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Restless Waters

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Fossil Fuel Emissions Conditioning a Reduction in Hydroelectric Resources in Chile

CLIMATE CHANGE HAS BECOME A MAJOR concern worldwide. Major scientific organizations now agree that it is taking place, that human activities are contributing significantly to it, and—most important—that climate change and the resulting global warming pose significant future risks to humanity. Increasing the average global temperature by even a degree or two will lead to serious consequences worldwide, with reductions in the yields of crops, increases in rainfall amounts and thus increased flooding risks, and decreases in stream and river flows, among other effects. According to the Economic Commission for Latin America and the Caribbean, climate change is expected to cause losses of around 1% of annual GDP in the countries of Latin America and the Caribbean between 2010 and 2100.

The recent publication of *Climate Change 2013*, the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), a scientific

intergovernmental body established under the auspices of the United Nations, has further fueled these concerns about climate change's impacts, the world's vulnerability to them, and the need for global adaptation. It argues with high confidence that there are systemic risks due to extreme weather events and other multiple interacting hazards that will lead to the breakdown of infrastructure networks and critical services such as electricity, water supplies, and health and emergency services. It warns of the great dependency of people on these critical services. IPCC has evidence that climate change may influence the integrity and reliability of electricity grids and may therefore require changes in design standards for the construction and operation of power transmission and distribution lines. It suggests that utilizing existing technology developed for various geographical and climatic conditions could reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing grids.



figure 1. Thermoelectric generation from burning coal in Huasco, Chile (photo courtesy of Horacio Parrague).

One aspect of climate change that particularly concerns power engineers in the developing world is the changes taking place in relation to hydroelectric resources, particularly the reduction of those energy sources in countries heavily dependent on them, like Central and South America, where 60% of electricity demand is met through hydropower generation. The need to assess climate change impacts at the national level, the resulting effects on electricity supply and on hydroelectric power, and the tools that can be used to mitigate those effects and adapt the power infrastructure to them are all exemplified in the country of Chile.

Electricity as a Principal Contributor to Climate Change

Energy supply, including electricity generation, is one of the sources of the greenhouse gas (GHG) emissions that are

causing climate change worldwide. In effect, the burning of coal (see Figure 1), natural gas, and oil for electricity generation and heat production is the largest single source of GHG emissions (41%). Road, rail, air, and marine transportation that requires the burning of fossil fuels (mainly gasoline and diesel) is the second-largest contributor (22%). Industry is the third-largest source, again from the burning of fossil fuels (20%). Emissions from forestry management, deforestation, fires, land clearing, and the management of agricultural lands and livestock are next.

Carbon dioxide (CO₂) makes up the vast majority of the GHGs emitted by the electricity sector, along with smaller amounts of methane (CH₄) and nitrous oxide (N₂O). As reported by the United States Environmental Protection Agency (EPA), while electricity generation from coal accounts for about 42% of the electricity generated in the

