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LONG-TERM ENERGY PROSPECTIVE FOR SOUTH AMERICA – APPLICATION TO CLIMATE NEGOTIATIONS

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Long-Term energy prospective for South America – Application to climate negotiations

Central and South America and the Caribbean stand out in the global energy landscape for the outstanding contribution of renewable sources to energy production. Maintaining this level of renewable energy in the future might prove a challenging task, as 'historical' energy sources (hydropower, biomass) run into sustainability issues and 'new' options (wind, solar, geothermal) still depend on public support. However, South America's small fossil endowment and excellent renewable potential make it the ideal candidate for pioneering a renewable energy transition. The energy sector's contribution in fueling economic growth in a socially and environmentally sustainable way is also an issue that is particularly significant in the developing context of the continent. Climate change is also a region-scale concern: while the continent's emissions per capita are above the global average, the region is likely to be one of the most impacted by climate change. South America's energy sector is vulnerable both on the supply side (hydropower and biomass resources) and the demand side (increased demand for e.g. agriculture and air conditioning). Despite shared regional strengths and concerns, however, South America appears as a highly heterogeneous and fragmented continent: the region's layout is a stumbling block for regional integration; two centuries of regional wars complicate political cooperation at national level; and the historical evolution has created strong disparities between national energy sectors. Various attempts to cooperate on transnational infrastructure have ended up as costly failures.

The aim of this PhD work, half of which was conducted in France and half in Chile, was to develop a mathematical model adapted to the study of long-term energy issues, at a regional scale, for South America. This model, *TIMES-América Latina y el Caribe*, was applied to studying the impact of national climate policies on regional energy, as the world prepares for a new global climate agreement at the Paris conference in December 2015.

This document is divided in five chapters. Chapter 1 offers a historical overview of South America's history with a focus on energy, followed by a description of the specificities and challenges of South American energy today. Chapter 2 presents the concepts of prospective and scenario modeling, along with a historical overview and a state-of-the-art of energy prospective in South America. Chapter 3 details the model's main features: its ten-region disaggregation, its modeling rules and the main assumptions for supply and demand. Chapter 4 presents the climate change issue and its implications for South America; it also describes international climate negotiations, from their beginning to the current tentative contributions. Finally, chapter 5 analyses the impacts of these pledges on South America's energy sector, and the contribution of the latter to fulfilling these pledges, as a direct application of the model developed in this thesis.

América Central, América del Sur y el Caribe destacan en el escenario energético mundial por la contribución espectacular de las fuentes renovables en la matriz energética regional. Mantener tal participación en el futuro es un tremendo desafío, entre los problemas de sostenibilidad vinculados a las energías 'tradicionales' (hidroelectricidad, biomasa), y la falta de autonomía financiera, todavía, de las energías no-convencionales (eólica, solar, geotérmica). Sin embargo, la escasa disponibilidad de recursos fósiles en el continente, así como su excelente potencial renovable ponen América latina en una posición privilegiada para liderar una transición mundial hacia una matriz energética más renovable. La contribución del sector energético al desarrollo regional, sin comprometer el medio ambiente o la equidad social, también es un tema de estudio relevante para el futuro energético del continente. El cambio climático, a su vez, es un tema energético regional: Sudamérica emite más gases de efecto invernadero por habitante que el promedio mundial, y los impactos previstos del calentamiento global son más adversos en la región que en muchas otras partes del mundo. El sector energético sudamericano es vulnerable a estos impactos por ambos lados –demanda, y oferta. Pese a estas preocupaciones comunes, la situación de la América del Sur es la de un continente heterogéneo y fragmentado: la configuración física del continente es un obstáculo mayor para las infraestructuras de integración, las tensiones heredadas de la historia reciente no facilitan la cooperación política, y la conformación de los sectores económicos nacionales es muy diferente de un país sudamericano a otro. Muchas tentativas recientes hacia una cooperación infraestructural supra-nacional fracasaron con altos costos.

El propósito de este doctorado, desarrollado por la mitad en Francia y la mitad en Chile, fue desarrollar un modelo matemático enfocado en el estudio de las dinámicas energéticas de largo plazo en América latina, con un enfoque regional. El modelo *TIMES-América latina y el Caribe* se aplicó luego para estudiar el impacto de los compromisos climáticos nacionales en el sistema energético regional, semanas antes de la cumbre mundial del clima en París (COP21).

Este documento se divide en cinco capítulos. Capítulo 1 presenta la evolución histórica sudamericana, enfocada en su parte energética; luego, se presentan algunos puntos salientes de los sistemas energéticos sudamericanos de hoy. El capítulo 2 presenta los conceptos de prospectiva energética, así como las experiencias prospectivas pasadas de América del Sur, y un estado del arte de los ejercicios prospectivos y modelos vigentes hoy. El capítulo 3 detalla los elementos principales del modelo: su desagregación en 10 regiones, las reglas de modelación, y las hipótesis principales para la demanda y oferta. El capítulo 4 presenta el tema del cambio climático, así como un estado del arte de las negociaciones internacionales respecto al clima. También se agrega una reseña de las contribuciones nacionales propuestas con vista al acuerdo buscado en COP21. El capítulo 5 analiza el impacto de estos compromisos para el sector energético sudamericano, y el papel de este sector en el cumplimiento de estos compromisos, como una aplicación directa del modelo desarrollado en este trabajo de tesis.

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Acronyms

$_{2000}$	US dollar, expressed in 2000 current value
AFOLU	Agriculture, Forestry and Other Land-Use
ALADI	*Asociación Latinoamericana de Integración* – Latin American Integration Association
ALBA	*Alianza Boliviana para los Pueblos de nuestra América* – Boliviarian Alliance for the People of our America
AMPL	A Mathematical Programming Language
AND	Andean States
ANP	*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* – National agency for Oil, Natural Gas and Biofuels
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
ARG	Argentina
ARPEL	*Asociación Regional de Empresas del Sector Petróleo, Gas y Biocombustibles en Latinoamérica y el Caribe* – Regional Association for oil gas and biofuel companies in Latin America and the Caribbean
ATEsT	Analysing Transition Planning and Systemic Energy Planning Tools for the implementation of the Energy Technology Information System
BAU	Business-As-Usual
BCO	Brown Coal
BKB	*Braunkohlenbriketts* – Brown Coal Briquettes
BNDES	*Banco Nacional de Desenvolvimento* – National Development Bank
boe	Barrel of Oil Equivalent
BPU	Bolivia, Paraguay, Uruguay
BSE	Brazil – South and East
BTU	British Thermal Unit - 1 BTU = 1,055 J
BWC	Brazil – West and Center
CAF	*Corporación Andina de Fomento* – Andean Development Corporation
CAREM	*Central Argentina de Elementos Modulares* – Argentine Plant of Modular Elements
CATE	*Compañia Alemana Transatlantica de Electricidad* – German Transatlantic Electricity Company
CBDR	Common But Differentiated Responsibility

CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CEPAL	*Comisión Económica para América Latina y el Caribe* – see UN-ECLAC
CEPE	*Compañia Estatal Petrolera Ecuatoriana* – National Oil Company of Ecuador
Ceplan	*Centro Nacional de Planeamiento Estratégico* – National Division for Strategic Planning
CHL	Chile
CHP	Combined Heat and Power generation
CIER	*Comisión de Integración Energética Regional* – Regional Energy Integration Committee
CMIP5	Coupled Model Intercomparison Project 5
CNRS	*Centre National de Recherche Scientifique* – National Center for Scientific Research
COL	Colombia
Colciencias	*Fondo Colombiano de Investigaciones Científicas y Proyectos Especiales* – Colombian Fund for Scientific Investigation and Special Projects
COM	Commercial
Cond_Nat	Conditional INDCs, based on national BAUs
Cond_TALyC	Conditional INDCs, based on T-ALyC's BAU
COP	Conference of the Parties (to the UNFCCC)
COPPE	*Instituto Alberto Luis Coimbra de Pós-Graduação e Pesquisa de Engenharia* – Alberto Luis Coimbra's Institute for engineering investigations and post-graduate formation
Corfo	*Corporación Nacional de Fomento* – National Development Agency
CSA	Central and South America
CSP	Concentrated Solar Power
CYC	Central America and the Caribbean
DNP	*Departamento Nacional de Planeación* – National Planning Department
DSE	*Dirección Sectorial de Energía* – Sectorial Direction for Energy
ECLAC	See UN-ECLAC
ECOPETROL	*Empresa Colombiana de Petróleos S.A.* – Colombian Oil Company S.A.
EGR	Enhanced Gas Recovery
EJ	ExaJoule (10^{18} Joule)

ELC	Electricity
ENAP	*Empresa Nacional de Petróleos* – National Oil Company
ENSO	El Niño - Southern Oscillation
EOR	Enhanced Oil Recovery
EPE	*Empresa de Pesquisa Energética* – Energy Investigations Company
ESMAP	Energy Sector Management Assistance Program of the World Bank
ETSAP	Energy Technology Systems Analysis Program
EU-27	European Union in its 27-member form (2007-2013)
FAO	Food and Agriculture Organization
FARC	*Fuerzas Armadas Revolucionarias de Colombia* – Colombia's Revolutionary Armed Forces
FB	*Fundación Bariloche* – The Bariloche Foundation
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Giga-Joule
$GtCO_2eq$	Giga-ton (10^9) of CO_2 equivalent
Gtoe	Gigatonne of oil equivalent
GW	Giga-Watt (10^9 Watt)
GWP	Global Warming Potential
HCO	Hard Coal
Hydro	Hydropower
IAEA	International Atomic Energy Agency
IBGE	Instituto Brasileiro de Geografia e Estatística
ICE	*Instituto Costarricense de Electricidad* – Costa Rican Institute for Energy
IEA	International Energy Agency
IER	*Institut für Energiewirtschaft und Rationelle Energieanwendung* – Institute for Energy Economics and the Rational Use of Energy
IIASA	International Institute for Applied Systems Analysis
IIRSA	*Iniciativa para la Integración de la Infraestructura Suramericana* – Initiative for the Integration of the Regional Infrastructure of South America
IMF	International Monetary Fund
IND	Industry sector

INDC	Intended Nationally Determined Contribution
Inesad	*Instituto de Estudios Avanzados del Desarrollo* – Institute for Advanced Development Studies
INP	*Instituto Nacional de Planificación* – National Planning Institute
IPCC	Intergovernmental Panel on Climate Change
kW	kiloWatt
kWh	kiloWatt-hour
LCOE	Levelized Cost Of Electricity
LEAP	Long-Range Energy Alternatives Planning
LNG	Liquefied Natural Gas
LULUCF	Land-Use, Land Use Change and Forestry
MAED	Module for the Analysis of Energy Demand
MAPS	Mitigation Action Plans and Scenarios
MarkAl	Market Allocation model
MERCOSUR	*Mercado Común del Sur* – Southern Common Market
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MHE	*Ministerio de Hidrocarburos e Energía* – Ministry of Hydrocarbons and Energy
MMBTU	Million British Thermal Units
MME	Ministerio de Minas e Energia
MPD	*Ministerio de Planificación del Desarrollo* – Ministry for Development Planning
MPPEE	*Ministerio del Poder Popular de Energía Eléctrica* – Ministry of People's Power for Electric Energy
MSW	Municipal Solid Waste
$MtCO_2eq$	Million tonnes of CO_2 equivalent
Mtoe	Megaton (10^6 tonne) of oil equivalent
MW	MegaWatt
MWh	MegaWatt-hour
NAE	*Núcleo de Assuntos Estratégicos* – Department of Strategic Affairs
NAMA	Nationally Adapted Mitigation Action
NREL	National Renewable Energy Laboratory
NRJ	Energy
O&M	Operation and Maintenance

Odeplan	*Oficina de Planificación* – Planning Bureau
OECD	Organization for the Economic Co-operation and Development
OLADE	*Organización Latinoamericana de Energía* – Latin American Energy Organization
OPEC	Organization of the Petroleum Exporting Countries
PDVSA	*Petróleos de Venezuela S.A.* – Venezuelan Oil S.A.
PEMEX	*Petróleos de México S.A.* – Mexican Petroleum S.A.
PJ	Peta-Joule
PND	*Plano Nacional de Desenvolvimiento* – National Development Plan
PPA	*Plano Pluri-Anual* – Pluri Anual Plan
PSR	Power Systems Research
PUC	*Pontífica Universidad Católica de Chile* – Pontifical Catholic University of Chile
PV	Photovoltaic solar panel
RCP	Representative Concentration Pathways
REDD	Reducing Emissions from Deforestation and forest Degradation in Developing countries
RES	Reference Energy System
RNW	Renewable energy
RSD	Residential
SEI	Stockholm Environment Institute
SEU	Specific Electricity Uses
SRES	Special Report on Emissions Scenarios
SUG	Suriname, Guyana, French Guyana
T&D	Transport and Distribution
T-ALyC	*TIMES-América Latina y el Caribe* – TIMES for South America and the Caribbean
tCO_2eq	Ton of CO_2 equivalent
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated Markal-EFOM System
toe	Ton of Oil Equivalent
TPES	Total Primary Energy Supply
TRA	Transport
UFRJ	*Universidade Federal do Rio de Janeiro* – Rio de Janeiro's Federal University

UN	United Nations
UNASUR	*Unión de Naciones Suramericanas* – Union of South American Nations
UNDP	United Nations Development Program
UN-ECLAC	United Nations Economic Commission for Latin America and the Caribbean
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
Uni_Nat	Unilateral INDCs, based on national BAUs
UNIDO	United Nations Industrial Development Organization
UPME	*Unidad de Planeación Minero Energético* – Mining and Energy Planning Division
US	United States (of America)
US$	US Dollar
USAID	United States Agency for International Development
USDA	US Department of Agriculture
US-EIA	US Energy Information Administration
USSR	Union of Soviet Socialist Republics
VEN	Venezuela, Trinidad & Tobago
VMDE	*Viceministerio de Desarrollo Energético* – Viceministry for Energy Development
WTE	Waste-To-Energy
WWI	First World War
WWII	Second World War
YPF	*Yacimientos Petrolíferos Fiscales S.A.* – National Oilfields, S.A.
YPFB	*Yacimientos Petroleros Fiscales de Bolivia* – Bolivia's National Oil Fields

Que veut-on, et que faut-il vouloir?
– *Paul Valéry*

Introduction

Together, Central and South America and the Caribbean represent more than 450 million people and 18.5 million square kilometers of land area – twice the size of the United States and 12% of the Earth's total emerged land. The continent's final energy consumption in 2010 was 460 Mtoe, close to 40% of the final consumption of the EU-27 countries put together, and its greenhouse gas (GHG) emissions accounted for nearly 8% of global emissions in 2011 (World Resources Institute, 2015).

Figure 0-1: South American borders and capitals

The region stands out in the global energy landscape for the outstanding contribution of renewable sources to its energy production: 68% of the continent's electricity in 2012 was of renewable origin (CIER, 2013), against a world average of 20%; hydropower alone accounted for roughly 64% of South American electricity production. 30% of Brazil's liquid fuels are bio-sourced; sugarcane alone accounted for 17% of the country's total primary energy supply (TPES) in 2010. Maintaining this level of renewable energy in the future might prove a challenging task, as 'historical' energy sources (hydropower, biomass) run into sustainability issues and 'new' options (wind, solar, geothermal energy) still depend on public support schemes (feed-in tariffs, specific auctions, renewable portfolio standards, etc.). However, South America benefits from a small fossil resource endowment and excellent renewable potential for hydropower, biomass, solar, wind and geothermal energy, which make it the ideal candidate for pioneering a renewable energy transition.

Most South American countries are experiencing rapid growth that drives fundamental changes in many economic sectors, including energy. The continent has more than doubled its electricity production in the past 20 years. The electrification rate jumped from 75% in 2009 to around 90% in 2012 in Peru and Bolivia, following average economic growth of more than 4.5% per year from 2004-2012. Chile multiplied its GDP by nearly ten between 1985 and 2008; however, its GHG emissions increased threefold in the same period (O'Ryan et al., 2010), and the country is now facing serious concerns about its mid-term electricity supply due to soaring demand, heavy dependency on imported fossil fuels, and lack of investment in electricity generation during past decades. The energy sector's contribution in fueling economic growth in a socially and environmentally sustainable way is an issue that is particularly significant in the developing context of the entire continent.

Climate change is also a relevant region-scale concern. The continent's emissions per capita are above the global average, and the region is also likely to be one of the most impacted by climate change, with a 1.5% to 5% permanent GDP loss by 2050 (ECLAC, 2014). South America's highly renewable energy mix is vulnerable to climate change both on the supply side (hydropower and biomass resources) and the demand side (increased demand for e.g. agriculture and air conditioning). Adaptation is of utmost importance, since envisioned mitigation policies can fall short of expectations or put the system under strong pressure, to the point that in some regions the cost of damage is estimated to be less than that of mitigation measures.

Despite shared regional strengths and concerns, however, South America appears as a highly heterogeneous and fragmented continent. The region's physical layout is a first stumbling block for regional integration: the Andes Mountains, the Amazon Rainforest, and desert areas such as Paraguay's Chaco, Northeast Brazil or Argentina's Southern Patagonia render most of the inlands inhospitable, driving human settlements to the coast. Two centuries of regional wars make political cooperation at national level difficult today. The region's historical evolution has also created strong disparities between national energy sectors, from Venezuela's state-owned monopolies to Chile's minimalist state interventions in the nation's economy. Various attempts to cooperate on transnational infrastructure, like Anillo Energético, the Great Southern Gas Pipe and

Chile-Argentina gas supply agreements have ended up as costly failures in past years. As of today, more than ten transnational integration initiatives are taking place in the region, with attributions and geographical scopes that intersect more than once.

Dealing with South American energy challenges at regional scale is thus both interesting and challenging. Some projects such as MAPS (*Mitigation Action Plans and Scenarios*) (Winkler et al., 2014) or the Climate Change Economics project (ECLAC, 2014) look at energy planning from a national perspective, but in a coordinated way. Such projects acknowledge the need for a regional perspective to tackle region-wide issues, yet they do not go so far as a unified representation of the Latin American region. Other authors, such as Acquatella (2008), consider the energy sector of the whole of Latin America, but lack the backing of a dedicated modeling tool. The CLIMACAP-LAMP project (see e.g. van Ruijven et al., 2015) proposes a coordinated evaluation of climate and energy issues for South America, through a multi-model comparison exercise involving models with different paradigms, time spans, geographical precision, or underlying assumptions. This exercise is highly interesting as it spans the existing range of assumptions and projections for South America, yet it is based on either national or global models, none of which have been specifically designed for regional studies. As a consequence, Latin America as a region remains either partially or coarsely represented.

The aim of this PhD work, half of which was conducted in France and half in Chile, was to develop a mathematical model adapted to the study of long-term energy issues, at a regional scale, for South America. This model was then applied to studying the impact of national climate policies on regional energy mixes, as the world prepares for a new global climate agreement at the Paris climate conference in December 2015.

A Document structure

This document is divided in five chapters. The first two chapters present the contextual elements necessary to a prospective modeling of South American energy. The third chapter presents the *TIMES-América Latina y el Caribe* (T-ALyC) model developed in this work; the last two chapters present a prospective application of this model to the study of regional climate commitments.

Chapter 1 offers a historical overview of South America's history since colonization, with a focus on the energy sector. It is difficult to understand the specificities of South American energy without these generic background elements; however, I discovered at my own expense that our knowledge of South America, here in Europe, is rather limited. These twenty or so introductory pages thus try to give some insights into half a millennium of history of a full continent. I then turn to the current specificities and challenges of South America's energy sector.

Chapter 2 presents the base concepts of prospective and scenario modeling, along with a short guide to prospective model classification. Then, building on this introduction and the historical elements presented in chapter 1, I present a historical overview of South American energy prospective, finishing with a state-of-the-art of the institutions, models and recent exercises for energy prospective in South America.

Chapter 3 details T-ALyC's main features. I present first a disaggregation of South America into ten regions, based on physical, political, economy and social criteria. The generic construction rules of T-ALyC, known as the TIMES paradigm, are then presented, along with the TIAM global model, from which T-ALyC is derived. I finally detail the structure and main assumptions for T-ALyC's supply and demand, including macroeconomic drivers, resource potentials, and extraction costs.

Chapter 4 presents the climate change issue and its implications for South America. The first half of this chapter is dedicated to presenting the potential impacts of climate change at global scale, and their implications for South America, relying heavily on the extensive literature review conducted by the Intergovernmental Panel on Climate Change (IPCC). The second half of this chapter describes the international climate negotiations, from their beginning in 1972 to the current tentative contributions prepared in view of the Paris conference, with a special focus on South America's contributions.

Finally, chapter 5 proposes an analysis of the impact of these pledges on South America's energy sector, and the contribution of the latter to fulfilling these pledges. This analysis is a direct application of the T-ALyC model described in Chapter 3. Given the weight of Agriculture, Forestry and Other Land Use (AFOLU) in South America's greenhouse gas emissions, a special emphasis is put on describing non-energy emissions and mitigation options in T-ALyC.

B Contributions

Two scientific papers were submitted to peer-reviewed publications:

- *TIMES-ALyC: A model for long-term energy prospective in South America* – Sébastien Postic, Sandrine Selosse, Nadia Maïzi – **Applied Energy**
- *Energy sector contribution to regional climate action: the case of Latin America* – Sébastien Postic, Sandrine Selosse, Nadia Maïzi – **Energy Policy**

The work described here was presented in various scientific conferences:

- *Energy trends in Latin America: a regional disaggregation meeting the requirements of the TIMES prospective approach* – Sébastien Postic, Sandrine Selosse, Edi Assoumou, Nadia Maïzi – **4th Meeting of Latin-American Energy Economics** – Montevideo – 8-9 April, 2013
- *Energy resources and sustainable response to climate constraint in Latin America: A long-term analysis with TIAM-FR* – Sandrine Selosse, Sébastien Postic, Nadia Maïzi Maïzi – **4th Meeting of Latin-American Energy Economics** – Montevideo – 8-9 April, 2013
- *Combating Climate Change in Latin America: the energy prospect* – Sebastien Postic, Sandrine Selosse, Nadia Maïzi – **UN Climate Change Conference 2014, COP20|CMP10** – Lima – 3 December, 2014
- *Considérations énergétiques regionals pour l'Amérique du Sud – Ressources et engagements climatiques* – Sébastien Postic, Sandrine Selosse, Nadia Maïzi **– Journée de la Chaire Modélisation Prospective au Service du Développement Durable** – Paris – 2 March, 2015
- *Energy sector contribution to climate action – The case of Latin America* – Sébastien Postic, Sandrine Selosse, Nadia Maïzi – **Semi-annual ETSAP Meeting**– Sophia-Antipolis, France – 22 October, 2015

One working paper was produced to synthetize the technical modeling work on T-ALyC:

- *TIMES Prospective Modeling for South America, and applications* – Sébastien Postic, Sandrine Selosse, Nadia Maïzi – **Working Paper n° 2015-01-15 of the Chair Modeling for Sustainable Development** – 15 January, 2015

Parallel to the development of T-ALyC, the role of active building control in European energy efficiency policies was investigated using the Pan-European TIMES model, and presented in a scientific conference:

- *Long-term assessment of energy efficiency solutions: Application to Active Control in the residential sector* – Sébastien Postic, Sandrine Selosse, Edi Assoumou, Vincent Mazauric, Nadia Maïzi **– Semi-annual ETSAP meeting** – Paris – 18 June, 2013

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Chapter 1: South American energy – Historical perspective and current challenges

América Latina, la región de las venas abiertas.
–Eduardo Galeano

South American energy issues cannot be understood without placing them in their historical, social, economic and political context: that of a highly contrasted continent, home to Fidel Castro and Augusto Pinochet, to Salvador Allende and Carlos Menem. From colonization to the Cold War, from commodity lotteries to debt crises, for South America the last half millennium has featured abrupt changes and violent crises, strongly influenced by external dynamics. Despite the common culture imposed by colonists, the continent's independence wars, post-independence conflicts and successive crises have created a highly fragmented region in which sub-regional relationships remain precarious. South American energy today bears both the common features and strong divergences of this tormented regional history. This preamble chapter presents a portrait of these past evolutions, as well as the present and future challenges awaiting South America's energy sector. Although limited, this background is fundamental to understanding the main determinants of South America's energy sector, as a prelude to any investigation about the sector's future.

A 1500-1825: Rise and fall of colonial empires

In 1492, Christopher Colombus set sail from Palos de la Frontera with the mission to discover the western sea route to the East Indies. After a 2-month trip, he set foot on what would come to be known as the Bahamas, thus starting the first lasting contact between Europe and America.

This contact did not really benefit South America's natives; the region, home to ancient civilizations, was conquered through violent wars in which most of its population was killed or died from European illnesses. The last Inca stronghold was conquered in 1572, extending the Viceroyalty of Peru to its maximum scope. The conquest of Mexico ended in 1697; the Viceroyalty of New Granada was definitively established in 1739 in what would become Colombia, Ecuador, Panama and part of Venezuela. In 1775, the State of Brazil was born from the union of the three colonies of Portuguese America. When the Viceroyalty of Río de la Plata was established in 1776 in what is now Argentina, Portugal and Spain had conquered a 20 million km² territory, killing roughly 40 million of indigenous American–80% of the native Latin Americans– in the process.

Following the French Revolution and the United States of America's independence, Latin American colonies profited from the Napoleonic wars that undermined their colons' influence, and claimed their independence. Military leaders such as Bolívar, San Martin, Sucre and O'Higgins fought violent independence wars to decolonize Argentina, Bolivia, Chile, Colombia, Peru and Venezuela. The Prince Regent Dom Pedro declared Brazil's independence in September 1822, becoming Pedro I, Constitutional Emperor of Brazil. By September 1823, the last Portuguese garrison had surrendered and Brazil's independence was formally recognized by Portugal in 1825, making the whole of South America independent.

B 1825-1870: The independence aftermath

The initial dream of Bolívar and San Martin to found new a United States of South America was quickly lost, as regional rivalries drove South American countries ever further apart. In spite of a very strong common administrative and cultural base and a shared language, the continent soon headed towards political fragmentation under the rule of the former colonial elite. Its pathway towards national states' emergence was marked by devastating wars whose lasting consequences are still embedded in regional relationships today. The Triple Alliance War (1864-1870), opposing Paraguay to Brazil, Argentina and Uruguay, killed over 70% of Paraguay's male population; in the War of the Pacific (1879-1883), lost to Chile by Bolivia and Peru, Peru ceded 66,000 km² to Chile, including 400km of littoral and saltpeter-rich territories, while Bolivia lost its Littoral Department, becoming a land-locked country in a treaty which is still challenged today. Brazil and Argentina engaged in the Cisplatine war during the first year of Brazil's independence, giving birth to Uruguay as an independent state in 1828. The consolidation of post-colonial institutions also took significant time and effort: towards the mid-19th century, only 2% of Latin Americans had voting rights[1], while Brazil, the last South American country to abolish slavery, outlawed it in 1888[2]. Together with internal and international struggles and the effort of consolidating post-colonial institutions, Latin American development was hindered by strong geographical barriers to physical integration; the region thus experienced decades of weak growth in the early 19th century (Halperín Donghi, 1969).

C 1870-1930: The golden era

From 1870 on, South America's dynamics evolved strongly in what has been called the 'first globalization'. Thanks to steam navigation and rail transportation, the region's sluggish economic development picked up speed, sustained by exports of mining products (silver, gold, tin, copper, nitrates, oil) and agricultural goods (corn, meat, fruit, sugar, coffee, cocoa beans, quinine, rubber, cotton) and sustained immigration from Europe and Asia. Argentina, for a while, became one of the wealthiest countries on Earth, with a per capita GDP reaching 70% of that of the US and salaries at the same level as French or German ones. However, apart from the Argentine[3] exception, this regional economic boom mainly benefitted a small and wealthy elite. Power and influence had shifted from colonial metropolises to local former colonial elites, land owners and foreign capital, in what has been called the 'new colonial pact', or the 'second conquest of Latin America' (Topik and Wells, 2010). While at first Great Britain headed this second conquest, the USA made themselves ever more present, becoming the first foreign power after WWI. Wealth was localized in space and time, based on primary commodities with little added value and heavy dependence on international prices. Such commodity dependence brought quick expansions and equally quick collapses in what came to be known as the 'commodity lottery' period (Diaz-Alejandro, 1982), while labor conditions under the rule of foreign investors often came close to slavery[4].

[1] (Dye, 2006; quoted by Bértola and Ocampo, 2010).
[2] Through the so-called Golden Law, or *Ley Áurea* (Galloway, 1971).
[3] And the Uruguayan one, as Uruguay's fate remained close to its former sister colony for a while.
[4] cf. the famous book by Literature Nobel Gabriel García Márquez (1967) on the rise and fall of the banana business in Colombia, or the very good portrait by Rivera Letelier (2002) of the repression of the Chilean saltpeter miners' strike in 1907.

Energy: early ages

After having kept a low profile during colonial times, energy emerged as a strategic issue in post-1870 South America. Oil was discovered first in Mexico (1868), then in Argentina (1907), Ecuador (1911), Bolivia (1913), Venezuela (1914), opening an era of quick industrialization: Argentina's national oil company YPF (*Yacimientos Petrolíferos Fiscales*, National Oil Fields) was created in 1922, Ecuador published its first hydrocarbon law in 1921, and by 1928 Venezuela had become the world's first oil exporter and second-largest producer behind the US (arguably, third-largest behind Russia)[5]. Oil, together with copper and tin, jumped from 4% of South American exports in 1913 to 14% in 1929[6]. Oil interests in Mexico in 1914 were already leading the US and Great Britain to meddle with the country's politics, bringing down Madero's government and Huerta's subsequent dictatorship (Meyer, 1988). Electricity was the new wonder of the moment: in 1883, Dom Pedro II, second Emperor of Brazil, inaugurated the first public electric lighting system in South America in the state of Rio de Janeiro. In Argentina, La Plata was the first city to get public lighting installed, and also saw the first electricity plant in the country, in 1886. The first Argentine hydroelectric plant, with a capacity of 1,000 kW, was built in 1891 near the city of Córdoba. In 1908, a six-generator hydropower plant was inaugurated in Brazil's Rio de Janeiro state, totaling a capacity of 24,000 kW; in 1910, the CATE electricity company inaugurated the Dock Sud Coal Plant in Buenos Aires, one of the most powerful in the world with 36,000 kW installed capacity. In 1930, 40 years after the first plant was installed, São Paulo state in Brazil counted 166 power plants alone, totaling more than 330 MW installed capacity (Ghía, 2012; Hesla, 2011; Paulo Pombeiro Gomes and Vieira, 2009). Electricity was initially used for public lighting, telegraphs, tramways and specific productive uses such as textile mills. Coal consumption grew steadily with the development of electricity and rail transportation; Argentina and Mexico displaced Cuba as the third coal consumer on the continent, behind Chile and Brazil (Yáñez et al., 2013). Coal exports, on the other hand, remained very low, as Colombia (today's main coal exporter) had not yet discovered its national reserves.

D 1930-1980: Shocks and recoveries

In 1929, this economic boom came to an abrupt end. The 1929 economic crisis, which brought the world's economy to its knees, marked the start of a troubled period for the world in general and Latin America in particular. The region was little involved in WWII; however its export-based, debt-fueled economy had been heavily dependent on outside lenders and buyers since the first commodity lottery episodes, prone to sharp economic booms and crises. In the two decades following 1929, it was severely impacted by the drop in export incomes and war-owed import shortages. Foreign capital flows dwindled, Western economies set up protectionist measures, the US stopped buying, and the weight of debt service grew unbearable. The paradigmatic change from commodity-based export economy to state-controlled industrialization by import substitution took place on a continent where political, economic and social instability became the rule. Between 1930 and 1980, Argentina saw 9 successful coups and 15 military governments. Brazil "only"

[5] (Cote, 2011; Gadano, 2006; Painter, 2012; PetroEcuador, 2013; Salas, 2009).

[6] (Bairoch and Etemad, 1985; quoted by Bértola and Ocampo, 2010).

experienced 2 coups, yet 30 years of civilian and military dictatorship did not prevent the country from undergoing deep restructuration and rampant inflation (Baer, 2008). Uruguay, Bolivia, Paraguay, Chile and Peru were also subject to military coups and dictatorships. The *La Violencia* civil war in Colombia between 1946 and 1953 resulted in 200,000 to 300,000 casualties, displaced 2 million people and made armed violence a feature of the country's political background for decades. The Cuban Revolution and the subsequent rise of Fidel Castro are a textbook case of Cold War history. On the other hand, the post-WWII period was the most prosperous so far for Latin America, whose production system remained intact after WWII. The continent benefited strongly from the Bretton Woods agreements and the second wave of globalization, registering its highest growth rates ever for both growth and productivity between 1945 and 1980. This growth was, however, quite unequal: while Brazil and Mexico over-performed, the more advanced economies of Argentina, Chile and Uruguay, which had fared well from 1870 to 1930, experienced severe regressions. Argentina's per capita GDP plummeted from 70% to 45% relative to the US (Bértola and Ocampo, 2010).

Energy: Strategic assets and power struggles

Regional wars for the control of mining resources added to the general instability. In 1932, Colombia and Peru clashed over the control of rubber-rich Amazonian territories. In the same year, Bolivia and Paraguay started the most destructive South American war in the 20th century, the Chaco war, which caused 90,000 death in 3 years and ended with Bolivia abandoning its territorial claims on three quarters of the Chaco desert – a zone nearly as big as France. Key to the war decision was the assumption that the Chaco's underground was filled with oil (Seiferheld, 1983); and peace was agreed when the Paraguayan army's progression began to threaten the oil-rich Santa Cruz region (Guachalla, 1978). Energy had invited itself into the foreground of political preoccupations in South America. In 1936, as a direct consequence of the war, Bolivia nationalized the Standard Oil's branch in the country and created its own national company, YPFB (*Yacimientos Petroleros Fiscales de Bolivia*, National Oil Fields of Bolivia) (Molina, 2011). In 1938, following in Bolivia's footsteps, Mexico expropriated all foreign oil companies operating in the country and created its own national company, PEMEX (Meyer, 1988). Energy gained consideration under the rule of military dictatorships, which came to consider it explicitly as a 'strategic sector'. This triggered the creation of state-controlled companies such as ECOPETROL in Colombia (1951), ENAP in Chile (1951), *PetroBras* in Brazil (1953), *PetroPerú* in Peru (1968) or the CEPE in Ecuador (1971). Venezuela, still the second producer in the world in 1940, prompted the creation of OPEC in 1960 together with Saudi Arabia. In 1975, in the wake of the first oil crisis, the country nationalized its oil sector and created the national oil company PDVSA, while Brazil launched its emblematic bioethanol program *Proalcool* (Moreira and Goldemberg, 1999). The power sector also went through a wave of nationalizations. Beyond the strategic aspects of electricity supply, nationalizing was seen as a necessary step to finance large, capital-intensive hydropower works. Argentina started nationalizing its power sector in 1945 and the state company *Agua y Energía* bought out the last private concession in 1979 (Ghía, 2012). The Argentine *El Chocón-Cerros Colorados* complex, totaling nearly 2 GW of installed capacity, was inaugurated in 1973. Brazil connected the giant *Paulo Alfonso* complex (4.1 GW on the São Francisco river) to its national network in 1955 (Moretto et al., 2012). In 1961, after 10 years of political struggle, it nationalized its power sector, giving birth to the national giant Eletrobras. Brazil, Argentina and Mexico started nuclear programs in the 1950s, which culminated with the inauguration of the Atucha I nuclear plant in Argentina in 1974. The works started in 1971 for Brazil's Angra I plant and in 1976 for Mexico's Laguna Verde plant. The key bi-national collaborations for the giant dams of Yacyretá (Argentina-Paraguay) and Itaipu (Brazil-Paraguay) were launched in 1973.

E 1980-2010: Stabilization without cooperation

The 1970s may have been South America's best decade from an economic viewpoint; yet, the 1980s was most probably the worst, confirming the cyclic nature of the region's economy. In 1979, the US Federal Reserve increased its interest rates, while primary commodity prices started plummeting, losing up to 40% of their historic value during two decades. South America's economy still depended heavily on exports and had been the focal point of more than half of the private debt that had been flowing towards the developing world since 1973 (Ocampo et al., 2003); the shock was tremendous, prompting what has been labeled the 'debt crisis', or 'lost decade' (United Nations, 1996). Argentina, Venezuela and Mexico experienced massive capital flights; inflation peaked at 2,477% in Brazil (Baer, 2008), and 5,000% in Argentina (Leiva Lavalle, 2010); per capita GDP went down by 8% in a decade; poverty, according to UN-ECLAC statistics, increased to 48%. State-planned industrialization had been the focus of growing criticism since 1960 due to its interventionist nature and inefficiency at tackling export dependence and inequality issues. In the Cold War context, this paradigm was overturned by US-supported military governments in the fight against socialism. The *Chicago Boys* intervention in Chile under Pinochet (Valdes, 2008) is the first and perhaps most emblematic case of neo-liberal market reforms[7]. North America's economic ideology was also promoted by the Bretton Woods organisms: the World Bank and the International Monetary Fund, whose help came at the price of structural reforms in the spirit of the neo-liberal 'Washington Consensus' (Williamson, 1990). On the other hand, these reforms were hindered by lasting political instability and social opposition in a polarized society: after one or two decades of 'state terrorism' (Wright, 2007), Argentina and Chile started a troubled transition to democracy in 1983 and 1990 respectively[8]. Colombia had to deal with the FARC rebellion resulting from *La Violencia* and Peru faced the *Sendero Luminoso* terrorist surge, while Central America sank into violent, endless rebellions.

Lifted by above average external loans and deep structural reforms, the Chilean economy was somewhat less impacted by the lost decade; its path diverged from Argentina's, and the country was the first to emerge from the debt crisis. The whole continent followed in the early 1990s, yet regional growth since then has been interrupted by two new crises in 1997-2003 and 2008-2009,

[7] Here, as in the rest of this manuscript, the 'neo-liberal' designation refers to the post-1980 acceptation of the word that emerged from the theories of F. Hayek and M. Friedmann, and more especially Friedmann's *Chicago School of Economics*. This word carries strong connotations today, yet its use hereafter is purely descriptive and does not imply any personal value judgment.

[8] For an in-depth portrait of state terrorism and the later return to democracy in Chile, readers may refer to Rivas (2007) and Cavallo (2012).

showing its lasting exposure to external dynamics. The debt crisis has had durable consequences on regional economies, as have the subsequent neo-liberal reforms, although their efficiency at buoying regional growth and reducing inequalities is widely challenged today. The economic opening of the continent was reinforced by its participation in interregional trade agreements such as the World Trade Organization (1994), despite the failure of the Free Trade Area of the Americas initiative. Trade with China and East Asia, mostly involving mining and energy resources, has become a major source of income, which strongly benefits Venezuela (oil) and Chile (copper), followed by Peru, Bolivia, Ecuador and Colombia. The past 30 years have seen the emergence of so-called 'multilatinas' or 'translatinas' which are Latin American champions with global outreach, mainly based in Brazil, Mexico and Chile (Olaya et al., 2012). Regional cooperation also increased strongly with the creation of MERCOSUR in 1991 and the evolution of the Andean Pact into the Andean Community in 1996. The emergence of UNASUR in 2008 may take this integration to the next level, from bi-national or local economic collaboration to continent-sized political integration; however, the pace of political convergence is still very slow.

