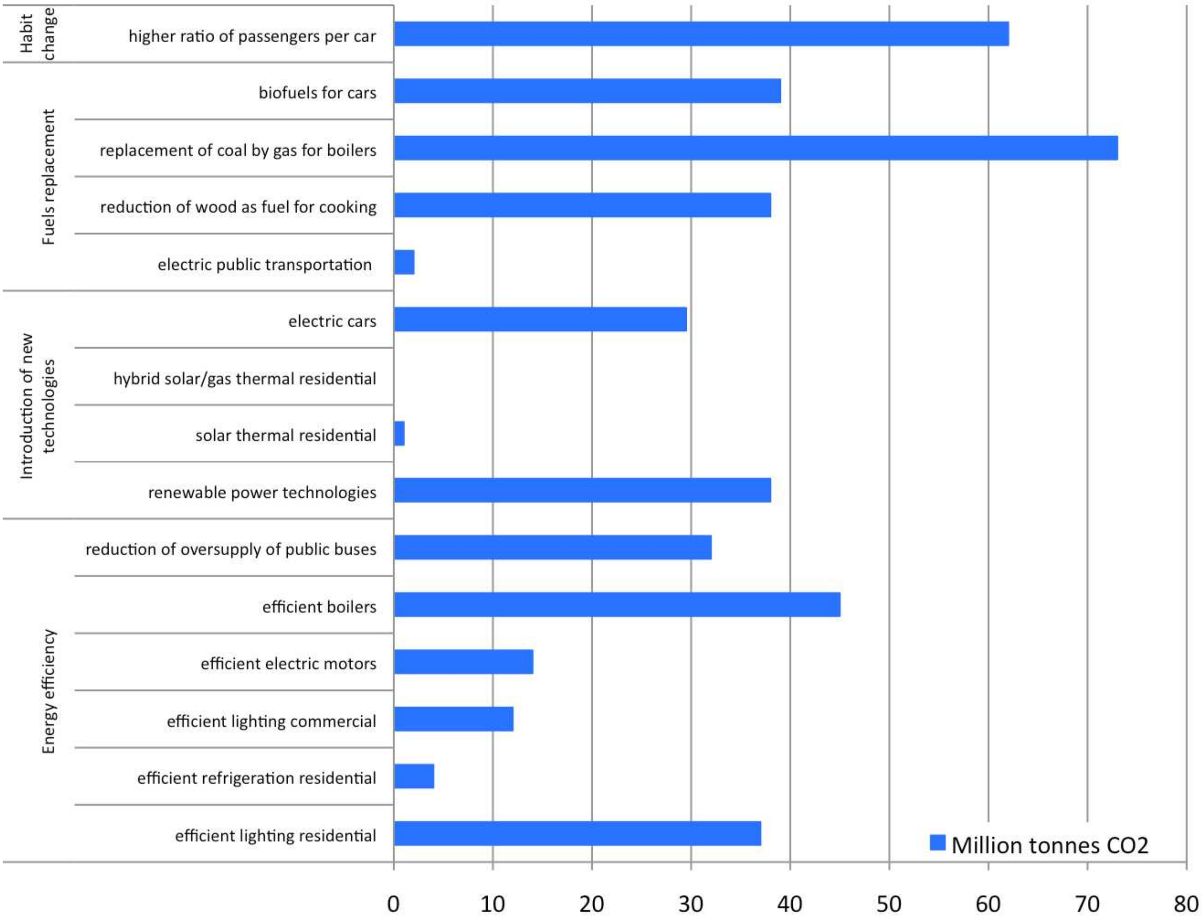


Figure 10-11 CO_2 reductions in the energy sector from 2010 to 2030

Source: Modified from Cadena et al 2009, p. 23.

The cost of abatement was also determined which proved that energy efficiency measures are economically feasible (negative abatement costs). The abatement cost for renewable was found to be between 20 and 35 USD/tonne CO_2 without considering transaction costs. The total emissions that can be mitigated in the Colombian energy sector are 365 million tonnes of CO_2 over the period from 2010 to 2030 with high economic growth and 363 million tonnes of CO_2 over the period from 2010 to 2040 under BAU scenarios (Cadena et al 2009, p. 23-26).

It is worth noting that the share of renewables in the power sector for the simulation described above is very modest, 712 MW in 2030 and 1,410 MW in 2040 including small hydropower (Ideam 2010 p. 166) and the competitiveness of renewable energy technologies is seen as the result of the combination of their investment cost and the emission certificates they might obtain (Cadena et al 2009, p. 31).

10.4 DEPENDENCE ON HYDROPOWER IN COLOMBIA'S POWER SECTOR

The second national communication on climate change in Colombia points out the contribution of hydropower as an alternative to address the GHG emissions of the power sector. This contribution is subject to technical, environmental and socioeconomic factors that may limit their implementation. In addition, the vulnerability of water resources due to climate change, which might also affect their implementation (Ideam 2010, p.186).

The GHG emissions attributable to power generation amount to 8.49% (15.3 million tonnes of CO_2 equivalent including self-generation power producers, gas treatment plants, refineries and smelting furnaces) by 2004. Due to the high share of hydropower, the contribution of renewable power technologies, apart from hydropower in the power sector, might be seen as a low priority for addressing climate change in Colombia. Nevertheless the current challenge of the power sector is to keep the high share of hydropower in electricity generation and/or introduce technologies powered by renewable energy sources with low lifecycle GHG emissions in order to maintain the low share of GHG emissions in the Colombian power sector.

The contribution of hydropower is dependent on the availability of the water resources, which is influenced by Colombia's seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO). The ENSO is characterized by a variation in the temperatures of the surface waters of the tropical eastern Pacific Ocean which causes extreme weather conditions (droughts and floods), which can have a significant impact on hydropower generation.

Most of the hydropower power plants are located in regions of the country with a rainfall deficit during El Niño (Corpoema 2010, p. 4-4) as shown in Figure 10-12. The blue dots are existing hydropower plants in the ranges of the Andes located in deficit areas.

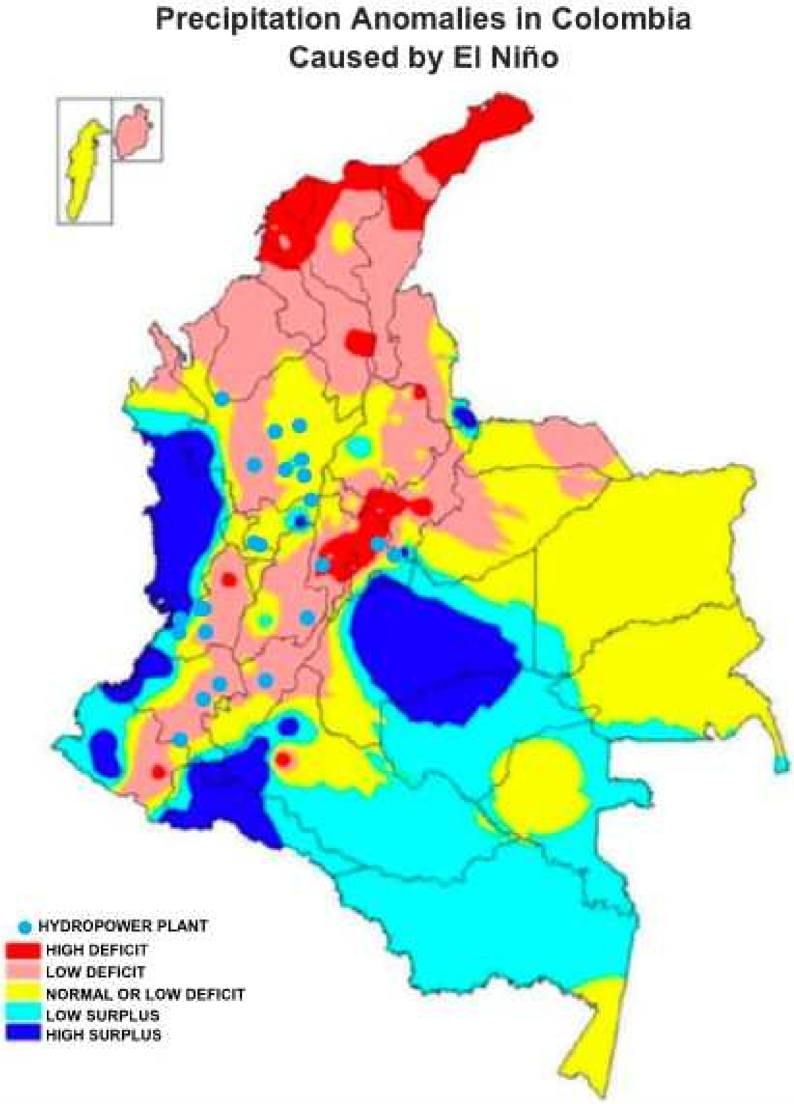


Figure 10-12 Rainfall deficit during El Niño and hydropower plant locations

Source: Modified from Corpoema 2010, p.4-3 and UPME.

Figure 10-13 shows the share of hydropower in electricity generation over the last 15 years and the effect of El Niño on hydropower generation (dotted circles) and electricity spot prices.

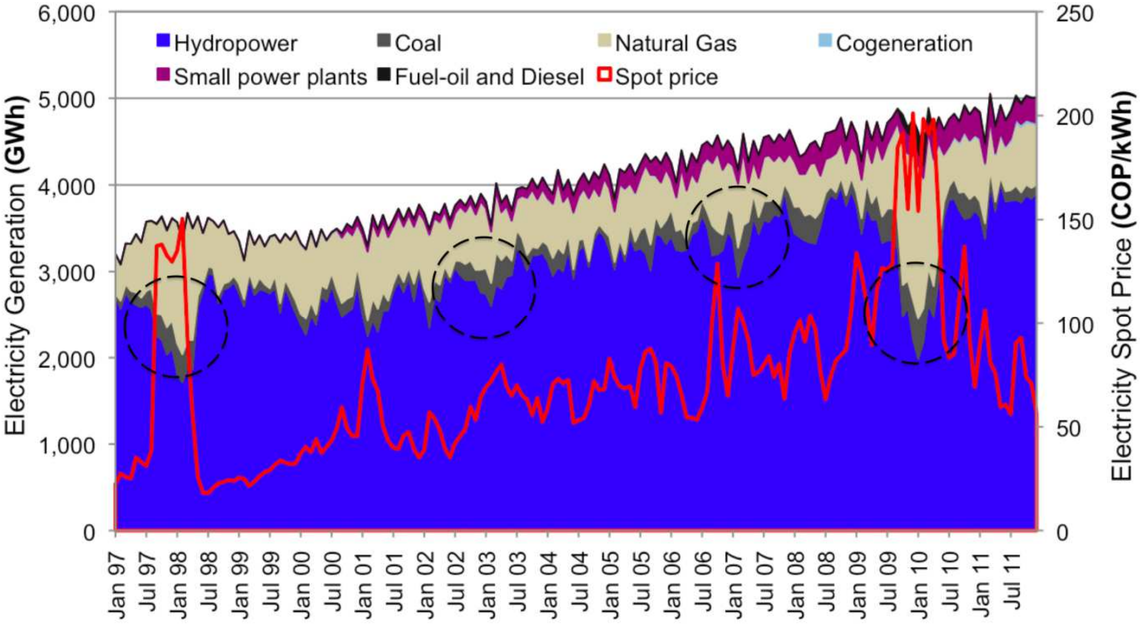


Figure 10-13 Contribution of hydropower and thermal power plants in power generation

Source: Data from XM 2011.

In an approximate five year-cycle of El Niño with differing intensities of rainfall deficits, the availability of the water resources decreased causing thermal power plants to back up the lack of generation from hydropower to cover the demand as can be seen in particular in 1998 and 2010. The effect is more evident by looking at single years as presented in Figure 10-14. A severe El Niño has already reduced the share of hydropower in power generation below 50%. Under normal conditions the contribution of hydropower is over 70%.