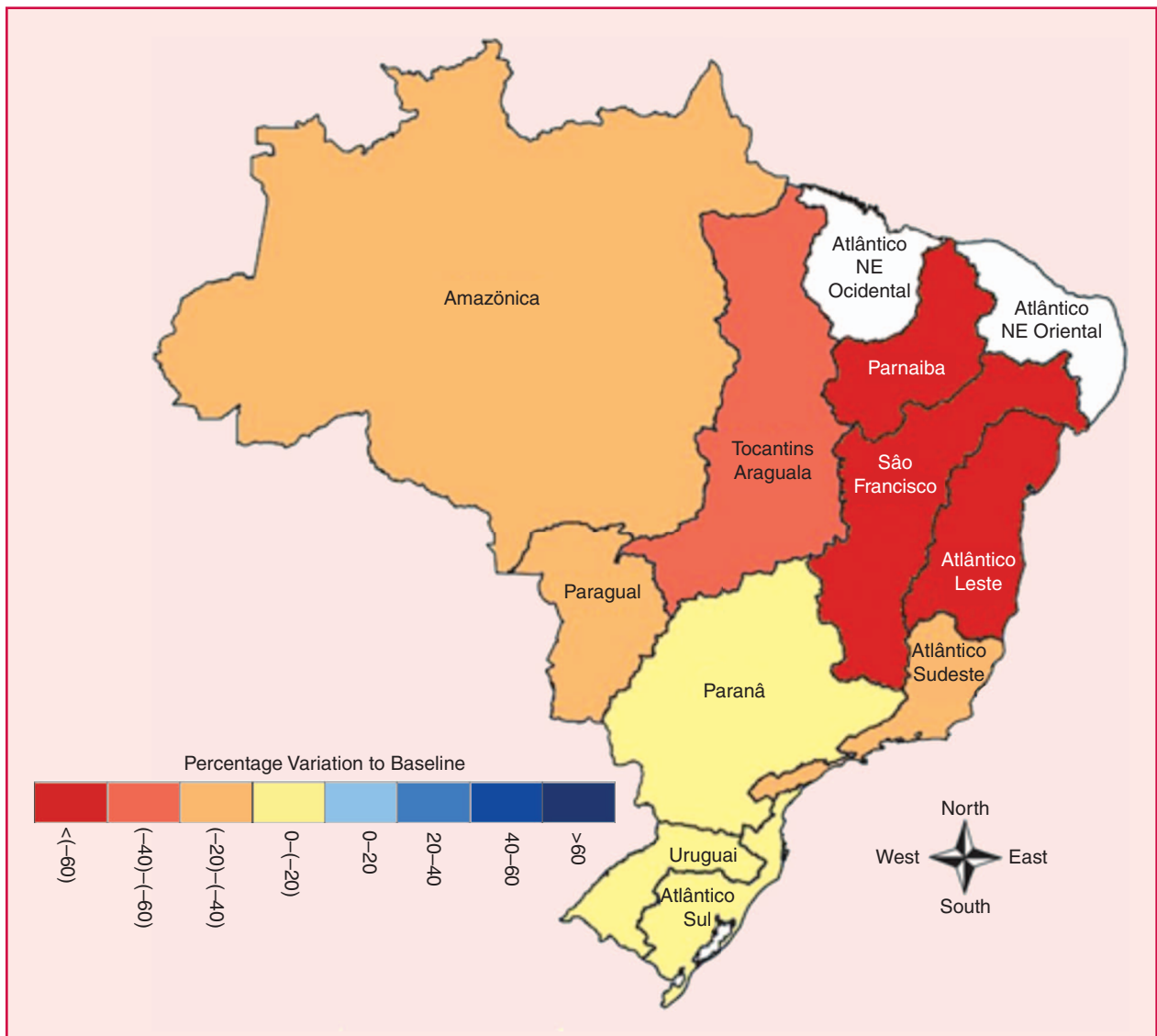


figure 2. Variations in firm energy produced in major Brazilian river basins according to GHG emission scenario A2 (source: Schaeffer et al.).

United States, it accounts for about 80% of the CO₂ emissions from the sector. That is because coal combustion is more carbon intensive than burning natural gas or petroleum for electricity. While 1 million Btu in the form of coal emits between 205 and 215 lb of CO₂, 1 million Btu in the form of natural gas emits only 117 lb. Emissions from coal-fired electricity generation are on the order of 1 t CO₂ per MWh, while this figure is only 0.45 t for electricity generated using natural gas as fuel. Natural gas is primarily methane and has a high energy content relative to other fuels and therefore a relatively low CO₂-to-energy ratio (although emissions from the shale gas fracking process used to obtain natural gas may increase the fuel's life cycle CO₂ contribution).

The main concern, however, is that GHG emissions from electricity production are increasing, as electricity demand has grown and fossil fuels remain a dominant source for generation worldwide.

Electricity Supply Affected by Climate Change

Climate change may affect both electricity demand and supply. An important concern in Central and South America, as mentioned before, arises in relation to future changes in supply from hydro resources, as 60% of electricity demand there is met through hydropower generation (in contrast to the 20% average contribution from this source elsewhere).

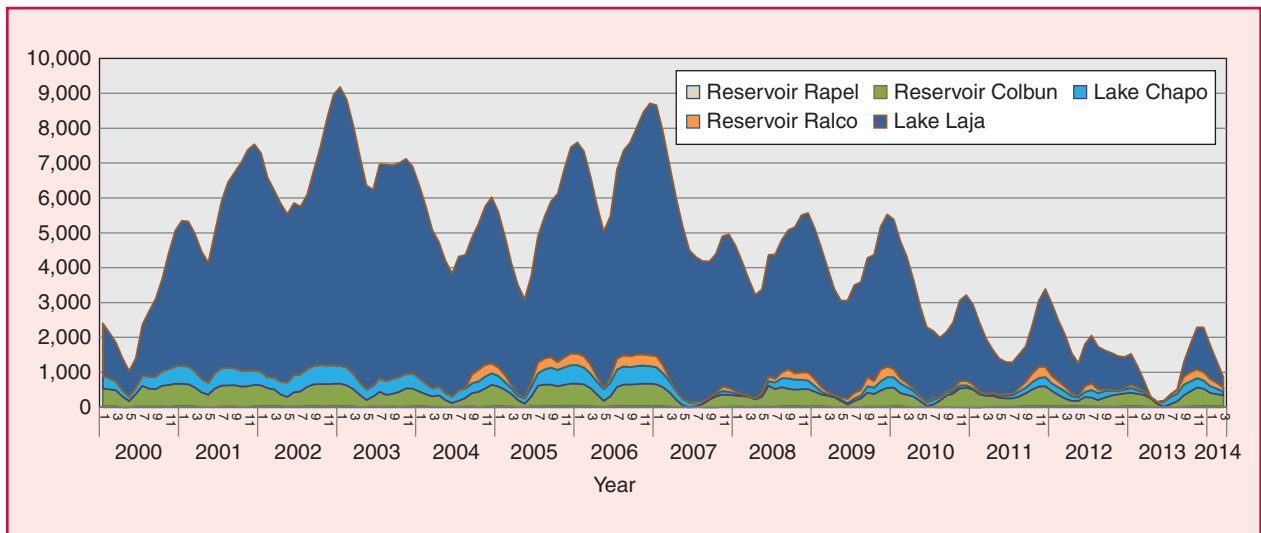


figure 3. Stored energy in the main Chilean hydroelectric reservoirs (source: Systep).