Energy: regional convergence versus national rivalries

The energy sector was unequally impacted by the vast privatization and opening movement that accompanied Latin America's market reforms. Oil remained untouched in a number of countries, starting with Mexico, where the public nature of oil-related activities was actually written into the Constitution. Petrobras in Brazil, PdVSA in Venezuela and even ENAP in Chile, the continent's neo-liberal champion, remained under government control. Ecuador extended its control over private companies operating in the country, transforming the CEPE into EP PetroEcuador in 1989. Argentina sold YPF to Repsol in 1992, only to re-nationalize it in 2012. The privatization of YPFB in Bolivia in 1996 provoked massive demonstrations throughout the country and the renunciation of two successive presidents (Roux, 2006). The company was re-nationalized in 2006 in amid strong commercial and political tensions with Argentina and Brazil. As an indicator of the magnitude of this re-nationalization process, foreign direct investment in Latin America's oil sector fell from USD 995 million per year to USD 616 million per year between 1983 and 1989 (Fontaine, 2003). This nationalization trend, which goes against the privatization tide, shows unequivocally that hydrocarbons still remain an internal and external political tool in South America, where two countries (Venezuela and Ecuador) are members of OPEC. Brazil's political and economic hold on the continent is offset, in the energy sector, by Venezuela's tremendous oil reserves and its radically different political ideology.

Brazil's efforts to build regional convergence through infrastructure project finance culminated in 2000 with the Brasilia Declaration and the creation of IIRSA (Initiative for the Integration of Regional Infrastructure in South America); yet they were thwarted from 2004 by Venezuelan-led opposition to liberalism and free trade, backed by a surge of left-wing governments on the continent. Venezuela drew on its oil bounty to push forward its own integration initiative: the ALBA, or *Alianza Bolivariana para los pueblos de nuestra América* (Bolivarian Alliance for the People of our America). The Venezuelan framework aims at state companies' collaboration rather than an integration supervised by regional development banks. The flagship project of this initiative was the Great Pipeline of the South, proposed by Presidents Chávez (Venezuela) and Kirchner (Argentina) to connect Venezuela, Brazil, Uruguay and Argentina. Yet Venezuelan projects faced Brazilian opposition, both on ideological grounds and in a struggle to influence the energy future of the continent. The divergence between the two leaders became blatant at the first South American Energy Summit in Venezuela in 2007; and the discovery of large deep-sea oil fields in the Brazilian pre-salt that same year dealt a new blow to Chávez's hegemony aspirations by restoring Brazil's credibility in Venezuela's main strong area: the oil sector. The Great Southern Pipeline was abandoned. Energy integration came to a standstill, with Venezuela and Ecuador pushing for full integration under the aegis of regional, state-owned energy companies on one side, and Brazil and Chile calling for limited integration and significant national autonomy[9]. Regional cooperation in the electricity sector achieved some success with the completion of the Itaipu Dam, still the biggest in the world for energy production (first turbine in 1984, last one in 1992) and the Yacyretá Dam (2010); nevertheless, its progress has been deemed unsatisfactory by various instances and experts (Ruchansky, 2013), while bi-national generation projects and transnational transmission lines have lost ground to transport axes in UNASUR's integration agenda. Today, energy and transport amount respectively to 32% and 68% of all IIRSA investments (COSIPLAN, 2013).

The overall picture of South America today is thus one of a highly contrasted region, home to strong inequalities and diverging trends between South American countries, and within these countries themselves. Paradoxically, these differences are underpinned by some fundamental shared characteristics: the recent and founding colonization shock imposed two similar languages on the whole continent (Spanish and Portuguese), along with a strong common cultural basis. The historical evolution since then has been both highly autarkic and highly similar between South American countries, with shared bounty periods and economic crises, and comparable policy developments. While in theory political and economic regional convergence present various valuable benefits, in reality the region is torn between international influences from the US, Europe and Asia, to the point that only 20% of South America's trade is directed inwards. The energy sector, as we will see in the next section, is emblematic of these trends, both in terms of similar regional assets and country-scale individualistic behaviors.

Year	Agreement	Antecedent	Year	Agreement	Antecedent
1951	OCAS	-	1991	MERCOSUR	-
1960	CACM	-	1991	SICA	ODECA
1960	LAFTA	-	1994	ACS	-
1964	CECLA	-	1995	G3	-
1965	CARIFTA	-	1996	CAN	GRAN
1967	ECCM	-	2000	IRRSA	-
1969	GRAN	-	2001	PPP	-
1973	CARICOM	CARIFTA	2004	ALBA	-
1975	SELA	CECLA	2004	CASA	-
1980	LAIA	LAFTA	2008	UNASUR	-

[9] For further reading, see (Céspedes and Agostinis, 2014).

1981	OECS	ECCM		2001	CELAC	CASA

Table 1-1: An excerpt from South American cooperation agreements (Adapted from Dabène, 2012)

F Energy in South America: Specificities and challenges

Sustainability of renewable energy

South America stands out in the global energy landscape for the outstanding contribution of renewable sources to its energy production: 68% of the continent's electricity in 2012 was of renewable origin (CIER, 2013), against a world average of 20%; hydropower alone accounted for roughly 64% of South American electricity production, even while 75% of the continent's hydro potential remains untapped today (IJHD, 2010). 30% of Brazil's liquid fuels are bio-sourced; used in ethanol production and bagasse burning, sugarcane alone accounted for 17% of the country's TPES in 2010. Brazil, Argentina and Paraguay were respectively the 2nd, 3rd and 6th soy producers in the world in 2012 with 84, 51 and 8 million tons produced (USDA, 2013). Soy provides 80% of Brazil's biodiesel, in a country where national regulations impose a minimum 5% share of biodiesel on all diesel vehicles: the production of this commodity reached 2.7 million m^3 in 2011, according to the country's 2012 energy balance (MME, 2012). This high contribution of renewable energy sources provides South America with one of the cleanest energy sectors in the world in terms of GHG emissions: as shown on Figure 2-1, only Africa's per capita emissions are lower than South America's[10]. South America is second only to Africa for its bio-energy potential by 2050 (Smeets et al., 2007); Brazil and Argentina's biofuel production has not yet reached its maximum level (Cremonez et al., 2015; Moreira et al., 2014). Solar irradiation in Chile is among the highest in the world (Escobar et al., 2014); official assessments estimate than over 2,500 GW of solar panels could be installed in the country (Minenergía and GIZ, 2014). Colombian winds are rated among the best in the world for energy production, with 18 GW installable capacity in the La Guajira region alone (Vergara et al., 2010).

However, scaling up renewable energies is a complex task. In Brazil, von Sperling (2012) estimates that new large dams would result in a loss of genetic patrimony, population relocations, land de-stabilization and a high amount of induced GHG emissions in flooded areas; as a consequence, Nogueira et al. (2014) consider that most of the country's economic potential for hydropower is not actually feasible. The extensive investigation of the Peru-Brazil bi-national Inambari hydro project by Serra Vega (2010) is more pessimistic still. According to this study, the consequences of this single project include relocating more than 8,000 people and deforesting 300,000 to 1,500,000 protected areas hosting a great variety of endemic species, ultimately to produce electricity that is more costly than at present. Small hydro catchments, although less detrimental to the environment, are significantly held back by inappropriate tariffs and unattractive borrowing terms from national development banks (Pereira et al., 2012). The social and environmental sustainability of biofuels is also a complex issue. According to Geraldes Castanheira et al. (2014), increasing Brazilian biodiesel production could trigger land-use and land-

[10] However, CAIT's data exclude fuelwood emissions, because of the lack of available statistics. This strongly downplays the per capita emissions of Asia, Africa and South America.

use change GHG emissions, biodiversity losses and water degradation. Sugar cane expansion, on the other hand, is limited by a lack of technological solutions to adapt to new environments (modified plants, mechanized harvesting, etc.). Solar PV is not yet an economically mature technology: its expansion requires specific tools such as separate national auctions, feed-in tariffs or preferential loans to offset high upfront investments. Brazil chose separate auctions in the mid-2000s; these policies work better for wind than solar so far and could cost up to USD$ 185 billion more than least-cost energy policies by 2040 (Lacchini and Rüther, 2015; Malagueta et al., 2013). In Argentina, Ecuador, Honduras and Nicaragua, national support policies rely more on feed-in tariffs, yet these tariffs remain ill-calibrated and have not triggered much market response so far (Jacobs et al., 2013). As a consequence of these various roadblocks, Pereira Jr. et al. (2013) consider that expanding Brazil's energy system without resorting to fossils would require up to 25% additional private investment. In Chile, this additional cost could be lower, yet would still be required: without any state incentive, Carvallo et al. (2014) consider that the country could generate nearly 47% of its energy from imported coal by 2030 and become a larger per capita polluter than most European countries. Taking a broader view, most of the Latin American projections compared in the recent CLIMACAP project foresee continued or increasing reliance on fossil fuels throughout the continent until 2050 if no specific policy is put in place (van Ruijven et al., 2015).

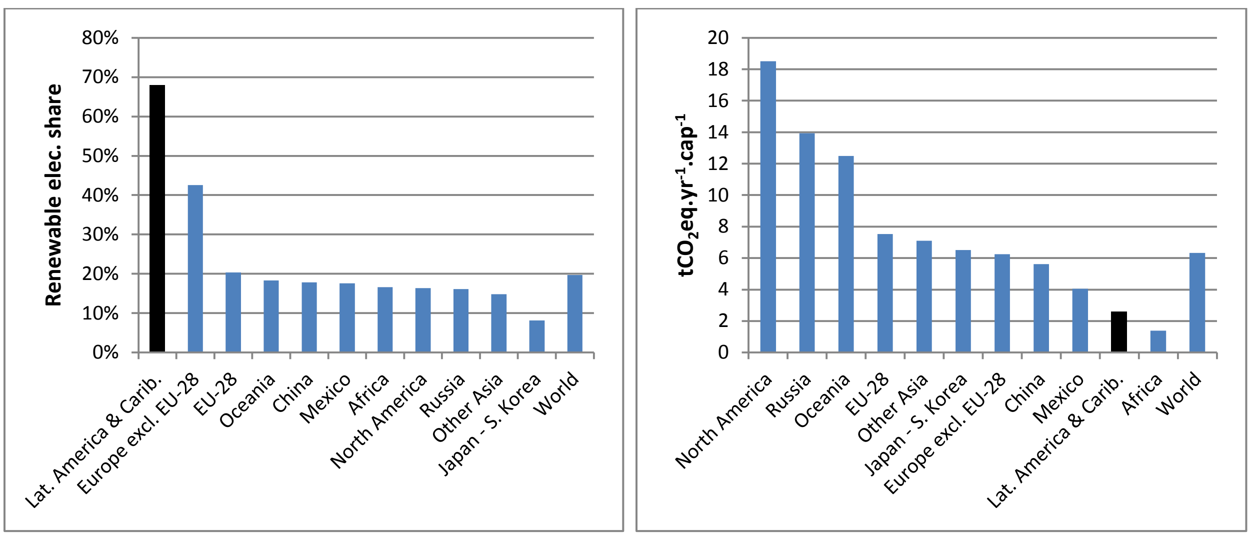

Figure 1-1: Renewable electricity share (left) and per capita emissions (right) in Latin America vs. the rest of the world (adapted from IEA, 2014; World Resources Institute, 2015)

Transportation issues

Transporting energy in South America is also an issue. Wind, solar power and hydro energy can only be transported in the form of electricity; the low heating value of biomass energy and Brazil's low-quality coal makes transportation costs prohibitive over long distances (Nogueira et al., 2014). The availability of most renewable resources is also time-dependent, at very different time scales, from daily load curves for solar power to seasonal ones for hydro reservoirs and biomass harvest; such variability also requires highly integrated networks to optimize operations. However, building such networks in South America is costly and complicated, due to the region's social makeup and physical layout. The average urbanization ratio on the continent in 2012 was 79%, the second highest in the world after North America (81.1%) and well above the global average of 52.6% (UNDESA, 2014). Furthermore, the Andes Mountains, the Amazon Rainforest, and desert areas such as Paraguay's Chaco, Northeast Brazil or Argentina's Southern Patagonia render most of the inlands inhospitable, driving human settlements to the coast (see the population density map of Figure 1-2). In Chile, the 2.7 GW HidroAysén project was cancelled in 2014 because of social opposition to constructing 2000km of transmission lines through some of Chile's wildest Patagonian natural parks. The Xingu-Estreito transmission line which will connect the giant Amazon Belo Monte Dam to São Paulo state will cover 2,087km and cross four states (BMTE, 2015). Porto Velho-Araraquara line, which connects Rio Madeira hydro plants (Jirau and Santo Antônio) with —again— São Paulo state, is 2,375 km long and could be extended by 810 km, crossing the Andes Mountains, if the Inambari Dam is constructed in the Peruvian Andes.

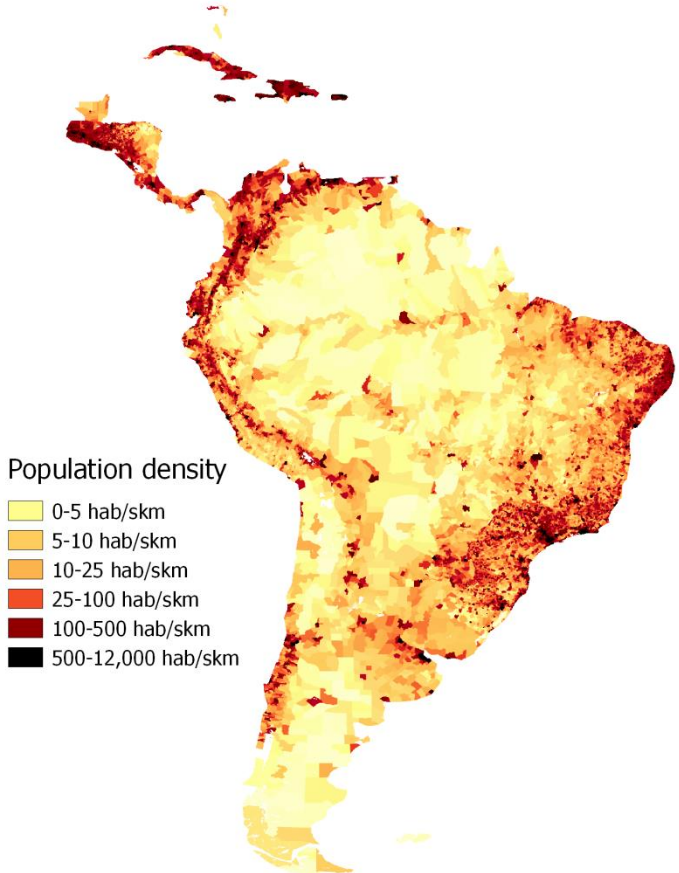

Figure 1-2: Latin America population density, 2000 (adapted from SEDAC, 2004).

Economic development issues

In terms of per capita energy consumption, South America belongs to the developing world; this is clearly shown on Figure 1-3 (left side). However, due to robust economic growth, the continent has more than doubled its electricity production in the past 20 years (see Figure 1-3, right side). The electrification rate jumped from 75% in 2009 to around 90% in 2012 in Peru and Bolivia (CIER, 2011, 2013), following average economic growth of more than 4.5% per year from 2004-2012[11], despite the 2008 crisis. Sustaining economic growth without compromising social equity or the environment is thus another complicated challenge. Chile, which multiplied its GDP by nearly ten from 1985 to 2008, is now facing serious concerns about its mid-term electricity supply (Bernstein et al., 2013). In Peru, isolated precarious communities pay more for their energy than people in wealthy areas; this fuel poverty penalty, as described by Groh (2014), hinders the development of entire regions of the country and weakens its economy as a whole. Ecuador's policy is torn between short-term economic needs, which require extracting and selling oil, and the long-term social and environmental consequences of this extraction: Dutch disease, destruction of endemic species in one of the Earth's most ecologically rich countries, etc. (Escribano, 2013).

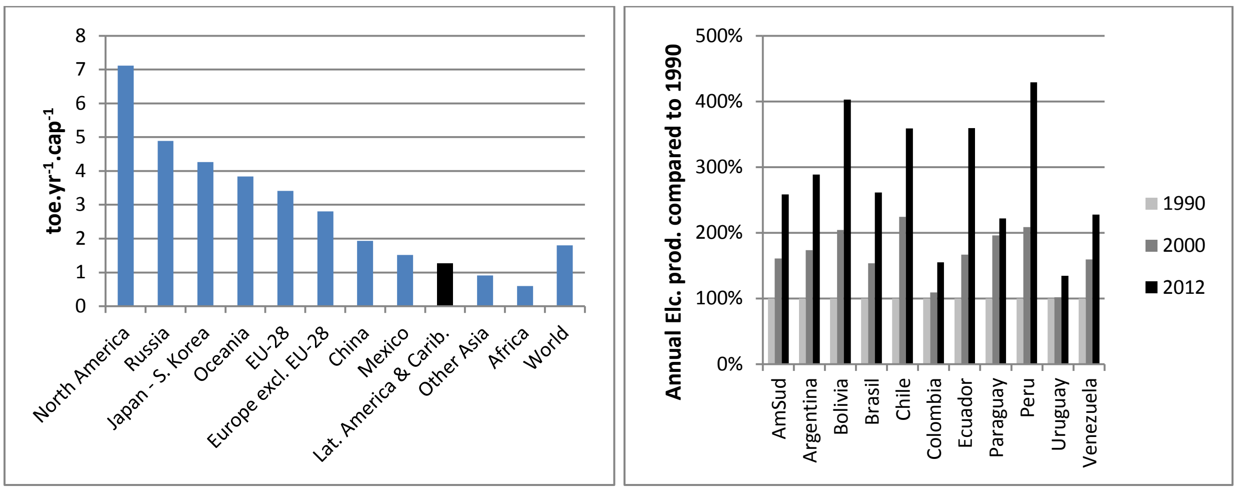

Figure 1-3: Per capita TPES in South America and the world (left) / Electricity production from 1990 to 2012 (right) (Adapted from UNDESA, 2012; IEA, 2014; CIER, 2013)

Integration issues

Last, South America is remarkably *non*-integrated as a region, both in terms of physical infrastructure and trade regulations. Energy integration is widely presented as a desirable future for the continent[12], yet it has long been, and still is, a real challenge[13]. As of today, more than ten transnational integration initiatives are taking place in the region, including UN-ECLAC, ALADI, the Andean Community, MERCOSUR, CIER, UNASUR, ARPEL and IIRSA. All of these organizations are dedicated, one way or the other, to political, economy, or physical integration of South America, with attributions and geographical scopes that intersect more than once. The region has a long tradition of integration processes that have fallen short of delivering continental convergence, and energy is only one of the aspects (see Table 1-1 and paragraph E above). The questions raised by energy integration processes include the form that the cooperation could take (e.g. market-borne vs. infrastructure-driven integration, future role of bi-lateral project-sized contracts), the actual schedule of this integration, and the trade-offs between cost and sovereignty.

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[11] Source: World Bank historical GDP growth database. The figures are geometric averages; the Peruvian average is actually much higher, at 6.5% for the same period.

[12] (Cornalino et al., 2013; Estrada et al., 2012; Ochoa et al., 2013; Rosenthal and José de Castro, 2010)

[13] (Caro, 2006; Céspedes and Agostinis, 2014; Dabène, 2012; OLADE and UNASUR, 2012; Ruchansky, 2013; Souza da Silva Lanzillo et al., 2013)

Various past attempts to cooperate on transnational infrastructure, like Anillo Energético, the Great Southern Gas Pipe and Chile-Argentina gas supply agreements have ended up as costly failures in past years[14]. The reasons for these failures are various, yet we can highlight three recurring factors. First, the convergence of national regulatory frameworks is a very far-sighted target: there is a huge gap between the role played by the socialist governments of Argentina and Bolivia in their respective energy sectors, and the approach of their liberal neighbor Chile. Second, national antagonisms and power struggles are still considerable on the continent, as mentioned in section E. Finally, South America is still far from stable as a continent, especially in the energy sector[15]. In such a context, small countries with large neighbors (e.g. Uruguay, Chile, Ecuador) must strike a complicated balance between bringing costs down and maintaining a reasonable level of energy security.

Concluding remarks

This introductory chapter presented an overview of South America's recent history and reviewed some of the challenges facing South America's energy sector. Among them, making the most of the continent's outstanding renewable energy potential requires solving economic, social and environmental issues; keeping pace with strong regional growth involves bringing new generation capacity on line in a short time and tackling strong national inequalities with respect to energy access and use; the emergence of efficient energy networks is impeded by strong polarization, physical barriers and weak regional cooperation. The next chapter will detail the tools involved in supporting decision for South American energy, from a technical and historical point of view.

[14] (Huneeus, 2007; Rodrigues and Gadano, 2012). For information on Chile-Argentina's gas crisis, refer to Box 2-2.
[15] (Melgarejo Moreno et al., 2013; Perreault and Valdivia, 2010; Roux, 2006; Zamora, 2014).

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Chapter 2: Overview of South American prospective

Regarder un atome le change, regarder un homme le transforme,
regarder l’avenir le bouleverse.
–Gaston Berger

A Energy prospective - concepts

A.1. Planning, prediction and prospective

By creating the State Planning Committee, better known as "Gosplan", in 1921, the USSR inaugurated the global era of state planning. The post-WWII Marshall Plan and Europe's reconstruction generalized the use of planning commissions and national plans to structure day-to-day policies and decisions around long-term targets and strategies for countries' development. These plans, in turn, brought the need for new tools and techniques to support decisions in the face of an uncertain future.

The first such tools, namely *forecasting techniques*, considered the future as exogenous and given. Their focus was on extrapolating past and current trends and mechanisms to build reasonably good *forecasts* for future parameters, with reasonably low incertitude. Predictive forecasts were then used to make the most of a given future situation, considering that the picture could only change – or be changed – marginally. Predictions are still used extensively today by governments and companies to design short-term economic, political and social plans. However, the need for precision and certainty implies that such an approach cannot envision breakthroughs, and the amount of information and calculations needed quickly becomes intractable. By nature, prediction barely escapes the short term.

As planners came to consider ever-longer timeframes in a world changing faster and faster, the need for another set of tools adapted to long-term strategic planning gave rise to *prospective techniques*, which rely on a different attitude towards the future. The fundamentals of prospective thinking, compared to a predictive approach, are well summed up by a quote from the French philosopher Maurice Blondel in 1930: "*The future cannot be foretold; we must build it*". The concept was further developed in France by G. Berger (1964), P. Massé (1965) and M. Godet (1977, 1985), who saw in the exploration of possible futures, the enabler of present actions. G. Berger conceptualized prospective studies as the headlights of a car –our society– on an unknown landscape at night. Headlights do not create the road, yet they help the driver make decisions. And the faster the car goes, the further the headlights must reach to avoid catastrophe. Following this philosophy, prospective studies aim at reducing risks, marking out the field, and ultimately curbing established trends rather than extrapolating them. The focus is on scanning for causes of change, rather than extrapolating continuities. The main tools in this exploratory approach to the future are the so-called 'scenarios' (see next paragraph).

Predictive and prospective approaches rely on quite different tools and techniques, yet they are not mutually exclusive and often, in fact, necessary to each other. It is a matter of understanding "towards what direction we should walk, and also where to set the next foot" (Berger, 1964). However, it was not until the end of the 1960s and the following decade that prospective techniques became widespread, when the Cold War's diplomatic and military fortunes and successive oil crises brought compelling evidence that human behavior was prone to unpredictable volte-faces. The relevancy of Royal Dutch Shell's scenario-based strategic planning approach (Wack, 1985a, 1985b), as well as emblematic publications —Hermann Kahn's *Year Two Thousand*

(1968), the Club of Rome's *Limits to Growth* (1972)— showed that the scale of issues facing mankind, and the variety of possible futures, called for new, specific long-term analytic tools.

A.2. Scenarios and models

In prospective planning, a *scenario* is the translation of a qualitative storyline for the world's future evolution, into quantitative indicators. It allows researchers and decision-makers to envision and compare contrasted possible future outcomes, and make decisions that are robust under a given class of uncertainties. Formulating scenarios aims at capturing core sensitivities and root mechanisms, rather than offering a valid forecast of future events. The approach focuses thus more on the *internal coherence* and *plausibility* of a given pathway than on its actual probability of happening. A scenario analysis can take a *normative* or *backcasting* form; in this case its aims at proving that a desirable future is attainable. At the other end of the scale, it can adopt a frank *exploratory* approach, in the form of a "*What if…?*" question. In this case, the focus is on identifying major risks and adapted recourse strategies, or understanding the influence of a given parameter on the course of future events. The usual modeling approach is thus to consider a "baseline", or "Business-As-Usual" (BAU) scenario which assumes continued historical trends and policies; then compare it with contrasted scenarios were relevant base assumptions are challenged, in the form of *"If… then…"* statements.

Deriving quantitative indicators from a given storyline implies making assumptions on the mechanisms linking the phenomena considered (political, economic, social, technological, etc.) to their consequences. These assumptions (or sets of assumptions) are called a *model*: a formal, simplified representation of the real world, representative enough to deliver valuable insights into the consequences of a given scenario, yet simple enough to be handled by researchers and decision-makers. Depending on the focus of the study and the information available, models may be relatively straightforward tools: for example, assuming that a country's aggregated energy demand depends linearly on its population is a –highly– simplified representation of the real world, yet it may prove sufficient to compare scenarios whose only difference is the future population, in terms of their impact on energy consumption. However, one may also want to consider that energy demand depends on the age structure of this population; on households' income; on national productive structure, and so on. The model then becomes more and more complicated, all the more so since the relationships assumed are not necessarily linear and may include feedbacks, and input parameters may also be (are, in fact) interrelated. As prospective techniques became widespread and data availability increased with the progress of national statistics, planners and researchers were able to formulate scenarios with growing precision and scope, and decision-making required increasingly detailed, far-reaching and consistent answers. As a consequence, the number of parameters and relationships increased; consigning calculations to computers was the logical next step towards handling greater complexity.

The generalization of computational resources brought a profusion of models to match the wide variety of existing issues, techniques, and viewpoints. In a reference attempt at energy model classification, Van Beeck (1999) underlines that every model, as a "*simplification of reality, includes only those aspects that the model developer regarded as important at that time*"; this makes any classification complicated at best –and at worst, illusory. However, for the exact same reason –i.e. being partial representations of the reality aimed at long-term prospective studies– models will naturally produce results that are different from each other, and different from any potential future[16]. The review provided by the IPCC for its 5th Assessment report and displayed on Figure 2-1 is self-explanatory: across the 31 models included in IPCC's database, global GHG emissions vary from 50 to 195 $GtCO_2eq/yr$, all under *Business-as-Usual* assumptions. In other words, future GHG emissions as projected by the IPCC's models vary from a factor of 1 to 4, without making any explicit assumptions on a hypothetical policy evolution or technology breakthrough. Under such circumstances, a basic understanding of the leading principles underlying energy models is crucial to pinpointing their strengths, limitations and areas of application, and interpreting their results correctly. The following paragraph proposes a very quick review of some base characteristics of energy models. For more information, the interested reader is invited to consult the conceptual works by van Beeck (1999), Lanza and Bosello and Crassous (2008), OLADE's Planning Manual (Abadie et al., 2014) and the exhaustive European ATEsT project, which designed a full model selection methodology aimed at policy-makers, and made a census of more than 80 European energy planning models (Manna, 2010).

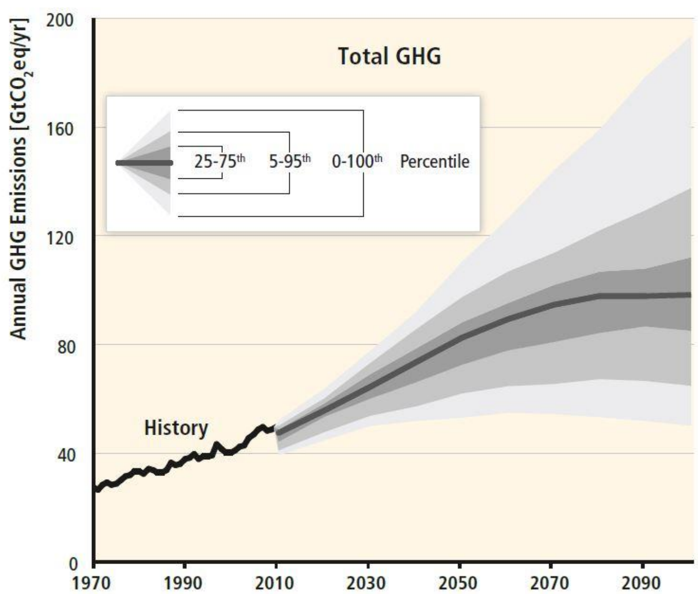

Figure 2-1: Baseline GHG emissions, according to IPCC's AR5 Database (IPCC, 2014)

Energy planning models could be described in terms of:

- Their **focus**, which relates to the kind of problem to be analyzed, the kind of insights looked for and the perimeter investigated;
- Their **approach**, which emphasizes the role of the energy sector versus the rest of the economy, and how the system components interact with each other;

[16] The philosophy and limitations of such long-term prospective models can be summarized in an elegant quote from Paul Valéry: "Ce qui est simple, est faux. Ce qui est compliqué est inutilisable." (Everything simple is false. All that is complex is useless).

- The **mathematical set of methods** used and their underlying simulation or optimization assumption;
- The **compromises** underlying their geographical, temporal or technological representation of the energy-economy system.

These parameters are neither independent nor hermetic to each other, and choosing one of them automatically impacts the others.

i) Focus

The first dimension of an energy model is its focus, which is closely linked with the issue to be analyzed. This focus, in turn, can be subdivided into three dimensions:

- The **stance regarding the future**: as stated above, prospective scenarios can be categorized as *normative* or *exploratory*. By construction, a normative approach will be much more constrained than an exploratory one; as a consequence, a model aimed at validating normative scenarios may not need optimization techniques (cf. p.34) which add unnecessary liberty to the model's outcomes.
- The **sectorial focus**: energy prospective can focus preferably on *energy demand*, *energy supply*, or *climate policy assessment*. Energy demand studies focus more on the political and social determinants of energy demand and/or how this demand relates to the rest of the economy. On the other hand, energy supply studies investigate how the economic structure of a region, its industrial base and available resources relate to the satisfaction of a given energy demand and how this structure reacts to external stresses (political and social changes, economic shocks on resources, etc.). In the case of energy supply, the emphasis may be more specifically on the operation of a given energy system (transmission issues, network stability), or on its expansion (investments in new plants/new lines, energy transition). Climate policy assessments, when considering energy, relate to both the impact of energy measures (e.g. renewable portfolio standards) on the environment, and the impact of environmental measures (e.g. emission reduction commitments) on the whole economy, or the energy sector alone.
- The **thematic investigated**, in the sense of an array of related energy issues. Following the ATEsT classification, the four main policy thematics for energy prospective are *strategic planning*, *transition planning*, *innovation and R&D* and *international cooperation*.

ii) Approach

The dominant criterion for the classification of energy models has historically been the *bottom-up/top-down* differentiation, which relates to the role given to the energy sector in the model. The precise definition of this distinction has fueled many discussions among modelers; moreover, it can be seen as a black-and-white vision that lost some of its technical relevance with the appearance of hybrid models that incorporate both top-down and bottom-up features to various degrees, as well as model coupling techniques. Crassous (2008) provides a thorough review of the various limitations of the bottom-up/top-down distinction. Despite its shortcomings, the bottom-up/top-down classification has a major advantage which makes it still widely used today: it segregates the engineer's energy prospective vision from the economist's.

For the sake of understanding, we present here a caricatured differentiation of these two approaches.

- *Top-down* or *economic* models adopt a holistic view in which the energy sector is one component of the economy. The advantage of these models is the realism with which they represent the interactions between energy and the rest of the economy, and the dynamic evolution of the whole economy itself. Energy production and consumption are represented through production functions with aggregated inputs (labor, capital, energy, raw commodities), thus often making top-down models less data-intensive than bottom-up ones; on the other hand, they often rely on more complex equations, with endogenous assumptions embedded in the form and internal parameters of these equations. Production is arbitrated through economic mechanisms (equilibria, elasticities, etc.). Efficient technologies are described according to an exogenous "production frontier". Technological learning is continuous and exogenous, described by a programed displacement of the production frontier. As for physical quantities and flows, they are strongly implicit, being subordinated to economy parameters.
- *Bottom-up* or *engineering* models consider the energy sector itself. They make use of the fact that an energy system is a physical construction before being an economic one, and focus on the physical representation first. As a consequence, their construction of the energy sector is much more disaggregated, often in the form of a technology-wise representation; the relationships between these technologies are thus represented by physical equations (energy transformation and flows) that are more straightforward. On the other hand, the rest of the economy is modeled with less realism, or through exogenous assumptions. They rely, in most cases, on accounting or linear programming techniques. Engineering models were prefigured by the Bariloche World Model (cf. paragraph B.1.1 in this chapter) and early work by Nordhaus (1973; 1979). However, two emblematic paradigms of the bottom-up approach, namely MarkAl and MESSAGE, both emerged in 1981[17].

Table 2-1 summarizes some of the comparative strengths and weaknesses of bottom-up versus top-down models, while Figure 2-3 (p.37, at the end of this paragraph) gives an overview of the role of energy in top-down and bottom-up approaches.

[17] See the work of Fishbone and Abilock (1981) on MarkAl, and that of Häfele (1981) on MESSAGE.

	Bottom-up paradigm	Top-down paradigm
Strengths	• Explicit representation of technologies and policies: no 'black boxes' • Respect of physical constraints • Description of physical flows • Better representation of endogenous technological change	• Holistic growth representation • Strives at economic realism (consumption patterns, social acceptation, etc.) • Accounts for macroeconomic effects of policies and feedbacks
Weaknesses	• Vision limited to the energy sector : no macroeconomic feedback • Economic assumptions implicit, embedded in exogenous macroeconomic data • No account of consumer preferences and market mechanisms	• Aggregated description of behaviors • Implicit technology description (input-output functions, econometric techniques); same for flows • Substitution elasticities do not account for physical and thermodynamic restrictions • Empirical weakness of elasticity factors • Exogenous technological change implies implicit assumptions (Hicks-neutrality, Autonomous Energy Efficiency Improvement, etc.)

Table 2-1: Comparative strengths and weaknesses of bottom-up and top-down approaches (adapted from Crassous, 2008; Lanza and Bosello, 2004; Van Beeck, 1999)

iii) Mathematical methodology

Mathematics-based conceptual representations of reality provide convenient tools for deriving the consequences of prospective scenarios, through the calculation capabilities offered by computer modeling. On the other hand, using a given mathematical toolbox to compute a possible future state of the world implies making strong assumptions regarding the rules underlying the world's evolution, and one must be conscious of this mindset when interpreting the results of a model. When it comes to energy planning, we can distinguish between two main classes of models: simulation and optimization.

- **Simulation models** try to reproduce realistic behavior of the energy sector or the economy as a whole. We can separate this generic approach into two different families: econometric and equilibrium models.
    - *Econometric models* rely on statistical techniques and historical data to derive the impact of future scenarios by extrapolating past correlations. Such models can easily be applied to scenario evaluation, making them valuable tools for prospective investigations. However, their strong link with past trends make them more oriented towards short- and middle-term evaluations, and in a sense, more predictive in nature; they are less adapted to handling exploratory scenarios, including major and lasting changes in established trends.
    - *Equilibrium models* balance a number of variables for one or more future points in time. They can be of two types: economic models, which reflect mainly micro- and macroeconomic mechanisms; and accounting models, which focus more on equilibrating physical and monetary flows. Macroeconomic models are most often *general equilibrium* ones, meaning that they cover the whole economy, while

accounting models most often simulate the equilibrium of a single sector (energy) with border conditions to represent the rest of the economy, which makes them *partial equilibrium models*.

- **Optimization models** adopt a stance somewhat more distant from reality, as they look for optimal decisions in a perfect world. This approach presents the major practical benefit of being easily handled by both computers and human modelers. On the computer side, the mathematical toolbox related to optimization is quite developed, and can handle vast problems with low resource requirements. On the human side, an optimality assumption is more easily understood and delimited than non-optimal decisions with unclear objectives. Following a 'simple is false, complex is useless' philosophy (cf p.31), this kind of representation of a perfect, optimal world is false, yet the bias is known and can be taken into account when interpreting results. In the context of an exploratory approach, the gap between a model's behavior and actual mechanisms is not the main issue, so long as the results are not considered to be what they are not, i.e. predictive ones. Optimization models can be further divided into energy systems optimization models, and optimal growth models.
    - *Energy System Optimization models* result from research on optimal resource allocation, which was used for complex system operations planning in the 1960s (transport, refineries etc.). An early example of optimal allocation application in long-term prospective with a global impact is the Bariloche model proposed by Herrera (1976). This model optimized the whole economy, with no specific focus on the energy system. Nordhaus (1973; 1979) provided one of the first dedicated energy models based on linear optimal resource allocation, applied to a long-term representation of the US energy supply.
    - *Optimal growth paradigms* stem from Ramsey's considerations of optimal growth models (Ramsey, 1928), perfected, among others, by Cass and Koopmans. The first emblematic application of an optimal growth paradigm to CO_2 emission control is Nordhaus' DICE model (1992), the foundations of which were laid by Nordhaus himself ten years before (Nordhaus, 1980). Instead of optimal resource allocation which solves a linear problem to optimize a discrete representation of the energy system, optimal growth models rely on control theory to maximize the utility of a representative consumer over a continuous time path, using consumption as the control. One interesting aspect of such an approach is that climate damage can be integrated directly into the model to provide real-time feedback on the agent's decisions, and that time dynamics are represented in a very fine-grained way due to the continuous-time form of the problem.

iv) Compromises

Technically, energy modeling is all about a compromise between representativeness and usability, yet this paragraph focuses on a specific type of compromises, i.e. those related to **geographical**, **temporal**, **economic** and **technological** perimeters and details. Representing things at a more disaggregated scale comes at the price of centering the focus and integrating implicit (exogenous) assumptions, or building a problem too complex to handle for both humans and computers. Plus, the effort of gathering information for disaggregated all-inclusive models and then interpreting their results afterwards quickly becomes unmanageable.

- The *geographical scale* is maybe the most clearly defined notion, illustrated by Figure 2-2. Energy modeling can support planning decisions for various entities, from district planning to global climate cooperation. What models can *not* do is to represent each and every urban district in the world with their specificities and assess the impact of long-term decisions for all of them at once. Any model covering less than the entire world will need *border conditions*, for example a price of energy commodities on national and international markets. In this case, a hypothesis on external energy prices hides further assumptions on the internal dynamics of all regions that are not endogenous to the model. When modeling a city, assuming the future behavior of 'all regions not endogenous to the model' actually means a lot of implicit or explicit assumptions. On the other hand, large-scale models that cover important parts of the world are compelled to adopt a more aggregated view, otherwise the model quickly becomes intractable both in terms of calculations, and in terms of information aggregation and interpretation.