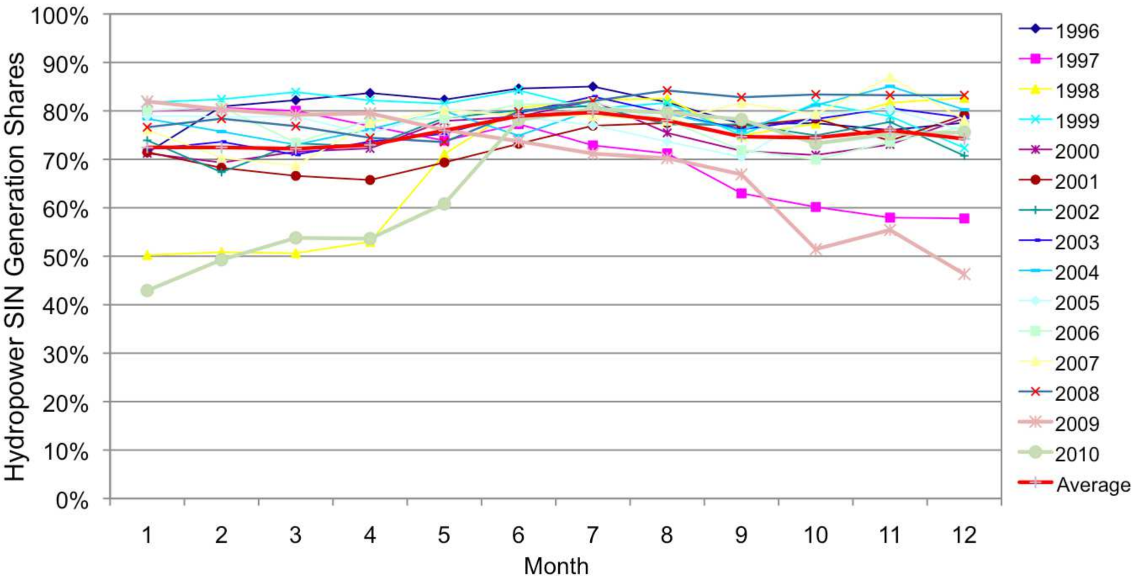


Figure 10-14 Hydropower share per month for total power generation

Source: Data from XM 2011.

The fluctuations of hydropower generation lead to variations in power generation prices in the spot market. Under normal conditions hydropower delivers most of the electricity and other generators maintain their share in production. This situation is illustrated in Figure 10-15 from July 2008 to December 2010. Generation per energy source and spot prices are plotted together. Spot prices oscillate between 50 COP/kWh (2.49 USD cent/kWh) and 100 COP/kWh (4.98 USD cent/kWh) in the second half of 2008. After that, the contribution of hydropower falls gradually through the first half of 2009 and prices abandon their normal range to be over 100 COP/kWh (Corpoema 2010, p.4-4, 4-5).

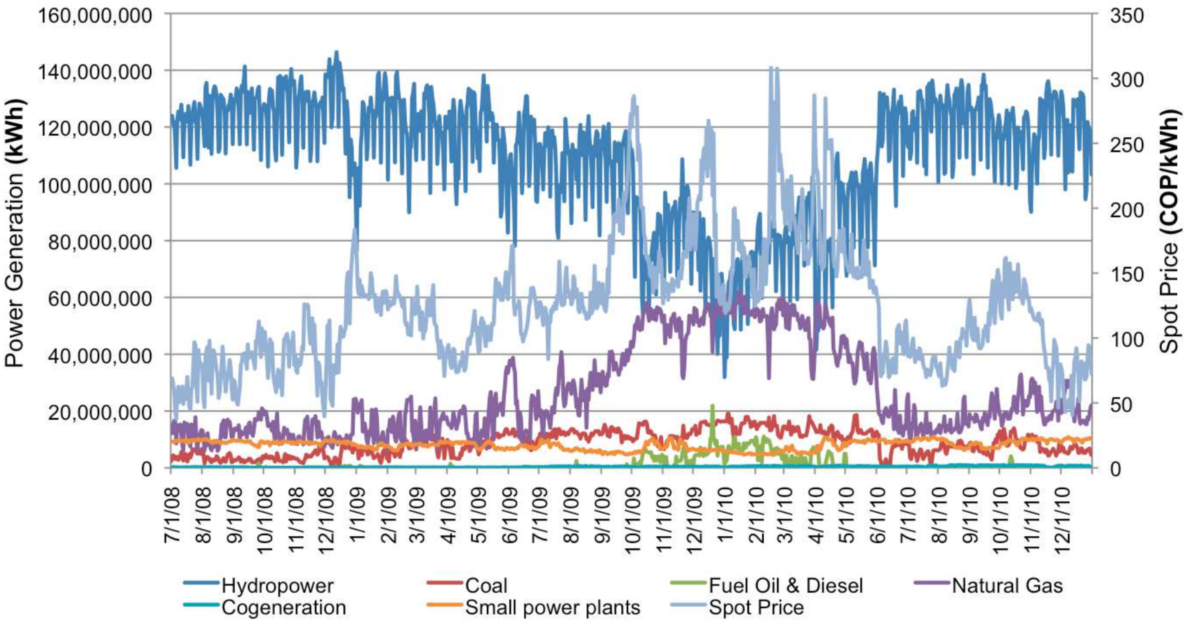


Figure 10-15 Power generation and spot prices under normal conditions and during El Niño

Source: Data from XM 2011.

As El Niño advanced through 2010, hydropower generation drastically reduced its supply of electricity into the system and gas power plants were mainly dispatched to cover the shortage of hydropower. Fuel oil power plants were dispatched sporadically under normal conditions. In such a situation prices oscillate between 100 COP/kWh (5.27 USD cent/kWh) and 300 COP/kWh (15.81 USD cent/kWh) for a period of 9 months. The average spot price in that period was 180 COP/kWh (9.48 USD cent/kWh). As soon as the hydropower generation recovers, normal spot prices are reached again.

10.5 WHY THE INTRODUCTION OF RENEWABLE ENERGY TECHNOLOGIES IN COLOMBIA'S POWER SECTOR

The main objective of this dissertation is to answer the research question, whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources.

Within this context, a simulation to assess the introduction of power technologies, including technologies powered by renewable energy sources, was conducted for the Colombian power sector for the period from 2010 to 2050. The simulation was based on economic and technical parameters such as fossil fuel prices, investment and operation costs, technical features of all technologies (conventional and non-conventional), CO_2 emissions and the particularities of the Colombian resources and power system. In addition other issues such as Colombia's dependency on hydropower, relative CO_2 emissions and climate change in the Colombian context for the power sector have been addressed.

The results of this dissertation allow a comprehensive analysis of the Colombian power sector, which is summarized as follows:

10.5.1 Facts and uncertainties for the Colombian power sector

Based on the topics reviewed in this dissertation, the Colombian power sector is characterized by:

(i) A high dependence on water resources for electricity production,
(ii) A high dependence on hydropower during both rainy and dry seasons, and thus variations of the contribution of fossil fuel power plants,
(iii) Periodic extreme weather conditions such as strong El Niño events which demands a robust power system that backs up the shortage of water resources for electricity generation,
(iv) Fossil fuel thermal power plants which back up the power system,
(v) A high reliance on natural gas to back up the system,
(vi) A dependency on fossil fuel power plants which are exposed to availability of fossil fuels and price fluctuations,
(vii) Electricity spot prices driven by the contribution of hydropower,
(viii) Electricity spot prices exceeding normal levels due to extreme weather conditions,
(ix) Low CO_2 emissions and low electricity prices due to hydropower.

These following facts are the source of uncertainties for the future:

(i) Availability of natural gas reserves and the discovery of new natural gas reservoirs for electricity generation.
(ii) Availability of water due to the impacts of climate change (e.g. droughts associated with strengthening ENSO events).
(iii) The scarcity of natural gas in Colombia may result in the energy sector becoming dependent on imports.
(iv) Price of fossil fuels, in particular natural gas (linked to oil prices).
(v) The role of CO_2 emissions in the shaping of the power sector.
(vi) Overall cost of the power system.

The simulations conducted with the energy models have addressed these uncertainties by showing the spectrum of possibilities for the development of the power sector and the outcome by introducing new technologies and energy sources as summarized below:

10.5.2 Simulation outcomes

Overall system cost

Both energy models deliver the overall cost of the system by means of the net present value approach. In the accounting framework model LEAP the entrance of renewable energy technologies in all scenarios resulted in an increase of the overall cost of the system (the overall cost of renewable scenarios are between 19.7 and 24.4 billion in 2006 USD), suggesting that BAU scenarios are the least cost alternative (the overall cost of the BAU scenarios are between 18.9 and 19.8 billion in 2006 USD). However, the exogenously given amounts for capacity and production of new technologies in the simulation were not adjusted to find a better energy mix in order to lower the overall cost.

On the other hand, the simulation with the optimization model performed with the same parameters suggests that despite all sensitivities renewable energy technologies will enter the system by their own economic merits in an ideal market as the optimization model assumes (the overall cost of the optimization results are between 13.1 and 15.1 billion in 2006 USD).

Figure 10-16 illustrates the shares of new technologies powered by renewable energy sources. In addition, this figure shows why the accounting framework model LEAP with the scenario approach differs from the optimization approach in MESSAGE. For instance, still not competitive wind and solar technologies are sooner introduced in the system by LEAP with much higher energy production shares in comparison to the optimization results. The energy mix of the scenarios in LEAP in comparison with the energy mix of MESSAGE shows how the scenario analysis based the expansion on high shares of biomass and CSP whereas the optimization approach of MESSAGE relies mainly on wind. The optimization also shows that renewables may be competitive after 2020 (without a sensitivity for hydropower) whereas LEAP shows already a share of renewables between 7 and 12 % by 2020. This explains the higher cost of scenarios with the scenario approach of LEAP.

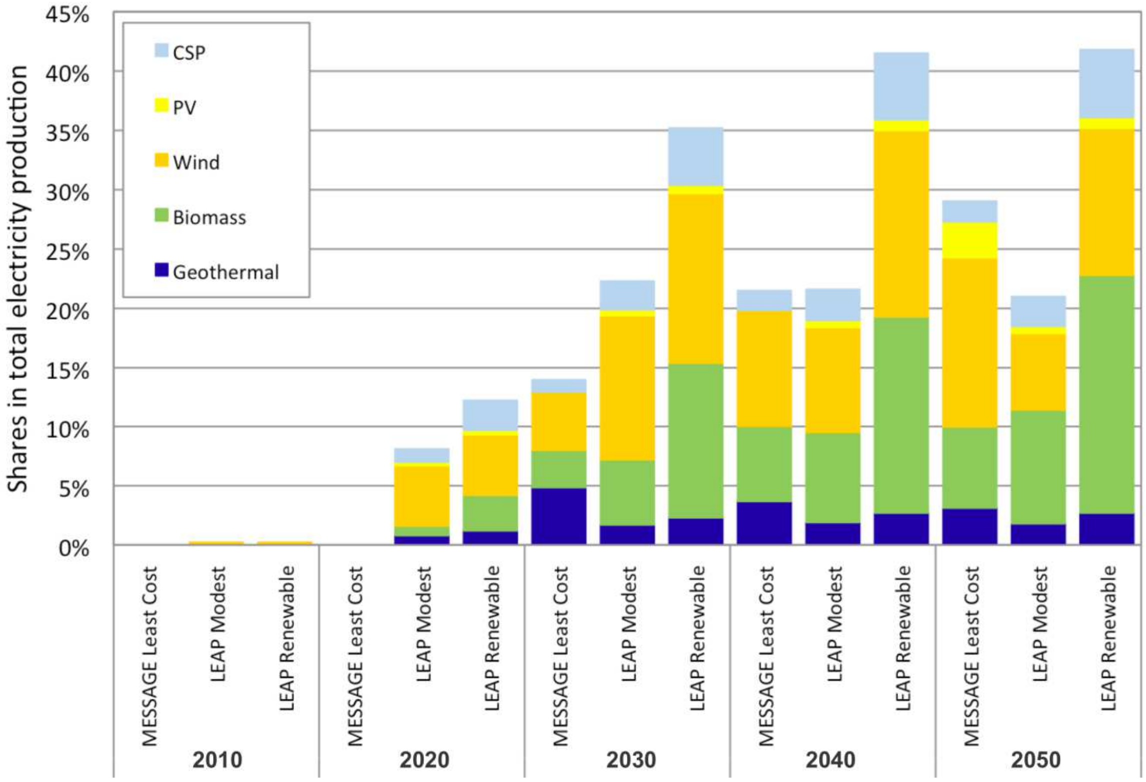


Figure 10-16 Renewable energy sources share in power generation. Results from LEAP and MESSAGE

According to the results of the sensitivities analysis, there is a period from 2015 to 2030 in which the conditions are given for renewable energy technologies to become part of the power system with diverse energy production shares depending on the evolution of economic and technical parameters.

The results of the simulation prove that investment in new technologies, especially the ones that rely on renewable energy sources, might contribute to a more optimized system from an economic point of view. The simulation also shows what shape the power sector may take if new technologies are not allowed to become part of the system (BAU scenarios) causing much higher emissions of CO_2 and a higher dependence on hydropower and fossil fuels.