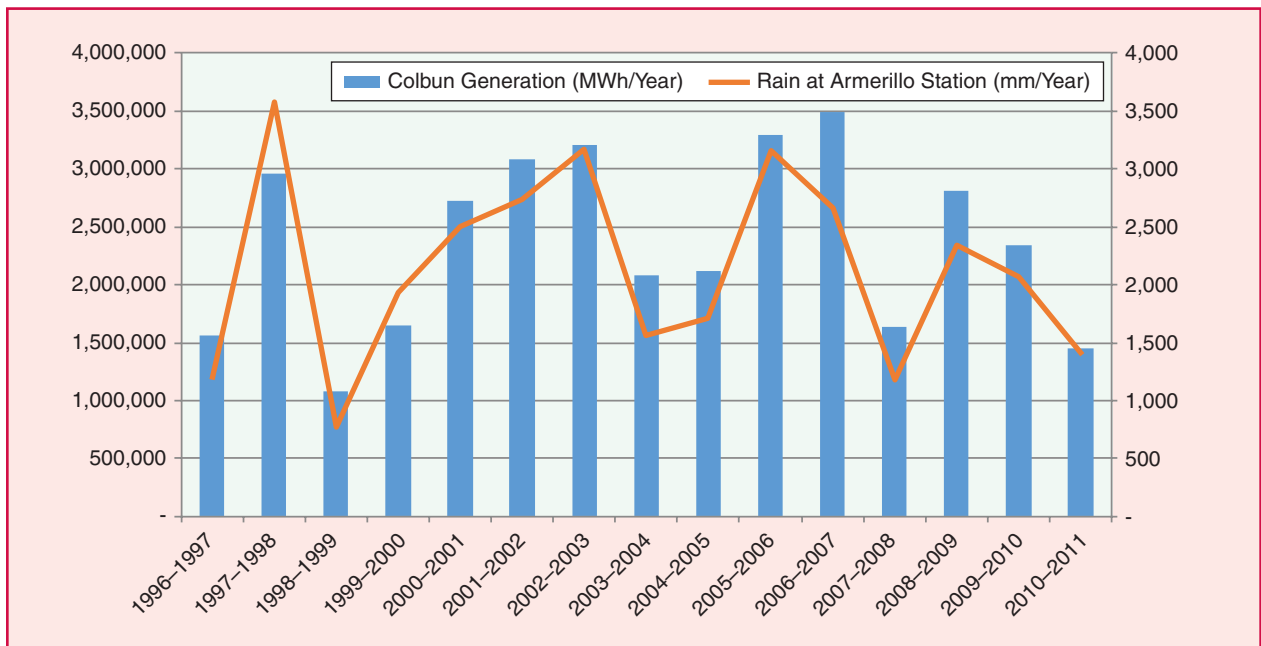


figure 4. The generation at Colbun hydroelectric plant and the precipitation recorded at a local weather station in the Maule river basin, Chile (courtesy of Sebastian Ellena).

Brazil and Colombia generate close to 80% of their electricity from hydro sources. Further, there is steady interest in the region in continuing to exploit hydro resources not yet harnessed for electricity generation. Major power plants are being built or planned in Brazil, Chile, Colombia, Ecuador, and Peru. Argentina and Chile share the world's third-largest store of ice, the Southern Patagonian Ice Field, with major rivers flowing out of it.

The latest IPCC report provides different case studies showing the impact in the region, where the production of energy from renewable resources such as hydro and wind may suffer, as it depends greatly on climatic conditions. It reports cases of rivers with potential reductions in hydropower capacity of from 35% to 53% by 2070–2099. While Brazilian hydropower generation may experience a minor increase in energy production in the south, the rest of the country could face a significant reduction. Figure 2 illustrates the expected variations in energy from hydro sources in Brazil, as reported by Schaeffer et al., with reductions as high as 60%. Such losses of hydropower generation could produce an impact amounting to US\$1.5 billion in the Peruvian electricity sector.

The potential loss of a large percentage of hydro generation—one of the main contributors to the mitigation of GHG emissions—is an unwelcome piece of news, not only because of that contribution but because of the need to replace the lost electricity using thermal generation. The IPCC indicates that in Brazil there would be an increase in natural gas and sugarcane bagasse electricity generation of roughly 300 TWh, with an increased cost of US\$7 billion annually. Changes in seasonality and the total availability of water could increase complexities in the operation of multiple basin schemes in Peru and Colombia.

Projected Changes in Hydroelectric Resources in Chile

One country in South America that is becoming very concerned with its emissions growth and the effects of climate change is Chile. Although Chile contributes only 0.2% of total global GHG emissions, it is concerned because its per capita CO₂ emissions have grown to 4.5 t in 2013 from 3.6 t in 2006. This is a trend in developing countries with high economic growth (more than 5% annually) and stable populations.

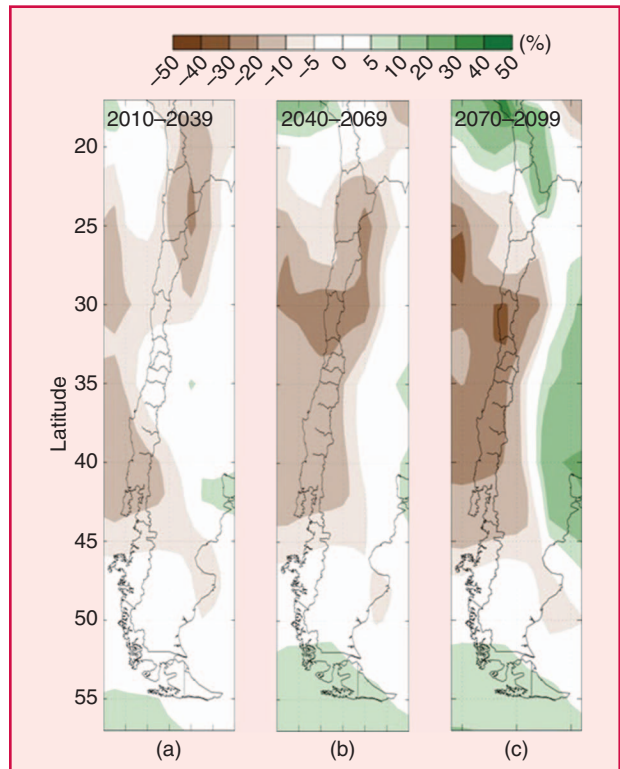


figure 5. Projected precipitation changes in Chile (source: CEPAL). (a) 2010–2039. (b) 2040–2069. (c) 2070–2099.