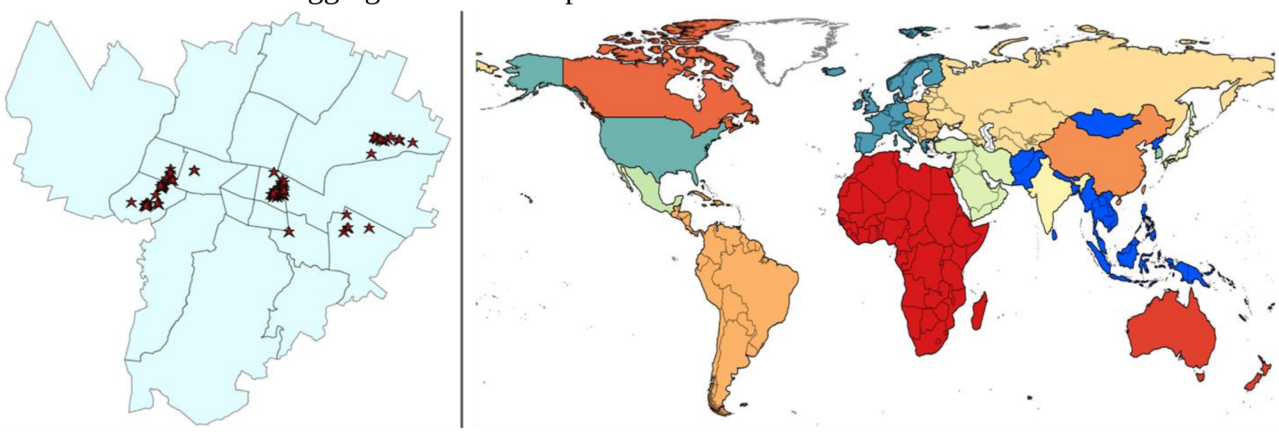

Figure 2-2: An illustration of geographical disaggregation choices.
Left: 18-region model of the city of Bologna (Assoumou et al., 2015). Right: 15-region world in TIAM-FR (Ricci and Selosse, 2013)

- Energy prospective considers, by nature, middle-term to very, very long-term time horizons: while the work of O'Ryan (2010) on Chile's GHG emissions and mitigation options takes 2030 as its time limit, Gerlagh and Van der Zwaan (2012) investigate the effects of geological leaking versus carbon capture and storage (CCS) efforts up to the year 3000. On the other hand, issues like grid stability refer to very short time spans, from milliseconds to, at best, 10-minute intervals (see Europe's 2006 black-out, for example). The time scale chosen will thus depend on the phenomenon, or phenomena to investigate or emphasize. Optimal growth models may get closer than others to a no-compromise stand towards time scales, due to their time-continuous approach; however, they embed a form of time granularity in the mechanisms represented in their utility and damage functions, and the actual formulation of these mechanisms. For equilibrium models, as well as linear optimization ones, time considerations translate into the number of time points for which the equilibrium is calculated/the optimization is run (the interval between two points being called a *time step* or *time period*). One way to work around this limitation is to develop indicators which reflect short-term mechanisms, yet can be computed on long time spans (Drouineau, 2011). Such techniques can deliver very useful insights into the long-term perspectives of e.g. Smart Grid technologies and mechanisms (Bouckaert, 2013), yet they only partially and imperfectly bridge the gap between short and long time scales.

- Economic aspects: while the bottom-up / top-down distinction opposes physical realism with an economic one, 'economic realism' itself is a multifaceted notion, of which the most visible aspect is the opposition between the macroeconomic and microeconomic descriptions. While macroeconomics accounts for the relationship between aggregated economic indicators, microeconomics focuses on tracking the complex determinants of individual choices. Crassous (2008) reviews various aspects of the theoretical and empirical complexity of reconciling these two visions in a single model for energy prospective applications.
- Technological aspects: as for economics, 'technological realism' covers a wide array of options, from an aggregated production function for the whole energy sector, to tracking the impact of remote-control room lighting in smart buildings. The compromise for technological description involves excluding either various technological options or sectors from the analysis, and aggregating technologies into 'representative' ones which are, in fact, increasingly less representative. A good example of sacrificing sectors is electricity-only models, which take fuel supply and end demand as exogenous data, delegating information on e.g. modal shift to external assumptions; on the other hand, 'integral' models settle for a restrictive technology portfolio in each sector and, most often, very little grid description.

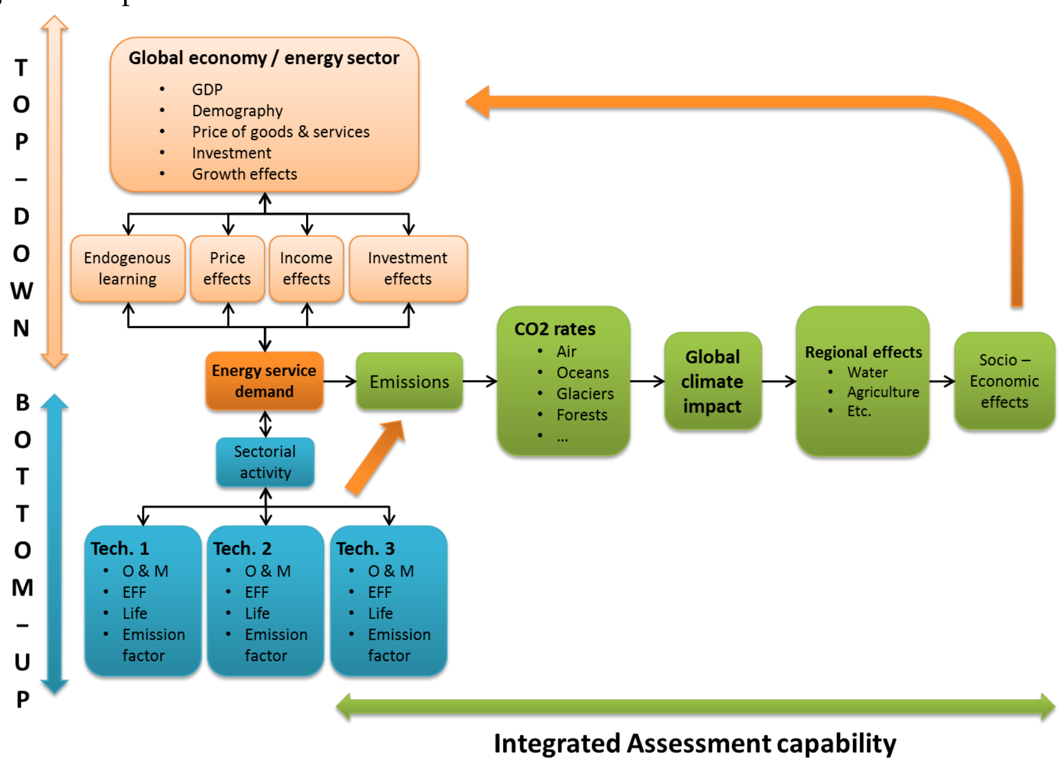

Figure 2-3: Top Down, Bottom-up and impact assessment coupling (adapted from Assoumou, 2006)

Hybridization and comparison

The multiplicity of energy models reflects two realities about energy modelers; the multiplicity of their viewpoints, and the limitations of their techniques. Two evenly spread approaches have been devised to mitigate technical limitations and capture the richness of diverse viewpoints: model hybridization, and model comparison.

In energy modeling, the most common hybridization cases bring together top-down and bottom-up models or add damage assessment capabilities to an energy model. A good example is the assessment of the climate-energy nexus, as schematized by Figure 2-3. While bottom-up models are quite adapted to track the impacts of energy consumption in terms of emissions, climate models compute the reaction of the climate system to these emissions, and their physical consequences. Top-down models, in turn, are useful to represent the reaction of an economy to climate change, and translate these results into economic consequences for the energy sector (demand, prices). Another emblematic case for hybridization relates to the temporal limitations evoked earlier: in order to account for both investment and operation in a satisfactory way, bottom-up energy models often hybridize a short-term representation of network operations, and long-term modeling for investment planning. This is for example the case for TIMES models which compute energy investments over long periods (several years) and use representative *timeslices* for plant operation, with disaggregation levels that in some cases go as far as hourly (Kannan and Turton, 2012) (cf. Chapter 3:C.2).

The two examples proposed here introduce two different types of hybridization, called *soft-linking* and *hard-linking*. Soft-linking is the term coined for two distinct models that 'talk to each other'. A common way to achieve such a link is to use one model's outputs as inputs for another model, and iterate this process until a form of convergence is reached between the models. Hard-linking refers to hybridizations similar to the second example, where the two paradigms/approaches co-exist within one model. This type of hybridization has also been experimented between bottom-up and top-down paradigms, see e.g. the IEA's *World Energy Model* (2014a) or the IMACLIM model described by Crassous (2008). The overall consistency is thus improved by eliminating the 'bottlenecks' associated with information transmission. On the other hand, the overall detail of these models must be reduced to keep calculations feasible and understandable. For models relying on e.g. a strong bottom-up base while integrating a small macroeconomic or climatic module, the term *pseudo-hybrids* is sometimes used. Examples of this include the global *TIMES Integrated Assessment Model* (TIAM)[18], which is by nature a bottom-up energy optimization model but also includes a climate module for studying energy and climate interactions in an integrated way.

Another way to exploit the complementarity of different models and partly overcome their limitations is to perform *model comparison exercises*. This technique was used in particular by the IPCC to reduce the individual uncertainty of the various existing climate models, yet it also applies to energy projections. Recent multi-model comparison experiments in the field of climate policy include a study by Böhringer et al. (2012) on border carbon taxes, in the framework of the Harvard project on climate agreements; the Asia Modeling Exercise on the role of Asia in addressing climate change, by Calvin et al. (2012); a work on near-term climate policy choices by Eom et al. (2015), based on Europe's AMPERE project; the LIMITS study on the implications of a 2°C target for a global climate agreement, by Kriegler et al. (2013); and the CLIMACAP exercise, which focused specifically on South America (van Ruijven et al., 2015); etc. To provide valuable insights, model comparison exercises require harmonizing sufficiently the base assumptions and exogenous parameters, otherwise comparing the results becomes a complex; in practice, this harmonization is

[18] See Chapter 3:B.3.

limited by the various levels of endogeneization and data formats of the models considered, and model comparisons serve mainly for delineating the state of the art of modeling knowledge for a given topic/region.

Box 2-1: Hybridization and comparison

B Latin American energy prospective – A panorama

The past few pages introduced the concepts of energy planning, prediction and prospective and proposed key differentiation principles to characterize energy prospective models and interpret their results. The next paragraphs offer a historical review of the development of energy planning and energy prospective in South America, finishing with an overview of the regional actors and the tools they employ today. Given the size of the region, I aimed at finding a balance between a tedious exhaustive inventory and limited focus points that would downplay the rich regional experience. All Spanish and Portuguese names for national publications and institutions have been translated to English; most translations are personal, not official ones, and the original names can be found in Annex p.**¡Error! Marcador no definido.** and following; some of them are also available in the Acronym list at the beginning of this book. Last, an extensive review of recent energy-planning exercises and tools is summarized in Table 2-2 at the end of this paragraph (page 65).

B.1. 1930-1980: The early ages of planning and prospective in South America[19]

In the wake of the 1929 crisis and the trauma of WWII, South American states increased their involvement in national economies and societies, to respond the deep social and economic crisis hitting the region (see Chapter 1 and the review by Leiva Lavalle, 2010). State-controlled industrialization brought the need for comprehensive national plans, while economic and social tensions led governments to interfere more in social and economic activities. Brazil and Argentina led the way towards state planning at the beginning of the 1930s, spurred by national infrastructure requirements (including energy production needs). The discipline was then disseminated by international institutions, as was the case for the World Bank's action in Colombia in 1949-1950 (Currie, 1950). The establishment of the United Nations Economic Commission for Latin America and the Caribbean (UN-ECLAC) in 1948 also represented a major step towards long-term economic thinking for the region. A major advance was then made in 1961 with the signature of the Charter of *Punta del Este*, which established the *Alliance for Progress* between the United States, the World Bank, the IMF and Latin American Countries. The Charter established a ten-year plan for Latin America, by which Latin American countries were to spend US$80 billion in a decade on specific development fields in order to reach quantitative economic and social targets (increase of per capita income by 2.5% annually, elimination of illiteracy, eradication of inflation and deflation, etc.). In return, the US committed to lend or guarantee loans by the IMF and World Bank, for up to US$20 billion during the same decade. One of the Charter's requisites was the establishment of national economic and social planning institutions. Regional coordinated planning

[19] The dates mentioned here are approximate, since our analysis is of a totally heterogeneous continent; they may vary by up to a decade according to a country's particular history.

was also backed by the creation of relevant regional institutions such as the Regional Energy Integration Committee (CIER by its Spanish acronym) in 1964; the Andean Community for the economic and political convergence of Andean countries in 1969; and the Development Bank of Latin America (CAF) in 1970. However, most of the plans that emerged during this period were deemed unrealistic, with inconsistent normative targets no attempt whatsoever to assess their attainability. No recourse strategy was mentioned, and even the longest-term plans (10 years) did not incorporate a global vision or prospective techniques. Latin American prospective shone briefly when the Bariloche Foundation published its famous Latin American World Model report (Herrera, 1976), yet the Alliance for Progress declined shortly after Kennedy's assassination, and most national planning programs were cut back during the neoliberal wave of the 1980s. The next paragraphs give a country-level review of these early experiments, with a focus on the energy system.

B.1.1. Argentina: From Perón's Quinquennial Plans to the Latin American World Model

The first Argentine experiment on national planning took place in 1933 with the Economy Action Plan; state planning was subsequently systematized by Perón's Quinquennial Plans starting in 1952. The Quinquennial Plans marked the institutionalization of state planning, with the creation of the Planning Ministry and the Secretary for Strategic Planning. Perón's plans were given a strategic planning orientation by the country's Post-War Council, whose role was to prepare for a potential WWIII; however, their approach to planning was more centered on assessing the feasibility of desired futures than on devising how to reach them, according to (Marí, 2009); furthermore, they relied on macroeconomic and social targets that were extrapolations of existing figures, leaving aside any prospective thinking. Following the requirements set by the Charter of Punta del Este, the National Development Council was founded in 1961 and published a *National Development Plan 1965-1969* four years later. Although not a fully prospective exercise in the current sense of the term, this Plan established the first retrospective effort to analyze the causes for failure of the previous Plans and look for potential levers for change with a holistic vision. These efforts, however, were thwarted by the 1966 military coup, which led the country into a multi-decade downwards spiral. The new military junta dismissed the entire National Development Council and created the National Planning System, which was in charge of national Development and Security Plans. Bureaucracy and political instability were such that this new entity produced only two sets of indications for national development, neither of which was ever implemented.

Latin American Prospective, however, had its moment of glory, with the publication of the Bariloche Foundation's report *Catastrophe or new Society?: a Latin American world model* (1976) edited by Amílcar Herrera. The Bariloche Foundation was founded in 1963 in San Carlos de Bariloche, Argentina. As some technical and methodological choices of the *Limits to Growth* report were challenged in Rio de Janeiro in 1970, prior to its publication, the Foundation was commissioned to produce an alternative prospective investigation. This work was published four years after *Limits to Growth*. Herrera's team took a resolutely normative approach, in contrast to the exploratory approach of the Club of Rome. Where *Limits to Growth* proved that growth paths which followed current economic paradigms were not viable, Herrera's work demonstrated that optimal resource allocation in an egalitarian society was attainable and that it maximized social welfare. In terms of model classification, the Foundation's tool (known as the *Latin American World model*, or the Bariloche model) was a multi-regional (four-region) time-stepped model, maximizing life expectancy at birth through the optimal allocation of capital and labor until the year 2060. It could be classified as a top-down model, in the sense that it relied on Cobb-Douglas functions to represent the world's economy; its highly disaggregated representation and resource allocation approach, however, prefigured bottom-up models. The *Catastrophe or new Society* report had considerable and lasting repercussions in the prospective community, both for its normative methodology and its use of optimization techniques, heralding a whole class of 'bottom-up', 'optimistic' models. Nonetheless, the fate of this optimistic message in Argentina was quite different: in March 1976, a military coup brought the infamous Jorge Rafael Videla to power and triggered the darkest episode of Argentina's dictatorship era. Institutions that questioned established models, such as the Bariloche Foundation, were put under strong pressure and Amílcar Herrera himself went into exile in Brazil, closing the Argentine prospective chapter.

B.1.2. Brazil : Consolidation of national planning under the liberal dictatorship

State planning in Brazil started roughly at the same time as in Argentina, with the first mandate of the iconic Getúlio Vargas. The 1930 Revolution marked Brazil's answer to the 1929 crisis and the beginning of the country's industrial era. The first comprehensive national plan was the Special Plan for Public Works and the Preparation of National Defense, with good reported results; among them, the creation of the National Steel Company would lead Brazil to being one of the world's top iron producers today. A series of national plans followed, including the ambitious 1950-1954 SALTE plan (Health, Alimentation, Transport and Energy), which finally failed because of the high inflation that started at this time. The first lasting planning structure –the Council for Development– emerged in 1956 after Vargas' suicide, to coordinate political action towards economic development. Its main outcome was the *Program of goals*, which outlined 30 priority measures for four economic sectors (energy, transport, agriculture, industry). The *Program of goals* inaugurated indicative planning in Brazil and obtained very good results; its success led to the creation of the Planning Ministry in 1962. The 1964 military coup ended this initiative; however, unlike most of South America, the right-wing military dictatorship that lasted until 1985 did not end with national planning and even implemented various national plans with longer-term objectives than previous ones. The Program for Governmental Economic Action (PAEG) showed the compatibility of market policies with state planning in Brazil, while the 1967-1976 *Decennial Plan* (never implemented) represented a first experiment towards national long-term planning. The series of National Development Plans (PND) between 1972 and 1979 offered a clear differentiation between long-term goals and implementation paths. PND II, designed in 1974 in response to the oil crisis, launched the construction of dams throughout the national territory and highlighted the need to reduce dependency on Middle-East oil, leading to the launch of the *Proalcool* Program in 1975[20].

Some isolated prospective studies appeared towards the end of the 1970s, yet it could be said that long-term prospective really entered the country in 1979. At this time, the Getúlio Vargas

[20] (Moreira and Goldemberg, 1999; Moretto et al., 2012).

Foundation published the first national prospective reference book, written by H.Rattner (1979); A. Herrera, recently exiled from Argentina, founded the Geoscience Institute and took the lead of the Science and Technology Policy Department at Campinas' State University (dos Santos and Fellows Filho, 2009). In the same year, energy planning began receiving special academic attention with the creation of the Energy Planning Program in Rio de Janeiro's Federal University (UFRJ), Brazil's leading university[21].

B.1.3. Chile: aborted experiment at national planning

National Planning also started before the end of the 1930s in Chile, leading to the creation of the National Development Agency, known as *Corfo*, in 1939. Corfo served as an implementation tool for state plans through direct investment. One of the main areas of work of the Agency at that time, according to Rivera Urrutia (2009), was to develop the national energy system. After 1950, planning acquired a more systematic and long-term focus with the creation of the Department for Planning and upstream Studies within Corfo, and the publication of the first *National Program for the Economic Development 1961-1970*, heavily based on Corfo's experience of energy sector development. The institutional base for national planning was reinforced in 1967 by the Frei Montalva government, which created the Planning Bureau or *Odeplan*. This Bureau started to control government spending in the beginning of the 1970s; however, Pinochet's coup in September 1973 marked the beginning of a strongly neoliberal regime in which planning was reduced to the strict minimum and 'market first' became the rule. The Odeplan survived in a very reduced form, its role being limited to planning the shift from state planning to market control, and assessing limited public investment projects. In the particular case of the energy sector, most regulation capacity was delegated to the private sector, and public experts left.

B.1.4. Colombia: building a nation-wide prospective culture

Although Colombia is not the biggest power in Latin America, it stands among the most experienced countries on the continent when it comes to state planning and prospective, according to Medina Vásquez and Mojica Sastoque (2009). The obligation for Congress to use plans and programs to steer public investments and promote economic development can be traced back to the 1945 constitutional reform, according to Leiva Lavalle (2010). The first comprehensive plans took shape with the help of a World Bank mission in 1949-1950; state planning was institutionalized with the creation of the National Planning Department (DNP) in 1958. The first Plan issued by this Department in 1962 opened the way to international financing within the brand-new framework of the Alliance for Progress. However, its targets were deemed unrealistic, and the DNP lacked a strong political backing to influence national politics; the impact of this first plan thus remained limited. The new 1966 Constitution changed the order of things by obliging each new government to validate a national plan before Congress, and draw up each year's state expenses according to the priorities identified in this plan. The head of DNP was also given the status of minister, answering only to the president. Last, the DNP had controlling rights over foreign investments, validating them on a project-by-project basis. This gave the department significant power and

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[21] Although energy planning was a new field from an academic perspective, national companies like Electrobras had already taken steps towards such planning with e.g. an exhaustive inventory of the country's hydro potential as early as 1962.

influence over state policy but proved detrimental to devising an actual long-term vision, since financing decisions were often assessed on a 'by project' basis, and each plan was linked to a government that it did not outlive. Such a project-based bias strongly benefitted energy projects, which international financers considered among the most economically efficient, and which featured in each plan's priorities from 1970.

The long-term view and prospective approach took a leap forward with the creation, in 1968, of the Colombian Fund for Scientific Investigation and Special Projects, better known as *Colciencias* and its parent structure, the National Council for Science and Technology. Colciencias was (and still is) a national entity with great decision-making autonomy. It quickly backed the dissemination of prospective and its application to strategic plans, with the *Operación Desarrollo* prospective exercise conducted as soon as 1969, and the creation in 1970 of Colombia's Group for the Year 2000 to study long-term issues facing the country. It also attracted international prospective figures such as Nakamoto, Piganiol, Peccei, Masini, Godet and Ténière-Buchot, who supported the first steps of prospective application and dissemination in the country. However, the decade of 1970-1980 was more dedicated to learning, conceptual exercises, and dissemination, than to actually applying prospective exercises to political decision-making, due to the complex and fast-changing priorities imposed by the country's civil rebellion (cf. historical preamble).

B.1.5. Costa Rica: ambitious national plans with short-term preferences

Costa Rica's state planning began in 1963 with the creation of the National Planning Office, transformed into a National Planning System in 1974. Between 1965 and 1979, this state planning entity produced four National Plans, all of them tri-annual. The Planning Office was also in charge of making sure that public expenses followed the plan's priorities. The second plan, in 1969, initiated extensive hydroelectric works throughout the country. The Secretary for Sub-sectorial Energy Planning was created in 1978 and issued its first National Energy Plan 1986-2005 in 1986. Like in Colombia, however, the long-term vision of national plans was hindered by the short-term preferences of national governments. Costa Rican planning capabilities suffered from the 1980s neoliberal wave, although they did not disappear completely.

B.1.6. Cuba: Building on the international socialist experience

Fidel Castro's government resorted to state planning shortly after the end of the Cuban Revolution. The industrial sector came first, with the 1964 Perspective Plan backed by the then Industry Minister Ernesto Che Guevara. National expertise strengthened through Cuba's exchanges with the international socialist movement, in the framework of the Council for Mutual Economic Assistance (known as *Comecon*). Special emphasis has been put on long-term planning since 1971. The downfall of the USSR in 1989 created an even more uncertain future for Cuba and made strategic planning an unavoidable tool. García Capote and Lezcano Lastre (2009) highlight the example of biomedicine to illustrate how long-term planning was marked by risk-taking strategies that originated in a national prospective attitude.

B.1.7. Peru: National planning promoted by left-wing dictatorships

The military junta that took power in Peru in 1962 fulfilled the requirements of the Charter of Punta del Este and created the National Planning Institute (INP by its Spanish acronym) under the supervision of an interministerial Planning Council. The first *National Development Plan* was designed by the INP and approved by the government in 1967, yet it was rejected in Congress, foiling the government's expectations and showing the weakness of Peru's institutional set-up with respect to national planning. Effective planning only started after the 1968 military coup, under the new left-wing military dictatorship of Juan Velasco Alvaredo. Its first attempt under the new circumstances was the National Strategy for Long-term Development in 1969 (Leiva Lavalle, 2010). During this period, Peru also hosted the Lima conference in November 1973, which gave birth to the Latin American Energy Organization (OLADE), still one of the most relevant and inclusive cooperation frameworks for Latin American energy today. OLADE has its offices in Quito, Ecuador and provides expertise to Latin American governments on all energy-planning related themes, as well as a framework for policy coordination. However, the first planning experiments designed in this first period 1962-1975 lacked prospective vision and were almost exclusively based on trend extrapolation and formal future targets with no clear link to immediate implementation consequences.

B.1.8. Venezuela: Successful debuts under Cordiplan's leadership

Venezuela's state Bureau of Coordination and Planning (*Cordiplan*) was created in 1958 to influence national decisions through both direct investments and contributions to national policy-making processes. One of its early achievements was the creation of the Venezuelan Corporation for Guyana to plan and coordinate the development of hydroelectricity, iron mining and forestry resources in the Guyana region of Venezuela (Máttar, 2014). State planning reached its maximum influence in 1974 when its head was conferred with the status of state minister, explicitly handing the reins of the country's economy to Cordiplan. Cordiplan's national plans remained mainly short-term, reflecting the prevailing political and economic instability of the country, yet the energy and electricity plans developed an early long-term view, collaborating with the French company *Electricité de France* on 25-years *Electrification Plans* as early as 1960. Their success in developing Venezuela's electric supply and transmission was globally acknowledged in the 1960s and 1970s, according to (Aller, 2014).

B.2. 1980-1995: The neo-liberal wave[22]

Latin America's shift from state-controlled industrialization to neo-liberal models heralded one to three decades of discredit for state planning throughout the continent, with the notable exceptions of Brazil, Colombia and Venezuela. International organisms such as the World Bank and the IMF, promoting the Washington Consensus, stopped backing any form of state interventionism in national economies. Institutional planning all but disappeared in some countries such as Chile and Peru, while it was extremely reduced in e.g. Bolivia and Argentina. At the same time, however, long-term planning continued to be applied and improved by companies and regional institutions and prospective techniques even received renewed academic attention, driven by international

[22] As in the previous paragraph, the dates mentioned here are averages and vary according to each country's particular history.

investigation into the area. The Technology Prospective for Latin America (PTAL) project launched by A. Herrera from Brazil in 1983 followed in the Bariloche tradition, assessing various scenarios with a regional perspective. In 1987, Brazil, Colombia, Argentina, Mexico and Venezuela initiated the ATAL 2000 project[23] to coordinate the action of their Science and Technology ministries and agencies on the ground of technology prospective. The Regionalized Scenarios for Latin America project inherited from Europe's FAST[24] Program, involved academics from Argentina, Chile, Brazil and Venezuela for the construction of regional technology scenarios, with a focus on potential future integration between South American countries. Nevertheless, nearly all of these initiatives ended prematurely, without producing any political outcome[25]. ATAL 2000 was interrupted in 1990 without having produced any concrete result; no evidence was found in this work of the PTAL project having any political effect. The Regionalized Scenarios project was partly linked to the European Union; the part that was financed by this entity was successfully completed, yet its results were only used by the European Union, and the other goal (i.e. setting up a regional prospective network) was not implemented.

B.2.1. Argentina: Losing planning capacities in an unstable national context

Videla's neo-liberal shift in 1976 marked the start of a quick decline in Argentina's planning capabilities. The 1980-1982 crisis added economic chaos to political uncertainty, and the return of a Planning Secretary in 1983 did not revert the trend. Between 1983 and 1989, the Secretary published one draft economic plan and two actual plans, all of them focused on crisis management, with very few long-term considerations. Inflation climbed to 5,000% in 1989, making any long-term vision wishful thinking. The little control that the state maintained over its economy through state companies disappeared with Carlos Menem's accession to presidency in 1989. In the energy field, the emblematic oil company YPF was privatized between 1990 and 1992. The state planning department was dismissed until the return of the left-wing Kirchner government in 2003. However, the state Energy Secretary retained some planning capabilities, and even issued the first Prospective study for the Electric Sector in 1997[26], which focused on the relationship between natural gas and electricity production, and potential energy exchanges with Chile (gas) and Brazil (electricity). This first report relied on the MAED model for the projection of electricity demand, and on an optimization model developed in-house for the expansion of gas-fired electric generation capacity.

B.2.2. Brazil: Appropriation of planning practices by national monopolies

The first National Environment Policy emerged in Brazil in 1981. This initial attempt provided a new framework for energy planning, in a period when dams made up most of the new electric generation capacity (Moretto et al., 2012); however, it included few long-term views, consisting mostly in technical requirements such as zonification rules, impact assessment guidelines, etc. National planning at state level decreased slightly towards the end of the military dictatorship (1985) due to its failure to curb rampant inflation. However, the discipline was deeply rooted in the country' management practices and national companies started developing in-house strategic

[23] High Technology for Latin America 2000.
[24] Forecasting and Assessment in Science and Technology.
[25] Furthermore, none of these projects was linked to energy planning.
[26] (Secretaría de Energía, 1997).

planning programs, based on a strong prospective approach. Four early scenario experiments had considerable repercussions in the second half of the 1980s, as discussed by de Figueiredo Porto et al. (2010): the *Brazilian Economy Scenarios* designed by the National Development Bank (BNDES, 1984); the scenarios established by Eletrobras in its National Plan for Electric Energy (Tatit Holtz, 1987); the prospective analysis by Eletronorte to support its investment plan in Amazonian dams, also in 1987; and the prospective analysis conducted by Petrobras in 1989 to support its first Strategic Plan for the Petrobras System 1990-2000 (Porto, 2010). BNDES' scenarios paved the way for Brazil's transition from IMF-led recessive adjustments to its open economy era. Eletrobras' scenarios, with a 20-year horizon, inaugurated very long-term planning in the electricity sector. Eletronorte's Amazonian scenarios introduced the concept of sustainable development into the company's language and strategic reasoning. Its 1998 revision highlighted, ahead of time, the consequences of climate change for the hydroelectricity business, and the Amazon rainforest economy in general. Last, Petrobras' national oil and gas industry scenarios primarily prepared the company for the loss of its national monopoly in 1997. Although the new democratic Constitution imposed pluri-annual plans on each new government after 1988, national planning was only to retrieve its prominent role in Brazilian policymaking in 1995, with the left-wing Cardoso government.

B.2.3. Chile: The rule of 'market only' policies

As stated above, Pinochet's neoliberal dictatorship put an end to nearly all planning capabilites in Chile. The Pontifical Catholic University –Chile's second biggest university– maintained a Center for the Study of National Planning in the first years of Pinochet's era, yet its operations were gradually reduced as national planning only focused on small-scale social plans. In 1982, the little control that remained in the hands of the state through its public companies was handed over to the private sector in a wave of privatizations that impacted, among others, electric production utilities. Planning was not to be considered again as a state economic tool –let alone any kind of long-term prospective study to support it– until the return of democracy in 1990.

B.2.4. Colombia: focusing on national armed rebellion

As stated in Chapter 1, given its low debt ratio, Colombia was less impacted by the 1982 economic crisis than the rest of Latin America. The country's neo-liberal shift started in 1986, yet the best part of the reforms took place from 1990 with the Gaviria government, and never went as far as e.g. Chile or Argentina. The DNP conserved its control over state spending during the whole period. Paradoxically, the 1991 Constitution granted it responsibilities in the design of economic and social policies that furthered its role as a government advisor and investment controller, at the very point when neo-liberal reforms were reaching a climax. Indeed, contrary to most of Latin America, neo-liberal reforms in Colombia accompanied a shift in the focus of state interventions in the national economy rather than their decline. State-controlled industrialization gave way to transversal support policies targeting innovation, education and high-level training. As a consequence, four *National Development Plans* were produced between 1979 and 1994, and the Colombian prospective school continued developing to support renewed national planning.

The 1980 national decentralization trend fostered regional appropriation of prospective techniques. In 1983, following Colciencias' stimulus, the Calí region inaugurated regional strategic planning with the *Calí Valley 2000* exercise, then the National Education Institute launched its own exercise on the future of education in 1984, developing the first national mathematical models. The first *National Prospective Program 1986-2000* gave birth to more territorial plans in Calí and Medellín. However, the main focus of national prospective efforts remained reducing social exclusion and the various armed rebellions that plagued the country, and a dedicated energy planning unit did not come into existence until 1994.

B.2.5. Peru: The end of national planning

Following Velasco's deposition and the national economic and social crisis of 1974-1976, Peru's new military junta drastically restricted public expenses and planning exercises for half a decade. Despite an adverse national conjuncture, the INP grew again in the second half of the 1980s, creating specialized departments for production planning and territorial planning. The middle-term *National Plan 1986-1990*, in 1986, represented the first national planning experiment based on mathematical models according to Leiva Lavalle, although San Martin and Paz Collado (2009) consider that this first approximation cannot be assimilated to a prospective effort. The intense economic crisis that hit Peru in 1990, and the subsequent election of the neo-liberal Fujimori in 1992, ended all prospective capabilities in the country for a decade. The INP and all related agencies were dissolved.

B.2.6. Venezuela: Planning liberalism, losing the long-term focus

Cordiplan carried on losing influence between 1975 and 1989, due to the continued drop in oil prices that gradually worsened the country's economic and political situation. The office developed many planning exercises in the 1980s, some of them with a clear long-term focus conciliating a normative stance with advanced thinking on the path needed to reach long-term goals (Leiva Lavalle, 2010), yet all of them were hindered by the national conjuncture. The 1989 crisis and the subsequent neo-liberal turn put planning back at the center of the political scene, making Venezuela one of the three exceptions in Latin America in which neo-liberalism did not prove strongly detrimental to state involvement in the nation's economy. However, from 1989 to 1999 all planning capacities focused on applying the guidelines of the Washington Consensus, often downplaying strategic planning and prospective thinking. The energy sector was strongly impacted by this neoliberal shift, with a strong lack of investment reinforced by low oil prices, according to Aller (2014).

B.3. 1990-Today: Emergence of dedicated climate-energy prospective

After its prolonged absence from 1970-1990, national planning came back to Latin America with the arrival of left-wing democratic governments. Long-term and prospective studies developed in most South American countries throughout the 1990s, and dedicated energy and climate prospective started to become generalized in the 2000s, with the notable exception of Brazil, whose first dedicated energy prospective exercises date back to the 1980s. Nevertheless, due to the strategic nature of the energy sector, most countries had retained some planning capacity in this area despite the neo-liberal wave (in some cases, these planning capabilities were limited to short-term planning). Long-term planning for energy thus rose quickly in the continent; national independence bicentenaries were the occasion for South American countries to initiate extensive consultation processes and consolidate them into long-term national plans. The gas crisis between

Argentina and Chile (See Box 2-2, p.53) prompted the return of long-term planning as a central tool for policy-making in these countries; Peru, relying on regional cooperation, had addressed most of its historical lack of prospective expertise by 2010. Having stayed apart from this regional wave until 2005, Bolivia developed a series of energy planning institutions and exercises under Evo Morales' presidential mandates. Regional cooperation rose to unprecedented levels with the creation of various regional prospective institutes and exercises. The United Nations Industrial Development Organization (UNIDO) launched a Regional program for Technology Foresight that aimed at transferring the prospective methodologies used in the OECD towards Latin America, with a coordinated regional approach; the program, after a false start in 1996, was re-launched with the support of the Italian government in Trieste in 1999, with energy and climate issues as one of the collaboration's three top priorities (Medina Vásquez et al., 2014, p. 239). The Latin American Network for Prospective and Technology watch (RIAP), sponsored by the Latin American Program for Development-aimed Science and Technology (CYTED) was designed as a focal point to gather national experiences on prospective, at a regional level. A major contribution of this entity was the panorama book coordinated by dos Santos and Filho in 2009, and one of its major cooperation areas is energy prospective (San Martin and Collado, 2009). The UN Millennium Project in 2000 also supported the rise and regional coordination of national prospective institutions. Conferences organized by the Latin American Network for Prospective Studies and *Prospecta América Latina* promote academic and industrial exchanges on prospective at regional level (Medina Vásquez et al., 2014). Regional institutions dedicated to energy planning have started making extensive use of scenario analysis and disseminating it, as is the case for e.g. the OLADE[27], the UN-ECLAC[28], the CAF[29], the CIER[30] or the World Bank[31].

B.3.1. Argentina: A full-blown energy prospective sector

According to Marí (2009), the Argentine prospective sector continues to suffer from a lack of coordination between national organisms and research centers; as a consequence, a discrepancy subsists between the relatively high development of academic prospective in Argentina, and its actual application to national policy-making. However, this statement may not fully hold for energy prospective. As mentioned above, Argentina's Energy Secretary produced its first prospective study on the electric sector in 1996. This study was followed by another in 1999, for which the modeling tools of the Secretary's National Planning Direction were upgraded to a full-blown gas and electricity optimization model, namely the GASELEC model (Secretaría de Energía, 1999). The creation of the Ministry for Federal Planning, Public Investment and Services in 2003 marked the full return of planning activities in Argentina's political institutions after 30 years of partial absence. During the same year, the Energy Secretary, freshly transferred to the new Planning Ministry, issued its third long-term prospective study for the Argentine energy sector, *Prospective 2002*, inherited from the 1996 *Prospective for the Electricity Sector* report. This was the first post-crisis prospective study for Argentina's energy sector, and the panel of scenarios

[27] (Abadie et al., 2014; OLADE, 2009).
[28] (Acquatella, 2008; Medina Vásquez et al., 2014).
[29] (Franca, 2013).
[30] (CIER, 2010).
[31] (Yepez-García et al., 2010).

envisioned for energy demand remained way below actual figures, since Argentina's growth outperformed all expectations from 2002-2007. The prospective plan proved insufficient to satisfy the resulting soaring demand, triggering an energy supply crisis that had direct repercussions on energy exchanges with Brazil and Chile. Since then, Argentina continued to reinforce coordination between academic research centers (Center for Advanced Studies and Center for Future Studies in the University of Buenos Aires); independent research organizations, such as the Bariloche Foundation, which is the focal point for LEAP modeling expertise in South America; and state agencies. Beyond LEAP, MAED and GASELEC, the country also reports using the IAEA's MESSAGE model to support its energy planning exercises.