It is indisputable that at some point in time new technologies powered by renewable energy sources will become competitive (grid parity). The current challenge is how to pave the way to make sure new technologies can become part of the system and to channel investment decisions in that direction. Just by market forces alone, renewable energy technologies may not reach their economic and technical potential.

Hydropower sensitivities

The magnitude of impacts on hydropower due to seasonal variations of water availability and climate change is uncertain. Sensitivities in the simulation for hydropower contribution were defined in both models to account for lesser availability of water resources.

Assuming an expansion of the system with current technologies (BAU scenarios), less hydropower units automatically represent a higher cost for the system as more fossil fuel power plant units are required to back up the system and expenditures for fossil fuels increase. In such a scenario higher volumes of electricity are coming from coal sources. Likewise, renewable scenarios with less hydropower show higher costs. These results were also found in the optimization model. A higher share of hydropower is always the least cost alternative for the system over the years.

By having a lesser availability of hydropower the chances to introduce other technologies are naturally enhanced to become part of the system. Put simply, more coal power plants are installed and dispatched in the coming years before renewable energy technologies reach competitive costs. Afterwards a higher share of renewables are installed and dispatched to cover for less hydropower resources.

In summary, renewable energy sources will be needed to back up the Colombian power system. They will contribute to a reduction in the overall cost in comparison to an expansion of the power system based exclusively on fossil fuel energy sources. In addition, the Colombian power system will be much less affected by volatilities of fossil fuel prices and intermittency and availability of hydropower production affecting electricity prices.

Natural gas and coal consumption

According to the simulations, Colombia should rely on imported natural gas from 2018 onwards. The results of the accounting framework model LEAP for the BAU scenarios (Planned additions scenario in Section 7.1) show a natural gas consumption of 3.16 Gm^3 by 2018. The consumption of natural gas will increase to 3.05 Gm^3, 4.95 Gm^3 and 7.64 Gm^3 by 2030, 2040, and 2050 respectively, which represents the vast amounts of gas needed only for power generation in comparison with today’s levels (2008: 1.69 Gm^3). This is a scenario exercise to show the effects of continuing expanding the system with natural gas in the long term and how the system would depend on natural gas imports.

Unlike natural gas, coal is abundant in Colombia and imports are thus not expected. In a scenario based on coal (planned with coal scenario in Section 6.2) the share of natural gas in the system is drastically decreased to 0.70 Gm^3, 1.13 Gm^3, and 1.67 Gm^3 by 2030, 2040, and 2050 respectively. Nevertheless coal will have much higher shares in the system, increasing CO_2 emissions drastically in the years to follow.

By simulating an optimized system, the results suggest that other technologies will displace the use of the fossil fuel resources, improving the diversity of the system. The share of gas is reduced, however coal will continue to be a part of the system; this time in a system with renewable technologies.

The introduction of renewable technologies into Colombia’s power system will help to reduce the stress on natural gas resources and will help to avoid a high dependence on foreign natural gas sources; releasing the system from price fluctuations and high natural gas prices. In addition, the share of coal technologies in electricity generation will reach a maximum of 14% (18% for less availability of hydropower), which release more coal resources to supply foreign markets.

CO_2 emissions

By continuing to expand the system with current energy sources (*see* BAU planned additions scenario, Section 7.1), the emissions of CO_2 will surpass 12 million tonnes of CO_2 eq. per year after 2010 until reaching around 36 million of tonnes by the year 2050. In that case the system would release 793 million tonnes of CO_2 eq. into the atmosphere in a period of 40 years (1,079 million tonnes of CO_2 eq. with lesser hydropower). In the coal planned additions scenario (*see* Section 7.2), the emissions increase drastically, reaching 52 million tonnes by 2050 realising 1,021 million tonnes of CO_2 eq. over a period of 40 years (1,136 million tonnes of CO_2 eq. with less hydropower).

This shows the importance of avoiding future emissions of CO_2 for countries like Colombia, which will continue growing together with its appetite for energy sources. This highlights Colombia’s responsibility to address climate change in the global context.

According to the optimization results, emissions will be below 12 million tonnes of CO_2 eq. per year over the defined 40 year period due to more efficient conventional fossil fuel technologies and the entrance of technologies powered by renewable energy sources. They will reach a maximum of 16 million tonnes of CO_2 eq. with a sensitivity for hydropower resources. Thus, the power system would release between 350 and 405 million tonnes of CO_2 eq. over a period of 40 years (between 405 and 523 million tonnes of CO_2 eq. with less hydropower).

This demonstrates the immense potential of renewables including large hydropower to maintain current emission levels over the next 40 years despite electricity demand growth. Between 388 and 671 million tonnes of CO_2 eq. can be avoided and between 556 and 731 million tonnes of CO_2 eq for a scenario with lesser contribution of hydropower. These figures should be seen as a maximum to be reached, but it clearly proves the benefits of renewable energy sources.

CO_2 prices

In order to include in the analysis the effect of carbon prices in the expansion of the power system, the cost of abatement in the accounting framework model LEAP was determined and the introduction of a carbon price was simulated in MESSAGE.

The cost of abatement was determined by finding the cost of one tonne of CO_2 to be charged to fossil fuel power plants in renewable scenarios to match the lower cost of the BAU scenarios (overall system cost measured by the NPV). For instance, an expansion based on coal sources shows the lowest price per tonne since this BAU scenario releases the largest amount of CO_2. The CO_2 price ranges from 7.7 USD/tonne to 59.3 USD/tonne depending on hydropower availability, natural gas prices and capital cost of renewables. Similarly for planned BAU scenarios with more natural gas, the price ranges from 20.2 to 99.1 USD/tonne of CO_2.

In the optimization scenario, a price for CO_2 is not required to guarantee the entrance of renewables into the system. The least cost power system is achieved with renewables. However, a carbon price would both accelerate the competitiveness of renewable energy projects and their entrance in the system and would reduce the share of coal power plants in the future.

Assuming the introduction of a global carbon tax after 2020 of 20 USD/tonne of CO_2 (*see Section* 9.5), it was found that the contribution of coal and gas was further decreased. In other words, the shares of wind energy and biomass are higher from 2020 and CO_2 emissions are further decreased to reach levels below 10 million tonnes of CO_2 eq. per year (*see* Section 9.5). By conducting a simulation of a lesser contribution of hydropower it was however found that the carbon tax was not high enough to accelerate the introduction of renewable energy sources.

In summary, energy policies charging a cost to CO_2 emissions via a global carbon tax or carbon markets (CDM) would help the introduction of clean technologies into the market.

Promising new technologies

According to the optimization results, the most promising new power technology is wind energy. Wind energy reaches competitive costs in electricity production earlier than other technologies which may be explained by a combination of lower investment costs and the amount of hours per year that the technology delivers electricity (capacity factor of 33% was simulated in comparison to 25% of PV). In all sensitivities in the model, wind energy reaches a significant share in electricity generation up to 14.4% after 2040. The share of wind can already be around 7% in a situation of less hydropower resources by 2025. 7% wind energy injecting 7,675 GWh of electricity in the system requires 2.8 GW of wind capacity.

In all scenarios conventional geothermal technology was introduced. The result shows the potential of this technology, which is perfectly suitable for base load. Therefore, efforts to overcome the lack of information about the availability and quality of the resource need to be addressed.

The use of biomass sources with fluidised bio combustion and biomass IGCC is present in the system, notably in the scenarios with a lesser hydropower contribution. The key challenge here is the use of solid residues, especially from sugar plantations and their collection, disposal, and transport to power plants.

In contrast, solar technologies, such as concentrated solar power and photovoltaic, make a relatively modest contribution to the system. Concentrated solar power offers an interesting alternative with higher capacity factors with energy storage; however, high investment and operation costs make them prohibitive for higher shares. Photovoltaic systems will have very competitive prices per kW, but their lower capacity factor is presumably a disadvantage in the simulation. However, the methodology does not take into account the potential of solar power for attending the demand at the Caribbean coast, where high temperatures are connected to higher consumption of electricity from air conditioning systems. This issue will be addressed in Section 10.6.

Renewable energy will be a part of the Colombian power system. This means the current portfolio of technologies will be transformed from a system heavily based on hydropower to a more diversified portfolio of technologies. The electricity production will have not only intermittency from hydropower but also from wind and solar resources. State of the art coal and gas fossil fuel power plants together with geothermal and biomass will complement the system. This new picture of a power system for Colombia, as suggested by the results of this dissertation, brings new challenges into the integration of new technologies.

Further steps are necessary to achieve such integration, especially in a hydropower based system like the one in Colombia which will be addressed in the next sections.

10.6 INTEGRATION OF RENEWABLE ENERGY IN POWER SYSTEMS

A transformation in the power sector will not only be driven by market forces. The entrance of new technologies requires addressing, in addition to cost, their technologies' specific challenges (IPCC 2011, p. 13). Integration of renewable energies in power systems is not only a technical challenge but also requires addressing regulatory and institutional issues (*see* next subsection). In this subsection the focus is on the intermittency of energy sources in the energy production.

Intermittent energy sources such as wind and solar raises the question whether significant shares of electricity from wind or solar energy sources can be optimally integrated into a hydropower based power system like the one in Colombia. The results of the simulation of the Colombian power sector suggest that wind energy may contribute greatly to power generation. For that reason an analysis of their integration into the Colombian power system is relevant.

This issue has been addressed by two recent studies performed by the Energy Sector Management Assistance Program (ESMAP) for an increased reliance on wind energy in Colombia (ESMAP, 2010) and by the Consorcio Energético Corpoema (Corpoema and UPME, 2010) for a national plan for non-conventional energy sources in Colombia. Both studies analyse the complementarity of wind and solar power systems with hydropower. The output of hydropower with reservoirs can be managed to meet peak demands and to balance electricity systems that have a large amount of variable renewable energy (IPCC 2011b, p.4).

It was found by ESMAP that electricity production from wind energy is highest during the dry season, from January to May (ESMAP 2010, p.36). Figure 10-17 illustrates the complementarity based on the monthly electricity production from the Wind Park Jepirachi and the energy stored in the reservoirs of hydropower plants. In addition, during periods of extreme droughts associated with El Niño, the production of electricity from wind energy was found to be above average (ESMAP 2010, p.40).

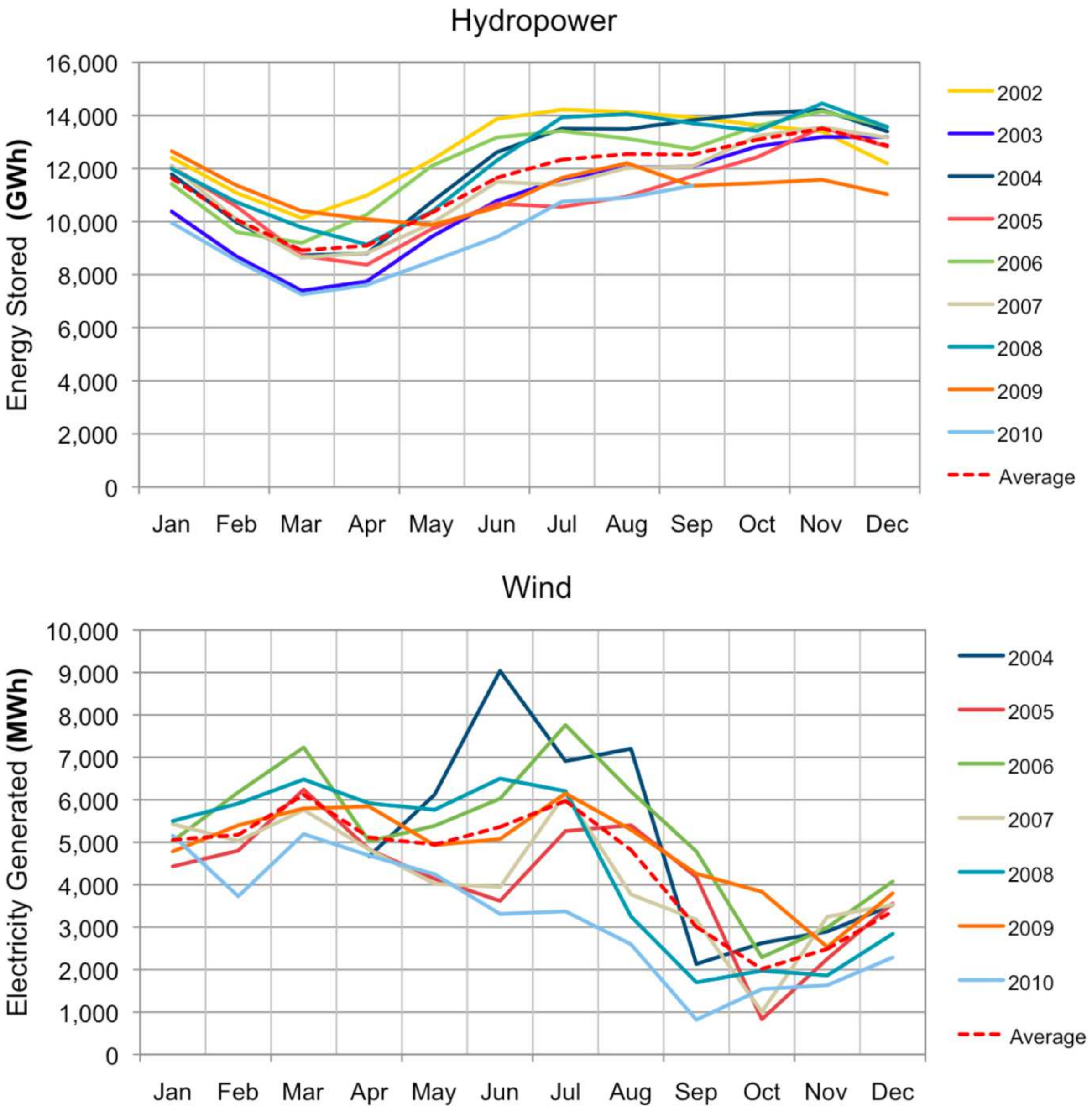


Figure 10-17 Complementarity of hydropower and wind energy

Source: Data from UPME 2010, p.110; XM 2011.