In particular, Chile is concerned with the potential impacts of climate change on hydroelectric generation. There have been significant decreases in rainfall in central Chile over the last 40 years, with a number of prolonged droughts lasting several years. Figure 3 shows the decrease in stored energy in the main Chilean hydroelectric reservoirs over the last 12 years. Although it is too early to attribute this decrease to climate change, these events demonstrate the effects that reduced water availability may have on the market, with high prices, reduced reliability, and an increase in fossil-fuel-based generation together with growth in GHG emissions.

The main problems that climate change can cause for hydroelectric generation occur as a result of changes in patterns, intensity, and extremes of precipitation; widespread snow and ice melt; changes in river flows; and evaporation. Many of these processes eventually affect the safety of dams if significant sudden changes of river flows take place. There is a direct correlation between amounts of precipitation and hydroelectricity generation (see Figure 4). Further, as higher temperatures increase snow melt, this affects hydroelectric

table 1. The effect on energy generation of precipitation projections for the principal river basins in Chile, given as percentage declines with respect to the historical base (source: CEPAL).								
	Aconcagua	Maipo	Cachapoal	Maule	Laja	Bio Bio	Others South	Total
Yearly Energy (GWh)	756	1,584	1,555	7,282	4,508	4,798	455	20,938
% Reductions								
2011–2040	–4%	–1%	–10%	–3%	–7%	–33%	–3%	–11%
2041–2070	–17%	–8%	–26%	–6%	–14%	–38%	–5%	–17%
2071–2099	–18%	–9%	–27%	–11%	–17%	–47%	–8%	–22%



figure 6. The Panguo Dam in Chile's Bio Bio basin (image used courtesy of Endesa).

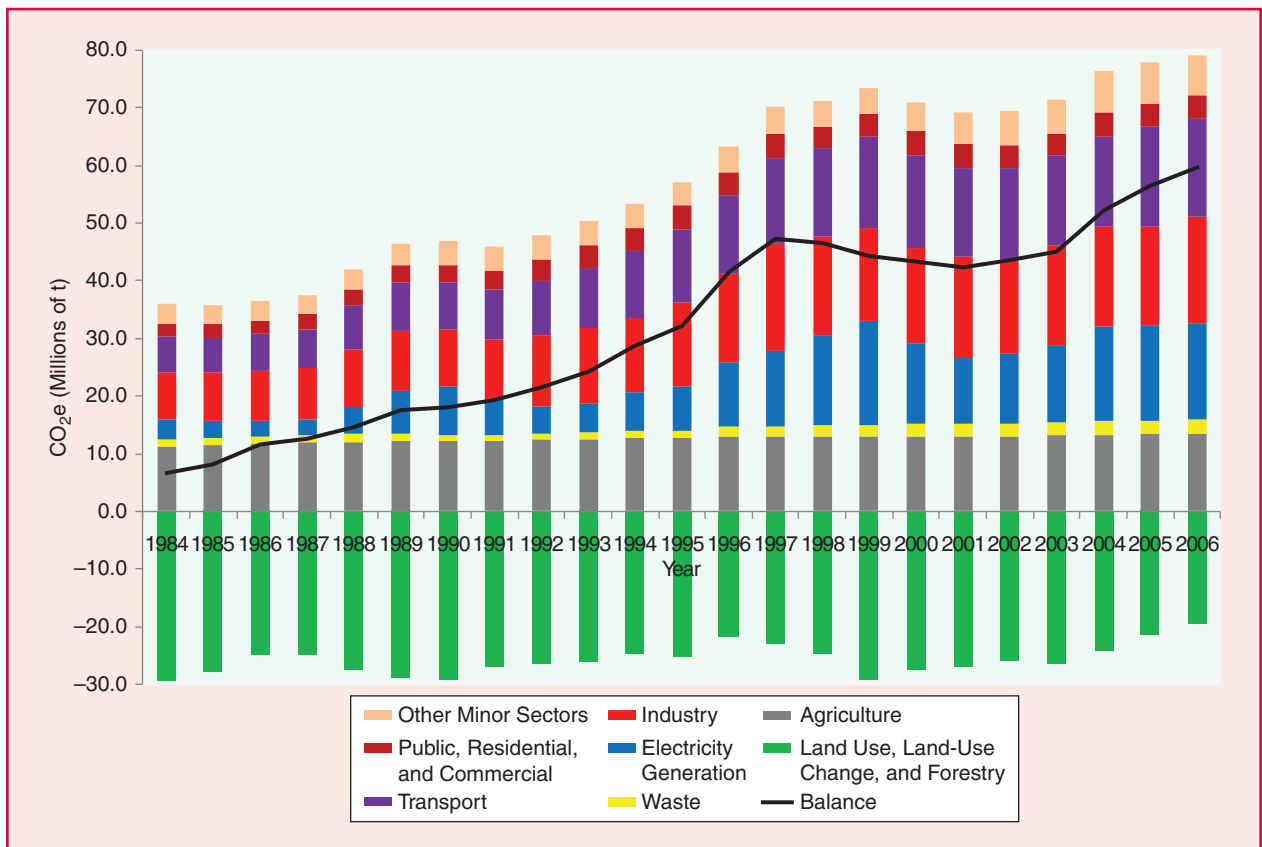


figure 7. The Chilean national GHG inventory, by sector, 1984–2006 (source: Chilean Ministry of the Environment).