B.3.2. Bolivia: catching up with the continent

Although oil and gas have long been major contributors to Bolivia's economy, the country's first energy statistics only date from 1984, and the first explicit attempts at energy planning were not made until the 1995 *Indicative plan for rural electrification*. Both works were mainly designed, subsidized and executed by multilateral organisms: the Cartagena Agreement for the former, and the ESMAP program of the World Bank for the latter (Guzmán Salinas, 2010). The situation changed in 2006 with the election of Evo Morales as president, which put an end to two decades of liberalism. Morales created the Ministry for Planning Development (MPD) during his first weeks as president and charged it with producing a *National Plan for Development*, which was published the same year (MPD, 2006). The document heralded an era of active state intervention in the economy. The energy sector was among the top priorities of the new government, which nationalized oil production four months after taking power. A vice-ministry of energy dedicated to energy planning (VMDE) was created in 2007 and produced a long-term *Bolivian Strategy for hydrocarbons* in 2008. In 2009, the *Plan for Energy Development 2008-2027* was the first Bolivian energy planning document in 30 years, and the first unified long-term energy strategy ever designed in the country (MHE, 2009). This plan drew heavily on prospective techniques, developing and analyzing four distinct scenarios for satisfying energy demand. In 2012, this first plan was followed by an *Optimal expansion plan for the National Interconnected System* that relied on optimization tools to project potential optimal expansion pathways of the electricity generation system to match demand scenarios. A new planning cycle is currently under way, with technical support from OLADE and the Bariloche Foundation, which should produce a new *National Energy Plan* by the end of 2015. The software used by the VMDE for its 2012 plan was the OPTGEN bottom-up model. A top-down, general equilibrium model was also devised by the Institute for Advanced Development Studies (Inesad) to analyze climate change impacts on the Bolivian economy, namely the BOLIXXI model (Jemio M. and Andersen, 2014).

B.3.3. Brazil: renewed vitality of national prospective

The 1988 constitutional reform included the obligation for governments to establish pluri-annual plans, and prompted the creation in 1990 of the Secretary of Strategic Affairs (SAE). In 1991, the first *Pluri-annual Plan* (PPA) replaced previous National Development Plans, proposing national strategic orientations for the next five years. However, Brazil's economic situation was at an all-time low, the *Collor Plan*[32] had not managed to curb the country's chronic hyperinflation and had

[32] Named after the then President Collor de Melo.

added unemployment to existing problems; the focus was on short-term policies and solutions to the national crisis. In this context, the first PPA was a mere administrative exercise, lacking serious political backing, and had very little impact (Rezende, 2009). The success of the 1994 Real Plan in stabilizing the country's economy and the subsequent election of Fernando Cardoso as President did not bring back political support for public planning; the following PPAs (1996-1999, 2000-2003, 2004-2007) were increasingly extensive, yet appealed to a diminishing audience. Moreover, the PPAs worked with short-term horizons (four years) which excluded any long-term strategic planning. The SAE was replaced in 1999 by a Department of Strategic Affairs (NAE) which produced national scenario analysis in the framework of the '*Projeto Brasil 2020*' (Mota Sardenberg, 1999) and the '*Projeto Brasil 3 Tempos*' (NAE, 2004). However, dos Santos and Filho underline the lack of repercussions of the first contribution.

As in Argentina, Brazil's energy sector differs from the national context with respect to long-term planning. As highlighted previously, Brazil is home to strong public companies and near-monopolies that developed an early prospective culture, some of which subsisted in spite of the dismantlement of the government's own capabilities. Moreover, national statistics have a strong tradition, including for energy: Brazil's *National Energy Balances* have been published since 1970, well before most of the continent. On the other hand, the critical lack of state planning in the 1990s sparked a national energy crisis in 2001, referred to as the *Apagão* (the Black-Out). This crisis proved the limits of national planning strongly driven by energy companies, and triggered the return of state planning to the energy sector (Hage, 2012). The government-run Energy Investigations Company (EPE) was created in 2004 to handle all energy-related statistics and planning investigation, extending the attributions of the former General Bureau of Energy Information. In 2006, the EPE published its first *Decennial Plan for Energy Expansion*, which went on to become a reference annual publication summing up all existing details relating to the future of energy generation and transmission in the country. These annual reports are supported by a variety of national and international economic scenarios, and the capacity expansion projections are provided mainly by the energy planning models NEWAVE and MIPE, developed by the same EPE (2013). The *National Energy Plan 2030,* published in 2007, is the first long-term prospective study issued by the EPE. It considers four contrasted national scenarios resulting from a wide consultation process and relies on a wide variety of long-term planning models to deduce Brazil's final energy demand (MSR, MIPE) and supply (MESSAGE, M-REF, MELP) from initial macroeconomic assumptions. Among other recent research on energy planning issues, Brazil was also part of the MAPS (2015) and CLIMACAP (van Ruijven et al., 2015) initiatives, and the Energy Planning Department of the UFRJ is particularly active in energy and climate prospective[33].

B.3.4. Chile: The energy crisis shows the limits of the energy 'no policy'

After Pinochet stepped down, Chile began its path back to democracy in 1990 and the *La Concertación* left-wing coalition initiated the restoration of Chile's national planning institutions by creating the Planning Ministry (Mideplan) and the Ministry of the Presidency's General

[33] (See e.g. Goldemberg et al., 2014; Herreras Martínez et al., 2015; Lucena et al., 2015; Malagueta et al., 2014; Nogueira et al., 2014).

Secretary (SegPres). The Mideplan theoretically replaced the former Odeplan as the entity in charge of long-term planning; however, it initially focused on specific social programs instead of playing a strategic planning and coordination role. According to Leiva Lavalle, this role is played *de facto* by SegPres, which still coordinates the actions of Chile's various Ministries without having the legal instruments to do so. Bronfman (2009) reports a first national prospective exercise in 2001, aimed at identifying strategic national sectors and defining sectorial strategies. This first report was followed by ten specific sectorial studies over the next four years.

In the energy sector, the 2004-2008 Argentine gas crisis (see Box 2-2) showed with crude clarity the limits of Chile's 'no policy' for energy and its institutional *laissez-faire* (Rivera Urrutia, 2009). The country had flaunted the total absence of public planning and limited legislation capacity in the energy sector as a proof of the successful implementation of its 'market only' ideology since the 1980s. However, the high price paid by Chile in rush-building two LNG terminals to solve the gas crisis brought this success story to a bitter end and prompted new national attention to the sector. The Ministry of Energy was created in 2007 as an independent structure that became official in 2010, taking control of the existing National Energy Commission. Energy Prospective entered Chile's toolbox in 2008 with the first national projections of long-term energy demand by O'Ryan (2008), followed by a first study on energy-related emissions and mitigation options, based on the LEAP simulation tool (O'Ryan et al., 2010). The Energy Ministry also created a Direction for Energy Prospective and Energy Policy, which in 2014 launched the *Energía 2050* project, a participative process for defining energy scenarios and a long-term energy strategy for Chile. The Energy Center created by the Universidad de Chile in 2009 is the first large-scale initiative for federating energy-related research around a focal academic point. Among other activities, the Center provided the energy-side assessments of the MAPS Program for Chile. The country also records the use of the MESSAGE (Watts and Martinez, 2012) and SWITCH (Carvallo et al., 2014) models for long-term energy planning studies.

B.3.5. Colombia: Emergence of a dedicated national energy prospective institution

As stated in section B.2.4, the main focus of Colombia's long-term planning in the 1990s was on the social issues related to armed violence in the country. The country's principal rebellion movement, Colombia's Revolutionary Army (better known as FARC, by its Spanish acronym) still numbered around 16,000 combatants in 2001, while other illegal armed groups gathered around 14,000 men, out of a total population of 47 million. The 1997 *Destination Colombia* national prospective scenarios, designed with the help of international experts, above all targeted the potential solutions to this national crisis. However, the creation of the Mining and Energy Planning Division (UPME) in the Ministry of Mines and Energy in 1994 launched Colombia's first dedicated energy planning institution, somewhat earlier than the rest of the continent. The subsequent Second *National Prospective Program* (2003 – 2007) led to rationalizing the prospective capabilities dispersed around the country and extended the attributions, abilities and vision of the DNP, turning it into an effective pilot entity, as national considerations shifted towards long-term multi-sectorial planning. The first 15-year *Reference Plan for the Expansion of Generation and Transmission* (UPME, 2004) was based on national macroeconomic scenarios by the DNP, and has been annually updated since. This publication is now supported, for the representation of energy supply operations, by the SDDP model (UPME, 2014). In 2005, as the DNP launched its national middle-term plan *Vision for the 2nd Centenary of Colombia: 2019*, the UPME inaugurated its own first long-term energy scenarios, described by Smith et al. (2005). The first full-blown very long-term exercise designed by the UPME, *Colombia: Energy Principles 2050* (UPME, 2015), was issued in 2015. The scenario analysis presented in this document is backed on its demand side by the MAED model. National exercises of long-term energy planning have also been developed using LEAP and MarkAl models[34].

[34] See, for example, (Cadena et al., 2008; Calderón et al., 2015; Delgado et al., 2014).

The Chile-Argentina gas crisis[35]

With low national reserves of oil and gas, Chile has historically been heavily dependent on energy imports to run its mining-based, energy-intensive economy. The 1970s oil crises motivated the country to diversify its energy mix: coal and hydroelectricity increased their share of energy production in the 1980s, along with oil derivatives. In the early 1990s, domestic hydrocarbon production provided less than 8% of national demand, Chile's indigenous coal production was almost entirely used to provide energy to its northern copper mines, and hydro energy was penalized by a series of droughts that triggered repeated rationings. The country started looking for alternatives to fuel its then soaring growth[36]. At the same time, Argentina was increasing its gas production and the country's gas reserves were considered virtually endless. Importing gas from Argentina to Chile was thus considered a good option by both countries. It allowed Chile to avoid buying hydrocarbons from unstable international markets; to reduce problematic air pollution in Santiago; and to reduce the extreme economic concentration of its energy sector. Exporting gas guaranteed Argentina a stable outlet for its national production and was likely to attract private capital in a privatization context[37] in an industry of strategic interest. It was also, for both countries, a means to reinforce neighborly ties following the near-war of 1978.

The first legal basis for Argentina's gas exports to Chile was included in the 1991 Argentina-Chile Economic Cooperation Agreement, and then modified in 1994-1995. The new version excluded some measures favoring YPF and included a clause of non-discrimination between Chilean and Argentine consumers. Once the legal agreement was signed, two consortiums battled for one year (1994-1995) over the construction of the gas pipe in what has been called the Pipe War (*La Guerra de los gasoductos*). The final winner, *GasAndes*, constructed a 463-km gas pipe below the Andes Mountain and various gas-fired electric plants, for a total investment of US$ 1.5 billion. These investments were backed by 25-year supply contracts established by *GasAndes* with Chilean gas distributors and electricity generators. The full installation became operational in 2007.

However, by 2003 Argentina was emerging from the severe 1998-2002 economic crisis and experiencing record growth rates. Domestic energy demand skyrocketed, and at the same time new gas reserve assessments showed that previous estimates had been largely exaggerated. In March 2004 (beginning of southern hemisphere winter), Argentina issued a decree suspending gas exports if and when the domestic market required, abolishing the non-discrimination clause of the 1995 Agreement, and sparking a 4-year crisis between the two countries. Gas supply reductions grew increasingly frequent and significant. In May 2007, for the first time, Argentina totally cut off its gas supply to Chile. The situation worsened in July and August and, despite an emergency agreement between the presidents of Chile and Argentina, 2008 and 2009 featured ever-longer outages. Residential Chilean consumers started being directly impacted by the outages, in the middle of winter, and the crisis evolved into a high-level political one, for Chile and for its relationship with Argentina.

In September 2009, Chile's new liquefied natural gas (LNG) gasification terminal in Quintero began operation, followed by a second (Mejillones) a few months later. In order to build these two plants in a very short time, Chile turned to consortiums led by its national champions CODELCO (copper mines) and ENAP (hydrocarbons) and spent US$ 2 billion more than the cost of the *GasAndes* pipe (MasEnergía, 2011). Various authors later analyzed the crisis as a logical consequence of the absence of state planning on the Chilean side, which allowed very short-term views from Chilean private stakeholders to drive national energy policy; and state intervention on gas tariffs, coupled with exacerbated liberalism, which removed the incentive to invest in exploration in Argentina. The crisis prompted the return of Chile to state energy planning, and prefigured YPF's re-nationalization in 2012.

Box 2-2: The Chile-Argentina gas crisis

[35] For more information, please refer to (Huneeus, 2007; Rodrigues and Gadano, 2012).

[36] Between 1986 and 1997, Chile's compounded annual growth rate was over 7.5%, leading to a more-than-doubling of national GDP in ten years (Bértola and Ocampo, 2010).

[37] The 1991 Agreement was signed during Menem's liberal mandate. Argentina started privatizing its state oil company (YPF) one year later.

B.3.6. Costa Rica: The return of national prospective

In Costa Rica, the Secretary for Sub-sectorial Energy Planning became the Sectorial Direction for Energy (DSE) in 1992, as energy planning became a state priority once more. The DSE maintained the activities and responsibilities of its parent institution, among them to '*formulate and promote integral national energy planning*' (Alvarado, 2008), and was transferred to the new Energy and Environment Ministry in 1995. In 2012, it issued the *6th National Energy Plan*, analyzing energy scenarios for the 2012-2030 period (DSE, 2011). This sixth plan was deemed heavily flawed due to a lack of participation from many major national energy stakeholders, and a seventh plan is due for publication in late 2015, or 2016. The *6th National Energy Plan* relies on the LEAP and MAED modeling tools for its demand and emissions analysis, and the DSE also reports the use of in-house models as well as the MESSAGE model for other investigations (Alvarado, 2008). The other major Costa Rican energy actor, the Costa Rican Institute for Electricity (ICE) is Costa Rica's state monopoly for electricity production and distribution. Based on its own energy planning models (OPTGEN and SDDP), it publishes the 20-year horizon *Plan for the Expansion of Electricity Generation*. The latest edition, covering 2014-2035, puts a special emphasis on so-called 'expansion pathways' (*rutas de expansión*) as a portfolio of strategic behaviors for facing future variations in demand scenarios (ICE, 2014).

B.3.7. Peru: Rebirth of national prospective and creation of CEPLAN

After disappearing during the neo-liberal period, planning activities took off again in Peru in the 2000s, initially in a disorganized and decentralized way. The creation of the Multisectorial Commission for Industrial Technology Prospective in 2001, in the framework of the *Latin America Technology Foresight* UNIDO Program, was a first step towards consolidating Peru's national expertise in prospective and long-term planning at national level. It led to the creation in 2005 of the National Division for Strategic Planning (Ceplan), which replaced the former INP. However, the Ceplan did not start operating until 2009[38], producing in 2010 the *Strategic Plan for National Development – Plan Peru 2021* (CEPLAN, 2010), a fundamental document listing national strategic priorities and prompting the creation of various state planning agencies.

In the field of energy, a national attempt at energy planning is recorded in 2002 with the *Energy Plan 2002-2005*, mostly supported by the expertise of the Bariloche Foundation. The (re-)creation of a national long-term planning entity in Peru was spurred by the 2004 and 2008 energy crises, when the vertiginous increase of energy prices and various black outs prompted the return of the Energy Ministry's intervention in Peru's energy sector. This intervention initially took the form of national tenders in 2006 (Luyo, 2012), then an extensive *Reference Electricity Plan 2008-2017* (MINEM, 2009), and lastly a 20-year *Strategy for the Development of Peru's Energy Sector* in 2009, still largely supported by the Bariloche Foundation's expertise. The *Peru 2021* plan prompted the creation, in 2010, of the General Direction for Energy Efficiency (DGEE), which is currently in charge of national energy planning in Peru. A *National Energy Policy 2010-2040* was adopted the same year[39], giving birth to national long-term projections of the energy mix over the

[38] Ceplan did not receive any actual funding or personnel until 2009. From 2005 to 2009, it could be said that this institution only existed on paper.
[39] (República del Perú, 2010).

2011-2040 horizon by Ceplan (Alejos, 2011), based on the design and analysis of mid- and long-term scenarios for Peru's energy mix (two mid-term scenarios and three long-term ones). Peru's most recent mid-term planning exercise is the *National Energy Plan 2014-2025*, published in 2014. Peru's *Reference Electricity Plan*s are supported by OLADE's SUPER planning model and an in-house economic tool –PERSEO– for the long-term part; instant energy flows are computed using the WIN-FDC model. Long-term scenarios in the 2010-2040 Ceplan report are translated into actual energy flows and investment decisions by means of the LEAP model; and the *National Energy Plan 2014-2025* reports the use of a 'linear optimization model minimizing the cost of energy supply' which may once again be SUPER-OLADE.

B.3.8. Venezuela: Reduction of prospective capabilities in Chavez's era

Chávez's ascension to power in 1999 led to profound transformations in Venezuela's state planning structure. Cordiplan became the Planning Ministry, later the Ministry of People's Power for Planning (MPPPF), with extended duties. The implementing agency of this new ministry is called the National Planning System. A national planning school was set up in 2006 to provide the ministry with planning experts, as national planning became more multi-scale and long-term oriented. A national plan, the so-called *Simon Bolivar Project – First Socialist Plan* was issued in 2007 for 2007-2013 and built around seven main strategic targets, one of which was to turn Venezuela into a global energy leader in the field of fossil fuels (Leiva Lavalle, 2010).

However, energy was little impacted by the consolidation of national planning capacities, since Venezuela's oil champion PDVSA was granted extended autonomy to serve Chávez's petro-policy. In the electricity sector, the centralization and nationalization of all energy companies into a state monopoly (CORPOELEC) in 2007 went hand in hand with an over-politicization of the sector. The main result, according to Aller (2014), was that the company's management was entrusted to non-professionals who deepened the ongoing electricity crisis, in the midst of increasing corruption and bureaucratization. A new Ministry for Electric Energy was created in 2009, only adding to the general confusion. In 2014 the country started massively rationing electricity consumption, reducing e.g. work hours from 8 to 6 hours a day in public ministries. Supply quality dropped, blackouts multiplied and outage times began to rank among the highest in the world; the government started censoring national statistics, making any planning attempts purely theoretical. The two national plans published by Venezuela's energy ministry in the last decade make use of scenario analysis techniques, yet they are based on rudimentary national energy balances and they do not record the use of any dedicated energy planning tool; the projections presented in the first study (MEP, 2005) are based on fairly straightforward macroeconomic regressions, while the 2014 projection (MPPEE, 2014) does not provide much detail on its data sources, and none at all on its modeling methodologies. A national attempt at model-supported long-time planning took place in 1997, prior to Chávez's election. At that time, the LEAP and ENPEP models had been deployed to support a ministerial study of the abatement options available to Venezuela, in the framework of the country's participation in UNFCCC talks (Pereira et al., 1997). The LEAP tool was used again in 2012 for an analysis of Venezuelan power sector scenarios (Bautista, 2012), yet the study was actually conducted by the German Flensburg University, and the country model had to be built from scratch again.

B.3.9. Cuba: Generalizing prospective in the post-USSR era

Scenario use generalized in Cuba in the 1990s, following the fall of the Soviet Union and the end of cheap oil imports (Vazquez et al., 2015). However, dedicated long-term energy prospective only appeared in 2001 in a study supported by tools from the ENPEP suite, such as MAED and WASP (Pérez Martín and López López, 2001). Somoza Cabrera and Álvarez (2012) proposed an updated base scenario, still based on the ENPEP suite, yet there is no evidence that energy prospective in Cuba is a fully developed investigation area. A MarkAl model was developed for the analysis of Cuba's power sector expansion, yet this investigation was funded by USAID and executed by American experts (Wright et al., 2009). The organisms related to energy planning in Cuba are the Ministry of Economy and Planning, the Cuban Observatory of Science and Technology and the Center for the Management of Information and Development of Energy (CUBAENERGÍA).

B.3.10. Ecuador: Long-term energy plans since 2002

The National Electricity Council (CONELEC) started publishing mid-term plans (ten years) for the expansion of the energy sector in 2002. These plans are now published annually; they consider four contrasted demand scenarios and their expansion estimates are based on the OPTGEN and SDDP models for the latest reports (MEER, 2012). Long-term prospective exercises with a 2030 horizon were also conducted under the leadership of the Ministry for the Coordination of Strategic Sectors, formulating long-term demand scenarios and evaluating their impact by means of the LEAP model (MICSE, 2012). This study was also performed with the technical support of OLADE and the Bariloche Foundation, however, Ecuador started an extensive national appropriation process for prospective techniques and tools in 2014 (INER, 2014). Also in 2014, the country published its first *National Energy Balance* after 25 years without such a publication. This balance was published again in 2015 and should become an annual publication.

B.3.11. Guatemala: First attempt at national, inclusive, strategic planning

Guatemala's Planning General Division (SEGEPLAN) issued a 20-year development plan, "*K'atun: Our Guatemala, 2032*" in 2013. This first effort is a start towards setting up a national planning system and specific sectorial planning for strategic sectors such as energy, according to Medina Vásquez et al. (2014); no previous investigations related to energy planning were found during this work.

B.3.12. Panama: Building up national planning capacity

Panama's National Energy Secretary produced a 15-year energy plan in 2009, supported by the SUPER-OLADE and SDDP models for the calculation of least-cost generation expansion based on national macroeconomic scenarios (SNE, 2009). The country is currently working with the UNDP on a long-term national energy plan 2015-2050. LEAP methodology has been applied by the Canadian researchers McPherson and Karney (2014) to study energy supply options in Panama up to 2026.

B.3.13. Paraguay: designing the first national energy prospective study

Paraguay's planning institution, the Technical Division for Planning produced in 1992 a national energy plan with medium term views (14 years) based on scenario analysis (STP, 1992). This plan was largely supported by the UNDP and was not updated for a long time when this support stopped. The next effort of long-term planning dates from 2004, with the 10-year national *Strategic Plan for the Electric Sector* (STP, 2004). This plan builds on short-term (five-year) planning studies conducted in 2003 by the National Electricity Administration (ANDE). López Flores and Lucantonio (2007), however, consider that the 2004 plan was a failed attempt at energy planning, given the lack of implementation by the national Vice Ministry of Mines and Energy. This situation may be changing as in 2013 Paraguay designed its first *National Energy Balance* accounting for useful, and not just final, energy, in what is described as 'a first step towards national energy prospective'. The national energy prospective process, triggered by the 2013 extended energy balance and the 2014-2030 *National Development Plan*, is currently being designed with technical support from the Bariloche Foundation.

B.3.14. Uruguay: Recent emergence of national energy planning

State planning has been continuously present in Uruguay's national landscape since 1960 through the Planning and Budget Office. However, the emergence of an in-house planning capability for energy is quite recent. The country adopted a firm energy policy document in 2008, including the obligation for the Ministry of Industry, Energy and Mines to '*develop energy planning based on modern mathematical planning tools*' (MIEM-DNE, 2008). The first energy prospective study conducted by the MIEM was produced in 2011, after two years spent training national experts. It relied on two scenarios and considered a 20-year horizon (2008-2030); the computation of quantitative impacts was carried out using the LEAP planning system. This energy prospective capacity building reached its final phase with the publication of Uruguay's full-blown *Energy Prospective Study 2014*, divided into demand-side scenarios built with LEAP (MIEM, 2014) and supply-side scenarios (yet to come). The National Administration for Fuel, Alcohol and Cement (ANCAP) developed its own energy prospective study, *Energy Prospective 2030*, in 2013. This study was based on four highly contrasted scenarios for the future state of the world; no mathematical modeling support is mentioned. LEAP was also used by the *Uruguay's Infrastructure 2030* initiative (Blanco et al., 2013); the UN-ECLAC also used it to model energy demand for its *Economics of Climate Change for Uruguay* report (ECLAC, 2010a).

B.4. Interest of a regional planning tool

The previous paragraphs proposed a historical overview of energy prospective and energy in Latin America in the past century, highlighting recent works and their associated models. Table 2-2, at the end of this chapter, extends this panorama with a review of the main energy models used in the region, together with a characterization following the criteria of paragraph A.2. Figure 2-4 below summarizes this review, focusing on the technological and geographical precision of the models studied: each model is associated with an ellipse featuring its overall perimeter and maximum detail, both from a sectorial and geographical prospect. Four main categories emerge through this representation:

Category 1: **Project-oriented models** (HOMER, SAM, RETSCREEN): These models are not, strictly speaking, prospective tools. Their planning capabilities focus on specific projects, both temporally and geographically. As a consequence, they cannot be used as a basis for evaluating contrasted, long-term, multidimensional scenarios. However, they provide a very useful plant-level analysis which can then be aggregated and inputted into national planning tools to provide country-level prospective insights (see e.g. Malagueta et al., 2014).

Category 2: **National energy-specific planning tools** (MARKAL[40], LEAP, MESSAGE, SWITCH, OPTGEN): Models from this family aim at assessing in a technology-rich way national pathways for energy investments and plant operation. Their technological perimeter goes from power production only to a representation of the entire energy sector. Although most models from this family rely on aggregated plant representation, some models –above all those used for mid-term expansion plans– go as far as detailed plant representation. National energy-specific models make use of insights from cat. 1 models to further increase their technological realism, while cat. 3 models provide them with a dynamic reaction of the overall economy (Wills, 2013; Winkler et al., 2014).

Category 3: **National economy-wide models** (MEMO, IMACLIM, MCM, BOLIXXI): These models are the top-down counterpart to cat. 2 models. Most of them include a vision of the whole nation's economy, yet their representation of energy is often restricted to a limited number of subsectors. These models are well adapted for representing the links between the energy system and the rest of the economy. They benefit from the technological realism of cat. 2 model outputs and their own outputs are used as inputs by cat. 2 models, as mentioned above.

Category 4: **Global pseudo-hybrid models** (POLES, TIAM, EPPA, WEM, GCAM, MESSAGE)**:** The focus varies slightly across the models listed here, yet they all provide relatively good technological precision, with a limited to very limited representation of the economy. They cover the whole world yet their geographical detail is often limited to a 1-region South America, and even the most detailed models (POLES, TIAM-ECN) do not discern more than 4 regions on the continent. These models deliver useful insights into South America's participation in e.g. climate global action (Calvin et al., 2015) or international energy trade (Babonneau et al., 2012), yet they fall short of assessing national scenarios and intra-regional flows.

[40] The MARKAL paradigm is the ancestor of the TIMES one on which our Latin American model is built (see chapter 3, part B).

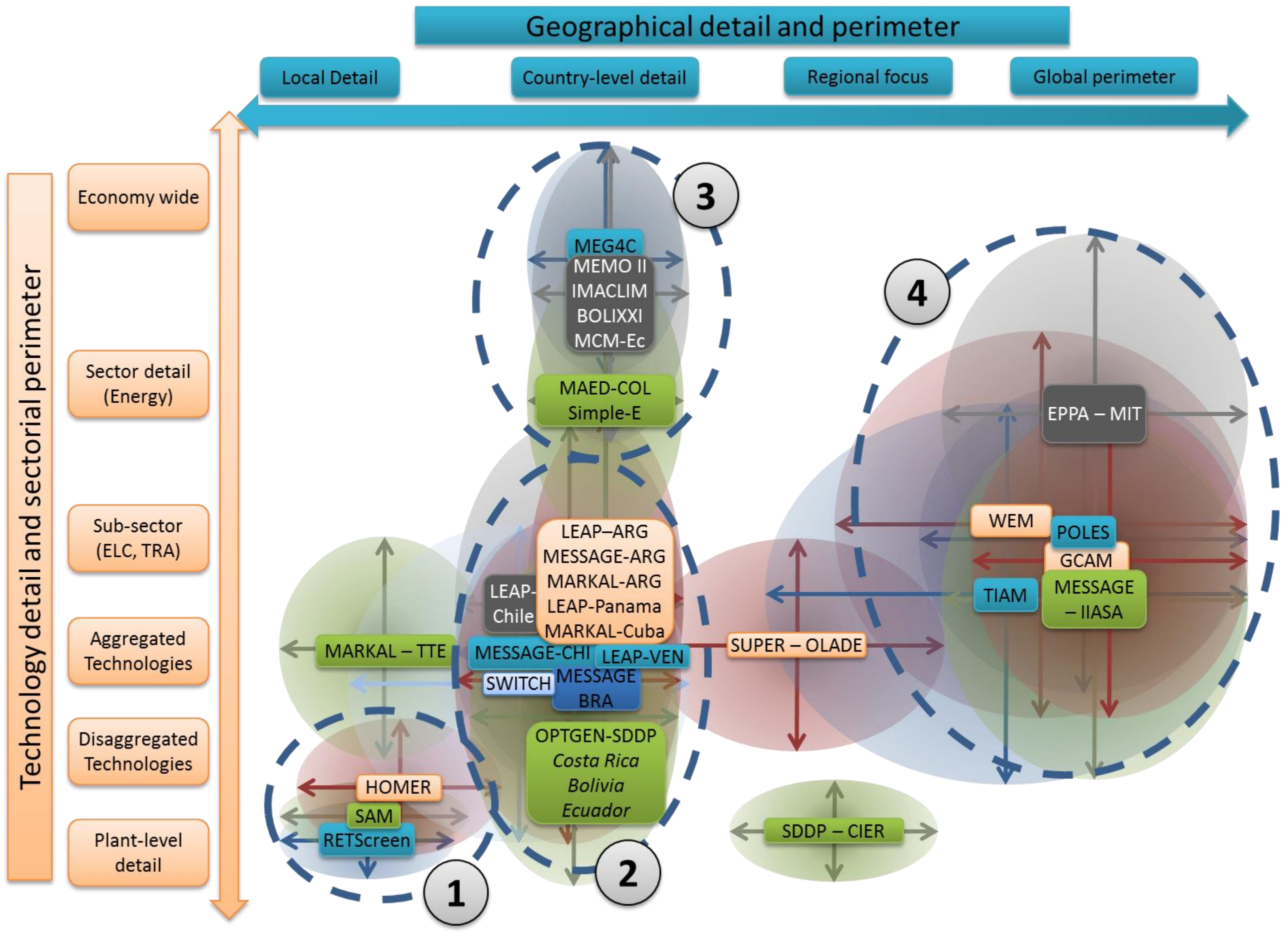

Figure 2-4: South American models – An overview

Global models benefit from regional detailed visions which refine their own insights; in turn, they enrich regional models with a dynamic rest-of-world. Nevertheless, the only model bridging the gap so far between global and national scales is OLADE's SUPER model (and, to some extent, CIER's SDDP). Some projects such as MAPS (*Mitigation Action Plans and Scenarios*) (Winkler et al., 2014) or the Climate Change Economics project (*Economía del Cambio Climático*) (ECLAC, 2010b) look at energy planning in a coordinated way, but from a national perspective. Such projects acknowledge the need for a regional perspective to tackle region-wide issues, yet they do not go so far as a unified representation of the Latin American region. Other authors, such as Acquatella (2008), consider the energy sector of the whole of Latin America, but lack the backing of a dedicated modeling tool. The global bottom-up model developed by Aboumahboub *et al.* (2012) considers a multi-regional (7-region) South America, yet its sectorial focus is on electricity only. On the other hand, global TIAM models cover the whole energy sector, yet the most detailed version (TIAM-ECN) aggregates Central and South America into four of its twenty regions (Calderón et al., 2015). Among the thirteen reference global models considered in the European AMPERE project (Kriegler et al., 2015), POLES features the most detailed disaggregation of Latin America, with four regions (Brazil, Argentina, Central America and the Rest of South America). The international CLIMACAP-LAMP project proposed a multi-model comparison exercise involving models with very different paradigms, time spans, geographical precision, or underlying assumptions (van Ruijven et al., 2015). This exercise was highly interesting as it spanned the existing range of assumptions and projections for South America, yet it was based on either national or global models, neither of which was specifically designed for regional studies. As a consequence, Latin America as a region remains either partially or coarsely represented. This state of things in Latin American is quite different from the European situation as presented by Figure 2-5, where the continuum from global to sub-national scale models is almost perfect. Together with the shared regional energy features and challenges highlighted in the previous chapter, these efforts towards regional energy prospective and the scarcity of regional dedicated models prompted the construction of the *TIMES-América Latina y el Caribe* (T-ALyC, TIMES for Latin America and the Caribbean) model.

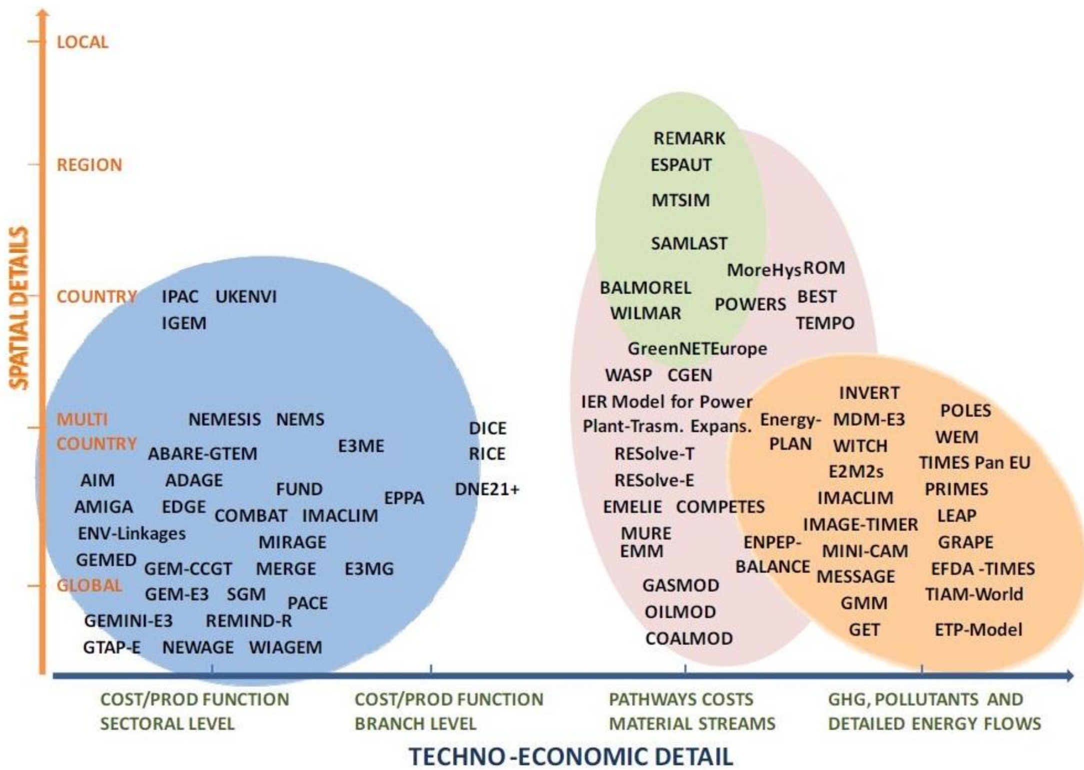

Figure 2-5: Models used for European energy prospective (Source: Manna, 2010)

Model Name	Institution	Focus	Approach	Math paradigm	Temporal horizon and scale[41]	Techno-economy coverage and detail[42]	Geographical coverage and detail[43,44]	Some references
SUPER	OLADE	Energy Supply	Bottom-up	Linear optimization	TH: 2030 TS: 1-Year	TP: Power sector TD: Agg. Tech.	GP: LatAm GD: Countries	(Betancourt and CNE, 2004; CNEE, 2009; Yepez-García et al., 2010)
SDDP-CIER	PSR	Energy dispatch	Bottom-up	Simulation (Dyn. Stoch.)	TH: 2017 TS: 1-Year, 5 timeslices	TP: Power sector TD: Plant-level	GP: LatAm GD: 8-region LAC	(CIER, 2010; CNEE, 2009)
WEM	IEA	Energy SUPP + DMD	Hybrid	Simulation	TH: 2040 TS: 1-Year	TP: Full energy TD: Agg. Tech.	GP: World GD: BRA/CHI/ Rest of LAC	(IEA, 2014a, 2014b)
TIAM	ETSAP	Energy Supply	Bottom-up (P-Hybrid)	Optimization (Linear Prog.)	TH:2050/2100 TS: 5-year, 18 timeslices	TP: Full energy TD: desagg. Tech	GP: World GD: BRA/COL/ ARG/rest of LAC	(Ricci and Selosse, 2013; van Ruijven et al., 2015)
MESSAGE	IIASA	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2050 TS: 5-Year	TP: Full Energy TD: desagg. Tech	GP: world GD: 1-region LAC	(IDB, 2013; Riahi et al., 2012)
EPPA	MIT	Climate policies	Top-Down (P-Hybrid)	Optimization	TH: 2100 TS: 5-Year	TP: Full Economy TD: agg prod func	GP: World GD: 1-region LAC	(Lucena et al., 2015; Paltsev et al., 2005)
GCAM	UMD	Climate policies	Bottom-up (P-Hybrid)	Simulation	TH: 2100 TS: 15-year	TP: Full Energy TD: Aggreg. Tech.	GP: World GD: 1-region LAC	(Calvin, 2011; Lucena et al., 2015)

[41] TH: Time Horizon; TS: Time scale
[42] TP: Techno-economy perimeter; TD technological detail
[43] GP: Geographical perimeter; GD: geographical detail
[44] The disaggregation informed here for global models corresponds only to Latin America and the Caribbean and its subregions.