This is also corroborated by the study of Corpoema and the Colombian utility EPPM who owns the wind park Jepirachi (Corpoema 2010, p. 5-5, 5-9). A greater generation from wind parks are expected in the dry season. However the study could not conclude if during El Niño occurrences, wind energy is above average (this is apparently because of lack of information).

By analysing data collected from meteorological stations at sites along the Colombian Caribbean coast in an hourly resolution, it was found that the first semester of a year exhibits higher wind speeds, which take place in the afternoon. In particular for the station at La Guajira at the Almirante Padilla Airport the wind speeds are above 5 m/s (at 10 meters height) between 9 am and 5 pm on a consistent basis as shown in Figure 10-18. Lower speeds are found from August to December and higher speeds from December to April (ESMAP 2010, p.36) confirming the higher production of the wind park Jepirachi in the dry season.

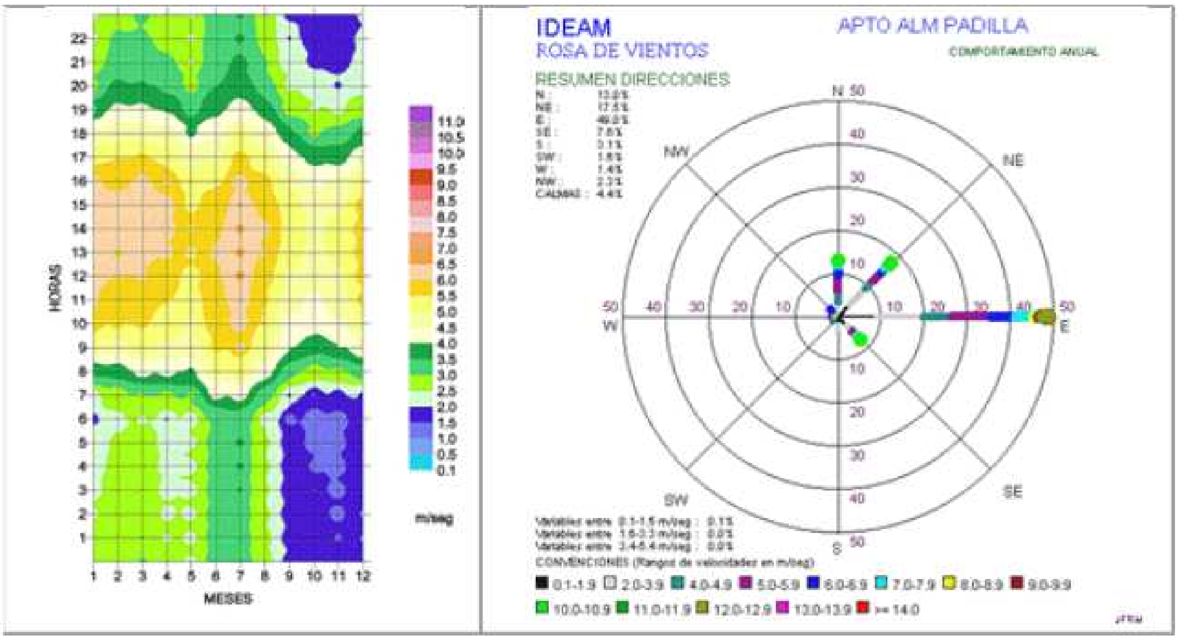


Figure 10-18 Wind resource at Almirante Padilla Airport in La Guajira

Source: ESMAP 2010, p. 38.

Figure 10-19 exhibits the wind resource at other locations along the Caribbean coast. The stations of Galerazamba and Cortizos Airport exhibit higher wind speeds above 7 m/s from 2 pm to 21 pm, suggesting that a wind park located in these regions could deliver energy in hours where mostly demand peaks take place between 6 and 8 pm. In addition these higher speeds are found from January to May corroborating the availability of the wind resource in the dry season.

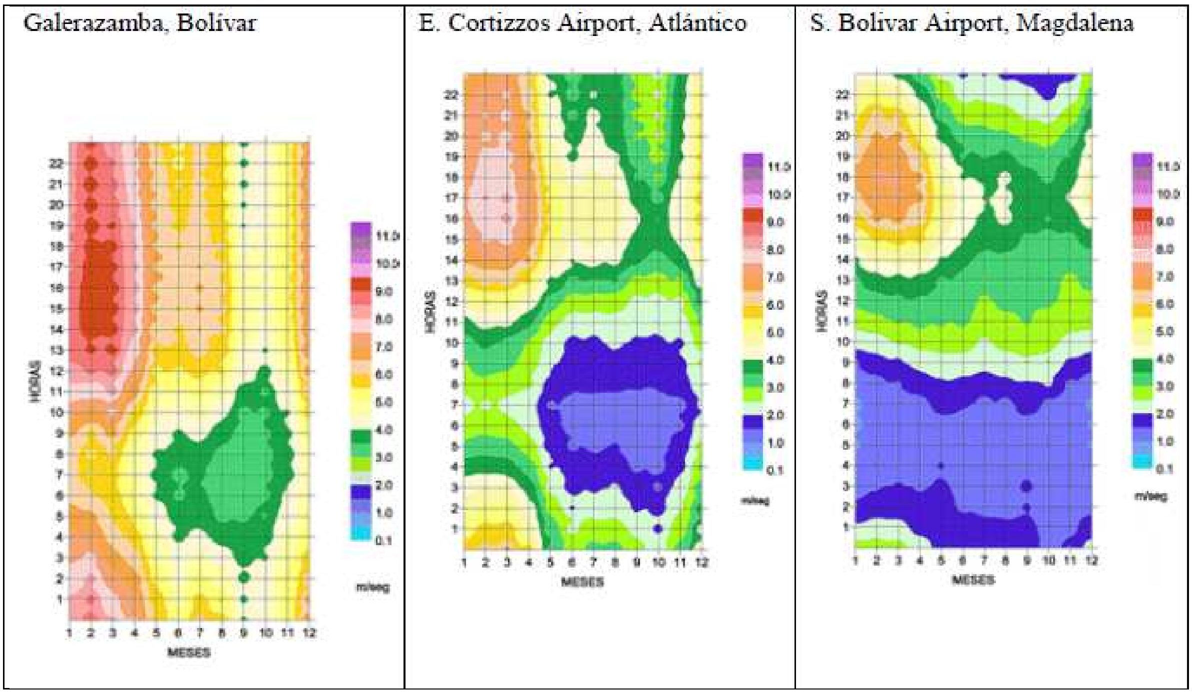


Figure 10-19 Wind resource for other stations on the Caribbean cost

Source: ESMAP 2010, p. 39.

An analysis of wind energy was also performed at hourly resolution by the study of Corpoema. The study combined the average electricity production of the wind park Jepirachi and a normalized electricity demand profile of the entire Colombian power system as shown in Figure 10-20. Electricity generation from Jepirachi has a peak around 3 pm which is between the secondary (11 am) and primary peak (7 pm) of the demand profile (Corpoema 2010, p. 5-10). This contribution should be seen as beneficial to the system since hydropower with reservoirs could be better regulated by storing water to dispatch, for instance, higher amounts of electricity at peak hours of the system. This is a form of indirect or virtual storage for wind energy due to the flexibility of hydropower plants in the system. Run of the river hydro power plants, which have in most cases some level of storage (from hours to weeks) and therefore a limited flexibility, can also offer the possibility to shift their production inside one day, helping also to balance the system (Acker et al 2012, p. 6).

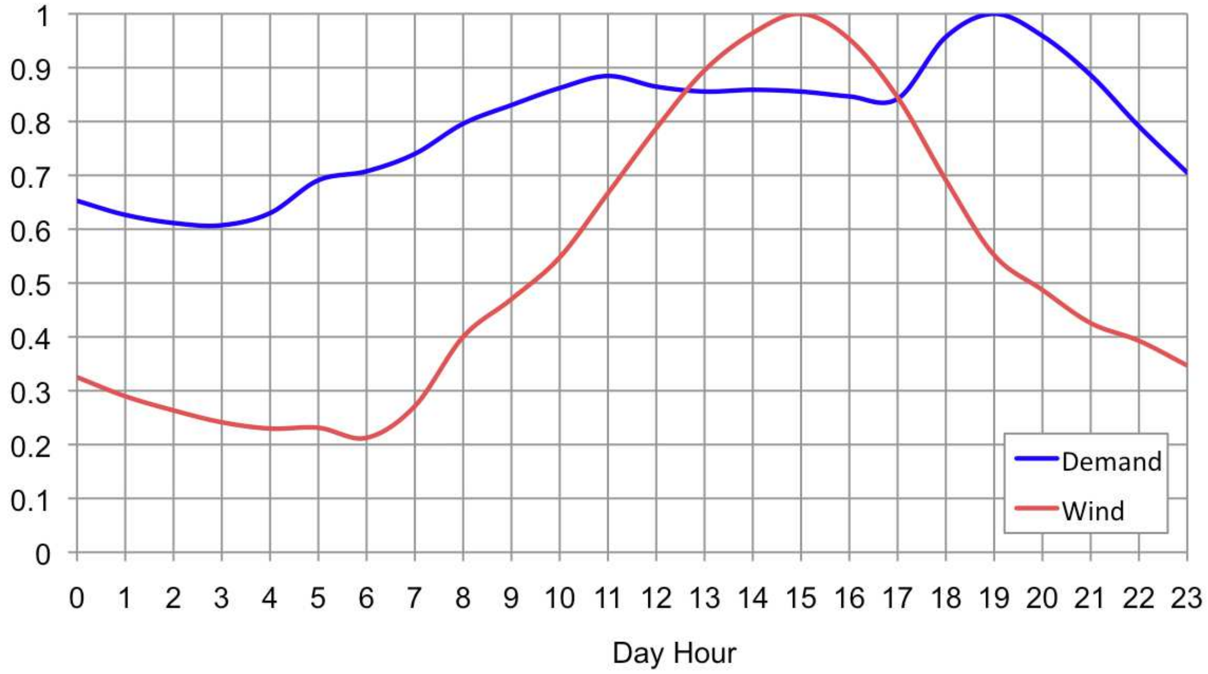


Figure 10-20 Normalized electricity demand vs. wind generation from Jepirachi

Source: Data from XM 2011.

The complementarity of wind energy and hydropower was also measured through an analysis of the joint operation of a hydropower plant and a wind park by the study ESMAP. ESMAP used an analysis which takes into account the reservoir size and river discharges of hydropower plants and the wind energy generation of Jepirachi. A simulation model was employed with hypothetical hydropower and wind parks of similar size (ESMAP 2010, p.41).

It was found that the joint operation of wind parks and hydropower plants exhibits a strong complementarity as the firm energy that results from the joint operation is greater than the firm energy of the isolated operation (ESMAP 2010, p.41-42). Firm energy is defined as the monthly maximum energy that can be produced without deficits during the analysis period including El Niño occurrences. Figure 10-21 and Figure 10-22 exhibit the advantage of the joint operation.