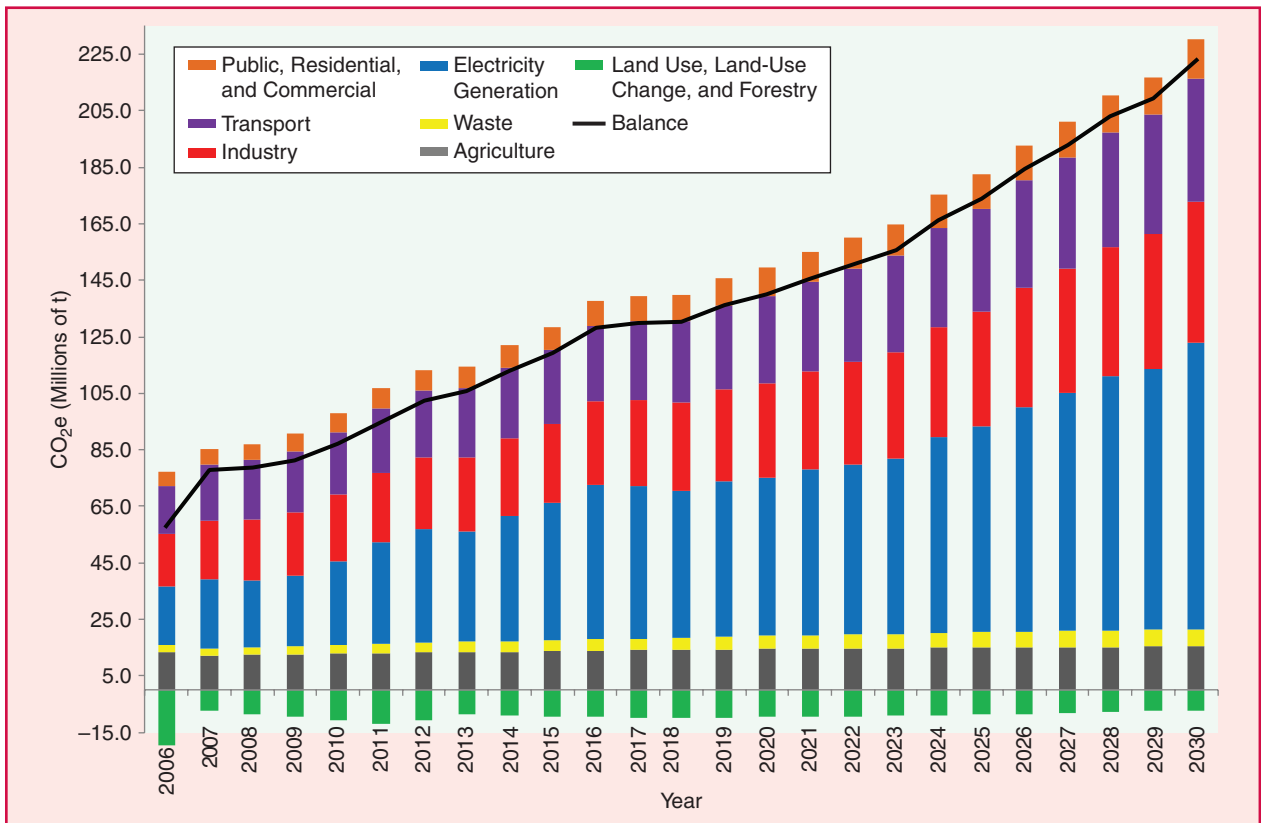


figure 8. Baseline 2007 projection of sectorial participation in the national GHG inventory from 2006 to 2030, using the medium-low scenario (source: MAPS Chile).

plants that depend on cycling periods of snow melt, as the melt patterns will change, challenging water usage.

Each hydroelectric plant is built taking into account historical changes in water flows, and its economic assessment is very much based on them. For this reason, a change in climatic conditions could affect existing hydro generation systems as well as future projects, with water flows that may be above or below historical patterns.

Various studies have been conducted in Chile on the impact that climate change will have on the flow of the main river basins, along with studies of the impact that will have on hydroelectric

generation itself. The general temperature for the country as a whole is predicted to rise by around 4 °C by the end of the century, and a significant reduction in glaciers is also expected. Figure 5 shows projections of significant precipitation reductions in the region of Chile where most of the hydroelectric plants are located. Rainfall is forecast to fall by 30% in the central part of the country during this period, with increases expected in the extreme northern and southern parts of the country.

A general decline in river flows for hydroelectric plants is projected to occur as early as 2040. Table 1 illustrates the effects on electricity generation of the expected changes in precipitation

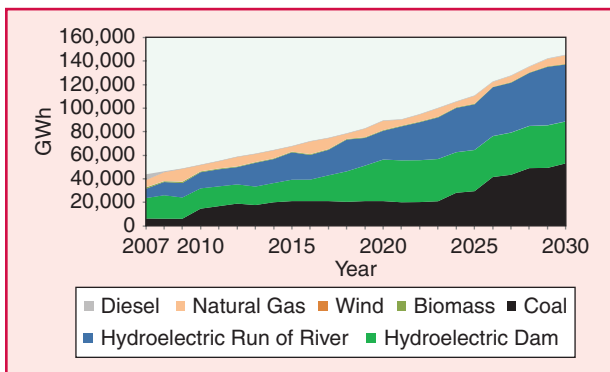


figure 9. Electricity generation by source in the SIC power system (source: MAPS Chile).