Model Name	Institution	Focus	Approach	Math paradigm	Temporal horizon and scale[41]	Techno-economy coverage and detail[42]	Geographical coverage and detail[43,44]	Some references
Phoenix	UMD	Climate policies	Top-Down	Simulation (recursive equilibrium)	TH: 2100 TS: 5-year	TP: Full Economy TD: Aggregated Tech.	GP: World GD: BRA/CYC/ rest of LAC	(Lucena et al., 2015; Wing et al., 2011)
POLES	CNRS	Energy SUPP + DMD	Top-Down	Simulation (Econometric)	TH: 2050 TS: 1-Year	TP: Full energy TD: Aggreg Tech.	GP: World GD: BRA/CYC/ rest of LAC	(Kitous, 2006; Kitous et al., 2010; Lucena et al., 2015)
LEAP (Argentina)	FB	Energy SUPP + DMD	Bottom-up Top-Down	Simulation (Accounting + Econometric)	TH: 2030 TS: 5-year, timeslices	TP: NRJ / no extraction TD: Disagg. Tech.	GP: Argentina GD: Argentina	(Di Sbroiavacca et al., 2015; Escenarios Energéticos, 2012)
MESSAGE (Argentina)	IAEA	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2025 TS: 6-year, 24 timeslices	TP: Full Energy TD: Aggreg. Tech.	GP: Argentina (w/o Patagonia) GD: 1-region	(Giubergía et al., 2003)
MARKAL (Colombia)	UniAndes	Energy Supply	Bottom-up (P-Hybrid)	Optimization (Linear Prog.)	TH: 2045 TS: N/A	TP: Full energy TD: Disagg. Tech.	GP: Colombia GD: 1-Region	(Cadena et al., 2008; Cadena and Haurie, 2001; Delgado et al., 2014)
MARKAL – TTE AMVA	UniAndes	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2020 TS: 2-Year	TP: Transport TD: Disagg. Tech.	GP: Aburra Valley GD: 1-region	(Janna et al., 2007; Vásquez et al., 2006)
MEG4C	DNP	Macroeconomic policy	Top-Down	Simulation (Equilibrium)	TH: 2040 TS: 5-year	TP: full economy TD: 15 sectors	GP: Colombia GD: 1-region	(Delgado et al., 2014)

Model Name	Institutio n	Focus	Approac h	Math paradigm	Temporal horizon and scale[41]	Techno-economy coverage and detail[42]	Geographical coverage and detail[43,44]	Some references
MAED (Colombia)	DNP	Demand analysis	Top-Down	Simulation (Accounting)	TH: 2050 TS: Hourly	TP: NRG demand TD: Sub-sector	GP: Colombia GD: 1-region	(IAEA, 2007; UPME, 2015)
LEAP (Chile)	Poch Ambiental	Energy Supply-Demand	Bottom-up Top-Down	Simulation (Accounting + Econometric)	TH: 2030 TS: 1-Year	TP: Full energy TD: Aggreg. Tech.	GP: Chile GD: 4-region	(O'Ryan et al., 2010; Poch, 2010)
MEMO II (Chile)	IBS	Climate policies Macroeconomi c Assessment	Top-Down	Simulation (Equilibrium)	TH: 2050 TS: 1-Year	TP: Full Economy TD: Aggreg. Tech.	GP: Chile GD: 1-Region	(MAPS Chile, 2014)
MESSAG E (Chile)	PUC	Energy supply	Bottom-up	Optimization (Linear Prog.)	TH: 2030 TS: 1-yr	TP: Power sector TD: Aggreg. Tech.	GP: Central Chile GD: 1-region	(Watts and Martinez, 2012)
SWITCH (Chile)	Cal	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2030 TS: 2-Year, 288 Timeslices	TP: Electricicty TD: Disagg. Tech.	GP: Chile GD: 23-region	(Carvallo et al., 2014)
MESSAG E (Brazil)	EPE, COPPE	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2040 TS: 5-Year 20 Timeslices	TP: Power sector + Upstream TD: Disagg. Tech.	GP: Brazil GD: 3-region	(Malagueta et al., 2013; EPE, 2007; Margulis et al., 2011)
IMACLIM (Brazil)	COPPE	Climate policies	Top-down (Hybrid)	Simulation (Equilibrium)	TH: 2030 TS: N/ A	TP: Full Economy TD: 19 sectors	GP: Brazil GD: 1-region	(Wills, 2013; Wills et al., 2014)
BOLIXXI	Inesad	Climate policies	Top-Down	Simulation (Equilibrium)	TH: 2100 TS: 1-Year	TP: Full Economy TD: 13 sectors	GP: Bolivia GD: 1-region	(Jemio M. and Andersen, 2014)

Model Name	Institution	Focus	Approach	Math paradigm	Temporal horizon and scale[41]	Techno-economy coverage and detail[42]	Geographical coverage and detail[43,44]	Some references
LEAP (Panama)	UToronto	Energy Supply-Demand	Bottom-up Top-Down	Simulation (Accounting + Econometric)	TH: 2026 TS: 1-Year	TP: Power sector TD: Aggreg. Tech.	GP: Panama GD: 1-region	(McPherson and Karney, 2014)
MCM-Ecuador	Millennium Institute	Climate policies	Top-Down	Simulation	TH: 2025 TS: N/A	TP: Full economy TD: 17 subsectors	GP: Ecuador GD: 1-Region	(Bassi and Baer, 2009)
MARKAL (Cuba)	IRG	Energy Supply	Bottom-up	Optimization	TH: 2025 TS: 3-Year	TP: Power sector + Upstream TD: Aggreg. Tech.	GP: Cuba GD: 1-region	(Wright et al., 2010)
LEAP (Dom. Rep.)	SEI	Energy Demand	Top-down	Simulation (Econometric)	TH: 2015 TS: 1-Year	TP: NRG demand TD: Aggreg. Tech.	GP: Dom. Rep. GD: 1-region	(Betancourt and CNE, 2004)
Simple-E	RG Consult.	Energy Demand	Top-Down	Simulation (Econometric)	TH:2040 TS: 1-Year	TP: NRG Demand TD: Subsectors	GP: Peru GD: 1-region	(RG Consultores et al., 2012)
OPTGEN/ SDDP (Costa Rica)	PSR	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2035 TS: 1-Year, Monthly Optn.	TP: Power sector TD: Plant-level	GP: Costa Rica GD: 1-region	(ICE, 2014)
OPTGEN/ SDDP (Bolivia)	PSR	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2022 TS: 1-Year, Monthly Optn.	TP: Power Sector TD: Plant-level	GP: Bolivia GD: 1-region	(MHE, 2012)

Model Name	Institution	Focus	Approach	Math paradigm	Temporal horizon and scale[41]	Techno-economy coverage and detail[42]	Geographical coverage and detail[43,44]	Some references
OPTGEN/ SDDP (Ecuador)	PSR	Energy Supply	Bottom-up	Optimization (Linear Prog.)	TH: 2022 TS: 1-Year, Monthly Optn.	TP: Power Sector TD: Plant-level	GP: Ecuador GD: 1-Region	(MEER, 2012)
LEAP (Venezuela)	EUF	Energy Supply	Bottom-up	Simulation (Accounting)	TH: 2050 TS: 10-Year	TP: Power Sector TD: Aggreg. Tech.	GP: Venezuela GD: 1-region	(Bautista, 2012)
RETScreen-EC	NRCAN	Project analysis	Bottom-up	Simulation	TH: Project life TS: N/A	TP: NRJ project TD: Project detail	GP: NRJ project GD: Project detail	(Soria, 2014; Soria and Carvajal, 2013)
SAM	NREL	Project analysis	Bottom-up	Simulation	TH: project life TS: Hourly	TP: NRJ project TD: Project detail	GP: NRJ project GD: Project detail	(Blair et al., 2014)
HOMER	NREL	Microgrid (supply)	Bottom-up	Optimization	TH: 1 year TS: Hourly	TP: micro-grid TD: Individual Tech.	GP: Micro-grid GD: Individual Tech	(Lambert et al., 2006)

Table 2-2: Review of Latin American energy planning models

Concluding remarks

Prospective and long-term planning have developed in an unequal way across South America during the past century. Broadly speaking, we can identify three main periods from 1930 to now: the first 50 years were a time of experimentation in which systematical planning developed over the whole continent, lifted towards the end of the period by the state-controlled industrialization trend. Then the right-wing dictatorships that ran from 1970 to 1990 adopted two contrary stances towards long-term planning: whereas countries such as Colombia and Brazil continued to rely on strong planning capabilities while moving towards economic liberalism, state planning all but disappeared in countries like Chile and Peru. The result of this episode today is a continent with highly unequal national planning capabilities and institutional settings. However, the past decade has seen an overall positive trend for energy prospective, with the emergence of numerous institutions, investigations and tools dedicated to long-term planning. On specific energy aspects, the sector benefitted from its strategic nature and the loss of planning capabilities was somewhat less than for other economy sectors. That said, some aspects of energy prospective are still under-investigated today. In relative terms, a comparison between European and Latin American energy prospective shows that the regional focus that is well-developed in Europe is nearly absent from South American considerations to date. The next chapter presents the regional prospective model developed to address this gap: *TIMES-América Latina y el Caribe*, or T-ALyC.

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Chapter 3: Construction of a dedicated South American prospective model

Essentially, all models are wrong, but some are useful.
– George Box

This chapter is dedicated to presenting the first version of the *TIMES-América Latina y el Caribe*, or T-ALyC, model, whose construction is the heart of this PhD. The aim of such a model is to consider regional energy challenges with a real regional focus which is not provided by aggregated global or specific national models. T-ALyC is a multiregional TIMES model, derived from TIAM's description of the world's *Reference Energy System* (RES). Creating T-ALyC out of such a model involved three major contributions: designing an *ad hoc* regional disaggregation allowing energy prospective investigations at a regional scale; updating the existing RES and data structure to get rid of outdated or inadequate parameters and representations; and finding and aggregating the information associated with South American energy potentials and final service demands. The first part of this work consisted in identifying the potential challenges for South America's energy sector and key drivers for regional energy trends. Potential challenges were detailed in Chapter 2, Section F. Sub-regional energy trends are described part A of this chapter, highlighting among others the key role and internal disparities of Brazil, the pivot position of Bolivia, Paraguay, Uruguay, and the proximity and divergences of Chile and Argentina. Given the size of the model, individually describing all of the modifications from TIAM to T-ALyC is a cumbersome task which was conducted separately, in (Postic, 2014). Instead, Part B of this chapter presents the general rules for TIMES energy systems modeling, and the specific TIAM experiment; Part C focuses on describing T-ALyC's final architecture and potentials for primary energy supply, specifying the assumptions underlying energy demand projections, and describing energy trade between the model's regions (structure and costs).

A Organizing South American energy trends

A.1. Brazil: A heavyweight with strong internal disparities

Brazil is the fifth country in the world in terms of population (nearly 200 million people) and the sixth in terms of GDP. It accounts for about 40% of the continent's GDP and energy consumption (cf. Figure 3-1). The second economy of South America, Argentina, is three times smaller.

Figure 3-1: Share of CSA countries in regional GDP and primary energy consumption (BP, 2014; CIA, 2012)

Brazil is also the most prominent political figure in South America. After a long stint as the *de facto* leader of the MERCOSUR alliance (Roett, 2012), it was the country which prompted the creation of UNASUR with the 2000 Brasilia Treaty (Sorj and Fausto, 2011)[45]. It has historically taken a leading role in international environmental negotiations, ever since the 1992 Rio Earth Summit (see Chapter 4). In the energy domain, Venezuela, which boasts the biggest oil reserves in the world, has long been the only counterweight to Brazil's hegemony in South America (Ríos Sierra, 2011). However, even this position might be significantly weakened by the gigantic 'pre-salt' offshore oil fields recently discovered off Brazil's coastline (Pottmaier et al., 2013).

Accurate modeling of the country's energy behavior, and some insights into its inner dynamics, thus seem of paramount importance in capturing the energy trends in South America. According to Perobelli and Oliveira (2013), "*few studies exist that address the energy sector in Brazil in a spatial dimension, yet [...] the heterogeneous spatial dimension of the recent Brazilian economic development and the large discrepancies among Brazilian regions reinforce the importance of this kind of study*". Following the same lines as these authors, we take into account the fact that the picture in the Northern and Center regions of Brazil is quite different from that of the Southern and coastal regions.

Population density is a key determinant of energy distribution and consumption patterns. The difference between coastal states and the rest of the country is striking here. With the notable exception of Goiás, population density in the Center and Northwest administrative regions is much lower than in the Northeast, South and Southeast. The Southeast region alone accounts for 42% of the country's population (IBGE, 2011) and 10% of its territory (IBGE, 2015). Economic activity is also much more intense in the Southeast and South, which together accounted for 71.9% of the country's GDP in 2010 (IBGE, 2014).

As a consequence, the energy consumption of the South and Southeast is much higher than in the rest of the country: 67% of the electricity consumed by Brazil's residential sector in 2013 was consumed in the South and Southeast regions (EPE, 2014). These differences translate into more plants and a much denser transport and distribution network in these two regions. The North-South orientation of the electricity transport network, along the coast, is clearly visible on Figure 3-2 below, despite an incursion into Mato Grosso State[46].

[45] See chapter 1.
[46] Mato Grosso is the main soybean producer in the country. As such, it is significantly more populated, active, and energy-consuming than its neighbors, making it more like the Eastern states than the Western and Northern ones. In our model, we include this region in the "Center, West and North" block, but purely electricity-oriented studies (see e.g. Shapiro et al., 2013) tend to consider it separately.

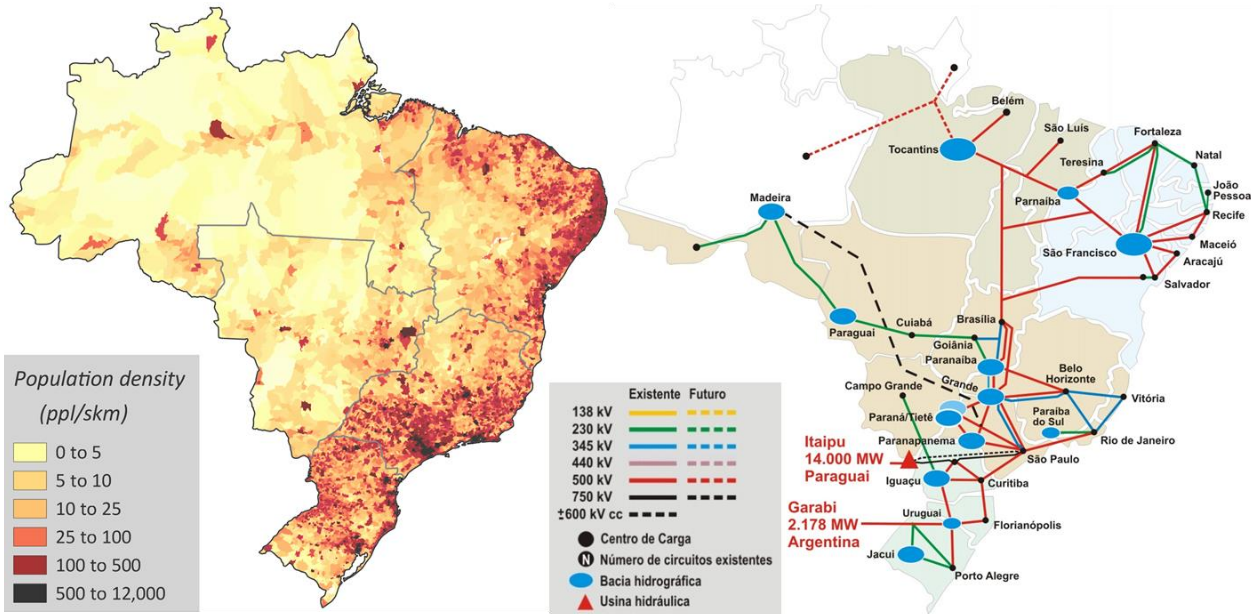

Figure 3-2: Population density, hydroelectricity generation and electricity transmission in Brazil (ONS, 2014; SEDAC, 2004)

On the supply side, the South and Southeast have quite different assets from the rest of the country:

- For fossil fuels, in 2013 the South and Southeast regions together produced 90% of Brazil's national oil, 60% of national gas and 100% of the country's coal (EPE, 2014). The pre-salt offshore oil discoveries should reinforce this position in the coming years.
- 57% of existing hydropower capacity belongs to the South and Southeast regions; however, only 35% of Brazil's estimated potential has been tapped to date. The North, Center-West and Northeast regions account for more than three quarters of untapped potential (Eletrobras, 2012). Thus, while Brazilian hydropower's past and present are dominated by the South and Southeast, the future of this energy in Brazil lies in its Northern, Northeastern and Center West regions.
- The Northeast's wind potential (75 GW, 144 TWh/hr) outdoes the four remaining regions combined, according to Juárez (2014). This domination is already visible in the installed capacity, with the Northeast accounting for 72.6% of the installed wind production capacity in 2013 (cf. Table 3-1 below).
- Although the advantage is somewhat lower, solar potential is also more promising in the Northeast and Center-West regions than in the South and Southeast (Malagueta et al., 2014; Pereira, 2011). Together, the Southeast and South only represent 27% of the solar production capacity installed to date in Brazil.

Region	Hydro	Thermal	Wind	Solar	Nuclear	Total
North	**13,167**	**3,702**	**0**	**0**	**0**	**16,869**
(%)	*15.3*	*10.1*	*0.0*	*0.4*	*0.0*	*13.3*
Northeast	**11,551**	**9,116**	**1,466**	**4**	**0**	**22,137**
(%)	*13.4*	*25.0*	*66.6*	*72.6*	*0.0*	*17.5*
Southeast	**24,941**	**15,243**	**28**	**1**	**1,990**	**42,204**
(%)	*29.0*	*41.7*	*1.3*	*25.3*	*100*	*33.3*
South	**24,505**	**4,397**	**708**	**0**	**0**	**29,610**
(%)	*28.5*	*12.0*	*32.2*	*0.0*	*0.0*	*23.4*
Center-West	**11,853**	**4,070**	**0**	**0**	**0**	**15,923**
(%)	*13.8*	*11.1*	*0.0*	*1.6*	*0.0*	*12.6*

Table 3-1: Brazil - Installed electric capacity by regions in 2013, in MW (EPE, 2014)

The case of soy and sugar cane is also quite interesting (cf. Figure 3-3). Both products are potential energy crops and rank among the most significant agricultural products in Brazil. Soybean accounted for USD 25bn in Brazil's GDP in 2012 (IBGE, 2013)[47]. Its main use is cattle feed, yet it also provides 80% of Brazil's biodiesel (Salomão, 2013), whose production reached 2.7 million m^3 in 2012 (ANP, 2013)[48]. Soy is mainly produced in Mato Grosso State, which is also Brazil's biggest firewood producer. Sugar cane contribution to Brazilian GDP is slightly lower than soy (USD 25bn in 2012, according to IBGE, 2013), yet 55% of the harvest goes to ethanol production (MAPA, 2015), which peaked at 28 million m^3 in 2010. Furthermore, sugarcane residues (*bagasse*) are also a valuable energy commodity and provided 20% of industrial energy supply in 2010; as a consequence, sugarcane alone accounted for 17% of Brazil's TPES that same year (EPE, 2014). Contrary to soy, sugar cane production is driven by Eastern states such as São Paulo, Paraná, Minas Gerais (ANP, 2013). Energy crop culture is thus another differentiating element between the North and West parts of the country, and its South and Southeast regions.

[47] Brazil, Argentina and Paraguay are respectively the 2nd, 3rd and 6th biggest soya producers in the world with 84, 51 and 8 million tons harvested in 2012 (USDA, 2013).
[48] Other oilseeds include palm, sunflower, cotton, peanut, castorbean and rapeseed. However, the second main contributor to biodiesel is bovine fat (10% of production, cf. Salomão, 2013).

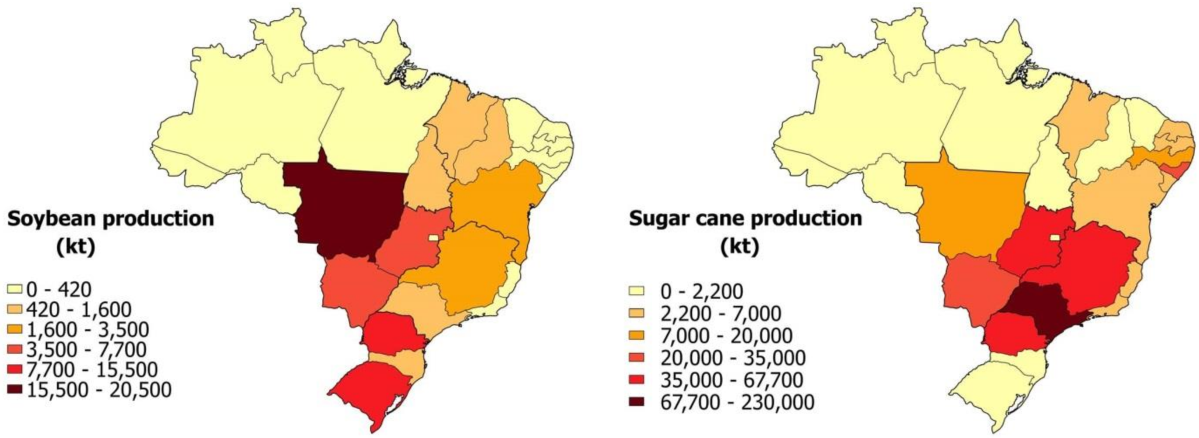

Figure 3-3: Sugar cane and soybean production in Brazil (Source IBGE, 2013)

Ultimately, Brazil is both a South American giant that accounts for nearly half of the continent's activity, and a two-tier country whose energy determinants and economic activities vary greatly between the Center and Northern states, and the Southern and Eastern ones. The consumption centers are mainly located in the South and Southeast regions, which mostly contribute to national energy supply with fossil oil and sugar cane. The Northern, Center and Western regions specialize in fuel wood and soy. They also possess the greatest potential for solar, hydro and wind electricity production. These are two realities that a long-term prospective model for South America ought to take into account to capture energy sensitivities in the region.

A.2. Other relevant dynamics in Central and South America

Aside from Brazil's hegemony and heterogeneity, the following elements are also crucial to shaping the energy structure of the continent:

- Colombia and Venezuela are the gateway to Central America, the Caribbean and the US:
    - Colombia and Venezuela, together with Argentina and Brazil, are the four biggest actors in South America. Venezuela boasts the largest oil reserves in the world and is the main South American OPEC member; the other member, Ecuador, is the smallest producer of all OPEC States. Despite tense diplomatic exchanges, 10% to 20% of the oil consumed in the US in the past 20 years came from Venezuela (US-DoE, 2013).
    - Colombia is the continent's main coal exporter. In fact, the only other country to extract any significant amount of coal is Brazil, and Brazilian coal has a low heating value, high ash content and is mainly consumed close to extraction sites (Nogueira et al., 2014). Colombia is also the only South American country with an overland link to Central America.
- Although Bolivia, Paraguay and Uruguay have small economies and low energy consumption, they are crucial to energy flows throughout the continent (cf. Figure 3-4):
    - Bolivia produces only 10% of all the gas produced in South America, far behind Brazil or Argentina (BP, 2014). However, it is the continent's main exporter –

towards Brazil and Argentina– through the GASBOL and YABOG pipelines. The country enjoys a strategic position in orienting regional gas flows and this power should increase if projects such as *Anillo energético* (energy ring) or the Great Southern Gas Pipe come back to life, bringing in new actors such as Chile, Peru and Venezuela[49]. So far, on the whole continent, only Trinidad and Tobago and Peru have liquefaction facilities for natural gas and there is little installed capacity for regasification (IGU, 2013), which makes terrestrial transport an unavoidable option for all energy consumers in South America. However, Bolivia's small size and low development make it vulnerable with respect to its powerful neighbors, Argentina and Brazil (Roux, 2006). When combined with the effect of recent unilateral nationalizations, Bolivia's long-term behavior is quite hard to predict.

- Uruguay is the shortest path between the two most dynamic regions of the continent, Southeastern Brazil and Northeastern Argentina, from Rio de Janeiro, São Paulo and Porto Alegre to Buenos Aires, Córdoba and Rosario. Its electrical interconnection capacity with its neighbors is above 3,500 MW, compared with a 2,843 MW national installed capacity.
- Paraguay exports 80% of the electricity it produces to Brazil, following the Itaipu bi-national agreement. It shares the Yacyretá Dam (3 GW) with Argentina. Together with Uruguay and Bolivia, it occupies most possible paths between the North and East of the continent (Brazil, Venezuela) towards the South and West (Argentina, Chile). The very high hydropower production of the country, together with its relatively low domestic consumption, gives it a highly strategic arbitrage position for electricity trade on the continent.

[49] The *Anillo Energético Sudaméricano*, or South American Gas Pipe, aims at interconnecting all Southern Cone countries (Argentina, Bolivia, Brazil, Chile, Paraguay, Peru, Uruguay) and Venezuela (depending on the project versions). It was proposed in 2005 by Chile as a reaction to the then Chile-Argentina gas supply crisis (cf. Box 2-2). This infrastructure was never constructed. The Great Southern Gas Pipe, already mentioned in chapter 1 (p.26) was proposed by Venezuela and Argentina (also in 2005) to connect Venezuela, Brazil, Uruguay and Argentina. It was officially abandoned in 2007.

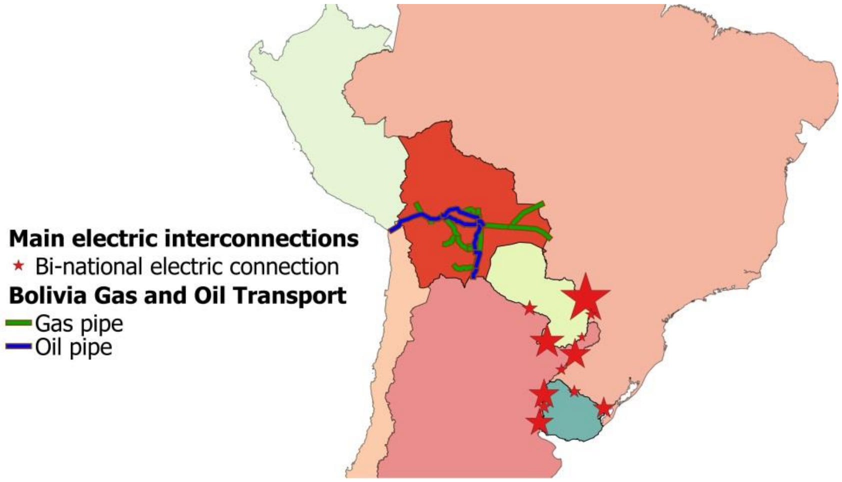

Figure 3-4: The strategic location of Bolivia, Paraguay and Uruguay in South America
(Adapted from HCB, 2015; CIER, 2013)

- Chile and Argentina share many common differences from the rest of the continent, if not great synergies:
    - As presented in Chapter 1, both countries experienced similar growth trajectories until their paths diverged during Argentina's economic crisis. They both stand apart from the rest of the continent: Chile's interactions with its immediate neighbors Bolivia and Peru are still tense, while Argentina struggles against Colombia and Venezuela to remain the second actor in South America, and takes a stand against Brazil's hegemony. Chile is not a full member of MERCOSUR, the most advanced regional integration initiative so far from an economic point of view.
    - Their energy mix is also quite different from the rest of the continent, with less hydroelectricity and more gas. Energy integration with the rest of South America is weak, although Argentina does exchange electricity with Brazil and Paraguay and gas with Bolivia (CIER, 2013). Chile, Argentina, Bolivia, Paraguay and Uruguay use a 50Hz electricity network, while the rest of the continent runs on 60Hz. After exporting natural gas for years, Argentina is now a net importer, mainly from Bolivia; Chile has long been a net energy importer of gas, coal and oil[50].
    - However, there are too many differences to consider these two countries as a block (Negrete Sepúlveda and Velut, 2006). The Chilean economy is based on mining (the country is the world's leading copper producer), while Argentina depends strongly on agriculture and livestock farming. The role of the state in Chile is still strongly inherited from its past liberal dictatorship, with minimal state intervention coupled with strong centralization. In Argentina, the autonomy of federal provinces hindered a strong reduction of state intervention, although it was

[50] For more detail on Chile's energy dependency, the reader can refer to Box 2-2: The Chile-Argentina gas crisis.

indeed reduced to some extent under Menem's presidency; state intervention actually grew back afterwards during Néstor and Cristina Kirchner's successive mandates. The main trade route between Chile and Argentina, the Buenos Aires-Mendoza-Santiago axis, is still of secondary importance compared with e.g. the São Paulo-Rio de Janeiro track or the interconnections between European megalopolises.

- **Peru and Ecuador, at the heart of the Andean Community**, may not have such an easy relationship, yet they share a close history and are both central to exchanges between the North of the continent (Colombia, Venezuela) and the South (Chile, Argentina), along the West coast. The Andes Mountains and Amazon Forest represent a natural barrier to trade and drive inhabitants to live on the coast[51]. These countries together initiated the oldest regional alliance in Latin America, namely the Andean Community[52]. Ecuador is ten times smaller than its neighbor, yet it is an OPEC member with a relevant part to play in the energy field (Escribano, 2013).
- **Central America and the Caribbean account for less than 3% of the continent's GDP.** This complex galaxy comprises more than 20 states and microstates, with a variety of political alliances. Given the complexity of the region versus its size, an accurate representation would be unnecessarily costly. However, its existence as a region is of great value, since it is also the only overland trade route to Mexico and the United States. An electrical interconnection from Mexico to Colombia, all the way through Guatemala, El Salvador, Nicaragua, Costa Rica and Panama is currently entering its last construction steps (CIER, 2013).

A.3. Subregional disaggregation of T-ALyC: a 10-region approach

Following the regional dynamics highlighted in the previous paragraphs, as well as the potential prospective interests listed in Chapter 1, our first version of *TIMES-América Latina y el Caribe* is based on a 10-region description of South America and the Caribbean:

- **Brazil is divided into two blocks**, according to administrative regions:
  - The South and Southeast regions are aggregated into the 'Brazil South and East' block.
  - The North, Northeast, and Central regions form the 'Brazil West and Center' block.
- **Bolivia, Paraguay and Uruguay together form the 'Interconnection states' region.**
- **Peru and Ecuador are aggregated into a single 'Andean states' region**;
- **Central America and the Caribbean are aggregated into one block;**
- **Suriname, Guyana, French Guyana** are aggregated into one block.

[51] Except for the Altiplano plateaus shared mainly by Bolivia and Peru and, to some extent, Chile and Argentina.
[52] The Andean Community, or *Comunidad Andina de Naciones*, was founded in 1969 through the Cartagena Agreement. It is a customs union, including free movement of persons and a common passport (the Andean passport) since 2005.

- Last, **Argentina, Chile, Colombia and Venezuela** are neither aggregated nor disaggregated.

This disaggregation is detailed Table 3-2; Figure 3-5 displays its transcription in a more visual way.

Code	Full name	Description
AND	Andean States	Peru and Ecuador
ARG	Argentina	Argentina
BPU	Bolivia – Paraguay – Uruguay	Bolivia, Paraguay, Uruguay
BSE	Brazil – South and East	Brazil's *Sul* and *Sudeste* administrative regions
BWC	Brazil – West and Center	Brazil's *Nordeste*, *Norte* and *Centro Oeste* administrative regions
CHL	Chile	Chile
COL	Colombia	Colombia
CYC	Central America and the Caribbean	Central America and the Caribbean, excluding Trinidad and Tobago
SUG	Suriname – Guyana – French Guyana	Suriname, Guyana, French Guyana
VEN	Venezuela – Trinidad and Tobago	Venezuela, Trinidad and Tobago

Table 3-2: T-ALyc's regions and description

Figure 3-5: Regional disaggregation of South America in T-ALyC

B Presentation of the TIMES paradigm and the TIAM platform

For the actual implementation of our regional energy prospective tool, we used the MarkAl/TIMES energy modeling framework. T-ALyC's technological representation or *Reference Energy System* (RES) is more specifically inherited from the TIAM platform for large-scale, long-term energy modeling. This sub-chapter presents TIMES concepts and equations and their TIAM implementation. Concrete examples of the notions presented here are available in the next chapter. More information about the TIMES paradigm and the TIAM platform can be found in their respective seminal papers, (Loulou et al., 2005a, 2005b, 2005c) and (Loulou and Labriet, 2008; Loulou, 2008), or in Anandarajah et al. (2011).

B.1. TIMES: general considerations

The TIMES (*The MarkAl-EFOM Integrated System*) paradigm allows bottom-up representations of the entire energy system, relying on highly disaggregated technology-rich data; it inherits the characteristics of two former modeling paradigms, MarkAl and EFOM. Although the first market allocation models can be traced back to the 1970s, the first full-blown version of the MarkAl paradigm was created and disseminated in the early 1980s (Fishbone and Abilock, 1981). The IEA's *Energy Technology Systems Analysis Program* (ETSAP) drew on thirty years of global experience with MarkAl models to design its TIMES successor from 2000-2005. MarkAl and TIMES models are used in more than seventy countries across the world and have been applied to a wide range of studies with various geographical scopes, from very local scales (Bouckaert et al., 2014) to national (Maïzi and Assoumou, 2014),(Jia et al., 2011), regional (Blesl et al., 2010) and global (Dubreuil et al., 2013) models.

TIMES is not exactly a model, but rather a model generator; that is, a set of generic equations that define the relationships upon which data provided by the user will be linked into a full coherent mathematical model. A generic computer solver is then used to solve the problem, without knowing the energy nature of the equations handled[53]. TIMES builds on the great flexibility of algebraic programming languages[54] to build models shaped around user-provided data. This is a large-scale implementation of informatics notions of *object* and *class* used in Object-Oriented Programming: the model built by the user is an *object*, which contains data and the rules to handle this data. TIMES could be represented as the model *class*; that is, the abstract rules and structure allowing the concrete object (model) to be instanced, but without the data that give a model its final shape. Programmers often use the example of the pie and pie pan to explicit object/class difference; in that view, TIMES would be the pie pan used to form all TIMES-built models –the pies. For convenience's sake, however, a TIMES-*based* model is often called a TIMES model, and we also use this naming convention in this manuscript.

[53] The default solver for TIMES models is IBM's CPLEX solver.
[54] In this case, GAMS. However, a reduced version (ETEM) of the TIMES structure exists in GMPL (a subset of AMPL).

In order to build and run a TIMES model, the user must provide the *technological structure* of energy conversion and consumption of the energy system he wants to study, also known as the *model topology*: the full description of every single energy carrier and technology that may be installed and operated by the model, and the links between them. This representation is complemented by a series of constraints: *supply constraints*, *technical constraints* (technology characteristics), *non-technical constraints* (environmental specification, political decisions, etc.) and *end-use constraints* (exogenous demand scenarios) (Loulou et al., 2005d). The solution found is the **least total discounted cost configuration for the entire energy system[55] over the whole time horizon**. Useful model outputs based on this least-cost solution are the investment and operation decisions, the energy flows and balances and the emission levels for the entire system over the whole time period considered.

The following figure is a sketch description of a TIMES model for only one demand, including:

- In the middle, a simplified structure (*topology*) of the *Reference Energy System*. Diamond-shaped boxes represent energy carriers (called *commodities*), while square ones represent the technologies involved in their production, transformation and consumption (in this context, their generic name is *processes*). Each process is described by its investment, operation and maintenance costs, its life, and its efficiency, thus defining a linear relationship between inputs and outputs.
- In blue, the other constraints that the user must provide to complete the model;
- In green, calculation outputs.

[55] Summed over all model's regions.

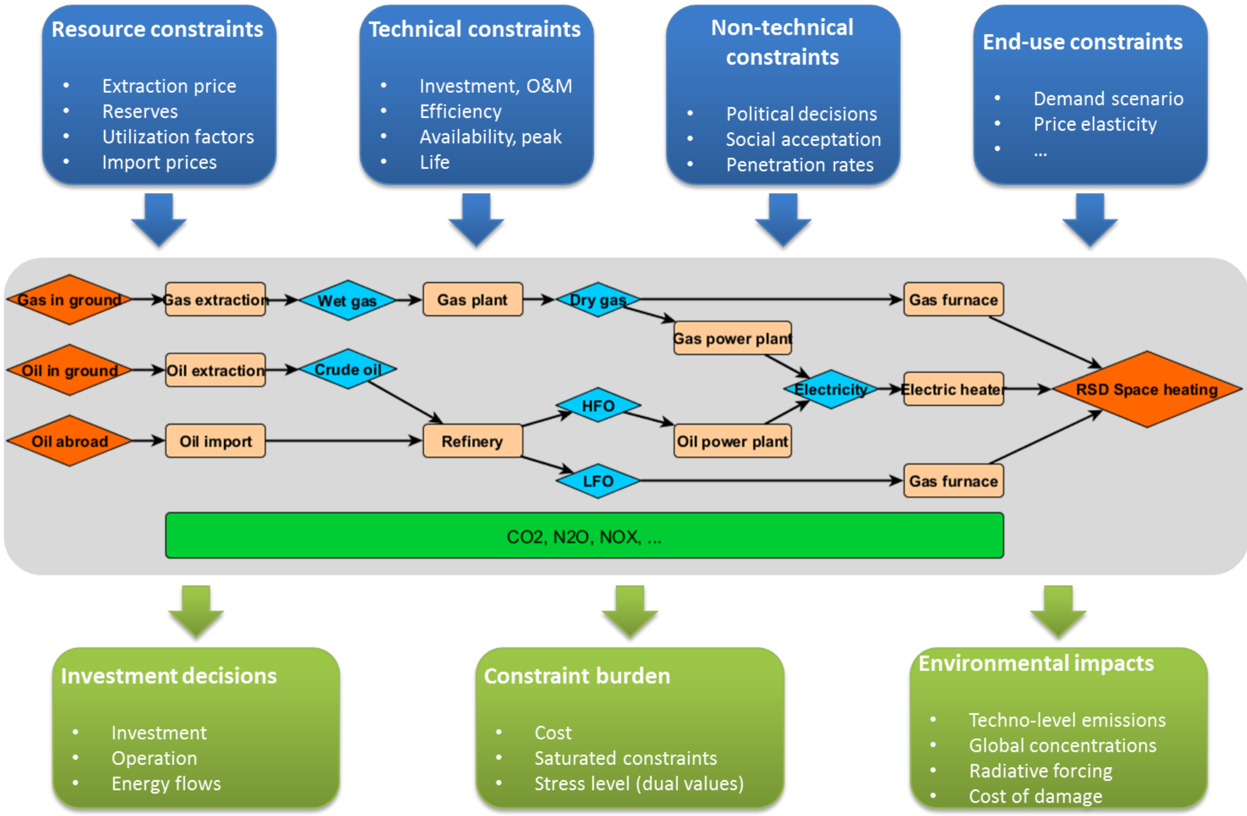

Figure 3-6 : Schematic description of a TIMES-based model

B.2. TIMES equations and structure

The mathematical model constructed by TIMES takes the form of a **linear optimization problem**, whose solution is the least cost configuration for the energy system satisfying all constraints (exogenous demand, resource availability, technical constraints and policy scenarios). A generic description for such optimization problems is

$$\min\left(\sum_i c_i X_i\right) \qquad (E)$$

With

$$\forall i \; Xi \geq 0$$

$$\forall j, \sum_i a_{ij} X_i \geq b_j \qquad (E_j)$$

Where (E) is called the *objective function* of the model, representing the criterion to be minimized; X_i are the *decision variables*, whose value is chosen to minimize the objective function; and (E_j) are the *constraints* that delineate the problem and must be respected by the final solution. All a_{ij}, b_j and c_j parameters are fixed values provided by the user, prior to the optimization.

TIMES indexes the variables, constraints and parameters through various sets whose existence and role are predetermined; their size, however, depends on the data fed by the user. The main indexes in TIMES are:

- $r \in R$ Regions of the model;
- $t \in T$ Time periods of the model;
- p Processes (technology) of the model;
- s Timeslices (only relevant for processes/commodities tracked at a finer than annual level);
- c Commodities (material, energy carrier, emission, end-use demand).

The generic objective function represents the **net present value of the total cost of the energy system over all regions and periods**:

$$\min(NPV) = \min\left(\sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y)\right)$$

Where:

NPV is the Net Present Value of the total cost for all regions over the whole time horizon;

$\boldsymbol{d_{r,y}}$ is the general discount rate;

REFYR is the reference year for discounting;

YEARS is the set of years in which costs are incurred;

R is the set of regions in the scope of the study[56].
ANNCOST(r,y) is the total annual cost in region r and year y;
The "annual cost" *ANNCOST(r,y)* mentioned above is a complex expression, described in detail in (Loulou et al., 2005b). It includes eight main components:

- **Capital costs** incurred while setting up or dismantling processes;
- Fixed and variable **Operation and Maintenance Costs;**
- Costs incurred for **importation or extraction of energy commodities**, and revenues from export;
- **Delivery costs** (e.g. distribution cost of electricity);
- **Taxes and subsidies** associated with commodity consumption (e.g. oil) or production (e.g. CO_2), or investments (electric car);
- **Decommissioning revenues** when a commodity embedded in a process can be sold after dismantling it (accounting for recycling);
- **Salvage value** to account for what happens to processes after the model's time horizon (getting rid of the border effect);
- And **welfare loss**, when the elastic demand option is used, to materialize the demand curve in the model (in this case the total cost minimization objective becomes one of total welfare maximization).