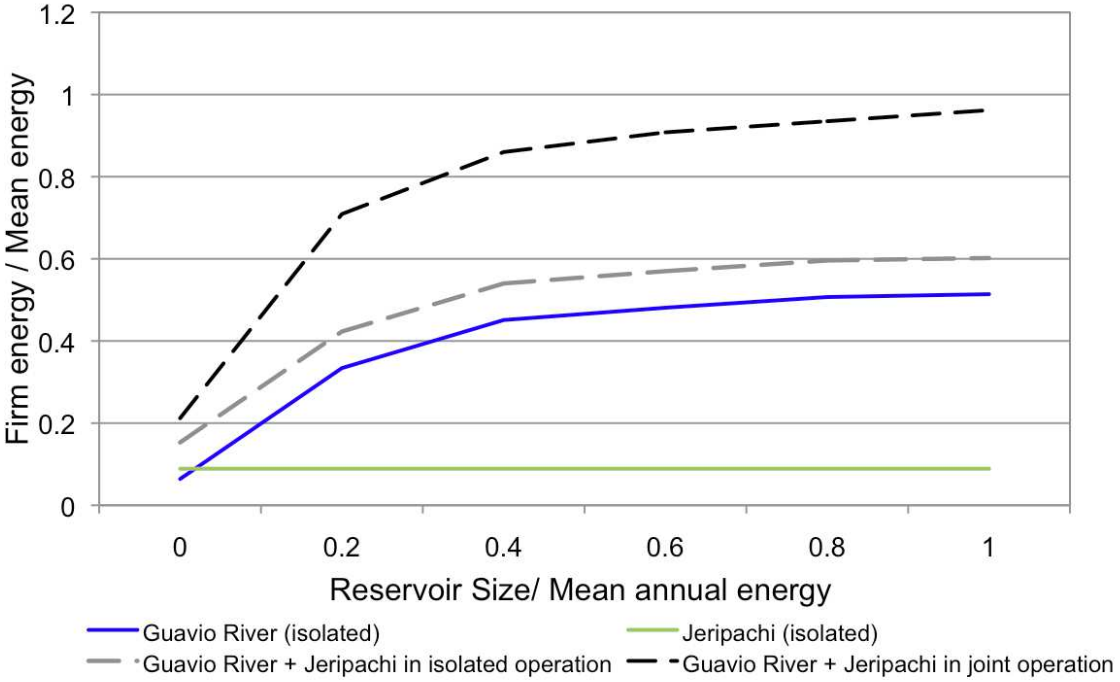


Figure 10-21 Complementarity of joint operation of hydropower and wind

Source: Data from ESMAP 2010, p. 43. 0=run of river plant 1= substantial regulation capacity.

The analysis suggests that critical periods of energy inflows from rivers do not correlate with electricity production from wind parks. In addition extreme scarcity of water resources caused by El Niño which affect the power system (represented with the green bars in Figure 10-22) may be overcome by regulating hydropower with wind energy. This theoretical exercise proves that wind energy may help to reduce the vulnerability of the system due to climate extreme events, if the operation of the Colombian power system manages to optimize the operation of intermittency sources as hydropower, wind and solar power.

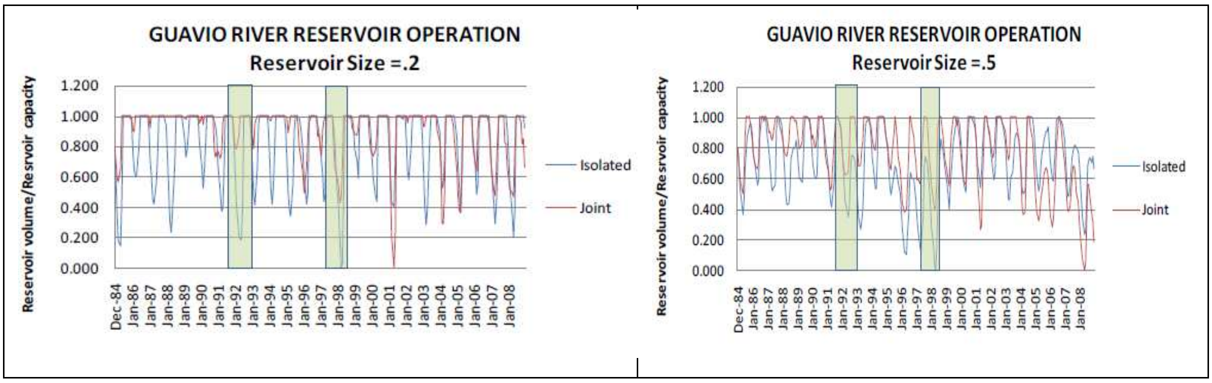


Figure 10-22 Joint operation of hydropower and wind parks

Source: ESMAP 2010, p. 44. 0=run of river plant 1= substantial regulation capacity.

Regarding solar resources, the study of Corpoema performed a complementary analysis by normalizing the Colombian electricity demand of typical days in January and a theoretical production of a photovoltaic solar plant during a day. Electricity generation with a solar plant could contribute to cover the peak before noon for the system between 11 am and 12 am. This contribution could also be beneficial for the system as hydropower with reservoirs could be better regulated by storing water to cover the peak of the system. (Corpoema 2010, p. 5-4).

In addition, the Corpoema study analysed the complementarity of solar sources for dry season of hydropower. Unfortunately with the information available this complementarity in the dry season cannot be concluded (Corpoema, 2010, p.5-2). However based on the Colombian solar map (*see* Section 4.2) the monthly contribution of solar sources is rather constant over the year (UPME - IDEAM 2005, p.28-39).

What the analysis of both studies does not consider is the electricity demand at the Caribbean coast. The use of air conditioning systems might show a different curve demand profile in comparison to the whole system as shown in Figure 10-20 for wind energy. In that case the generation from solar power plants may follow the demand profile when temperatures, in particular those around noon, are high. The use of solar energy sources may contribute to shave these peaks at noon, thereby allowing a better regulation of the hydropower plants and the overall system.

The complementarity of solar and wind energy sources as described above complement the results of this dissertation. A high share of new intermittency sources such as wind and solar may reduce the vulnerability of the system to climate and hydropower availability. The advantages shown by the simulation with wind energy are basically more from a cost perspective; however the models do not simulate the dispatched in an hour resolution including transmission constraints, which is beyond the analysis of this dissertation. But they confirm that having new power technologies combined with renewable energy sources should be considered as a serious option for the future Colombian power sector. It is also important to note that firm energy technologies such as geothermal and biomass are still a part of this solution.

With geothermal power technologies, an assessment of the resource to determine the potential is fundamental. Regarding biomass power technologies, it should be ensured that sustainable practices are in place to control changes in land and forest use and ultimately to avoid an alteration of carbon stocks (IPCC 2011, p.4).

10.7 POLICIES FOR THE INTEGRATION OF RENEWABLE ENERGY

The entrance of power technologies into Colombia's power system can be achieved in a period between 2015 and 2030 as suggested by the results of the simulation. This entrance will not be only dependant on market forces as the simulation suggests, but also requires paving the way for their implementation not only for their technical integration but also to accomplish an electricity market allowing a level playing field for the new technologies to come.

At the time of competitiveness of renewable energy technologies, these technologies will face barriers to become part of the power system assuming the current Colombian power market and regulatory framework. The Colombian studies reviewed concluded that current market and its regulatory framework is a barrier for the entrance of renewable power technologies in Colombia. Table 10-1 summarizes these findings.

Table 10-1 Barriers for the entrance of renewable energy technologies into Colombia

Capital Intensity: - Generation costs are not competitive and up-front costs are higher than conventional technologies.
Local financial market limitations: - Lack of financing of development phases. - Short financing terms, which do not allow for amortization. Finance based on cash flow of renewable projects often requires long term financing over a course of 10 years.
Production uncertainty and reliability: - Current regulation incentives with a premium for income electricity suppliers who can contribute to strengthening the resilience of the system in cases of high demand and/or variability of hydropower production. - By their intermittent nature, wind and solar energy sources do not contribute to firm energy according to current legislation. This is an entry barrier in comparison to thermal power plants.
Market structure: - Few large players dominate the market
Regulatory uncertainty: - A competitive market has not been successful in attracting private investment
Tax structure: - VAT and tax on exported goods perceived to be very high for upfront high costs of the technology such as wind and solar technologies.
Information Barriers: - Lack of adequate data to assess renewable energy resource availability - Difficulties in accessing renewable energy data - Lack of access to information on regulations - Limited access to technological know-how and trained personnel - Difficulties accessing R&D results and reports
Regulatory barriers: - Lack of clear rules for non-conventional supply technologies to enter the market - Bias in favour of conventional technologies - Lack of legislation tailored to the particularities (i.e. intermittency and contribution to firm energy) of the technology to create a level playing field for all technologies.

Source: ESMAP 2007, p.53-60; Corpoema 2010, p.3-9, Cadena et al 2009, p. 31; ESMAP 2010, p.70.

Assuming that cost and financial barriers are solved, the regulatory barriers may still continue to hinder the entrance of renewable energy technologies. In that regard, a recent examination of barriers for wind energy found that the lack of recognition of the contribution of wind energy to firm capacity represent a key regulatory barrier. Conventional power plants receive an additional income for their contribution to firm energy (ESMAP 2010, p.12; Diaz et al 2007, p.10). The result of the ESMAP study for wind energy shows that the single most effective policy instrument is the granting of access to reliability payments recognizing the firm energy and complementarity of wind energy (*see* Figure 10-21 in Section 10.6). This mechanism is enough for wind park costs around 1,800 USD (2010 dollars) to attract investors[1]. Otherwise access to attractive financial conditions and fiscal incentives are required[2] (ESMAP 2010, p.13).

These findings suggest the necessity to adjust the regulations to consider the contribution of wind and solar to firm energy and in general to avoid bias in favour of conventional technologies. At the time of competitiveness cost barriers should not be an issue if a level playing field is achieve for all technologies.

There exist a set of policies for renewable energies that allow a drastic intervention in the power market to accelerate the integration of renewable energy sources. In this case, instead of waiting for the time to come when new technologies are competitive as simulated with the energy models in this dissertation, a set of policies are put into place in order to commence their integration in advance. The target of these set of policies is to create a demand for renewable energy technologies, for instance, through financial incentives and market obligations.

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[1] The assumptions of the calculation are a rate of return for the investor of 14% with a 30% of the reliability payment, if the contribution of firm energy to wind energy is granted (ESMAP 2010, p. 17).

[2] The clean technology fund cited by the authors mention conditions of 0.65% interest rate with 20 year and 40 year repayment period and 10 years of grace. For project finance of renewable energies in Europe financing of commercial banks are typically for maturities lower than the life span of the technology (lower than 20 years) and for periods of time with guaranteed revenues (e.g. Feed-in Tariffs or Power Purchase Agreements), interest rates are easily over 5% in the current market environment.

Table 10-2 shows the most common types of renewable energy policy strategies. They consist of voluntary approaches, regulatory price driven strategies, and regulatory capacity driven strategies.

Table 10-2 Policy strategies

Policy Strategy		**Direct**		**Indirect**
		Price Driven	*Capacity Driven*	
Regulatory Based	Investment Focused	Rebates	Quotas (RPS) / TGC	Environmental Taxes/ Permits
		Tax Incentives		
	Generation Based	Feed-in Tarrifs	Bidding	

Source: Hohmeyer and Mora 2004, p. 68.

The *voluntary approaches* are mainly based on the willingness of consumers to pay premium rates for renewable energy and/or private initiatives to purchase clean power. They are not regulatory instruments, which intervene directly in the market system and enforce a desired environmental goal.

In the *regulatory price driven strategies*, renewable energy projects receive financial incentives in diverse ways via, e.g. contributions to the investment, financing at low interest rates, tax credits, fixed or premium tariffs per unit output (e.g. Feed-in Tariffs). In the *regulatory capacity driven strategies* the desired level of energy or market penetration of renewable energy systems is set by the authority in charge (e.g. renewable portfolio standards RPS or tradable green certificates TGC). The energy price is established afterwards through competitive bidding among the energy suppliers.

The *indirect strategies* target the non-renewable electricity generation capacity of the electricity market (conventional power technologies) by, e.g. levying a tax, issuing tradable permits or removing subsidies previously given to fossil or nuclear generation instead of promoting directly renewable energy projects. In that way renewable energies have a chance to compete and penetrate the market.

Figure 10-23 illustrates the direct strategy by levying a tax on a polluting technology, which might match the cost of a renewable technology or the indirect strategy by reducing the cost through an incentive. For instance currently existing feed-in tariffs should be regarded as mechanisms to reduce the cost gap between a mature technology and the renewable system.