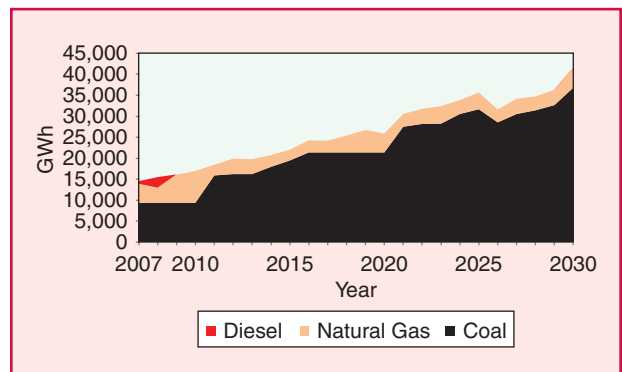


figure 10. Electricity generation by source in the SING power system (source: MAPS Chile).

in the principal Chilean river basins through 2099, expressed as percentage declines with respect to the historical base. Major contributors of hydroelectric energy, such as the Maule and Bio Bio rivers (see Figure 6), may face flow reductions by 2071–2099 of 11% and 47%, respectively. In general, all basins with hydroelectric generation will be adversely affected by climate change, with an overall reduction of 22%. The only exception would be future plants in Patagonia, which would suffer minimal impact.

Projected Electricity Contributions to GHG Emissions in Chile

The most recent official Chilean GHG inventory (see Figure 7) shows that the industry, transport, and electricity generation sectors were the main emitters in 2006, contributing emissions equivalent to 18.5, 17.1, and 16.8 million tons of CO₂, respectively. It represents 66.2% of total emissions, leaving out the forestry CO₂ capture. The emissions of the industry sector include produced by manufacturing, construction, mining, and industrial processes.

MAPS Chile (www.mapschile.cl) has recently devised future projections of GHG emissions for Chile. Mitigation Action Plans and Scenarios (MAPS, www.mapsprogramme.org) is a collaborative initiative among developing countries to establish the evidence base for their long-term transition to robust economies that are both carbon efficient and climate resilient. The initiative began in South Africa and currently has programs in Brazil, Chile, Colombia, and Peru. Each country’s project is driven by a scientific team that performs detailed projection studies and is supported through a participatory process that involves people from the public, private, nongovernmental, and academic sectors.

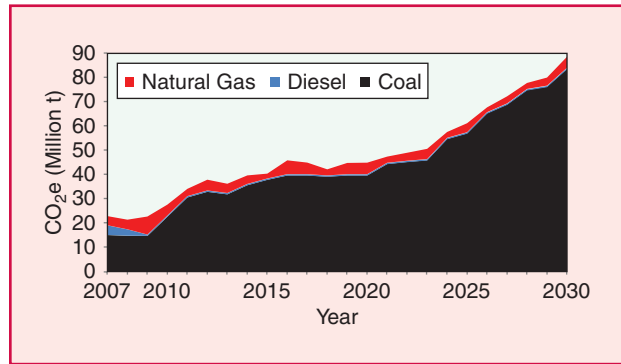


figure 11. GHG emissions for the SIC and SING power systems, as projected in Baseline 2007, using the medium-low GDP scenario (source: MAPS Chile).

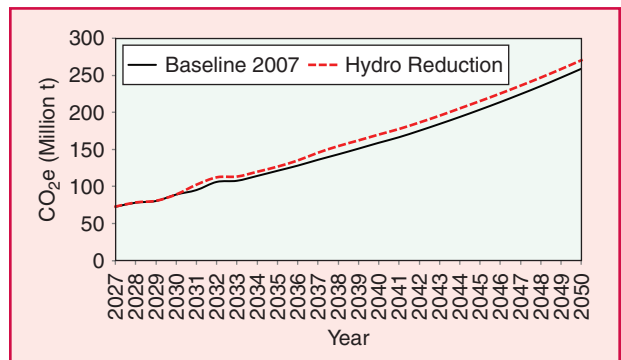


figure 12. The baseline 2007 projection of the impact of hydroelectric generation reductions on the trajectory of GHG emissions from electricity generation (source: MAPS Chile).

table 2. Mitigation actions in the electricity generation sector (source: MAPS Chile).

Sectors	Mitigation Actions	Description/Implementation
Electricity generation	Modification of the nonconventional renewable energy law	The current energy law states that 20% of all electricity sold should be generated using sources of nonconventional renewable energy (NCRE) by 2025. This action would increase the quota to 30% by 2030.
	Incentivizing specific forms of NCRE: geothermal, solar photovoltaic (PV), wind, small hydroelectric, and so on	This action would encourage the installation of a specific technology according to its technical potential. For example, the targets for additional capacity by 2030 for solar and wind energy are 6,903 MW for PV and 9,520 MW for wind. Chile issued, in 2013, a renewable energy law based on a quota system with a target of 20% of NCRE supply by year 2025.
	Exploiting the hydroelectric resource in Chile’s extreme south	This action would use the hydroelectric potential of the Aysen region. Two specific projects have been evaluated in this zone: HidroAysen (2,750 MW) and Cuervo (640 MW). This action envisions adding a total of 3,750 MW of hydroelectric capacity by 2030.
	Creating incentives to install clean-coal technologies	This action would discourage the installation of new subcritical pulverized coal technology plants, beginning in 2020.
	Creating incentives to generate electricity using liquefied natural gas (LNG) as fuel	This action would replace 50% of the coal plants installed after 2020 (to provide the additional coal-fired capacity required under the Baseline 2013 scenario) with plants using LNG.
	Nuclear energy	This action would result in the installation of 6,000 MW of nuclear energy from 2030 to 2050.
	Carbon tax	This action would impose a carbon tax of US\$20 per ton of CO ₂ equivalent beginning in 2017.