The **decision variables** of the model include:

- *NCAP(r,t,p)* — New capacity investment for technology *p*, in period *t* and region *r*.
- *CAP(r,t,p)* — Installed capacity of process *p* in region *r*, at period *t*. Depends on *NCAP* and decommissioning decisions.
- *ACT(r,t,p,s)* — Activity of process *p* in region *r*, at period *t* and timeslice *s*. It defines the utilization rate of plants for each timeslice.
- *FLOW(r,t,p,c,s)* — The amount of commodity *c* produced or consumed by process *p* in region *r*, at period *t* and timeslice *s*. It relates the activity *ACT* of process *p* to the structure of the input/output flows.
- *SIN(r,t,p,c,s)* — The amount of commodity *c* stored or discharged by storage process *p* in region *r*, at period *t* and timeslice *s*.
- *TRADE(r,t,p,c,s)* — The amount of commodity *c* traded through process *p* in region *r*, at period *t* and timeslice *s*. Depending on the process, it could be imported, or exported. This is also how resource extraction is modeled in TIMES.

[56] All equations and notations here are exactly copied from the TIMES reference manual (Loulou et al., 2005a).

The associated **constraint equations include**:

- **Capacity transfer** Investing in a technology increases its capacity throughout the life of the process:

$$CAP(r,t,p) = \sum_{\substack{t'<t \\ t-t'<LIFE(p)}} NCAP(r,t',p) + RESID(r,t,p)$$

- **Process activity** Relating *ACT* decision variable to *FLOW* one[57]:

$$ACT(r,t,p,s) = \sum_{c \in PCG(p)} \frac{FLOW(r,t,p,c,s)}{ACTFLO(r,p,c)}$$

- **Use of capacity** Taking into account maximal availability factors, e.g. for intermittent sources[58]:

$$ACT(r,t,p,s) \leq AF(r,t,p,s) * CAP2ACT(r,p) * FR(s) * CAP(r,t,p)$$

- **Commodity Balance** Production plus imports must balance consumption plus exports[59]:

$$\sum_{p,c \in TOP(r,p,c,'OUT')} FLOW(r,t,p,c,s) + \sum_{p,c \in 'Imports'} TRADE(r,t,p,c,s)$$
$$\geq \sum_{p,c \in TOP(r,p,c,'IN')} FLOW(r,t,p,c,s) + \sum_{p,c \in 'Exports'} TRADE(r,t,p,c,s)$$

- **Flow relationships** Defining flow relationships for input/output flows of a process:

$$\sum_{c \in Outputs(p)} FLOW(r,t,p,c,s) = FLOFUNC(r,cg1,cg2,s) * \sum_{c \in Inputs(p)} FLOW(r,t,p,c,s)$$ [60]

---

[57] The PCG notation used in this summation refers to the user-defined "Primary Commodity Group" of the process, consisting exactly in the commodities used for the computation of the process's activity; *ACTFLO* is a conversion factor, also user-defined, most often equal to 1.

[58] Where *CAP2ACT* is the conversion factor from capacity units (most often, PJ/year) to activity units (most often, PJ), *AF* is the aforementioned availability factor, and *FR* is the duration of timeslice *s*. Last, the inequality can also be set as an equality.

[59] Terms relative to storage process, and embedding/release of commodities due to commissioning/dismantling have not been shown here for simplicity's sake.

[60] *FLOFUNC* could be assimilated to the efficiency of the plant. Some terms related to timeslice harmonization have been omitted here.

- **Limiting flow shares** Constraining flow shares when Inputs or Outputs consist of more than 1 element:

$$FLOW(c) \leq, \geq, = FLOSHAR(c) * \sum_{c' \in Inputs} FLOW(c') \;\; if\ c\ is\ an\ input$$

$$FLOW(c) \leq, \geq, = FLOSHAR(c) * \sum_{c' \in Ouputs} FLOW(c') \;\; if\ c\ is\ an\ output$$

- **Peaking Reserve** Total installed capacity must satisfy a user-defined peaking reserve constraint

$$\sum_{p\ producing\ c} Peak(r,p,c,s) * FLOW(r,t,p,c,s) + TRADE(r,t,p,c,s,i)$$
$$\geq [1 + RESERVE(r,t,c,s)] * \left[\sum_{p\ consuming\ c} FLOW(r,t,p,c,s) + TRADE(r,t,p,c,s,e) \right]$$ [61]

- **User defined bounds** All the above "standard" bounds can be complemented with virtually any user defined bound to commodity production, consumption, process capacity, capacity growth, etc.

B.3. Focus on the TIAM experiment

The global *TIMES Integrated Assessment Model* (TIAM) was chosen as the starting point for building a South American regional model. TIAM is a reference structure that describes the entire global energy system. Development started in 2004 under the IEA-ETSAP Agreement; since then, it has been continuously improved and developed through agreements and experience-sharing of national members of the ETSAP program, has given birth to various national adaptations (SAGE, EFDA-TIMES, TIAM-UCL, TIAM-ECN, TIAM-FR, etc.) and has been used in a wide variety of investigations (see e.g. Ricci and Selosse, 2013; Syri et al., 2008; Vaillancourt and Tosato, 2011). The model also includes a simplified climate module that endogenously calculates the impact of energy-related GHG emissions.

In TIAM, the world is modeled through 15 regions and the cost of satisfying demand for the whole system is minimized on a time horizon starting in 2005 and ending in 2050 or 2100.

[61] *RESERVE* is the specific user-defined reserve constraint for this commodity in this region, to allow for incidents in demand (unexpected peak) and supply (loss of a plant). *Peak* (always smaller than 1) specifies which part of all processes *p* can participate in satisfying demand at peak times.

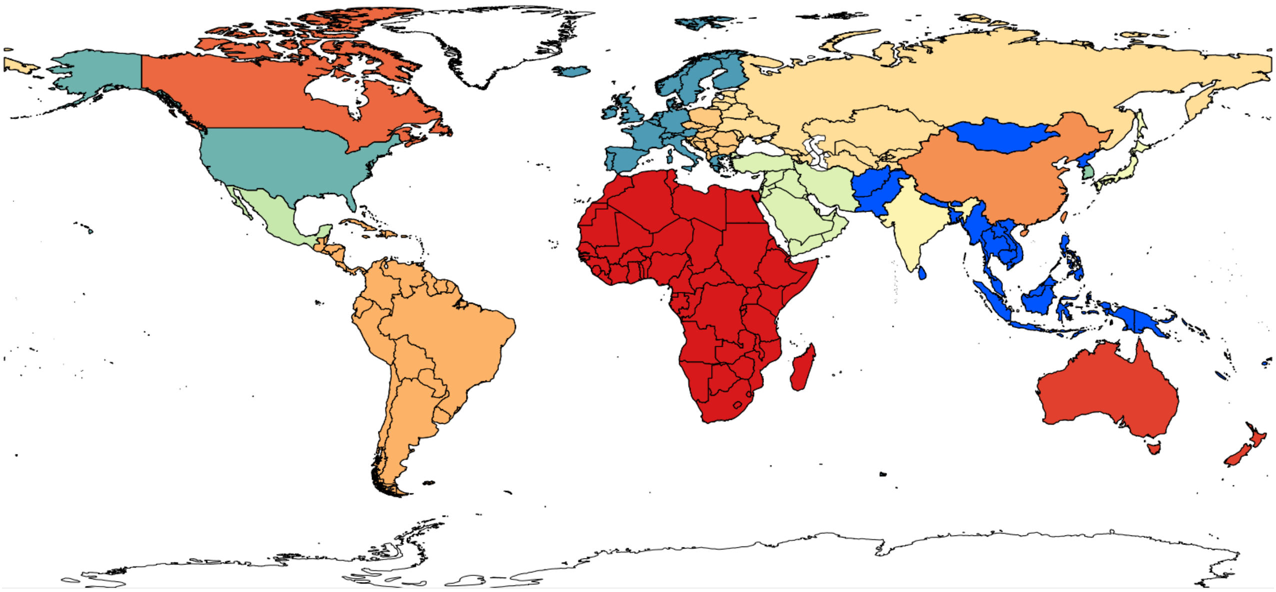

Figure 3-7: TIAM 15 regions (source TIAM model)

The Reference Energy System of the TIAM energy module is organized into 6 main components:

- **The "energy supply" or "upstream" module** comprises the extraction of fossil and renewable primary energy.
- **The "energy trade" module** allows for trade of energy commodities such as coal, crude oil, refined petroleum products, natural gas, electricity etc. and also GHG emissions, in order to study trading schemes like European EU-ETS, or Clean Development Mechanisms.
- **The "energy transformation" module** represents crude oil, coal and natural gas processing from crude to end-use commodities, through refineries, gasification, coal-to-liquid plants etc.
- **The "energy conversion" module** deals with electricity production.
- **The "energy consumption" module**, subdivided into 5 subsectors (Residential, Commercial, Agricultural, Industrial, and Transport) represents end-use demand and the technologies dedicated to satisfying it.
- Last, **the "emissions and emissions reduction options" module** deals with GHG emissions from the installed processes (tracked at process level), and existing mitigation technological options. GHG are then aggregated into a single CO2-equivalent potential, which is in turn passed on to the TIAM climate module for radiation and temperature elevation calculations.

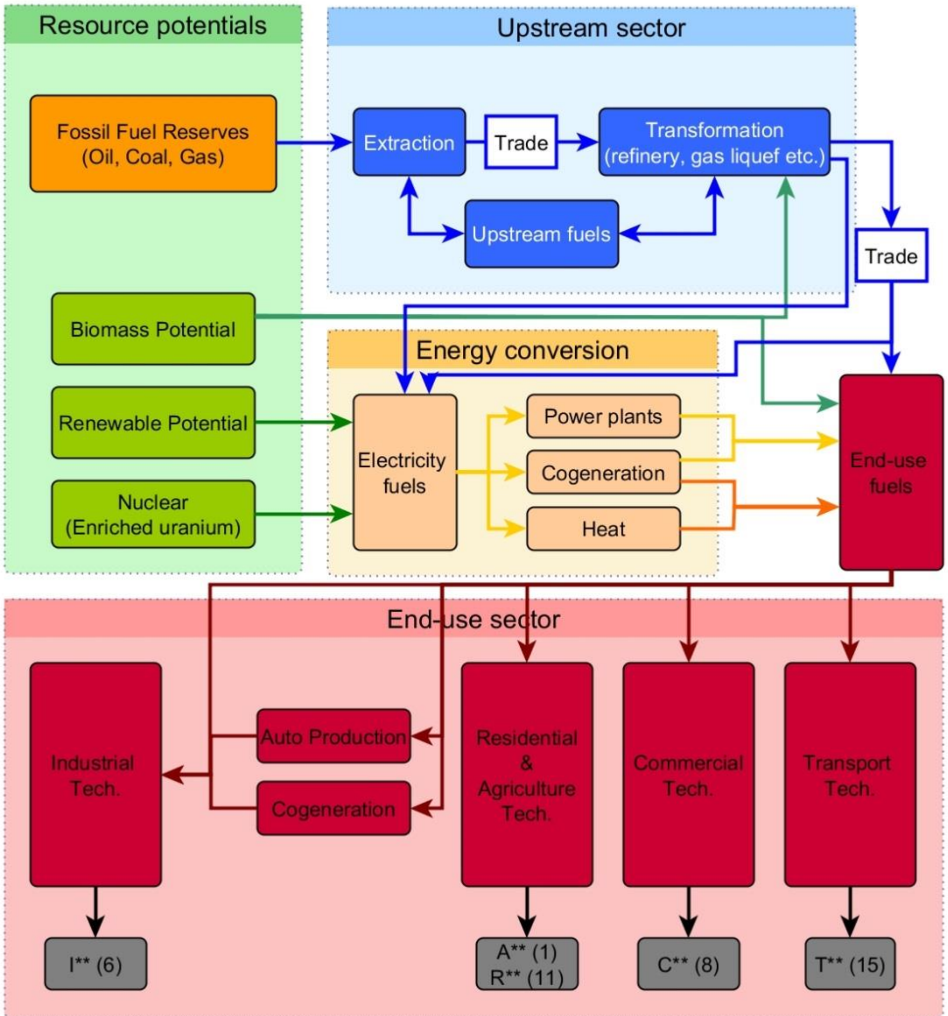

Figure 3-8: TIAM RES sketch view (adapted from Loulou and Labriet, 2008)

The energy service demand of TIAM is represented by 42 energy services. It can be fed into the model by two means:

- **In a completely exogenous fashion**, if the modeler is able to provide demand curves for each service and each region of the model, and their projection to the time horizon. One can even associate elasticity coefficients to each demand. This is the most precise and accurate way to define demand scenarios, but the cost in terms of data gathering is very high and might not be the modeler's priority. Plus, any change in the projection must be re-entered manually into the model, making it quite burdensome[62].
- **Using the built-in demand projection facility**. In this case, the modeler provides, for each demand

[62] However, it could be greatly alleviated by soft-linking TIAM with an external data source, most often a top-down model.

- A base-year demand[63] issued from exogenous calculations, e.g. IEA international energy statistics;
- One or more macroeconomic drivers for the demand, which could be GDP, population, number of households, GDP per capita, etc. and whose projection is easier to find/compute;
- Elasticity with respect to the main driver;
- The demand projection is then computed according to the formula

$$Demand_t = Demand_{2010} * k_t * \left(\frac{Driver(t)}{Driver(2010)}\right)^{Elasticity}$$

$$k_t = \begin{cases} 1 \; most\; often \\ Population, or\; Households, when\; main\; driver\; is\; a \text{ per capita } one \\ Actual\; exogenous\; demand\; projection, when\; available\; (The\; driver\; then\; is\; set\; to\; 1) \end{cases}$$

- This might be a coarse method for demand projection; however, it is still sufficiently accurate for a model whose purpose is not simulation, but rather the comparative evaluation of a range of scenarios.

All TIAM demands and their respective drivers are listed below:

Energy service	TIAM Code	Unit	Driver
Transportation services			
Cars	TRT	Billion vehicle-km/year	GDP/Capita
Buses	TRB	Billion vehicle-km/year	POP
Light Trucks	TRL	Billion vehicle-km/year	GDP
Commercial Trucks	TRC	Billion vehicle-km/year	GDP
Medium Trucks	TRM	Billion vehicle-km/year	GDP
Heavy Trucks	TRH	Billion vehicle-km/year	GDP
Two wheelers	TRW	Billion vehicle-km/year	POP
Three Wheelers	TRE	Billion vehicle-km/year	POP
International aviation	TAI	PJ/Year	GDP
Domestic aviation	TAD	PJ/Year	GDP
Freight rail transportation	TTF	PJ/Year	GDP
Passenger rail transportation	TTP	PJ/Year	POP
Domestic navigation	TWD	PJ/Year	GDP
International navigation	TWI	PJ/Year	GDP
Non-energy uses in transport	NEU	PJ/Year	GDP
Residential segments			
Space heating	RH1,RH2,RH3,RH4	PJ/Year	HOU
Space cooling	RC1,RC2,RC3,RC4	PJ/Year	GDP/Capita

[63] The base year for TIAM is 2005.

Energy service	TIAM Code	Unit	Driver
Hot water heating	RHW	PJ/Year	POP
Lighting	RL1,RL2,RL3,RL4	PJ/Year	GDP/Capita
Cooking	RK1,RK2,RK3,RK4	PJ/Year	POP
Refrigerators and freezers	RRF	PJ/Year	GDP/Capita
Clothes washers	RCW	PJ/Year	GDP/Capita
Clothes dryers	RCD	PJ/Year	GDP/Capita
Dishwashers	RDW	PJ/Year	GDP/Capita
Electricity specific uses	REA	PJ/Year	GDP/Capita
Other energy uses	ROT	PJ/Year	GDP/Capita
Commercial segments			
Space heating	CH1,CH2,CH3,CH4	PJ/Year	P-Services
Space cooling	CC1,CC2,CC3,CC4	PJ/Year	P-Services
Hot water heating	CHW	PJ/Year	P-Services
Lighting	CLA	PJ/Year	P-Services
Cooking	CCK	PJ/Year	P-Services
Refrigerators and freezers	CRF	PJ/Year	P-Services
Electric Equipment	COE	PJ/Year	P-Services
Other energy uses	COT	PJ/Year	P-Services
Agriculture and industrial segments			
Agricultural demand	AGR	PJ/Year	P-AGR
Iron and steel	IIS	Million tons/year	P-ISNF
Non ferrous metals	INF	Million tons/year	P-ISNF
Chemicals	ICH	PJ/Year	P-CHEM
Pulp and paper	ILP	Million tons/year	P-OEI
Non metal minerals	INP	PJ/Year	P-OEI
Other Industries	IOI	PJ/Year	P-OI
Other segments	ONO	PJ/Year	P-OI

Table 3-3: End-use demands of TIAM and their units (From Loulou and Labriet, 2008)[64]

Some remarks on this table:

- **Agricultural demand** is way too aggregated for the unit to mean anything in terms of *end-use service*. Instead, the demand represents the aggregated consumption by the end-use devices of the agriculture sector, and thus the unit is representative of this energy consumption (PJ/Year)

For **agriculture and industrial segments**, individual projections for the growth of a particular sector are more easily found than the projection for, say, Residential Hot Water demand. As a consequence, the driver for these segments is the actual growth of the segment.

[64] POP=Population, HOU=Number of Households, P-[Sector]=Projected Sector Activity

All of the elements described here, which are the fundamentals of TIAM models, also constitute a starting point for the T-ALyC model whose specificities will be described in the next section. By basing T-ALyC's structure on that of TIAM-FR, we facilitate its design and insertion in the energy modeling landscape and obtain two major benefits:

- First, substantial versatility: TIAM models describe the whole global energy system; the variety of assessments performed with these models demonstrates their relevance in investigating a wide range of energy-related issues[65];
- Second, the ability to link it with a global model: although T-ALyC is primarily designed as a standalone model, it can be linked to TIAM-FR, for the benefit of both TIAM-FR and T-ALyC:
    - T-ALyC will thus provide sub-regional insights as well as more realistic behavior for Latin America than TIAM-FR;
    - TIAM-FR, in turn, will enrich T-ALyC with a dynamic "Rest-of-World" and immediate feedback on energy prices, flows, etc.[66], as well as the climate assessment capabilities that come with its global representation.

C Model architecture and data

The following sections describe some prominent aspects of T-ALyC's architecture, including time representation, energy endowment and supply, assumptions related to demand projections, and trade representation. Supply description considers nine energy forms: coal, natural gas, oil, solar energy, hydropower, wind, geothermal energy, nuclear energy and biomass. Demand description does not cover the 42 demands mentioned above; it focuses on the assumptions and data sources behind the drivers' projection. The trade paragraph details the distances, transport costs and existing infrastructures in T—ALyC for electricity, gas (natural gas and LNG), oil and coal, both for regional and international energy trade. Some specific choices for e.g. CHP generation or biomass, where T-ALyC dissociates itself from TIAM following technical choices, are also commented in (Postic, 2014).

Table 3-4 below summarizes some global parameters for T-ALyC. The 5% discount rate was conserved from TIAM, to ensure similar decision dynamics in the two models. The number of regions has already been detailed; it was chosen relatively low, to allow for further ad hoc disaggregation if needed, and at the same time maintain reasonable computation times (below one hour) when running TIAM and T-ALyC together. Timeslices and time periods are defined in section C.2 below.

[65] See e.g. (Babonneau et al., 2012; Calvin et al., 2015; Dubreuil et al., 2013; Gracceva and Zeniewski, 2013; Kober et al., 2014; Ricci and Selosse, 2013; Syri et al., 2008)

[66] See paragraph C.4.2 in this chapter.

Parameter	Value
Main discount rate	5%
End-use demands	42
Time horizon	2050 (up to 2100)
Time periods	7
Timeslices	6 (3 seasons, 2 infradays)
Regions	10
Technologies (by region)	2,000
Commodities (by region)	630
Mathematical problem	Linear optimization
Typical size of the problem	280,000 rows; 370,000 columns; 2,000,000 non-zeros
Default solver	CPlex
Modeling paradigm	TIMES
User shell	VEDA

Table 3-4: T-ALyC: General parameters

C.1. Demand

The concepts of demand calculation for T-ALyC are taken from TIAM and were presented in Section B.3 of this chapter. This paragraph details T-ALyC's specific macroeconomic assumptions and resulting driver projections.

As a reminder, demand in T-ALyC is driven by nine primary drivers: GDP, population, number of households, agricultural activity, chemical production, steel and non-ferrous production, other energy-intensive industries, other industrial production, and services; and two secondary drivers – per capita GDP and per household GDP– which are calculated from GDP, population and the number of households. Drivers such as GDP, population and agricultural projections rely on national statistics; projections are thus publicly available in reasonable detail. On the other hand, all the drivers related to industry's sectorial growth resort to private and strategic information, which is often confidential, if it exists at all.

The projections to 2050 for these drivers are carried out as follows:

- **GDP**: the projection to 2020 is taken from the IMF World Economic Outlook database (IMF, 2014); post-2020 growth rates are based on the HSBC report *The world in 2050* (Ward, 2011). For Chile, these projections were updated based on (MEC, 2014).
- **Population and number of households**: base data is provided by the UN population database (UNDESA, 2012), where population is sorted into 5-year age groups and projected to 2050. Based on this repartition, the number of households in 2050 is projected using calculation methods from (Jennings et al., 2000):

$$h = 0.169 + 0.109 * (M/_Y) + 0.363 * (E/_M) - 0.251 * (M/_P)$$

Where

- h Household intensity (number of households per person);
- Y Youths (population aged 0-19 years);

- M Middle-aged (population aged 20-59 years);
- E Older people (population aged 60+ years);

- **Agriculture**: FAO projections are used until 2022. Then growth rates are taken from an update by Alexandratos and Bruinsma (2012), with two different growth rates from 2020 to 2030 and from 2030 to 2050.
- **Chemicals**: the driver for chemical demand is based on (UNEP, 2012) and (Valencia, 2013) and the CSA region of TIAM.
- **Iron, steel and other metals**: this driver is based on various sources. Steel production growth was taken from the statistical annual review by the Latin American Steel Association (ALACERO, 2013). Copper production, which makes up the bulk of Chile and Peru's metal mining, was taken from national sources such as Chile's national company Codelco (Keller, 2013). Brazilian figures come from the *Plano Nacional de Mineração 2030* (National Mining plan 2030) published by the Ministry for Mines and Energy (MME, 2011). Other non-specific figures were taken from an USGS (2011) world review for selected minerals.
- **Pulp and paper, non-metals**: the drivers are based on values from specific sectors if a stable, important economic sector with trustable data exists (e.g., paper production in Brazil). If not, growth rates are projected according to GDP.
- **Other industry and services**: Both drivers are projected based on GDP. The share of industry in the nations' economy is assumed to decrease as the countries develop, while on the other hand the share of services grows faster than GDP.

Figure 3-9 displays T-ALyC's final energy demand in 2010 and 2050. In order to harmonize reporting, I present the model's final *energy* demand, not the final *service* demand. This means that end-use devices as chosen by the model, with their own efficiency, stand between the consumption presented here and the energy service as seen by T-ALyC. In some cases this efficiency can be quite low (e.g. 10% to 25% for cars), meaning that actual final energy consumption could be significantly lowered while satisfying the same 'energy service', through e.g. building insulation solutions. This point was investigated in collaboration with Schneider Electric in 2012 (Postic et al., 2012). Actual demand projections for T-ALyC's regions can be found in Annex, p.**¡Error! Marcador no definido.**. An interesting trend of the maps presented here is the rise of the Andean States, the Bolivia-Paraguay-Uruguay conglomerate, Central America and Colombia; their increasing regional weight is bound to alter energy flows on the continent by 2050. We could also mention the –slight– rise of transport and industry in final energy consumption which reveals the development-induced shift in South America's economic structure.

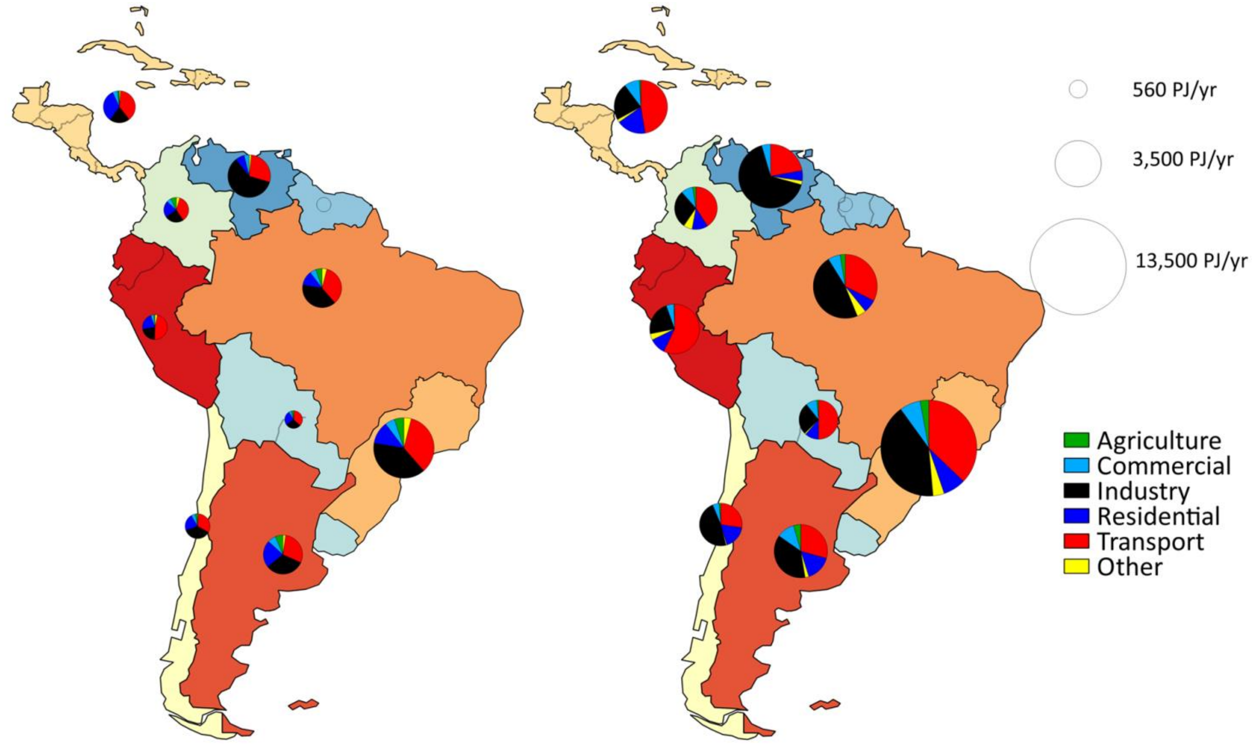

Figure 3-9: Final energy demand in T-ALyC in 2010 (left) and 2050 (right)

C.2. Time in T-ALyC

TIMES models compute energy investments and plant operation on two different time scales.

In the case of T-ALyC, the 2010-2050 time horizon is divided into 7 different periods[67]. In each period, investment and operation decisions are made for one representative year, the so-called *milestone year*, then repeated for the whole period. Milestone years thus represent an average of annual investments, capacities and energy flows over the period. T−ALyC's time periods and milestone years are represented in Figure 3-10.

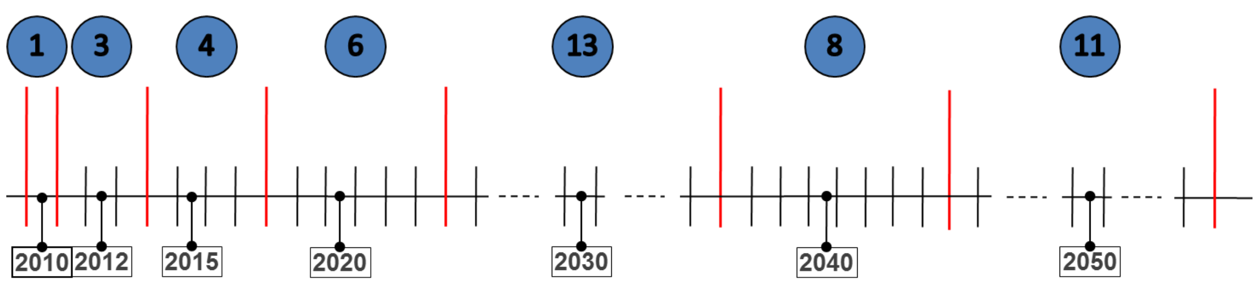

Figure 3-10: Time periods in T-ALyC (blue circles: period length – squares: milestone years)

While investment decisions take place at a yearly level, the representation of energy availability, demand and plant operation is more fine-grained. The representative year is divided into *timeslices* that aggregate similar time periods within the year, e.g. summer peak hours. T-ALyC's

[67] In default mode. Period division is actually quite user-friendly in TIMES and can be changed easily to adapt to specific needs.

timeslice tree is described by Figure 3-11 below. The version described here only includes 6 timeslices; a 24-timeslice version is being developed to track hydrological load curves at a monthly level. Generally speaking, the timeslice representation does not preserve the time structure of energy flows; that is, timeslices are representative fractions of the year, without any notion of a *previous* or *next* timeslice. Unless using specific constraints and reporting tools are used (see e.g. Bouckaert, 2013), operational information related to production ramps, network stability etc. is not available with such a description.

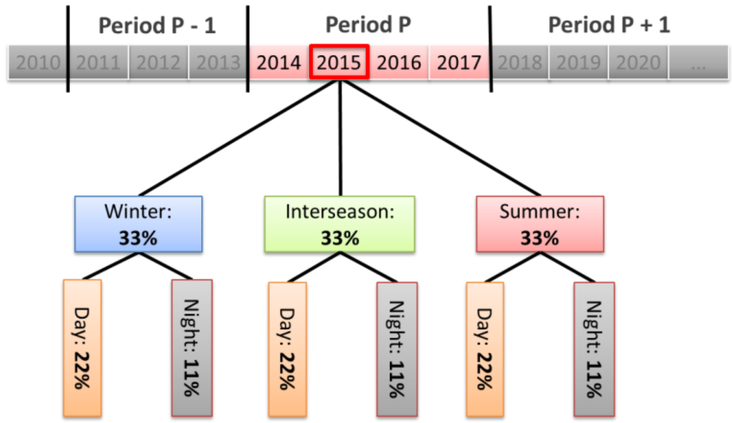

Figure 3-11: T-ALyC's timeslice tree

C.3. Supply

The main information related to energy supply in T-ALyC is the energy endowment of South America's respective regions. We present on Figure 3-12 an overview of T-ALyC's resource database. Sectorial information, along with the sources used, is detailed in the following paragraphs.

To visualize flow and stock potentials in a single map, we summed up renewable resource annual availability (e.g. sun, wind, biomass) over a 2010-2100 horizon, thus considering that fossil reserves would be depleted by 2100. This assumption is only used for reporting purposes, and presumes nothing about actual resource use. Oil, gas, biomass and coal potentials are given in primary energy; a conversion factor is applied to display geothermal, hydropower, nuclear, solar and wind potentials in terms of 'primary energy'. The coefficients chosen here are derived from the *primary energy content* method used by the International Energy Agency, Eurostat, the OECD, the World Energy Council, etc. For a discussion on existing alternative methods, see (Thiboust et al., 2011).

- The geothermal coefficient is 10, i.e. it is considered that one unit of geothermal electricity requires 10 units of primary geothermal energy;
- The nuclear coefficient is 3.03. This 33% efficiency considers only the conversion from reactor heat to final electricity;
- For hydropower, wind and solar energy, the coefficient is 1, assuming that one unit of electricity corresponds to one unit of primary energy.

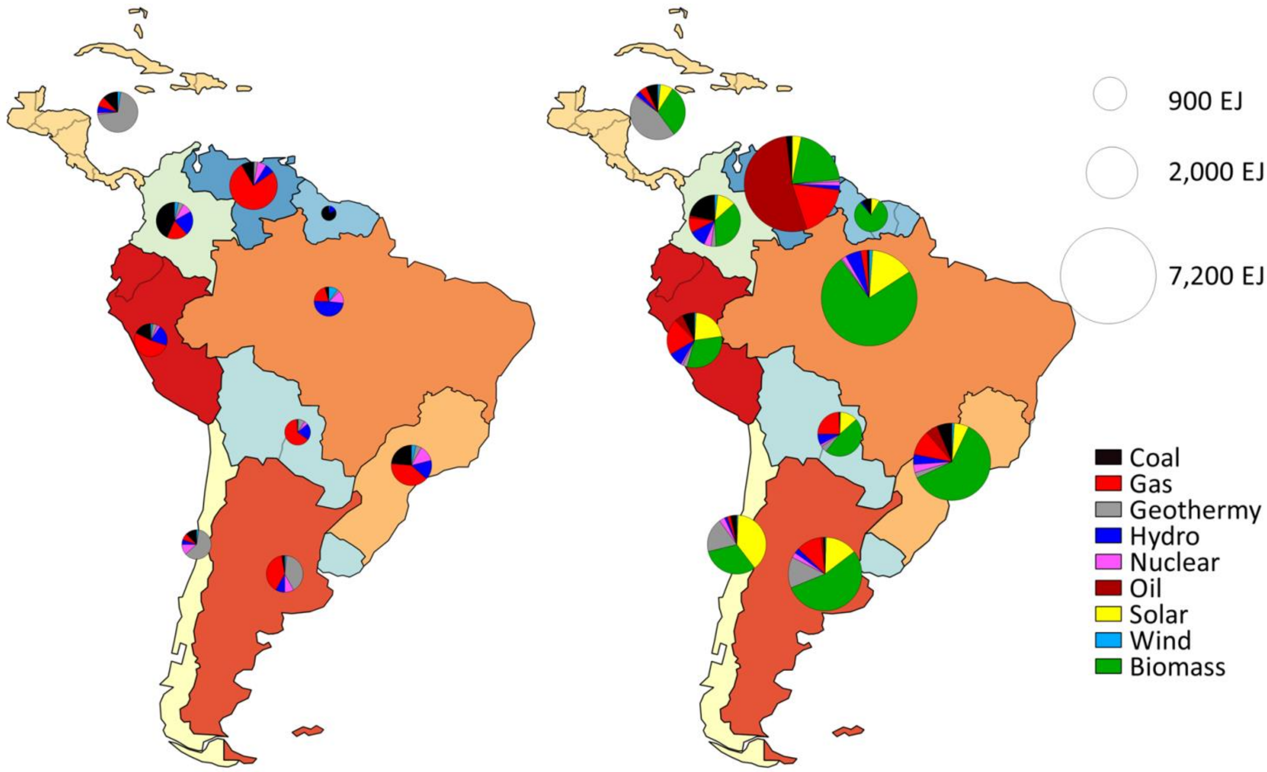

Figure 3-12: South America energy potentials, including (right) or not including (left) oil, solar and biomass potentials

Figure 3-12 displays, on the left, a map of South American potentials without oil, solar and biomass potentials, since these three energies together dominate the regional potential so much that they make the reading difficult. The most relevant insight here is Brazil's clear domination of South America's energy potentials. When solar, oil and biomass resources are not taken into account, Brazil's potential is the biggest by a fair margin (48.1 Gtoe against 40.0 Gtoe for Venezuela, 27.6 Gtoe for Argentina, 23.6 Gtoe for Colombia). When considering all energies, Brazil's lead increases even more: Venezuela's considerable oil reserves (90.9 Gtoe) cannot match Brazil's biomass resources (193.3 Gtoe over 90 years). Second, South America's energy potentials are dominated by biomass and solar energy, followed by oil resources. Hydro and wind power are penalized in this representation by their low primary conversion coefficient as mentioned above: let us remind the reader the hydropower provides more than 60% of the continent's electricity, and is far from having reached its full technical potential.

The following paragraphs, mostly descriptive, provide more details on the figures presented here and the sources used. Sectorial structures and names are based on the International Energy Agency categories, as the IEA's *World Energy Statistics* (2014) is the primary information source for residual installed capacity and base-year energy flows.

C.3.1. Fossil fuels

The three forms of fossil fuels (coal, natural gas, oil) are presented together, as they are quite similar in their structure. The RES for fossil fuel extraction in T-ALyC is highly similar to TIAM one, from which it is inherited[68].

i) Structure

a. Coal

Coal is modeled by two different commodities in T-ALyC: 'hard coal' and 'brown coal'. Hard coal covers the energy commodities referenced by the IEA as 'anthracite', 'patent fuel', and 'other bituminous coal'. Brown coal refers to 'sub-bituminous coal', 'BKB and peat briquettes', 'lignite' and 'peat'. The RES for coal extraction is presented in Figure 3-13.

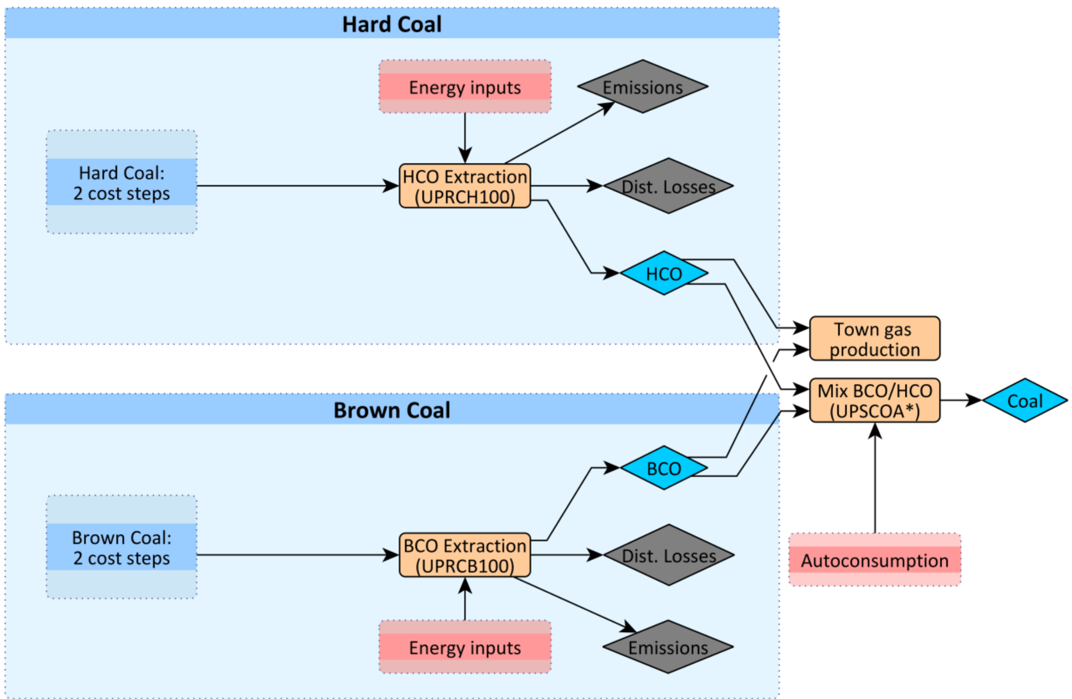

Figure 3-13: Structure of coal resources and extraction in T-ALyC

Coal extraction is modeled by three successive processes:

- Mining processes bear the constraints on extraction potentials and non-energy extraction costs (exploration, manpower, etc.). For each type of coal there are two processes, one to model economically exploitable reserves, and one for not-yet-exploitable resources.
- Production processes *UPRCH100* and *UPRCB100* hold the information about residual capacity at base-year; growth limitations for production; production and transportation losses; and extraction-related atmospheric emissions.