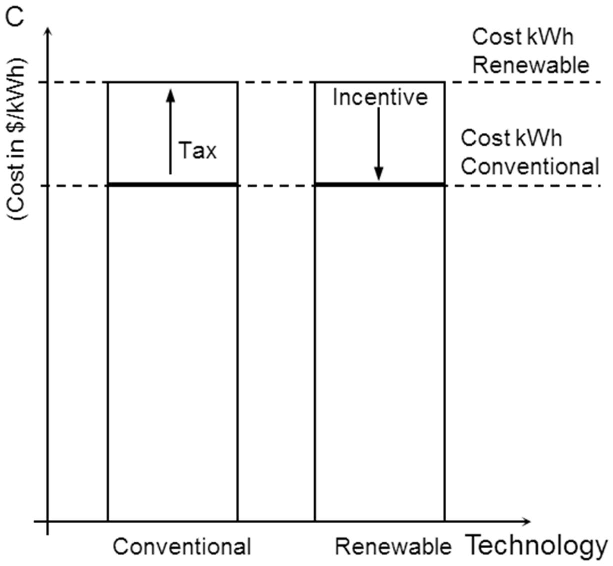

Figure 10-23 Indirect and direct promotion strategies

In other words, this kind of intervention will not wait for these technologies to be competitive as depicted in Figure 10-24. Point A represents the intersection of the electricity price curve and renewable electricity cost curve without a market intervention.

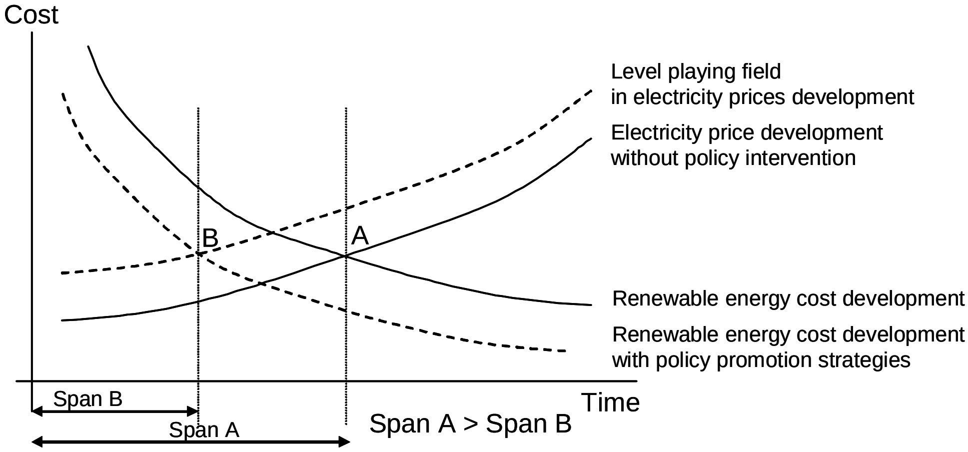

Figure 10-24 Effect of a level playing field on renewable energies

A level playing field and governmentally induced promotion strategies for renewables ensure competitiveness of renewable energy systems at an earlier point of time as compared to a situation when their penetration is solely left to the market forces as shown by point B in Figure 10-24. Therefore, a set of adequate policies promoting renewable energies and internalising external costs to pull the demand can secure earlier penetration of clean technologies.

Such an intervention is urged by the existence of external costs and their negative impacts on societies' welfare[1]. These policy instruments can internalise such external effects to encourage the implantation of clean technologies. Thus, diverse factors such as climate change mitigation, environmental protection, human health, as well as security of supply and employment creation (for instance rural development) become drivers for the intervention.

The results of the simulation based on market forces in this dissertation show an important penetration of renewable energy sources apart from hydropower, which did not include the factors relating to external costs. However, adjustments in the regulation may be necessary to allow the entrance of new technologies based on their economic and technical merits as simulated in the optimization model creating a level playing field of new technologies at the time of competitiveness.

An acceleration of the penetration of these technologies by means of policy strategies to intervene the market would mean a deviation of the least cost approach based on market forces simulated in this dissertation. It is a political decision to internalise the existence of external costs. In such a case the overall cost of the power system would be higher. The simulation of external costs in the Colombian power system was not conducted and is beyond the scope of this dissertation.

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[1] Energy supply systems give rise to impacts on the environment by, e.g. emissions to air, water and soil either during the production of the supply system itself and during its operation. The emissions (may) cause damages to a wide range of receptors like human health, natural ecosystems and the built environment. The damages are referred to as external effects of the energy supply and the costs associated with those damages are referred to as external costs of the energy supply. They represent a cost to society that is not taken into account by the polluter that causes the emissions (e.g. in the case of company operating a coal power plant). For renewable energies the external costs are usually lowest among all energy generation technologies (Hohmeyer and Mora 2004, p. 5).

11. SUMMARY AND DISCUSSION

This dissertation examined whether large scale integration of renewable energy sources for power generation in Colombia is a sensible alternative to current conventional energy sources such as hydropower, natural gas and coal. The objective of this dissertation was to test the following hypotheses:

(1) Renewable energy sources can fully substitute fossil fuel energy sources and can turn the hydropower based power system in Colombia into a 100% renewable energy system.

(2) The introduction of renewable energy sources in Colombia can be part of the least cost alternative for the expansion of the Colombian power system.

This final chapter summarizes the results of this dissertation. The results focus on the hypotheses to conclude about the opportunities of large scale integration of renewable energy sources for power generation in Colombia. The findings of the quantitative analysis brought about questions on how to make possible the introduction of renewable energy sources. A discussion on that issue and recommendations for future studies close this chapter.

11.1 RESULTS

To accomplish the objective, this dissertation applied quantitative analyses. The core analysis performed was the simulation of power generation in Colombia using energy models. Two bottom-up models were selected, the accounting framework model LEAP and the optimization model MESSAGE. A time horizon from 2010 to 2050 was selected for the analysis.

These selected models differ in their approach to simulate power generation systems. The LEAP scenario approach was used to explore energy futures. In that way an expansion of the Colombian power system with current energy sources (business as usual scenarios) was compared to an expansion scenario with both a modest and significant penetration of renewable energy sources (renewable scenarios). In contrast, the optimization model MESSAGE was used, which identifies autonomously the least cost expansion path for the power system.

The combination of the two model techniques proved to be essential to arrive at more precise conclusions. The results of LEAP's scenarios helped to understand the cornerstones of the expansion. For instance the BAU scenarios showed how high the consumption of natural gas and coal can be and how the growth of GHG emissions far exceeded current levels. The results of the simulation with MESSAGE found least cost expansion paths that include renewable energy technologies. Thus, the least cost approach suggests that renewable energy technologies will be competitive upon entering the system.

Therefore, the results of the simulation suggest that new technologies powered by renewable energy sources will be introduced at a large scale in the Colombian power sector by their own technical and economic merits. This was accomplished without driving their entrance by either forcing the expansion or giving any economic incentive to improve their competitiveness. The results of this study are summarized and discussed below:

(1) Renewable energy sources can fully substitute fossil fuel energy sources and can turn the hydropower based power system in Colombia into a 100% renewable energy system.

Colombia currently relies mostly on hydropower plants for power generation. The expansion of power generation will always consider hydropower, since this is Colombia’s more important energy source for electricity production. The results of this dissertation suggest that new renewable energy technologies powered by wind, geothermal, biomass and solar, will contribute to diversifying the supply of electricity in Colombia. Fossil fuel sources will be displaced as the main energy sources completing hydropower production by other renewable energy sources.

Figure 11-1 shows a pathway of the expansion of the power sector according to the simulation with MESSAGE (reference case with low prices for fossil fuels and low investment costs for renewable energy technologies) to better illustrate how renewable energy sources will enter the Colombian energy mix over the time horizon of the analysis and the importance of hydropower in electricity production.

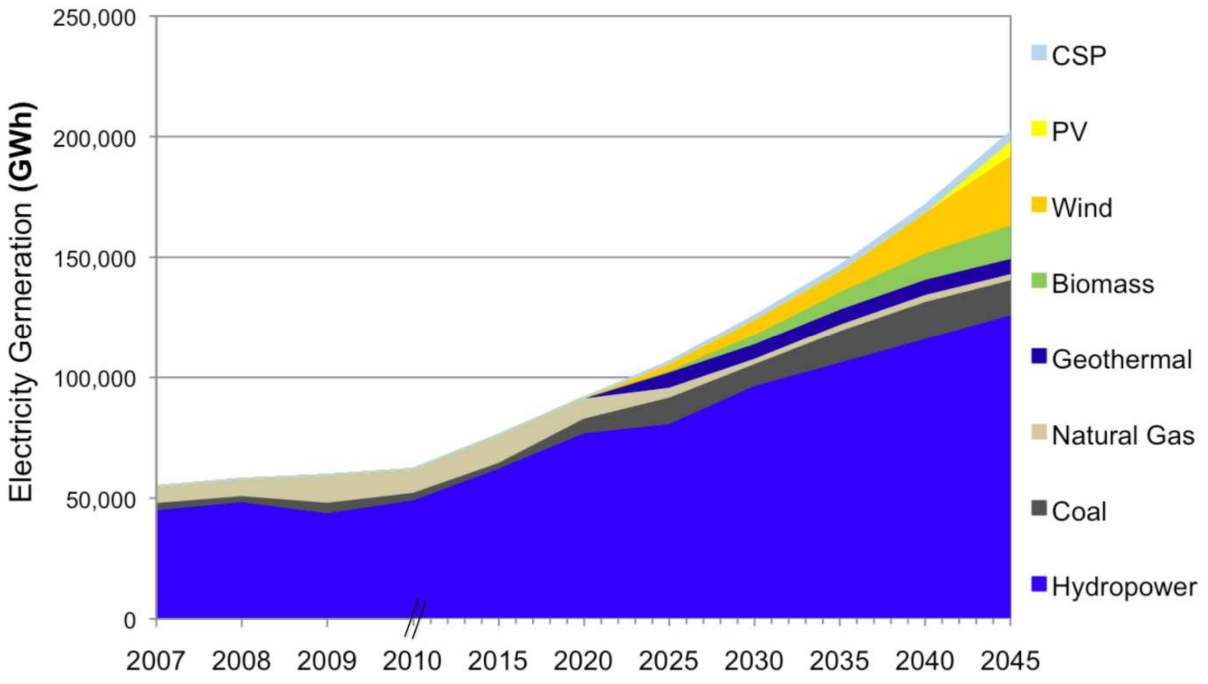

Figure 11-1 Least cost electricity generation for the reference case

In all sensitivities simulated with the least cost approach of MESSAGE, new renewable energy technologies were introduced to the power system regardless of fuel prices, investment and operation and maintenance cost sensitivities. The results suggest that in a period between 2015 and 2030, the introduction of new renewable energy technologies will take place in Colombia. Figure 11-2 shows the shares of renewable energy sources in electricity generation for all sensitivities in MESSAGE as an indication of when and which new technologies powered by renewable energy sources can be expected to enter into the system. A share of at least 8% in 2025 (not including hydropower) is expected to increase to 28% by 2050 with the introduction of renewable energy sources.

The most promising new renewable technology is powered by wind energy. In all sensitivities in the model, wind energy reached a significant share in electricity generation over 10% after 2040. In addition, the maximum potential of 10 GW set in the simulation is reached after 2040. This suggests the potential to continue expanding the system with wind energy by increasing and further developing suitable sites in Colombia including off-shore wind energy which was not included in the simulation.

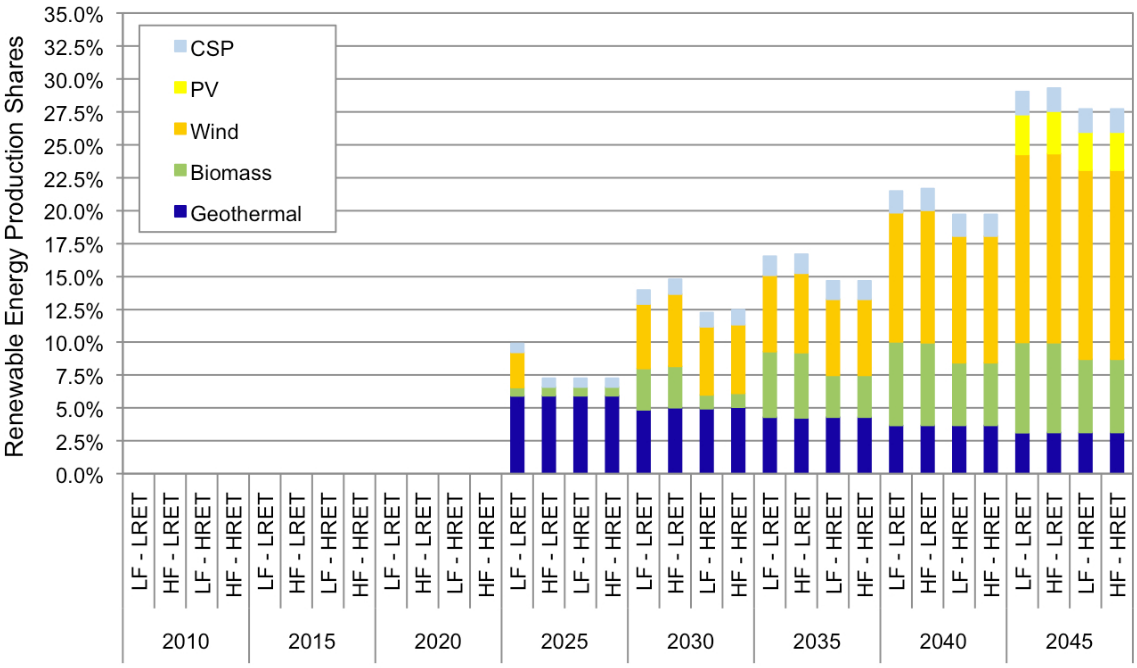

Figure 11-2 Renewable energy shares in least cost electricity generation

LF – HF: Low and high fuel prices, LRET – HRET: low and high investment costs for renewable energy technologies

In all scenarios conventional geothermal technology was introduced as well as biomass. In contrast solar technologies such as concentrated solar power and photovoltaic have a relatively modest contribution to the system.