MAPS Chile created a projection of the GHG emissions of the electricity generation sector in Chile that it called Baseline 2007. This projection takes into account available information and economic growth expectations as of 2007. It does not, however, consider the mitigation actions implemented in the country between 2007 and 2014. The results indicate that electricity emissions will grow from 20.8 million tons in 2006 to between 48.3 and 74.4 million tons of CO₂ equivalent by 2020, depending on the economic growth scenario used (five GDP projections were created, for optimistic, pessimistic, medium-high, medium-low, and reference scenarios). This projection also shows that the electricity generation sector will continue to be the main GHG emitter, followed by the industry and transport sectors. Figure 8 shows the GHG emissions for the medium-low GDP scenario for the seven sectors considered by MAPS. The scenario assumed an important reduction in the emissions capture by forestry, as compared with the national inventory.

The Baseline 2007 projection of the electricity generation sector was performed using the MESSAGE optimization model. This objective function minimizes the investment cost of new plants, operation costs, and the unserved energy cost. The problem is subject to several constraints: the energy balance between

electricity generation and projected demand, the upper and lower bounds to appropriate limits to electricity generation, and the maximum feasible amount of investment for each kind of technology that could occur annually, among others. The investment in new power plants and the electricity generation by source are the results of the optimization problem, for different hydrological scenarios. The expansion plan with the best average performance through all the hydrological scenarios is then selected.

The GHG emissions are projected by multiplying the primary energy consumed to produce electricity by emission factors given by the IPCC's 2006 guidelines. In Chile there are two main independent power systems, a hydrothermal system called the Central Interconnected System (SIC) and a purely thermal system, the Northern Interconnected System (SING). Figures 9 and 10 show the electricity generation by source for the two systems for the Baseline 2007 scenario.

The main source of GHG emissions in the electricity generation sector is coal, as shown in Figure 11 for the SIC and SING combined. As explained above, the Baseline 2007 projection was created by considering the available information and economic growth expectations as of 2007. It projected additions to coal generation capacity for the period 2007–2013 of

table 3. Mitigation actions in other sectors that may affect the generation sector (source: MAPS Chile).

Sectors	Mitigation Actions	Description/Implementation
Industry	Using nonconventional renewable energy in industry	This action would involve using nonconventional renewable energy sources in some industries to meet their own demand or inject excess power into the distribution network.
	Installing cogeneration	This action would install cogeneration plants; it envisions a potential installed cogeneration capacity of 208 MW by 2030.
	Replacing electric motors	This action would replace old electric motors with more efficient ones in the industrial and the mining sectors.
CPR (commercial, public, and residential)	Net billing	This action would require that 20% of Chilean households have solar PV panels by 2030. The energy thus generated would be injected into the distribution network.
	A minimum energy performance standard (MEPS)	A MEPS for refrigerators, lighting, washing machines, and air conditioners would be created, resulting in lower energy consumption.
	Improving the thermal regulation for residential buildings	This action considers improving the current thermal regulation for residential buildings every 10 years, projecting lower energy consumption.
	Qualifying residential energy-efficient property for residential building	This action would certify the energy properties of residential buildings.
Transport	Zero- and low-emissions electric vehicles	This action would require that a defined portion of passenger transport demand be met by electric (10%) and hybrid vehicles (10%) by 2030, thus increasing total electricity demand.
	Modal transport shift to subway	This action considers building additional 72 km of subway lines, increasing electricity demand.
Waste	Electricity generation in landfills	This action would install 7.2 MW of electricity generation capacity from landfills by 2030.
Forestry	Electricity generation from forestry biomass waste	This action would install 90 MW of biomass generation using waste from native forestry as fuel by 2030.
Agriculture	Pump water with renewable energy sources for irrigation use	This action would replace diesel and electric pumps with solar PV systems.
	Use electricity generation in dams for irrigation in agriculture	This action would install 480 MW of hydroelectric generators in dams built for irrigation by 2030.

800 MW for the SING and 1,500 MW for the SIC; these were used to arrive at the projected increases in GHG emissions by 2013 in comparison with the 2006 inventory. What actually happened was not much different in terms of additions to capacity: 885 MW and 1,266 MW for the SING and the SIC, respectively.

The national GHG emission projections between 2017 and 2020 do not increase due to the assumed incorporation of 2,750 MW of hydroelectric installed capacity in Patagonia in the period. In Phase 2 of the MAPS Chile project, a new baseline scenario was created, called Baseline 2013. Preliminary results show that fossil-fuel-based electricity generation will continue to be the main GHG emitter.

Projected Impact of Hydro Generation Reductions

Figure 12 shows the impact of the reduction in hydro generation on the GHG emissions trajectory in Chile, assuming a decrease of 15% in hydroelectric generation in the SIC system from 2030 onward. This energy is replaced by coal generation, with a resulting annual average increase in GHG emissions of 9.9 million tons of CO₂ equivalent. Prices would also rise, as higher-cost generation replaces hydropower.

Mitigation Actions for Climate Change

A mitigation action is understood as any activity that contributes directly or indirectly to the reduction of GHG

emissions. Chile has already taken some mitigation actions in the case of the electricity generation sector; these were not included in the Baseline 2007 studies reported earlier. In 2008, Chile introduced a nonconventional renewable energy law stating that 10% of total electricity should be produced from nonconventional renewable energy sources, i.e., all renewables except large hydro, by 2024. This law was modified in 2013, increasing the percentage to 20% by 2025.