[68] More information about the TIAM gas extraction module can be found in (IER, 2006).

- The so-called *Fuel technologies* (*UPSCOA**) are virtual technologies used to unify hard coal and brown coal into one single coal commodity. Conversion processes located after these fuel techs do not differentiate brown coal and hard coal for their energy inputs. They are also used to model all energy sector autoconsumption (lighting, heating, pumping, etc.) apart from direct energy input for coal extraction[69].

b. Natural gas

The structure for gas extraction in T-ALyC is represented on Figure 3-14. Gas extraction follows two steps:

- Mining processes represent the diverse options for gas extraction, according to gas well's nature. Their activity is constrained, both over the full horizon and on a yearly basis, to account for both the overall extraction potential, and maximum annual production. Their activity cost represents non-energy extraction costs (exploration, maintenance, etc.). The cost curve for mining supply is represented through 23 processes: 11 for conventional gas (located reserves, enhanced gas recovery, new discoveries, and additional occurrences), 12 for unconventional gas (coal-bed methane, tight gas, aquifer gas and shale gas).
- The *UPRNG100* fuel technology combines all extracted gases with natural gas issued from other sources (refinery gas, associated gas) and keeps track of the energy consumption, auto consumption and losses associated with the extraction process. The energy consumption associated with gas extraction is thus average, since the fuel technology processes undifferentiated gas. The fuel technology also holds the information about residual capacity at base year and extraction-related atmospheric emissions.

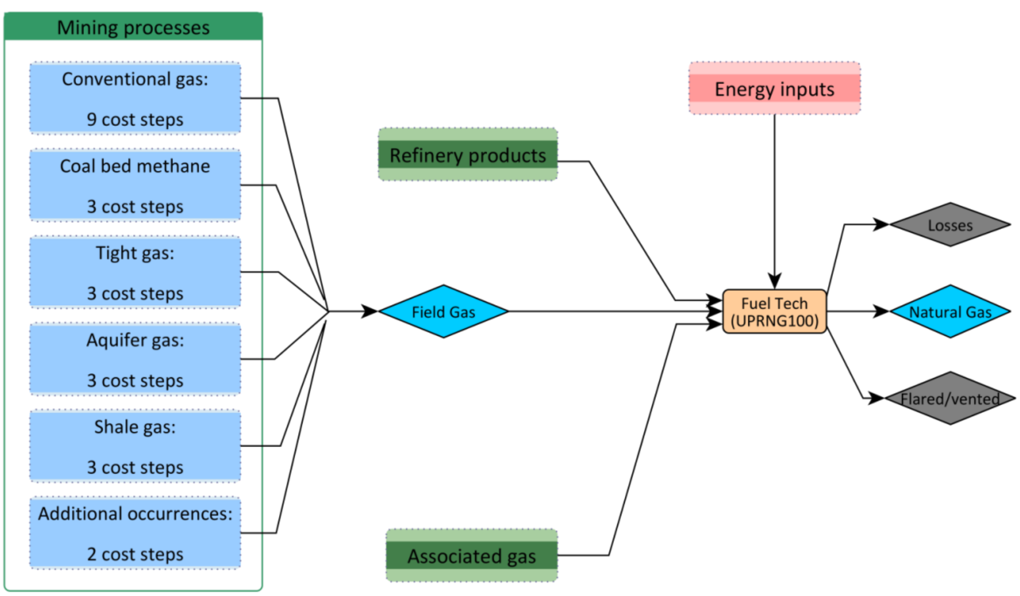

Figure 3-14: Structure for gas resources and gas extraction in T-ALyC

[69] An exception in the RES, town gas production uses brown coal and hard coal as direct inputs instead of generic coal.

c. Oil

The structure for oil extraction in T-ALyC is represented on Figure 3-15. Oil extraction follows three steps:

- Mining processes represent the diverse options for oil extraction, according to the nature of the oil field. Their activity is constrained, both over the full horizon and on a yearly basis, to account for both the overall extraction potential, and maximum annual production. Their activity cost represents non-energy extraction costs (exploration, maintenance, etc.). The supply curve for oil is represented through 21 processes, modeling seven extraction techniques with three cost steps each. Conventional oil extraction relies on 9 processes: located reserves, enhanced oil recovery (EOR) and new discoveries, with three cost steps each. Unconventional oil extraction is modeled through 6 processes: oil sands, extra-heavy oil –located reserves and enhanced recovery– and shale oil, with 3 processes each. No distinction is made between light and heavy conventional oil. The oil sand option, however existing in the model for future uses, is disabled for all practical purposes, with 0 extraction potential and an elevated extraction cost (see Table 3-7 and Table 3-10 below).
- "*UPRP**" fuel technologies keep track of the energy consumption, autoconsumption and losses associated with the extraction process. Contrary to gas extraction, the energy associated with oil extraction thus depends on the oil category. The fuel technologies also embed the information about residual capacity at base year, extraction-related atmospheric emissions, and associated gas production.
- Last, all oil grades are aggregated into a generic 'crude oil' commodity that will be consumed by refineries and productive sectors.

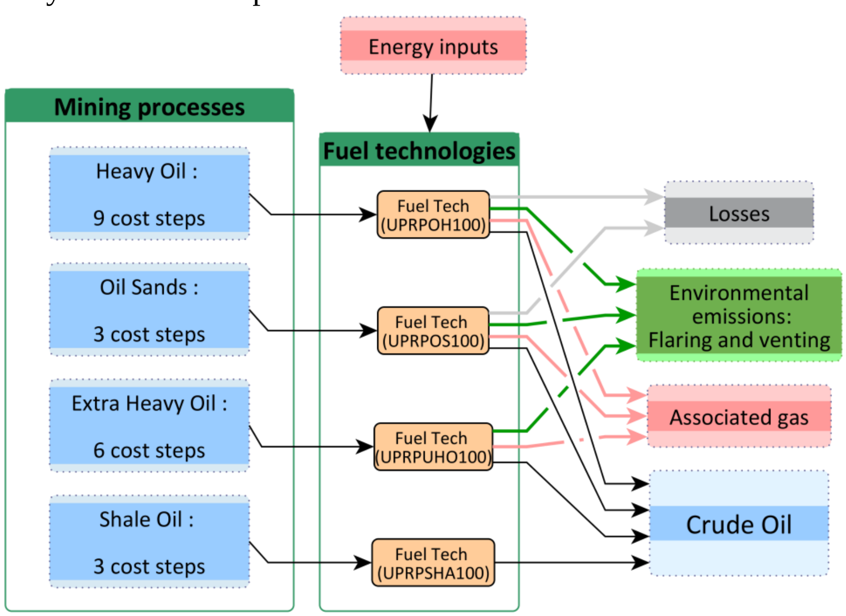

Figure 3-15: Structure for oil resources and extraction in T-ALyC

ii) Reserves

For fossil fuels, the potential displayed on Figure 3-12 is the total primary potential, as detailed in Table 3-5, Table 3-6 and Table 3-7. For oil and gas, the disaggregation of overall reserves into cost steps is based on ratios from (IER, 2006). When necessary, conversion factors were taken from (IEA, 2013).

a. Coal

Coal reserves as informed in T-ALyC are displayed in Table 3-5 below. Bituminous, sub-bituminous coal and lignite potentials come directly from the *World Energy Resources Survey* by the World Energy Council (2013). For peat, national areas of peatland come from the same source, considering that one square km of peatland can annually produce up to 1,000 tons of dry peat. The heat content of the resulting organic matter is 9.8 PJ/Mton on average (IEA, 2013). *Located reserves* refers to the reserves known today to be economically recoverable; *new discoveries* represents coal reserves that have not been discovered yet but whose existence can be assumed from existing statistical and geological information.

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Hard coal – located reserves	1.3	0.0	0.0	0.0	0.0	0.0	183.5	0.0	0.3	14.7
Hard coal – new discoveries	2.6	0.0	0.1	0.0	0.0	0.0	183.5	0.0	0.6	29.3
Brown coal – located reserves	81.4	15.7	2.7	148.4	16.5	47.2	30.7	76.6	40.7	48.9
Brown coal – new discoveries	81.4	15.7	2.7	148.4	16.5	47.2	30.7	76.6	40.7	48.9

Table 3-5: Coal extraction potential in T-ALyC (EJ)

b. Natural gas

Gas resources are taken from (WEC, 2013), except for Brazil, where we used national statistics from (ANP, 2013). The resulting potentials for gas extraction in T-ALyC are given in Table 3-6 below[70].

Gas type	Cost steps (tech name)	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Conventional – located reserves	**Step1** (*MINGASNAT1*)	5.8	5.3	4.5	5.8	1.8	0.7	2.1	1.2	0.0	14.9
	Step2 (*MINGASNAT2*)	4.3	4.0	3.4	4.4	1.3	0.5	1.6	0.9	0.0	11.2
	Step3 (*MINGASNAT3*)	4.3	4.0	3.4	4.4	1.3	0.5	1.6	0.9	0.0	11.2
Conventional – Enhanced Gas Recovery *(EGR)*	**Step1** (*MINGASNAT4*)	4.1	3.8	3.2	4.2	1.3	0.5	1.5	0.8	0.0	10.7
	Step2 (*MINGASNAT5*)	3.1	2.9	2.4	3.1	1.0	0.4	1.2	0.6	0.0	8.1
	Step3 (*MINGASNAT6*)	3.1	2.9	2.4	3.1	1.0	0.4	1.2	0.6	0.0	8.1
Conventional – New discoveries	**Step1** (*MINGASNAT7*)	9.7	8.9	7.6	9.8	3.0	1.1	3.6	2.0	0.0	25.1
	Step2	7.3	6.7	5.7	7.4	2.3	0.8	2.7	1.5	0.0	18.8

[70] As a reminder, VEN figures include Venezuela *and* Trinidad and Tobago. Of the two, the latter is the largest producer.

	(*MINGASNAT8*)										
	Step3 (*MINGASNAT9*)	7.3	6.7	5.7	7.4	2.3	0.8	2.7	1.5	0.0	18.8
Coal-bed methane *(CBM)*	**Step1** (*MINGASCBM1*)	0.4	0.4	0.3	0.4	0.1	0.0	0.1	0.1	0.0	1.0
	Step2 (*MINGASCBM2*)	0.3	0.3	0.2	0.3	0.1	0.0	0.1	0.1	0.0	0.8
	Step3 (*MINGASCBM3*)	0.3	0.3	0.2	0.3	0.1	0.0	0.1	0.1	0.0	0.8
Tight gas	**Step1** (*MINGASTIG1*)	1.4	1.3	1.1	1.5	0.4	0.2	0.5	0.3	0.0	3.7
	Step2 (*MINGASTIG2*)	1.1	1.0	0.8	1.1	0.3	0.1	0.4	0.2	0.0	2.8
	Step3 (*MINGASTIG3*)	1.1	1.0	0.8	1.1	0.3	0.1	0.4	0.2	0.0	2.8
Aquifer gas	**Step1** (*MINGASAQF1*)	61.8	57.0	48.1	62.5	19.2	7.0	23.0	12.5	0.0	160.0
	Step2 (*MINGASAQF2*)	46.3	42.7	36.1	46.9	14.4	5.3	17.2	9.4	0.0	120.0
	Step3 (*MINGASAQF3*)	46.3	42.7	36.1	46.9	14.4	5.3	17.2	9.4	0.0	120.0
Shale gas	**Step1** (*MINGASSHL1*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Step2 (*MINGASSHL2*)	285.5	263.2	222.4	288.9	88.8	32.4	106.1	57.8	0.0	739.4
	Step3 (*MINGASSHL3*)	35.8	33.0	27.9	36.2	11.1	4.1	13.3	7.2	0.0	92.7
Conventional – additional occurrences	Unconnected	21.5	19.8	16.7	21.7	6.7	2.4	8.0	4.3	0.0	55.6
	Connected	14.3	13.2	11.1	14.5	4.5	1.6	5.3	2.9	0.0	37.1

Table 3-6: Gas resources in T-ALyC (EJ)

c. Oil

Oil resources are issued from (US-EIA, 2014), except for Brazil, where we used national statistics from (ANP, 2013). Resulting potentials for oil extraction in T-ALyC are given in Table 3-7 below.

		AND	**ARG**	**BPU**	**BSE**	**BWC**	**CHL**	**COL**	**CYC**	**SUG**	**VEN**
Conventional oil – Located reserves	**Step1** (*MINOILHEA1*)	21.0	7.4	1.4	42.5	3.5	0.5	5.7	0.7	0.2	682.8
	Step2 (*MINOILHEA2*)	12.6	4.4	0.8	25.5	2.1	0.3	3.4	0.4	0.1	409.7
	Step3 (*MINOILHEA3*)	8.4	2.9	0.5	17.0	1.4	0.2	2.3	0.3	0.1	273.1
Conventional oil – Enhanced Oil Recovery	**Step1** (*MINOILHEA4*)	6.7	2.3	0.4	13.5	1.1	0.1	1.8	0.2	0.1	216.5
	Step2 (*MINOILHEA5*)	4.0	1.4	0.3	8.1	0.7	0.1	1.1	0.1	0.0	129.9
	Step3 (*MINOILHEA6*)	2.7	0.9	0.2	5.4	0.4	0.1	0.7	0.1	0.0	86.6
Conventional oil – New discoveries	**Step1** (*MINOILHEA7*)	7.7	2.7	0.5	15.6	1.3	0.2	2.1	0.3	0.1	250.4
	Step2 (*MINOILHEA8*)	4.6	1.6	0.3	9.3	0.8	0.1	1.2	0.2	0.1	150.3
	Step3 (*MINOILHEA9*)	3.1	1.1	0.2	6.2	0.5	0.1	0.8	0.1	0.0	100.2

Extra-heavy oil – Located reserves	**Step1** (*MINOILOBI1*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	Step2 (*MINOILOBI2*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	Step3 (*MINOILOBI3*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Extra-heavy oil – Enhanced Oil Recovery	**Step1** (*MINOILOBI4*)	16.6	5.8	1.1	33.5	2.7	0.4	4.5	0.6	0.2	538.8
	Step2 (*MINOILOBI5*)	16.6	5.8	1.1	33.5	2.7	0.4	4.5	0.6	0.2	538.8
	Step3 (*MINOILOBI6*)	8.3	2.9	0.5	16.8	1.4	0.2	2.2	0.3	0.1	269.4
Oil sands	**Step1** (*MINOILSAN1*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Step2 (*MINOILSAN2*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Step3 (*MINOILSAN3*)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shale oil	**Step1** (*MINOILOSH1*)	1.9	0.7	0.1	3.9	0.3	0.0	0.5	0.1	0.0	62.7
	Step2 (*MINOILOSH2*)	1.9	0.7	0.1	3.9	0.3	0.0	0.5	0.1	0.0	62.7
	Step3 (*MINOILOSH3*)	1.0	0.3	0.1	1.9	0.2	0.0	0.3	0.0	0.0	31.3

Table 3-7: Oil resources (extraction potentials) in T-ALyC (EJ)

iii) Costs

The extraction costs used in this version of T-ALyC were adapted from those proposed by (IER, 2006) for South America. They have not been detailed on a sub-regional basis so far.

a. Coal

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Hard coal – located reserves	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2	40.2
Hard coal – new discoveries	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4	54.4
Brown coal – located reserves	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
Brown coal – new discoveries	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5	167.5

Table 3-8: Extraction costs in T-ALyC ($\$_{2000}$ / toe)

b. Natural gas

Conventional – located reserves	**Step1** (*MINGASNAT1*)	3.03	**Unconventional – Tight gas**	**Step1** (*MINGASTIG1*)	6.05
	Step2 (*MINGASNAT2*)	3.07		**Step2** (*MINGASTIG2*)	7.15
	Step3 (*MINGASNAT3*)	3.11		**Step3** (*MINGASTIG3*)	8.11
Conventional – Enhanced Gas Recovery *(EGR)*	**Step1** (*MINGASNAT4*)	5.90	**Aquifer gas**	**Step1** (*MINGASAQF1*)	7.21
	Step2 (*MINGASNAT5*)	6.57		**Step2** (*MINGASAQF2*)	8.53
	Step3 (*MINGASNAT6*)	7.31		**Step3** (*MINGASAQF3*)	9.69
Conventional – New discoveries	**Step1** (*MINGASNAT7*)	3.48	**Shale gas**	**Step1** (*MINGASSHL1*)	5.38
	Step2 (*MINGASNAT8*)	3.61		**Step2** (*MINGASSHL2*)	6.61
	Step3 (*MINGASNAT9*)	3.75		**Step3** (*MINGASSHL3*)	10.18
Conventional – Additional occurrences	Unconnected	2.65	**Unconventional – Coal-bed methane (CBM)**	**Step1** (*MINGASCBM1*)	5.91
	Connected	20.58		**Step2** (*MINGASCBM2*)	7.06
				Step3 (*MINGASCBM3*)	8.05

Table 3-9: 2010 costs for gas extraction in T-ALyC ($\$_{2000}$ / MMBTU)

c. Oil

Conventional – located reserves	**Step1** (*MINOILHEA1*)	3.5	**Extra-heavy oil – Located reserves**	**Step1** (*MINOILOBI1*)	12.2
	Step2 (*MINOILHEA2*)	4.1		**Step2** (*MINOILOBI2*)	12.8
	Step3 (*MINOILHEA3*)	6.4		**Step3** (*MINOILOBI3*)	14.0
Conventional – Enhanced Oil Recovery	**Step1** (*MINOILHEA4*)	13.4	**Extra-heavy oil – Enhanced Oil Recovery**	**Step1** (*MINOILOBI4*)	13.4
	Step2 (*MINOILHEA5*)	15.7		**Step2** (*MINOILOBI5*)	14.6
	Step3 (*MINOILHEA6*)	17.5		**Step3** (*MINOILOBI6*)	15.7
Conventional – New discoveries	**Step1** (*MINOILHEA7*)	5.8	**Oil sands**	**Step1** (*MINOILSAN0*)	129,332.0
	Step2 (*MINOILHEA8*)	11.1		**Step2** (*MINOILSAN1*)	129,332.0
	Step3 (*MINOILHEA9*)	15.7		**Step3** (*MINOILSAN2*)	129,332.0
			Shale oil	**Step1** (*MINOILOSH1*)	32.6
				Step2 (*MINOILOSH2*)	39.6
				Step3 (*MINOILOSH3*)	48.3

Table 3-10: 2010 costs for oil extraction in T-ALyC ($\$_{2000}$/boe)

C.3.2. Solar energy

i) Structure

Solar energy modeling in T-ALyC is represented on Figure 3-16. We consider a unique solar potential by region, expressed as overall annual incoming energy. This energy is directed towards electricity production or direct use (e.g. residential water heating) by means of distinct fuel technologies. Solar potential is then transformed into actual energy services and/or electricity through dedicated technologies. The information related to resource availability (timeslice-specific availability) is embedded into these dedicated technologies, along with their investment cost, O&M cost, and conversion efficiency. The electricity produced can be either centralized or decentralized; in the first case, a premium is paid for electricity transport and distribution. It is considered that decentralized electricity is consumed near production centers, so its transport premium is lower.

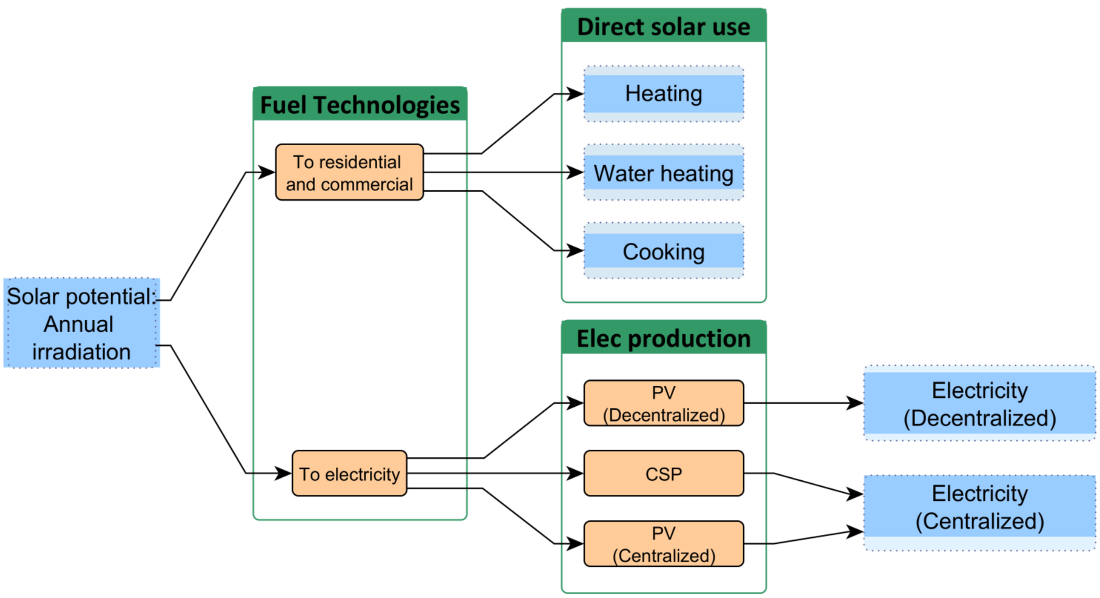

Figure 3-16: Structure for solar resources and extraction in T-ALyC

The efficiencies for solar technologies are 18% for photovoltaic (PV) generation and 10% for thermal water heating and Concentrating Solar Power (CSP), respectively.

ii) Potential

Solar potential for all South America minus Brazil and Chile is calculated on the basis of the work by De Martino Jannuzzi et al. (2010) who provided average annual irradiations on a country basis. We consider that 0.1% to 0.4% of national areas are theoretically eligible for solar projects; only 20% of this theoretical potential is available in 2010. Maximal authorized solar capacity then increases linearly, reaching its full theoretical potential in 2050.

Calculations for Brazil follow the same lines, however the irradiation values are taken from the country's *Second National Communication to the UNFCCC* (MCT, 2010). For Chile, installable capacity is directly taken from the recent assessment by Chile's energy ministry (Minenergía and GIZ, 2014). However, this assessment could be considered very optimistic, as the eligible area for CSP and PV together amounts to 10,000,000 hectares, nearly 15% of the country's area.

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Solar income (2010)	47	53	19	27	72	100	21	16	5	20
Solar income (2050)	235	266	95	133	361	502	107	79	23	101

Table 3-11: Annual exploitable solar income in T-ALyC (EJ/yr)[71]

The potential reported on Figure 3-12 considers an average conversion efficiency of 12% for solar panels to account for electricity production, and a 1 conversion coefficient from final to primary energy.

iii) Costs

There is no "extraction cost" for solar resource apart from investment in, and maintenance of, solar panels. These costs are embedded in the technology itself. As a first approximation, we can consider that the $Production/Surface$ ratio of a PV panel depends linearly on the irradiation. As a consequence, solar panels prices vary as $\frac{1}{Irradiation}$. Average prices of solar production technologies for each model's region are thus adapted following average radiation in the production zones. The resulting investment costs are displayed on Figure 3-17 below.

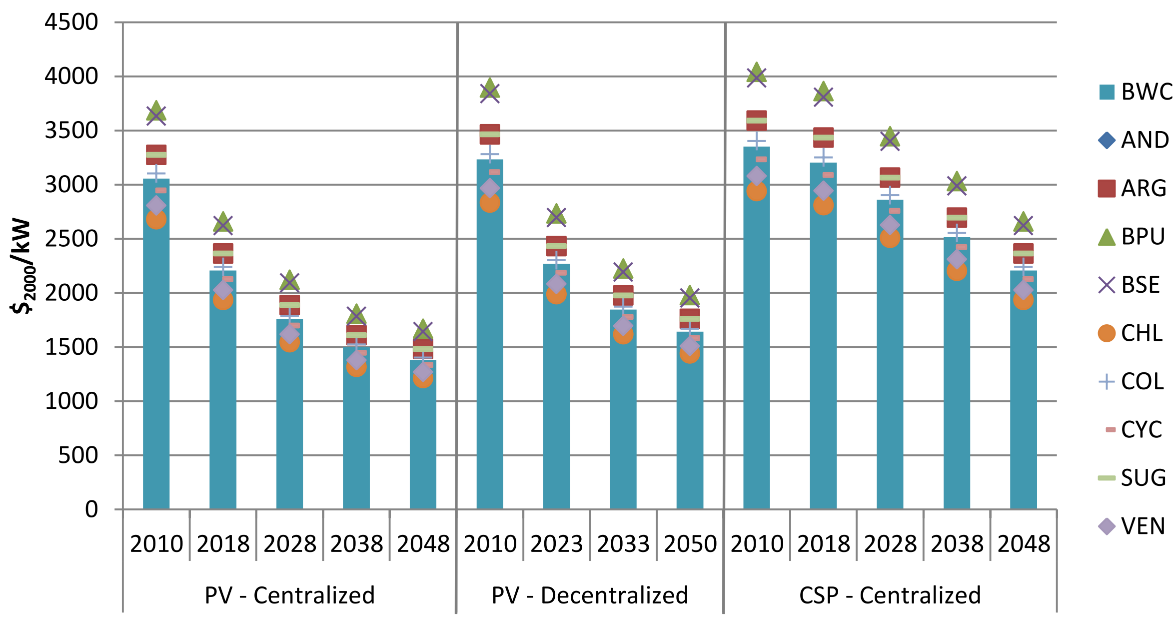

Figure 3-17: Investment costs for solar technologies in T-ALyC

[71] The potential presented here includes availability factors, but excludes conversion efficiency (10% to 15%).

C.3.3. Hydropower

i) Structure

The structure of the hydropower module in T-ALyC is represented on Figure 3-18. Hydro potential is split into five cost steps for dam technologies and one for run-of-river technologies. Each dam is associated with a reservoir, which can store up to two years of production with 90% storage efficiency. The maximal incoming flow for each dam represents three times its production capacity, allowing excess water to be stored. However, the inflow availability depends on the season, being at times lower than a dam's electric production capacity. All dams produce centralized electricity. The potential is expressed as a limit on installable capacity for dams; it is considered that the 2010 existing capacity does not decrease with time.

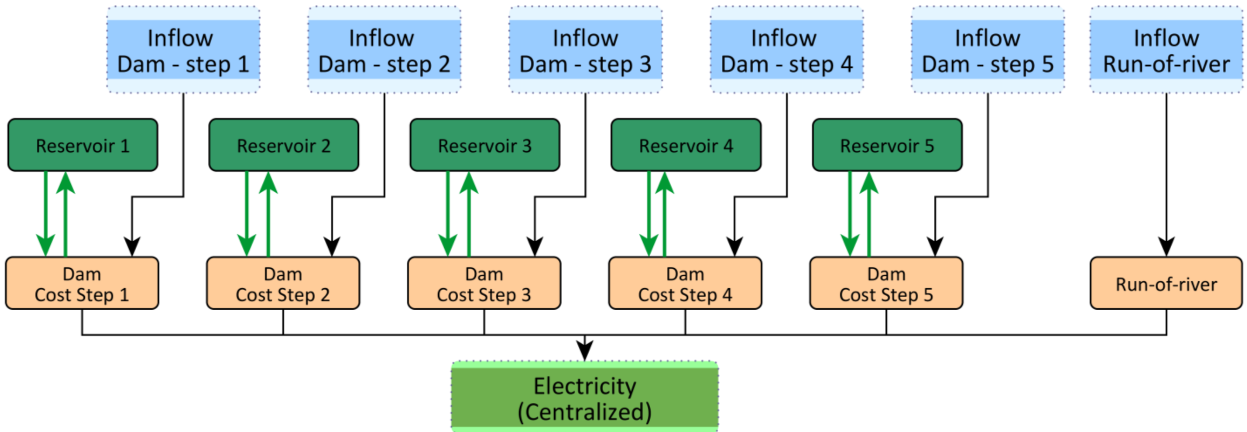

Figure 3-18: Structure for hydro resources and extraction in T-ALyC

ii) Potential

Hydropower potential for all South America minus Brazil and Chile is calculated on the basis of OLADE's *Energy Statistics* (2012) for total potential and the IEA's *World Energy Statistics* (2014) for installed capacity. A third of the untapped potential is considered as run-of-river; the remaining two thirds are split into five cost steps following Chile's recent assessment of hydro resources by plant size (Minenergía, 2015), displayed in Table 3-12.

Plant size range (MW)	0.1 – 50	50 – 100	100 – 200	200 – 500	500 – 1,000
Cost step	5	4	3	2	1
Fraction of remaining potential	24%	22%	28%	12%	14%

Table 3-12: split of hydro potential in T-ALyC

For Chile, existing plants as per (IEA, 2014) are summed with remaining potential from (Minenergía, 2015) to provide the overall national potential[72]. Brazilian information is based on

[72] This potential excludes the 4,480 MW associated with *HidroAysén* catchments in Southern Chile, as these projects have been removed from the political agenda due to strong social opposition. It is estimated by (Minenergía, 2015)

national assessments by the country's national electricity company Eletrobras (2012). The resulting potentials are listed in Table 3-13.

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Total Hydro potential	84.1	40.4	54.3	85.7	163.2	17.3	93.0	28.0	7.4	46.0
Potential already tapped	5.7	10.0	10.8	49.1	37.5	6.0	9.7	4.9	1.1	14.6
Available for dams	52.3	22.8	32.6	21.9	75.4	7.5	55.5	15.4	4.8	20.9
Available for run-of-the-river	26.1	7.6	10.9	14.6	50.3	3.8	27.8	7.7	1.6	10.5

Table 3-13: Hydropower potentials in T-ALyC (GWe)

The potential reported on Figure 3-12 considers 80% plant availability to account for actual energy production, and a 1 conversion coefficient from final energy (electricity) to primary energy.

iii) Costs

The costs for hydropower generation in T-ALyC are inherited from the TIAM-FR model. By comparison with the review performed by Kumar et al. (2011), they are rather optimistic, yet all six cost steps fall within the range of Kumar's review for their investment costs, as shown by Figure 3-19.

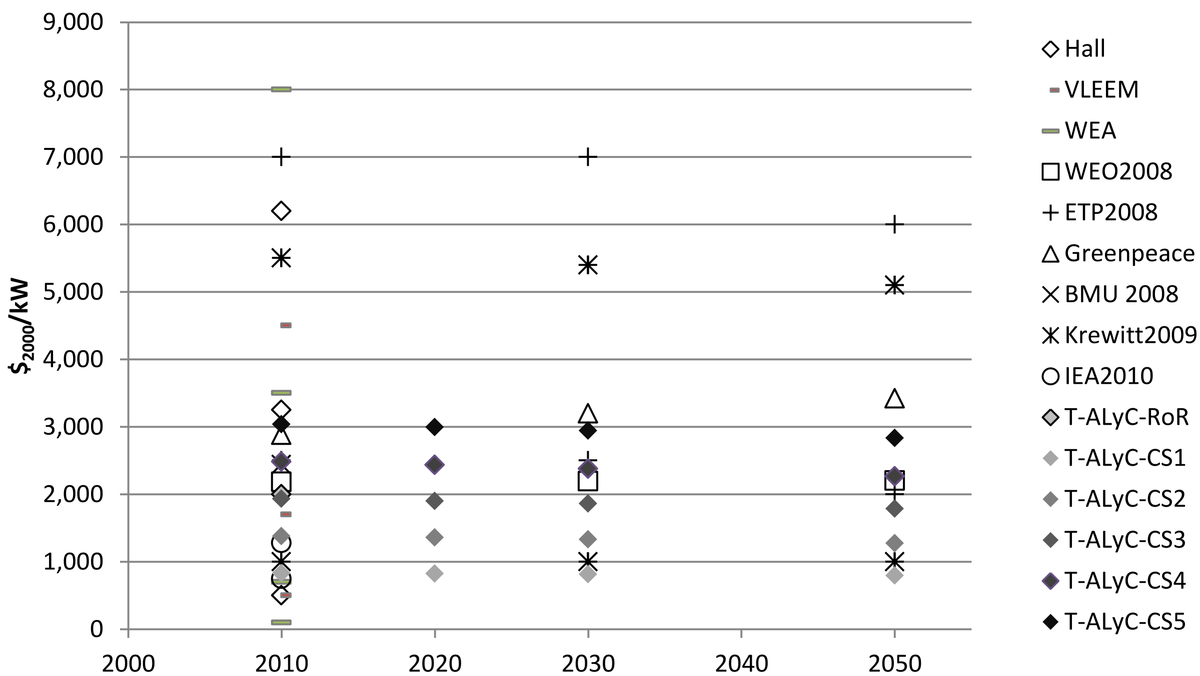

Figure 3-19: T-ALyC hydro costs – comparison with existing literature (adapted from Kumar et al., 2011)

that 64% of Table 3-13's potential for Chile could be installed with little or no impact on High Conservation Value objects.

C.3.4. Wind

i) Structure

The structure of T-ALyC's wind module is given on Figure 3-20. Wind-sourced electricity production is modeled, apart from existing capacity, through three processes representing centralized onshore, centralized offshore and decentralized onshore wind production. The availability of these processes varies from 30% to 40% during the year.

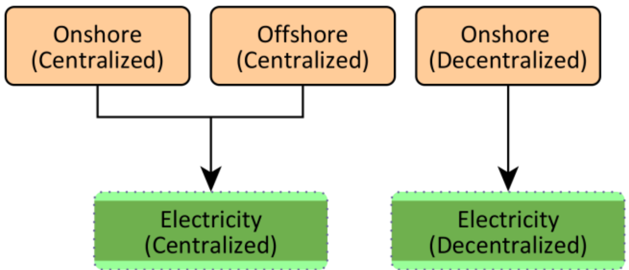

Figure 3-20: Structure for wind resources in T-ALyC

ii) Potential

As a consequence of the technological description, wind potential in T-ALyC is divided in three:

- Potential for centralized onshore production: **2/5 of total potential;**
- Potential for centralized offshore production: **2/5 of total potential;**
- Potential for decentralized onshore production: **1/5 of total potential.**

These three potentials are represented, as for hydropower, through capacity constraints.

Data available in literature is not quite unanimous. T-ALyC figures as presented in Table 3-14 aggregate data from various sources, the main publication being the *World Energy Resources Review 2013* by (WEC, 2013). The very optimistic data issued from this review has often being scaled down by comparing it with other estimations.

Alternative sources used here include (Castano, 2011; CEPEL, 2001; De Martino Jannuzzi et al., 2010; Dolezal et al., 2013; Fiestas, 2010; MEER, 2013; Molinelli, 2011; NREL, 2006; Vergara et al., 2010).

	AND	ARG	BPU	BSE	BWC	COL	CHL	CYC	SUG	VEN
Onshore – centralized	9.2	8.0	3.0	21.0	36.4	8.0	16.1	14.8	1.2	3.2
Offshore – centralized	9.2	8.0	3.0	21.0	36.4	8.0	16.1	14.8	1.2	3.2
Onshore – decentralized	4.6	4.0	1.5	10.5	18.2	4.0	8.1	7.4	0.6	1.6
Total wind potential	22.9	20.0	7.5	52.5	90.9	20.0	40.3	37.0	3.0	8.0

Table 3-14: Wind potential in South America (GWe)

The potential reported on Figure 3-12 considers 30% plant availability to account for actual energy production, and a 1 conversion coefficient from final energy (electricity) to primary energy.

iii) Cost

The costs used in T-ALyC are the same as in TIAM-FR. They are presented on Figure 3-21 below.

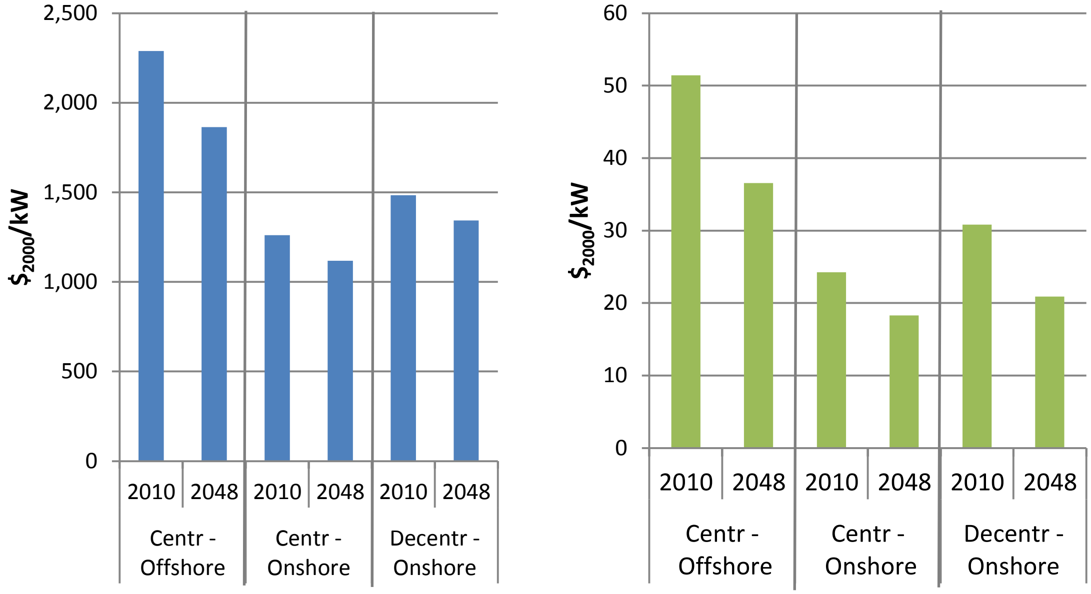

Figure 3-21: Investment (left) and O&M (right) costs for wind power generation in T-ALyC

C.3.5. Geothermal energy

i) Structure

The structure for geothermal energy in T-ALyC is presented on Figure 3-22. T-ALyC features three types of geothermal resources: shallow, deep and very deep. However, this distinction is not modeled the same way for electricity production and the other sectors.

- For electricity, geothermal potential is constrained at production level. Three different technologies represent electricity production from shallow, deep and very deep geothermal resources, each with its own cost and efficiency. The fuel technology represented on Figure 3-22 only exists for reporting purposes. Heat and steam production is slightly less detailed, yet follows the same principles.
- For industrial, residential and commercial uses of geothermal (including auto-produced industrial heat), the potential is constrained at fuel technology level; however, productive consuming devices are generic, consuming undifferentiated 'geothermal energy', due to the complexity and lack of data for modeling different techno-economic parameters for e.g. three types of geothermal residential heaters. Geothermal energy satisfies energy services in combination with other energy carriers (electricity).