However, the results show an expansion path does not reach a 100% renewable system until 2050 including large hydropower. Despite an important decrease of fossil fuel sources for power generation over the years, the system still needs these sources to be part of the least cost solution. The results suggest that during the time horizon in the analysis, the Colombian power system will not turn into a 100% renewable system based on market forces. It is worth noting the combination of existing and new hydropower plants with the introduction of technologies powered by wind, geothermal, biomass and solar turning the heavy based hydropower system in Colombia gradually over the years into a diversified renewable energy system. Thus, the current share of up to 80% of the electricity supply coming from hydropower plants will be reduced to approximately 60%. The introduction of new renewable energy sources together with hydropower will increase the share of all renewable energy sources to 90% as shown in Figure 11-3.

Renewable energy sources can contribute significantly to diversifying the supply of electricity within the Colombian power sector

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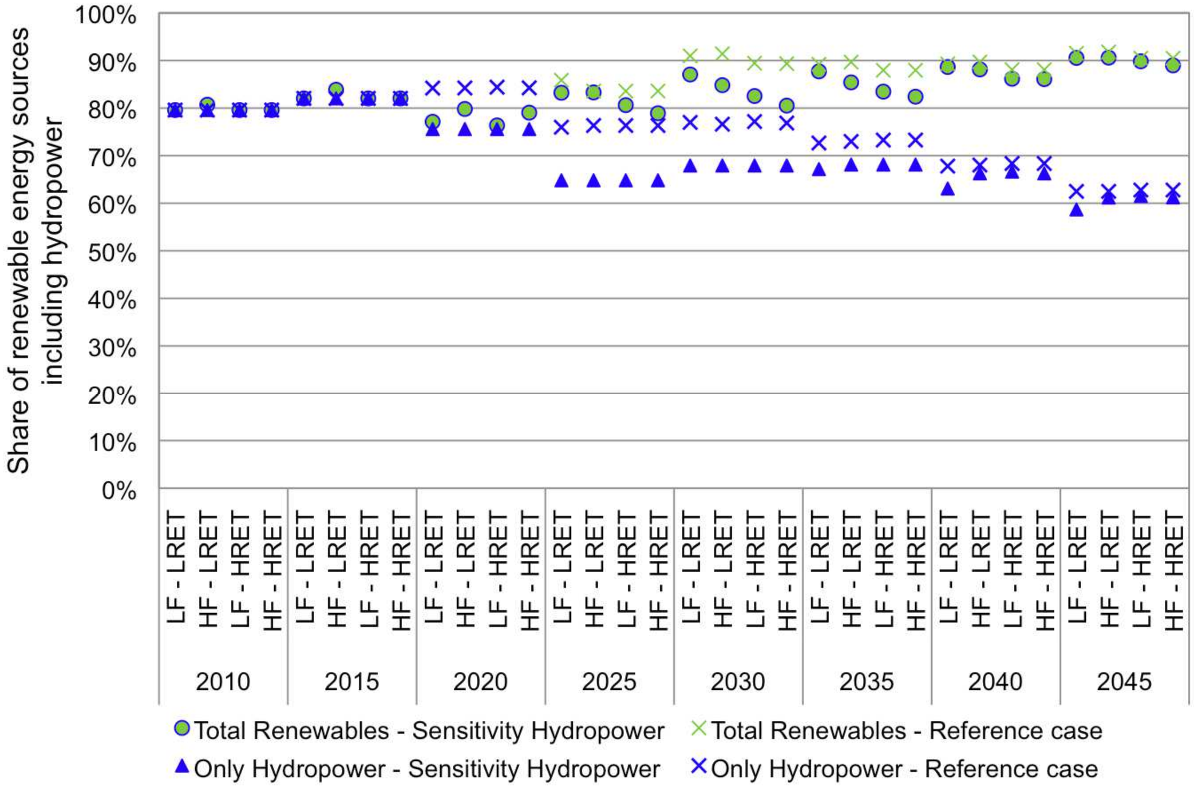

Figure 11-3 Total share of renewable energy sources vs. total hydropower share in electricity generation

In the same order of ideas, the results suggest that a growing introduction of renewable energy technologies over the years will substitute a great portion of energy that otherwise should be coming from fossil fuel sources. However, renewable energy technologies do not fully substitute or avoid the use of fossil fuel sources. In spite of this the share of gas is drastically reduced, whereas coal will continue to have a small share in the system. Figure 11-4 summarizes the results in relation to fossil fuel sources by comparing BAU and Least Cost scenarios. Renewable energy sources will contribute to decrease the dependence on natural gas for the power sector and to release carbon resources to supply international markets and so improving Colombian’s balance of payment.

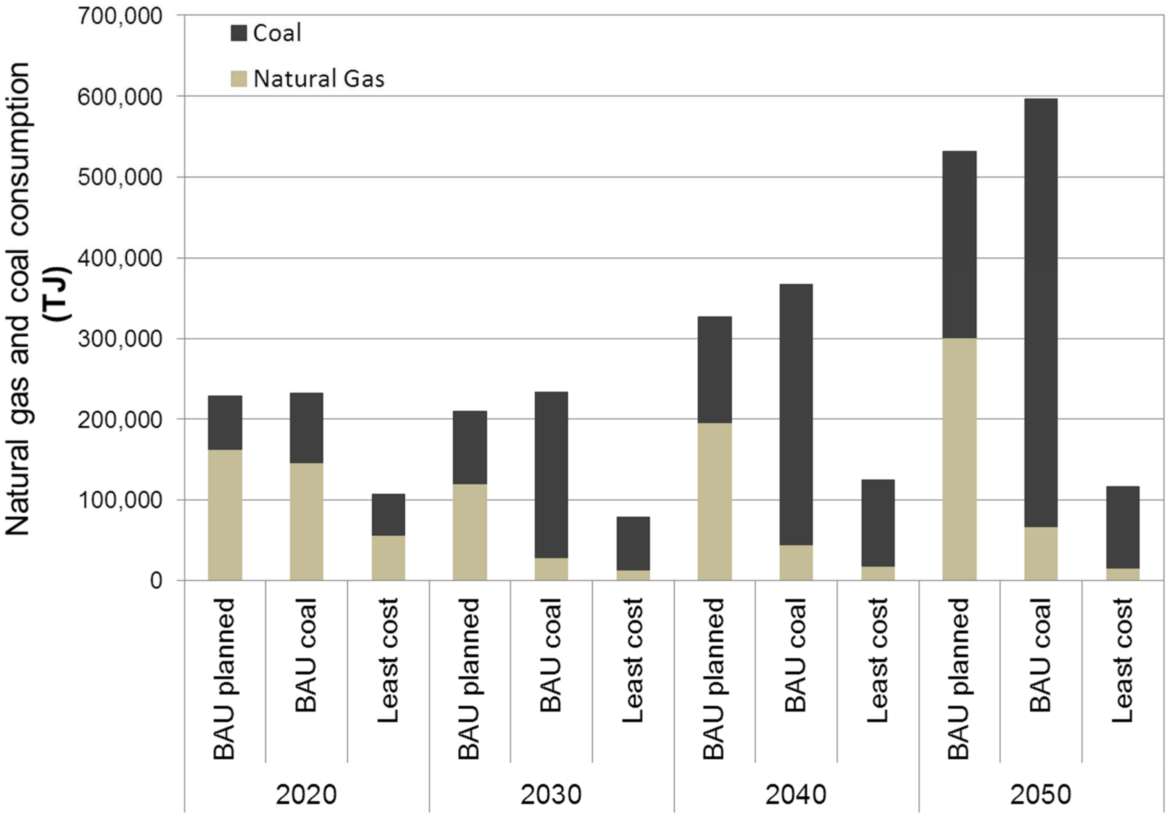

Figure 11-4 Consumption of natural gas and coal for BAU scenarios vs. least cost approach

Higher shares of electricity coming from fossil fuel power plants may affect security of supply by relying on scarce energy sources such as natural gas. The BAU scenarios simulated with LEAP showed how much more fossil fuel sources may be necessary to continue expanding the system with natural gas and coal together with hydropower as shown in Figure 11-4.

The results from analyses performed with MESSAGE and LEAP showed that Colombia will rely on imported natural gas from 2018 onwards. In a BAU scenario the natural gas consumption of the power sector may increase from current levels (2008: 1.69 Gm^3) to 3.05 Gm^3, 4.95 Gm^3 and 7.64 Gm^3 by 2030, 2040, and 2050 respectively. In a BAU scenario based on coal the share of natural gas in the system is drastically decreased to 0.70 Gm^3, 1.13 Gm^3, and 1.67 Gm^3 by 2030, 2040, and 2050 respectively. Nevertheless coal will have much higher shares in the system, rising CO_2 emissions drastically.

A logical effect of reducing the contribution of fossil fuel energy sources in the Colombian power sector is the avoidance of CO_2 emissions. Otherwise the emissions of CO_2 will surpass today’s levels. This situation was simulated with BAU scenarios using LEAP.

By continuing to expand the system with conventional energy sources, the emissions of CO_2 will surpass 12 million tonnes of CO_2 eq. per year after 2010 until reaching around 36 million tonnes by the year 2050. In that case the system would release 793 million tonnes of CO_2 eq. into the atmosphere in a period of 40 years. In the BAU scenario based on coal power (scenario of coal planned additions), the emissions increase drastically reaching 52 million tonnes by 2050, releasing 1,021 million tonnes of CO_2 eq. over a period of 40 years.

The optimization results suggest that emissions will be below 12 million tonnes of CO_2 eq. per year during the time horizon of 40 years due to entrance of technologies powered by renewable energy sources. Emissions could reach 16 million tonnes of CO_2 eq. per year if hydropower no longer provides the same levels of capacity and production. Thus, the power system would release between 350 and 405 million tonnes of CO_2 eq. over a period of 40 years. This shows the immense potential of renewable energy technologies including large hydropower to maintain current emission levels over the next 40 years despite electricity demand growth. Between 388 and 671 million tonnes of CO_2 eq. or between 556 and 731 million tonnes of CO_2 eq. for a scenario with lesser contribution of hydropower can be avoided.

In addition, the introduction of a carbon tax was simulated. Assuming a global carbon tax after 2020 of 20 USD/tonne of CO_2, it was found that the contribution of coal and gas was further decreased. In other words, the shares of wind energy and biomass are higher from 2020 and CO_2 emissions are further decreased to reach levels below 8 million tonnes of CO_2 eq. per year. By a simulation of a lesser contribution of hydropower it was however found that the carbon tax did not have the same impact suggesting that more coal power plants are indeed needed together with more new renewable sources to cover for less hydropower.

Renewable energy sources can contribute to significantly reduce the dependence on fossil fuels and avoiding greenhouse gas emissions

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The issue of the dependence of the Colombian power sector on hydropower was also analyzed. The availability of water resources, which is influenced by Colombia's seasonal cycle, which includes a dry and rainy season and more drastically by the El Niño and La Niña Southern Oscillation (ENSO), which causes extreme weather conditions (droughts and floods respectively), have a significant impact on hydropower generation. In addition the vulnerability of Colombia to climate change may adversely affect the contribution of hydropower. For that reason diversifying the Colombian power system with other power technologies to reduce this dependence is crucial.

Figure 11-5 shows the shares of all energy sources in electricity generation for all sensitivities in MESSAGE. The entrance of renewable energy sources into the system beginning in 2025 caused a reduction in the contribution of hydropower from current levels, around 80%, to 62% during the time horizon of the simulation. Thus renewable energy sources contribute not only to reducing the shares of fossil fuel sources but also the dependence on large hydropower plants.