More than 120 mitigation actions have been identified by MAPS Chile for the seven main GHG-emitting sectors. More than ten mitigation actions have been formulated for the electricity generation sector. In addition, actions have been formulated in the other sectors that also relate to the energy sector, for example, energy efficiency initiatives. Tables 2 and 3 show the mitigation actions that directly or indirectly involve the electricity sector.

Adaptation to Climate Change

The issue of adaptation to climate change has gradually been gaining importance worldwide. An example of adaptation is the development of a reservoir infrastructure for more efficient water management (for both irrigation and drinking water) in a region experiencing less rain because of climate change. This initiative moderates the harm from climate change but is not related to producing fewer GHG emissions.

Adaptation to climate change goes hand in hand with deploying less vulnerable energy-related technologies. There

table 4. Potential adaptation measures in the energy sector.

Sectors	Technologies and Climate-Resilient Practices
Oil and gas exploration and production	<ul style="list-style-type: none"> Reusing hydraulic fracturing fluids to reduce freshwater requirements Building flood walls to protect oil refineries from floods Prepositioning portable generators to provide electricity to critical facilities during outages
Thermoelectric power generation	<ul style="list-style-type: none"> Adding cooling towers to reduce water withdrawals Adopting innovative cooling towers fitted with condensing technology that reduces the release of water vapor Implementing dry-cooling systems in natural-gas-fired combined-cycle power plants, instead of recirculating cooling systems, to reduce water requirements
Renewable energy resources	<ul style="list-style-type: none"> For concentrated solar power plants: employing dry-cooling systems that convert steam into water in a closed-loop cycle For hydropower: building new storage reservoirs, modifying spillways, and installing turbines better suited to expected conditions (since greater water flows may require higher and more robust dams and/or small upstream dams) Stimulating use of solar energy in homes and buildings Improved management of groundwater resources
Energy demand	<ul style="list-style-type: none"> Installing energy efficiency upgrades to help offset the energy use impacts of additional market penetration of air conditioning Encouraging tree planting and green roofs to reduce peak electricity Replacing conventional roofs with cool white roofs to increase solar reflectance and thus reduce energy demand Improving end-use efficiency for buildings
Energy distribution	<ul style="list-style-type: none"> Installing network automation and storm management systems

has been progress made in several countries in that direction, and current practices described by the U.S. Department of Energy and the United Kingdom, among other countries, show that there are various climate-resilient technologies currently available, as illustrated in Table 4.

In recent years, Chile has improved the understanding of climate change impacts in the country. As indicated before, Chile is highly vulnerable to climate change, and the changes that will take place may directly and indirectly influence the country's productive activities, environment, and biodiversity. Adaptation is therefore a must and has become a central part of climate change policy in Chile. The Climate Change Strategy (2006) and the National Action Plan on Climate Change (2008–2012) defined adaptation as one of the three pillars of climate change policy, together with mitigation and capacity building. The National Action Plan established priority sectors for adaptation, guidelines and specific actions, responsible institutions, and deadlines for compliance. The specific actions aimed at generating knowledge about future climate scenarios, vulnerability, and expected impacts on different sectors, as well as adaptation options. In 2006, the first set of climate scenarios, with a 100-year time horizon, was developed. Then, in 2009, more immediate climate scenarios (with horizons of 30 and 60 years) were developed. In 2012, additional studies were undertaken that considered the new scenarios developed by IPCC, called Representative Concentration Pathways. The latest results are consistent with the scenarios modeled in 2006.

The instrument used to articulate nationwide, long-term adaptation efforts in Chile is called the National Adaptation Plan. This plan will provide a general framework and guidelines for adaptation in Chile and will coordinate the adaptation plans for nine sectors: agriculture and forestry, biodiversity, fisheries and aquaculture, health, infrastructure, cities, tourism, water resources, and the energy sector.

Regarding the energy sector, as indicated previously, Chile is highly dependent on the availability of water resources. Currently, the adaptation plan for the energy sector is at an early stage of development. Other than the studies estimating changes in the hydrological cycles of some basins reported above, little work has been done in identifying options for adaptation. As mentioned earlier, the development of a dam infrastructure could become an effective adaptation strategy in the face of water scarcity. This infrastructure could also operate in synergy with a national mitigation strategy that improves hydroelectricity generation. Further, the development of a nationwide transmission network and interconnections with other countries with more abundant renewable resources would allow energy exchange among the continent's different regions.

Increases in energy consumption will lead to an increase in the production of GHGs. The sector therefore requires comprehensive measures that harmonize with mitigation strategies and at the same time help adapt Chile to the effects of climate change.

Conclusions

Climate change may result in a significant reduction of hydroelectric resources, worrying countries that are heavily dependent on it like many in Central and South America, where most electricity demand is met through hydropower generation. The impact in Chile was described, but Chile can serve as an example for the entire region, where climate change and GHG emissions have become a public concern.

Preliminary analyses of the evolution of GHG emissions in the region show the great impact of electricity generation. The need for more accurate analysis and models for various countries in the region is clear. Specifically, mitigation and adaptation strategies should be carefully designed, exploiting potential synergies. Future development of the hydroelectric infrastructure should be analyzed, along with other water usage patterns in the areas of irrigation, drinking water, and industrial processes. The cooptimization of water and energy is therefore envisioned as a path to follow. This must also be considered in the energy market design and its revisions.

For Further Reading

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