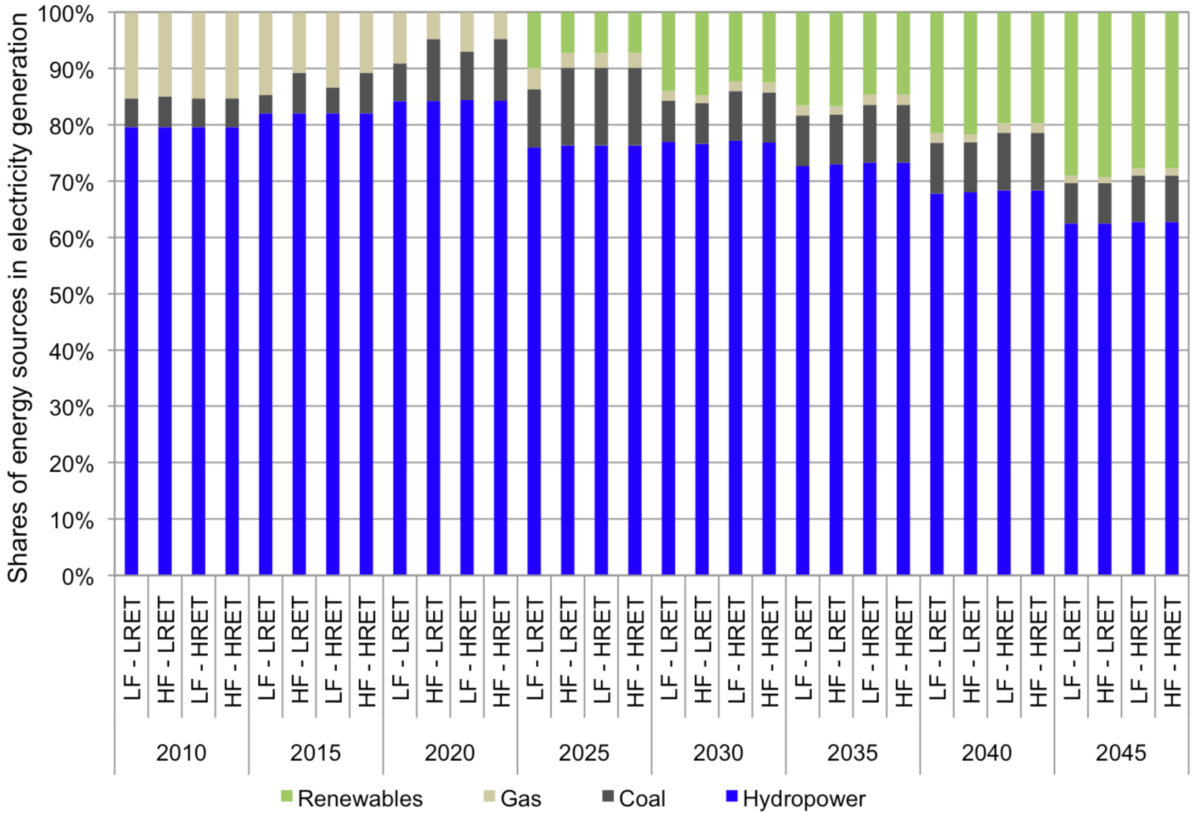

Figure 11-5 Energy sources shares in least cost electricity generation

LF – HF: Low and high fuel prices, LRET – HRET: low and high investment costs for renewable energy technologies.

Included in the simulation was the possibility that hydropower will no longer provide the same levels of capacity and production as observed in recent years due to technical, environmental and socioeconomic factors that may limit their implementation and the vulnerability of the water resources due to climate change. This was achieved by capping the contribution of hydropower to 70% of total electricity production. The results are shown in Figure 11-6. The entrance of other renewable energy sources from 2015 in the system caused a reduction of the contribution of hydropower under 70% from 2025 during the time horizon.

By having a lesser availability of hydropower, the chance for the introduction of other technologies into the system is naturally enhanced. Put simply, more coal power plants are installed and dispatched in the coming years before renewable energy technologies reach competitive costs. Afterwards a higher share of renewables are installed and dispatched to cover for the reduction in hydropower resources.

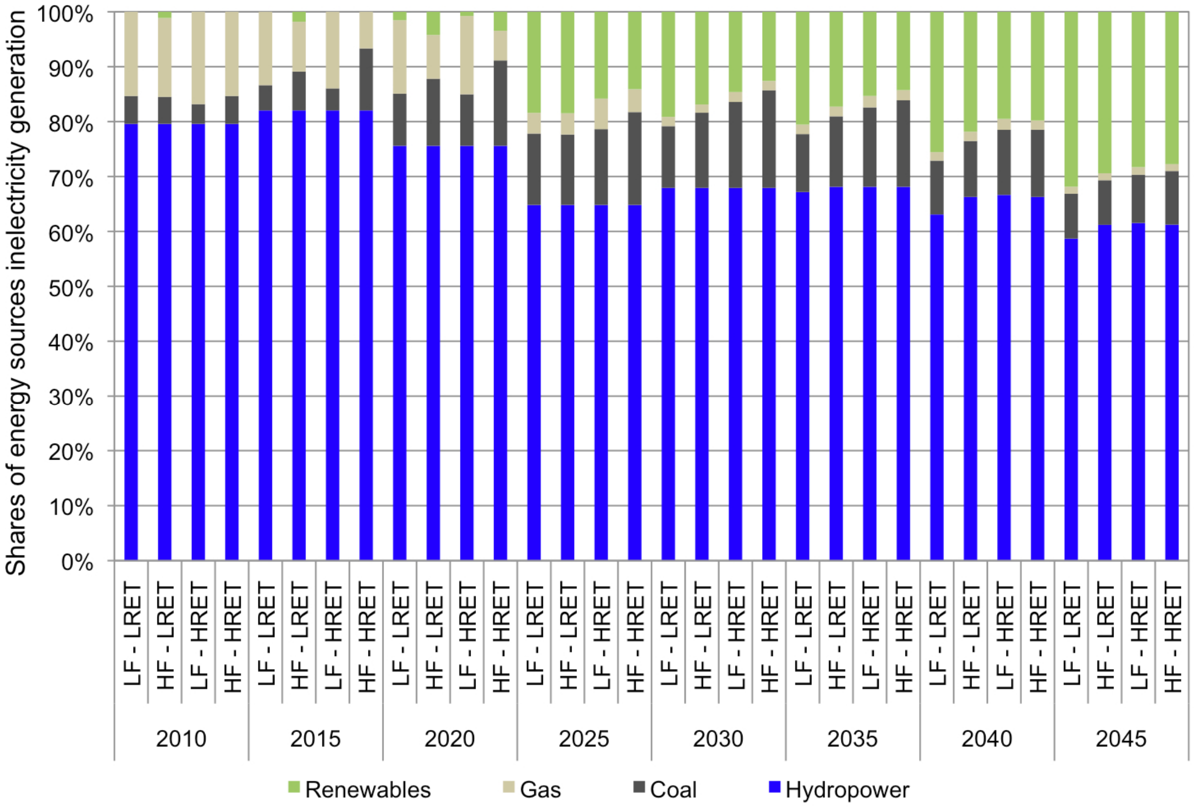

Figure 11-6 Energy sources shares in least cost electricity generation with less contribution of hydropower

LF – HF: Low and high fuel prices, LRET – HRET: low and high investment costs for renewable energy technologies.

Under a scenario of a lower contribution of hydropower and low investment costs for renewable energy technologies, the entrance of renewable energy sources can be expected after 2015. Regardless of fossil fuel prices and investment costs for renewable energy technologies in the analysis, a significant share of over 14% for renewable energy sources apart from hydropower can be achieved after 2020.

Renewable energy sources can contribute to reducing the dependence of the Colombian power sector on large hydropower plants

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The results of this dissertation suggest that the Colombian power system may be transformed from a system heavily based on hydropower to a system composed of a more diversified portfolio of technologies and energy sources such as wind, geothermal, biomass, solar and hydropower. State of the art coal and gas fossil fuel power plants will also be introduced into the power system. A 100% renewable system by 2050 was not obtained. Therefore fossil fuel energy sources are not fully substituted but they will be displaced as main energy sources after hydropower.

(2) The introduction of renewable energy sources in Colombia can be part of the least cost alternative for the expansion of the Colombian power system.

The results of the simulation with MESSAGE found least cost expansion paths that include renewable energy technologies. In all sensitivities conducted in MESSAGE, the least cost approach suggests that renewable energy technologies will be competitive to enter the Colombian power system between 2015 and 2030 depending on the development of fuel prices, investment, operation and maintenance cost and the contribution of hydropower.

The time of introduction and shares of renewable energy sources for electricity production varies over the years according to the sensitivities simulated. For instance, the scenarios with a low cost of renewable energy technologies and a lesser contribution of hydropower showed a more rapid expansion with renewable energy sources as shown in Figure 11-5 and Figure 11-6.

Figure 11-2 shows how the share of wind energy would grow over the years suggesting that expected further investment cost reductions in combination with the Colombian wind resources will boost the introduction of the technology after 2025. The least cost approach also showed an important contribution of technologies such as biomass and geothermal which do not have the high learning rates of wind and solar photovoltaic but higher capacity factors.

In terms of system expansion, a combination of intermittent energy sources such as wind and natural base load energy sources such as biomass and geothermal were obtained. This makes the Colombian power system much less dependent on fossil fuel price volatilities and intermittency and availability of hydropower production which have an important effect on electricity prices.

11.2 DISCUSSION

The least cost approach of MESSAGE can be seen as the simulation of electricity supply in an ideal market environment in which an electron from a wind turbine is not treated differently from an electron from a coal power plant apart from their technical features and generation cost. Thus, the results of this dissertation suggest the competitiveness of new renewable energy sources in all sensitivities in the simulation. This approach does not necessarily reflect the power market environment that technologies face in reality.

It is indisputable that at some point in time these technologies will become competitive (grid parity). The cost of renewable technologies has declined and additional technical advances are expected to result in further cost reductions. The challenge is to ensure that power markets allow new technologies to be part of the system at the time of their competitiveness.

An example of that dissimilarity in the current Colombian power market is the economic incentive for electricity suppliers, such as fossil fuel power plants that can contribute to firm energy in cases of high demand or variability of hydropower generation. This is an additional incentive that intermittent energy sources such as wind and solar cannot profit from. Such an incentive suggests the bias of market rules towards some technologies and the importance of developing a level playing field for all technologies in the Colombian power system. Incentives for renewable energy sources could also be implemented, for instance for the complementarity of wind energy with hydropower or the contribution of solar power plants to intermediate and peak loads at the Colombian Caribbean Coast.

A level playing field for renewable energy sources in the Colombian power market should be ensured to capture their full economic, technical and environmental potential at the time of competitiveness

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Regarding the integration of new technologies for the Colombian power system such as wind, solar, biomass and geothermal, a level playing field in the power market is not the only issue to be assessed, but also the technical integration of new technologies into the system. The issue of intermittency requires an assessment to better understand the operation of the Colombian power system to optimize the operation of intermittency sources such as hydropower, wind and solar power.

In that regard, hydropower offers the opportunity to integrate a high penetration of wind energy in the system due to its flexibility providing a form of indirect or virtual storage for this energy source. The power system in Colombia may not only benefit from the storage capacity of hydropower to accommodate intermittent sources such as wind energy but also from the strong complementarity of wind energy during the dry season which may improve the firm energy of the system. For that reason the integration of wind energy and hydropower should be assessed in the context of the entire system in detail.

Regarding solar energy technologies such as CSP and PV, the results of this dissertation suggest a small participation at the very end of the time horizon after 2040. Solar energy deserves a better and fairer analysis. An assessment of the potential of solar power should be conducted to attend the demand at Colombia’s Caribbean coast, where high temperatures are connected to higher consumption of electricity driven by the use of air conditioning systems. That makes solar technologies ideal for daily and seasonal operation matching peak and intermediate loads. Such a contribution releases other energy sources to cover these loads and could also optimize the grid operation.

For technologies such as geothermal and biomass, the lack of information about the availability and quality of associated resources should be overcome. The use of solid residues from sugar plantations, in particular the collection, disposal and transport, should be assessed in detail. These technologies are key since they are not intermittent, therefore contributing to the supply of firm energy into the system.

Finally, the results of this dissertation should be complemented with a study to determine transmission expansion and enforcements to make sure that the Colombian power system can realise its potential and profit fully from new energy technologies powered by renewable energy sources.

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