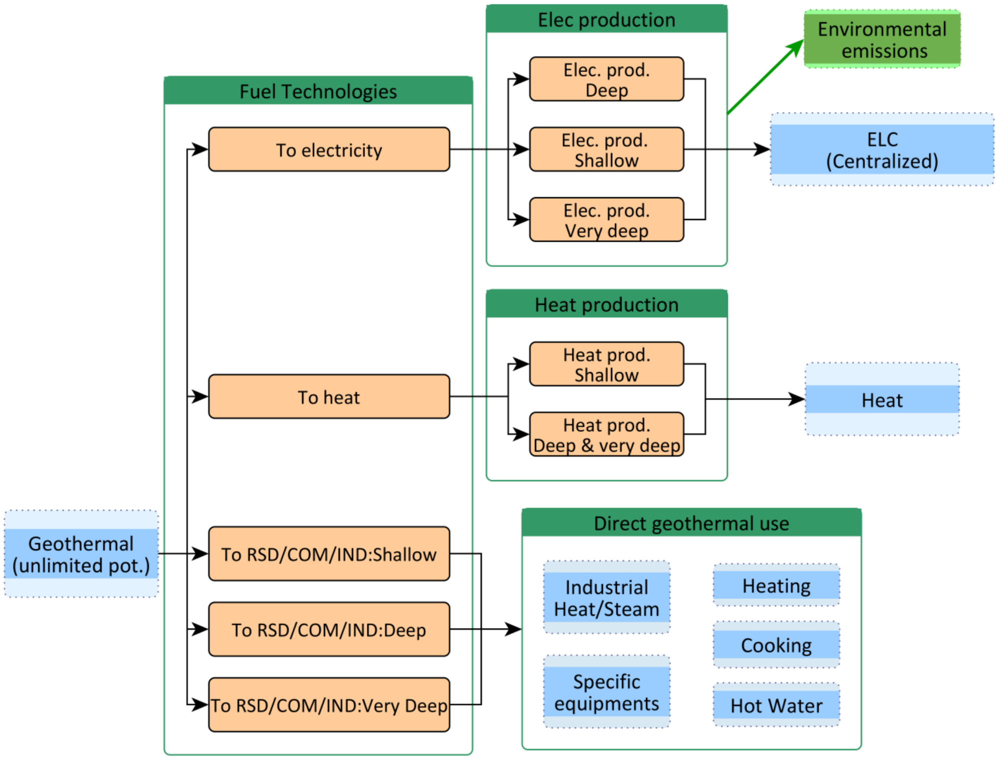

Figure 3-22: Structure for geothermal resources in T-ALyC

ii) Extisting potential

Geothermal potential for South America is listed in Table 3-15. T-ALyC considers an availability factor of 80% for power plants and 60% for thermal ones. As for wind, data sources for geothermal potential are numerous, including (Battocletti, 1999; Cardoso et al., 2010; Geothermal Energy Association, 2013; Haraldsson, 2012; International Geothermal Association, 2013; Vieira and Hamza, 2014).

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Electricity production – shallow	19	2	0	0	0	24	4	17	0	0
Electricity production – deep	2	141	9	1	1	144	8	273	0	9
Electricity production – very deep	4	282	18	2	2	287	17	545	0	17
Heat production	0	9	0	0	0	3	4	1	0	0
Potential for industry direct use	13	54	16	35	11	38	11	80	0	11
Potential for residential direct use	18	72	21	46	14	50	14	107	0	14
Potential for commercial direct use	13	54	16	35	11	38	11	80	0	11

Table 3-15: Geothermal potential in T-ALyC (PJ/yr)

The potential reported on Figure 3-12 is the maximal output presented in Table 3-15, multiplied by its physical energy content coefficient. This coefficient is 10 for electricity production and 5 for heat production.

iii) Costs

Geothermal energy production in T-ALyC does not imply extraction costs as was the case for fossil fuels. As for solar and hydropower, the costs are all embedded in the production technologies themselves. Figure 3-23 below presents the investment and Operation and Maintenance (O&M) costs for the three geothermal-based electricity production technologies in T-ALyC; these are TIAM-FR costs for South America. They would merit serious refining, yet were kept “as is” due to data availability issues.

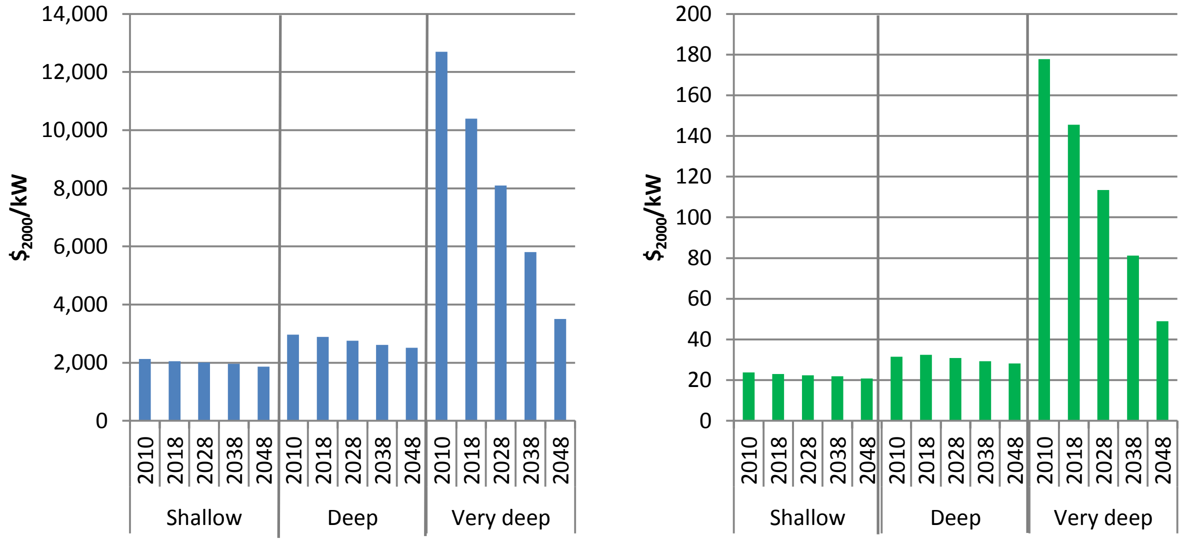

Figure 3-23: Investment costs (left) and O&M costs (right) for geothermal-based electricity production in T-ALyC

C.3.6. Nuclear energy

The structure for nuclear production in T-ALyC, as presented Figure 3-24, is quite poor. Uranium extraction and enrichment is not modeled, there is no supply cost for combustibles, and the new plant portfolio is limited to three generic technologies, one of which is nuclear fusion –whose industrial use is all but impossible in the next forty years. Plant auto-consumption is not modeled. However, improving this shortcoming may prove unnecessarily costly since nuclear energy is not, by far, the main contributor to electricity production in South America. Argentina and Brazil are the only two states operating nuclear plants in Latin America today, and this energy form provided 2.1% of the electricity generated in the region in 2012 (CIER, 2013). Some countries (e.g. Chile, Bolivia) have been considering introducing this energy into their mix, yet no major advance is foreseeable in this area in the near future.

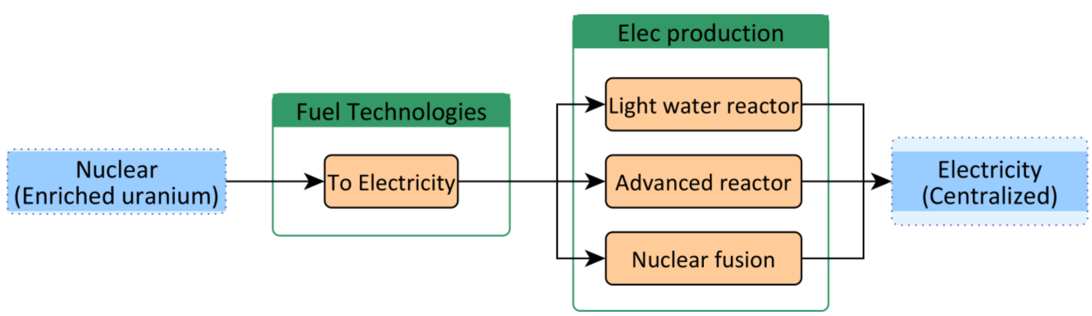

Figure 3-24: Structure of the nuclear module in T-ALyC

Base-year capacity is constrained by specifying the five existing plants[73] and their characteristics. Then, the minimum and maximum nuclear capacity is constrained according to national communications and future projections by the World Nuclear Association (2008), revised to take into account the post-Fukushima global context (e.g. national moratoriums in Venezuela and Peru[74]). Brazilian national forecasts are based on a presentation by the Brazilian National Energy Commission to the International Atomic Energy Agency (Gonçalves Filho, 2011).

Low and high scenarios for future nuclear use in South America are reported in Table 3-16:

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Nuclear production 2050 – High	134	268	80	483	214	402	268	80	0	536
Nuclear production 2050 – Low	0	80	0	214	80	0	0	0	0	0

Table 3-16: High and low scenarios for nuclear production in 2050 in T-ALyC (PJ/a)

The potential reported on Figure 3-12 is the average between these scenarios, although this may over-consider the weight of the "high scenario" in potential future outcomes.

C.3.7. Biomass

i) Structure

'Biomass' is defined by the European Union as '*the biodegradable fraction of products, waste and residues from agriculture, forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste'* (European Commission, 2001). This sector is thus a complex one, aggregating very different products, from distinct sources and competing with a wide variety of potential other uses[75].

The model architecture for biomass transformation and use is presented on Figure 3-25. T-ALyC distinguishes five types of biomass potential, namely municipal waste, industrial waste, biogas, purpose-grown energy crops, and other solid waste. The latter category covers, among others, agricultural and forestry residues (pelletized or not). It is further divided into 3 different cost steps for primary commodity supply in each region. Biomass resources satisfy three main energy demand categories: electricity production, transportation biofuels demand, and direct use by productive sectors (most of all, industry). A small share of purpose-grown energy crops also satisfies specific non-energy demand, e.g. petrochemical feedstock for industrial and pharmaceutical purposes.

[73] Argentina: *Atucha* I, *Atucha* II, *Embalse*. Brazil: *Angra* I and II.
[74] Bolivia declared a moratorium on nuclear energy in 2011. However, the country started negotiations with Argentina to install the new low-cost, low-power Argentine reactor CAREM in 2014, and President Morales visited the brand-new Atucha II plant in 2015.
[75] For more information on energy uses of biomass in the French case, please refer to (Hugues, 2015).

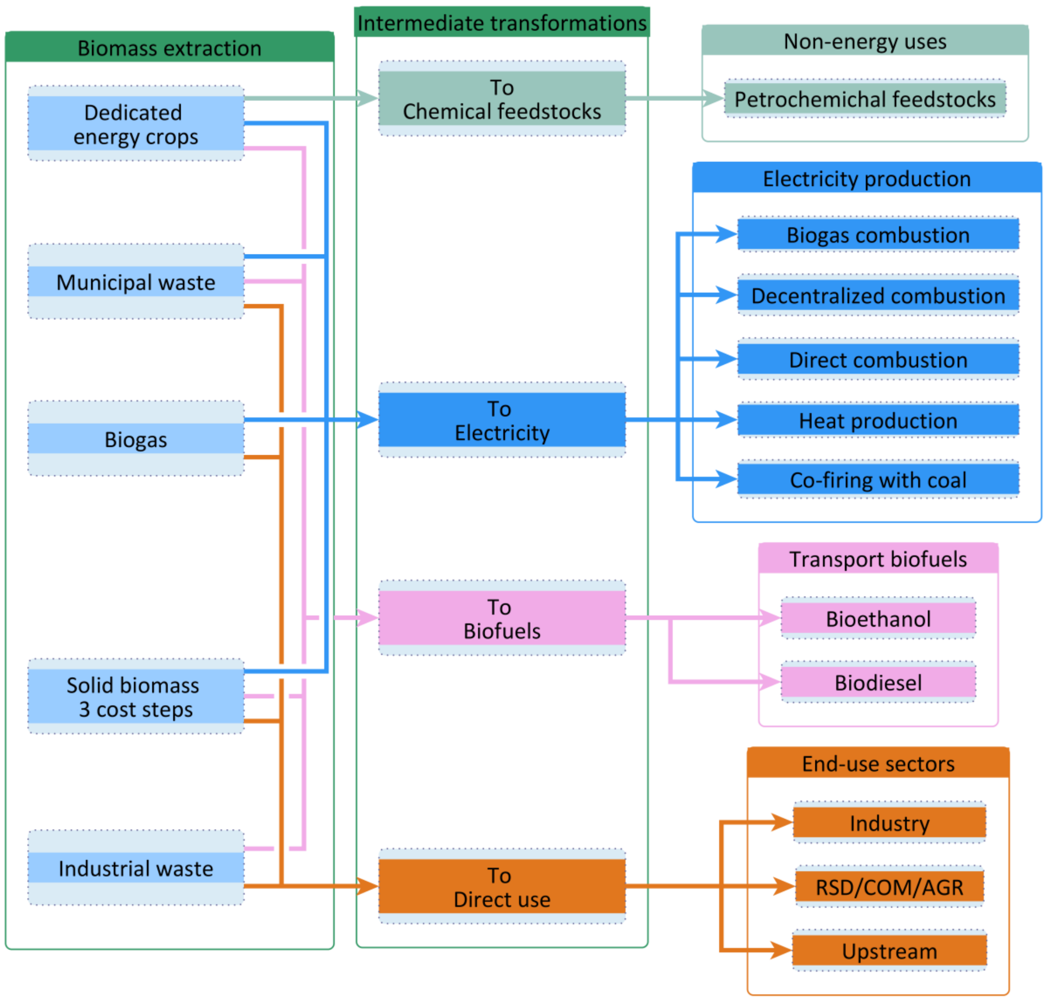

Figure 3-25: Architecture of the biomass module in T-ALyC

ii) Potential

Biomass potential for the seven primary biomass commodities (four unique sources plus three cost steps for solid biomass) is detailed Table 3-17. T-ALyC considers only sustainable potentials; in the case of energy crops, these potentials are based on a mixed agricultural production system (pastoral and landless); in the case of forestry, only forest growth surplus is harvested.

- For overall regional solid biomass potential (crop and other solid biomass), I used the global review by Smeets et al. (2007); although not most recent, this work remains a global reference on biomass potentials for energy production. The subsequent regional disaggregation is based on the Latin American and European project BioTOP[76] (Riegelhaupt and Chalico, 2009) and on work by Pontt O. et al. (2008) for Chile.

[76] The 3-year BioTOP project ran from 2008 to 2010. It aimed at assessing the technical potentials and opportunities for biofuel production and use in Latin America, and identifying the associated research needs.

- The World Bank's municipal waste assessment and projections (Hoornweg and Bhada-Tata, 2012) provided the basis for municipal waste potential for the whole continent save Brazil, where I used a national study of the Brazilian Association of Special Waste and Public Cleansing (ABRELPE, 2012).
- For industrial waste, few quantitative data were available. When reliable projections were found for industrial outputs, I correlated industrial waste both to municipal waste and industrial outputs for the region. Otherwise, it was correlated with municipal waste production only.
- The same holds for biogas-related data. When relevant national data were not available, I used municipal waste and solid biomass as a proxy, correcting the figure based on the importance of national agriculture & livestock production[77]. The review by the UN Habitat agency (2010) on the WTE industry in Latin America also provided useful figures for the sector.

Latin America's biomass potential, as mentioned above, outdoes all other resources by a fair margin. However, this potential is primary, involving significant conversion and transport losses for most outputs contrary to hydro- or wind power.

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Industrial wastes	355	489	184	1443	827	304	568	323	4	507
Municipal wastes	69	103	15	269	154	34	85	132	2	69
Dedicated energy crops	2,557	7,796	3,000	18,739	10,090	3,103	2,343	2,373	3,000	5,680
Biogas	426	1,678	640	3,408	1,582	574	499	404	601	894
Solid Biomass – Low price	1,656	5,051	1,500	2,802	15,876	2,010	1,518	1,537	1,500	3,000
Solid Biomass – Medium	1,893	5,772	1,500	3,202	18,144	2,297	1,735	1,757	1,500	3,000
Solid Biomass – High price	1,183	3,608	1,500	2,001	11,340	1,436	1,084	1,098	1,500	3,000

Table 3-17: Biomass potential in T-ALyC (PJ/yr)

[77] The main source of biogas is the anaerobic digestion of biomass, both in landfills (municipal waste) and biogas digesters (rural areas).

iii) Electricity generation - Costs

Figure 3-26 and Figure 3-27 present the costs for electricity generation from biomass in T-ALyC.

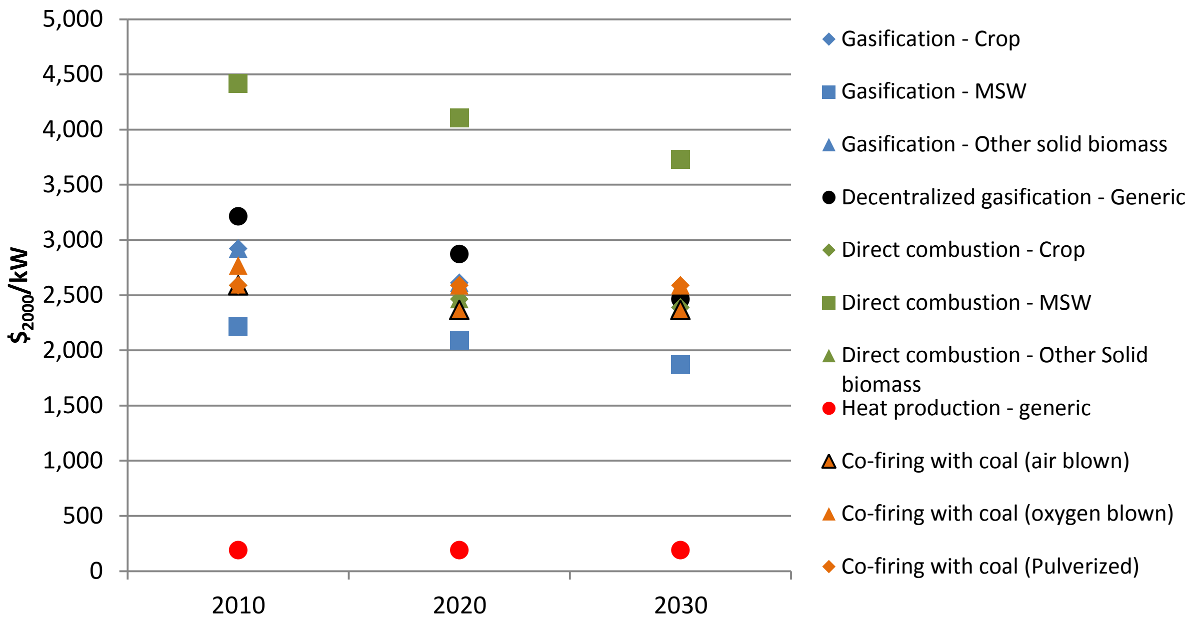

Figure 3-26: Electricity and heat generation from biomass – Investment costs

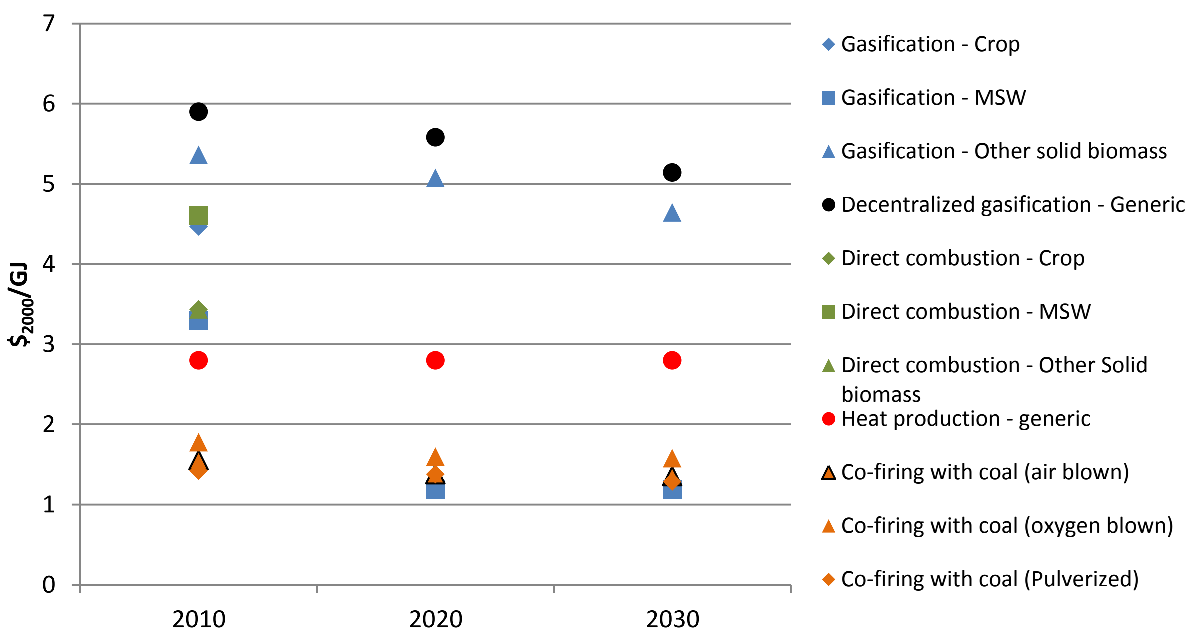

Figure 3-27: Electricity and heat generation from biomass – Combined fixed and variable costs

In order to present a compact view of model assumptions, the variable costs presented in Figure 3-27 aggregate fixed and variable operation and maintenance costs, assuming that plants are used at 100% of their capacity all year round. This is an optimistic assumption that artificially reduces the weight of fixed costs in total production costs; however, it gives a reasonably good picture of the comparative costs of biomass technologies.

Despite a definite downwards trend in costs, biomass-based electricity production remains quite a capital-intensive activity, with investment costs comparable to hydro. As for hydropower, the resource cost –embedded in activity costs in T-ALyC– is quite low, with the result that biomass becomes a competitive means of production before 2050. Direct biomass burning for heat production, on the other hand, has remarkably low capital costs (yet its uses are quite limited, being only local).

iv) Biofuel production – lower bounds

T-ALyC includes lower bounds for the production of first-generation biofuels, mainly based on (ANP, 2013; Dufey and Stange, 2011; FAO and OECD, 2013). These production bounds are presented in Table 3-18. Argentina compares quite well with Brazil on biodiesel production; however, with respect to ethanol production, the whole continent is literally negligible compared to Brazil's tremendous installed capacity, showing the scale and success of the national *Proalcool* support program (Moreira and Goldemberg, 1999).

	CHL	AND	ARG	BPU	BSE	BWC	COL	CYC	SUG	VEN
Min Ethanol – 2014	1	16	12	6	1457	800	9	16	0	0
Min Ethanol – 2020	1	21	20	10	1895	1040	17	20	0	0
Min Biodiesel – 2014	1	2	159	2	123	148	14	0	0	0
Min Biodiesel – 2020	1	20	206	12	160	193	20	0	0	0

Table 3-18: Biofuels production from 2015 to 2020 (PJ/yr)

C.4. Trade and transport

C.4.1. Generic description

T-ALyC is a multi-regional TIMES model. The total cost of satisfying a given demand is minimized not only through sub-regional investment and operation, but through energy trade between the model's regions. Trade in T-ALyC is bilateral, as described by Figure 3-28: the Reference Energy System includes *trade technologies* that transform a given commodity from one region into the same commodity, in another region. These processes are described through activity costs and conversion efficiency to account for transportation costs and losses; electricity and gas transport infrastructures also include in their description investment and O&M costs and an existing capacity, which is pictured below on Figure 3-29. Coal, oil and LNG trade are represented by variable costs only. Such a linear representation does not account for network-related behaviors, such as power flow dynamics; some investigation is under way on these topics (see e.g. Lehtila and Giannakidis, 2013). However, at the time and space scales considered, a linear representation retains some relevance.

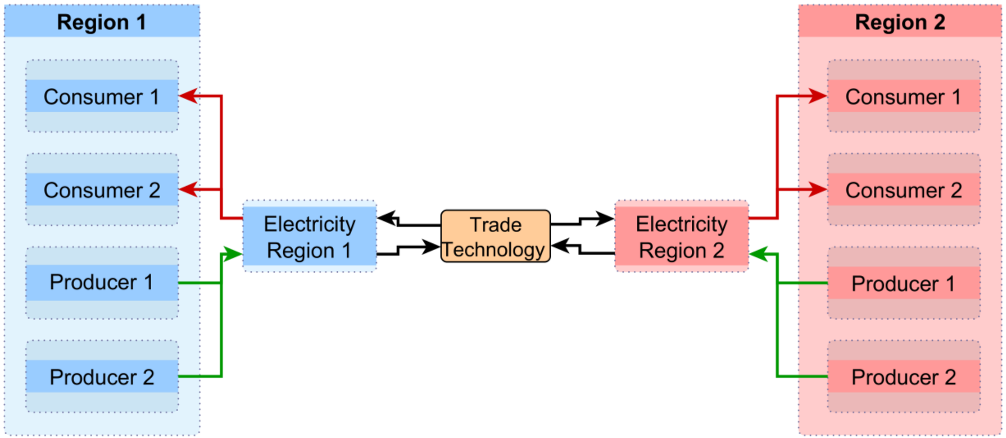

Figure 3-28: Trade in T-ALyC: concept

The electricity and gas networks existing in South America in 2010, as represented in T-ALyC, are depicted in Figure 3-29. Except for Brazil's domestic electricity network and the Argentina-Chile gas pipes[78], the most significant infrastructures all go through or around the interconnection region of Bolivia-Paraguay-Uruguay. Although the Bolivia-Peru and Brazil-Peru axes are quite weak today, they are poised to take off with the rise of Peru as a new economic power on the continent.

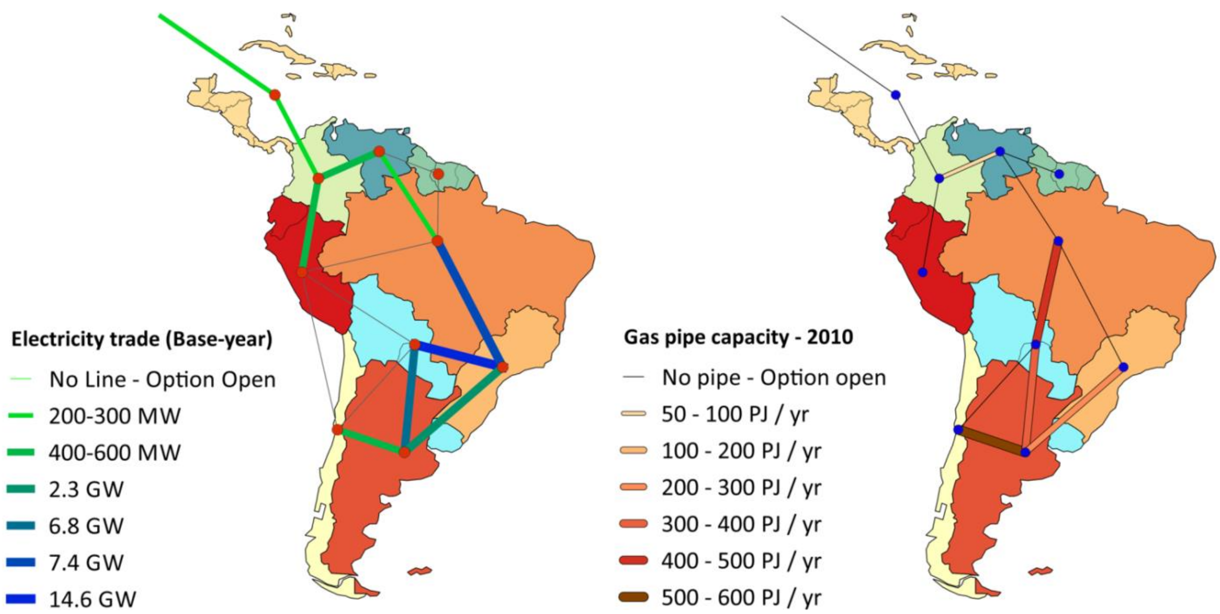

Figure 3-29: Electricity and gas infrastructure in South America as of 2010

C.4.2. Costs elements

We describe here some assumptions and resulting figures for the costs associated with energy trade in T-ALyC. These costs are of two kinds: pure transportation costs for both intra-regional and international trade; and commodity costs when buying from, or selling on, international markets. Transportation costs, in turn, depend on infrastructure and the distance traveled.

[78] These are currently not in use, following the 2005 Argentina-Chile gas crisis (see Box 2-2).

i) Distances

The distances considered for domestic trade are listed in Table 3-19 below. For international trade, shipping mileages depend on the commodity traded; moreover, they are not unique for each sub-region, since each country buys e.g. its coal from various providers. The assumptions and distance tables are presented in Annex (p.**¡Error! Marcador no definido.**).

FROM \ TO	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
AND		4	1.5	4	2.5	3	1	3.5	4.5	3.5
ARG			3	2	4	1.5	5.5	8	6	7.5
BPU				3	1	2	3.5	5	3.5	5
BSE					2	3	6	8.5	4	5.5
BWC						5	4	6	1.5	3.5
CHL							5	7	6	6
COL								2.5	2.5	1
CYC									5	3.5
SUG										1.5
VEN										

Table 3-19: Intra-regional distances in T-ALyC (thousand km)

ii) Infrastructure costs

Transportation costs were calculated based on the following rules:

- For natural gas, transportation costs are related to pipeline use. They are split into two investment and operation costs. The latter accounts for both non-energy variable costs and energy losses, which are modeled as a cost (instead of efficiency).
- For LNG, transportation is modeled through a kilometric cost accounting for transportation non-energy costs and energy losses. Liquefaction and re-gasification costs include investment costs in LNG plants, fixed O&M costs, and variable O&M costs.
- For coal, the costs are only variable. It is considered that coal is transported by tanker overseas and by rail/road overland. Transportation by land is around 4 times more expensive than by sea.
- Oil is transported by tanker at sea and by pipe overland. Pipe kilometric cost is roughly twice that of tanker one. As for other energy forms, this cost covers both non-energy transportation costs and energy auto-consumption and losses.
- The description of electricity transmission lines includes the existing capacity in MW, investment costs, fixed O&M costs and transmission efficiency. Investment and O&M costs are based on a detailed project-by-project description. They stem from an extensive bibliographic review which included, among others,(CIER, 2010; COSIPLAN, 2013; EPE, 2013; Estrada et al., 2012; Sauma et al., 2011; Serra Vega, 2010).

Investment costs for electricity transmission projects are described in Table 3-20.

		TO									
FROM		AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
	AND			520		1077	402	140			
	ARG			150	306		276				
	BPU				284		170				
	BSE					134					
	BWC									194	242
	CHL										170
	COL								345		
	CYC										
	SUG										194
	VEN										

Table 3-20: Investment costs for electricity interconnection projects (thousand $ / MW)

iii) International commodity costs

T-ALyC optimizes the whole energy chain from extraction to end-use consumption, assuming perfect energy markets. As a consequence, its representation is one of energy *costs*, not of energy *prices*: the model considers perfect markets in which producers sell their goods at the exact marginal price, without making any extra profit. However, T-ALyC can import its commodities from (or export them to) international markets; international commodities thus compete with domestic commodities. Calibrating international trade then becomes a difficult task, since T-ALyC's endogenous commodity costs can be appreciably lower than their actual price on international markets[79]. One option is to test various scenarios with fixed export volumes determined by external statistics (for today) and projections (for tomorrow). One can thus model the impacts of e.g. oil shocks on regional energy policies; however, not much can be said about the impacts of domestic policies on international trade.

Another option is to link T-ALyC to a global model to capture the dynamics of the relationship between South America and the rest of the world. In our case, we worked with TIAM, building on the two models' RES similarities. The link between the two models can take two forms:

- A static link through prices: the price of international commodities in T-ALyC is TIAM's internal shadow cost for the same commodities. Trade volumes in T-ALyC then adapt to these exogenous global prices;
- A dynamic link based on a feedback loop for prices and volumes, considering South America as a price-taker: TIAM prices are fed into T-ALyC and cause a certain amount of

[79] This is not an issue in a global model such as TIAM, where all costs are calculated endogenously for every part of the world; nor in a pure electricity model, where all fuel prices are determined exogenously and thus do not compete with endogenous prices.

exports. TIAM, in turn, runs with fixed trade volumes for South America from T-ALyC and a new shadow commodity cost is determined. This loop is performed until volumes and prices stabilize in both models.

The results presented in chapter 5 rely on static linking.

C.4.3. Centralized and decentralized electricity

As mentioned on page 115 in the description of T-ALyC's solar module, T-ALyC distinguishes between centralized and decentralized electricity for transport and trade. Centralized electricity is penalized by transportation costs, as well as network inefficiencies; decentralized electricity, on the other hand, is supposedly consumed on-site, without incurring any transportation cost or loss. Only centralized electricity can be traded between regions.

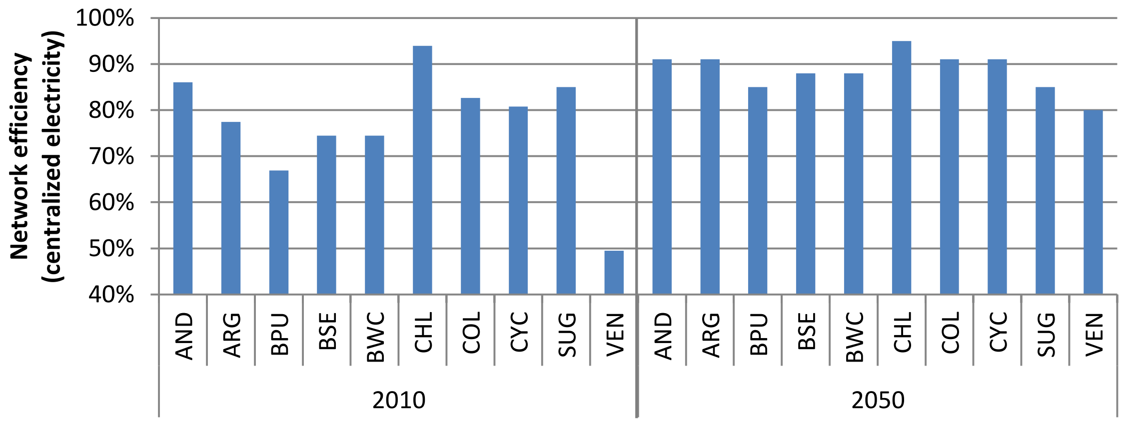

Figure 3-30: Network efficiency for centralized electricity in T-ALyC

Figure 3-30 presents T-ALyC's sub-regional network efficiencies. 2010 figures are based on IEA data. Venezuela's low network efficiency is mainly due to non-technical electricity losses. The premium paid for transporting and distributing centralized electricity is $7 cents per kWh. Table 3-21 presents the ratio between the shadow cost of centralized electricity and this transport premium. Although the weight of transport in actual Levelized Costs of Electricity (LCOEs) is lower, T&D costs heavily burden centralized electricity in T-ALYC. This is especially true towards the end of the period studied, when marginal costs drop under *business-as-usual* conditions due to a strong increase in renewable energy production (See Chapter 5). The share of decentralized electricity in industrial production and transport services is limited to 25% so far in T-ALyC, to respect the system's inertia.

	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Delivery premium – 2010	77%	49%	38%	35%	39%	54%	59%	54%	91%	24%
Delivery premium – 2050	310 %	258 %	200 %	341 %	282 %	242 %	265 %	235 %	241 %	200 %

Table 3-21: Delivery premium for centralized electricity, as a percentage of electricity cost

C.4.4. *Liquefied Natural Gas (LNG)*

Table 3-22 provides data about LNG facilities in T-ALyC, based on (IGU, 2013) and (San Pablo, 2010). Historically, Trinidad and Tobago was the only South American country exporting enough gas to own and operate a liquefaction plant. Peru caught up in 2010 with the *Camisea* project.

	CHL	AND	ARG	BWC	BSE	CYC	COL	BPU	SUG	VEN
Liquefaction		228.7								714.4
Regasification	354.4	0.0	393.8	242.5	60.6	138.7	0.0	0.0	0.0	0.0

Table 3-22: Residual capacity for LNG liquefaction and gasification in 2010 (PJ/yr)

Concluding remarks

This chapter presented an overview of the *TIMES-América Latina y el Caribe* (T-ALyC) model. The 10-region description adopted for this first version of T-ALyC highlights the main determinants for spatial differentiation of regional energy trends: Brazil's weight and heterogeneity, the importance of Bolivia, Uruguay and Paraguay for regional energy flows, Chile and Argentina's outsider position, the privileged link of Central America with Mexico, Venezuela's unique position as an oil giant on the continent, etc. T-ALyC's time division into seven periods and six timeslices is then detailed. The description of regional energy endowment reveals the importance of renewable energy sources for South America, while the description of energy trade highlights the relevance of linking T-ALyC with the global TIAM-FR model. The next chapters will now present a contribution made with T-ALyC in view of the ongoing climate negotiations.

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Chapter 4: Climate change, climate negotiations and their implications for South America

Try and leave this world a little better than when you found it.
– *Lord Baden-Powell*

This chapter sets the stage for the study of one specific challenge facing South America's energy sector, i.e. the pressure on regional energy policies created by climate change and global climate negotiations. Part A reviews existing literature on potential climate change impacts for South America, based on the main reference work for global climate change assessment to date: the International Panel on Climate Change's (IPCC) Assessment Reports. Part B presents the global framework for climate talks, from a historical perspective to the current context of on-going negotiations, and then focuses on South America's recent contribution to these talks.

Before starting, let us remind the reader that IPCC's Reports are political tools as much as scientific works: their focus is on prompting national and international commitment and voluntarist policies in the field of climate change. Despite this bias, they offer the most extensive literature review for global ongoing investigation on climate change effects and climate policies around the world; they form the main basis for global climate negotiations in the framework of the UNFCCC; and they are a reference work for all climate researchers, whether they agree with the conclusions or not. As a consequence, these reports constitute a fundamental piece of my working framework, and are much used here. However, investigating the *consequences* of such projections and commitments on the energy sector is done without questioning the relevance of their *assumptions and underlying reasoning*, which are beyond the scope of this work.

It is also worth mentioning that the challenges facing South America's energy sector are not limited to climate issues. The scope of energy modeling as presented in Chapter 2 extends beyond climate policy analysis, and the model presented in Chapter 3 was built bearing in mind a large range of long-term energy issues. However, the modeling application presented in this thesis will focus on climate policy assessment, due to time limitations and the current focus of the international energy agenda which is dominated by the international climate agreement that must be reached at the COP21 in Paris.

A Climate change: From global patterns to South American implications

A.1. Background elements: climate research, the IPCC and its Fifth Assessment Report

Research on the human impact on the environment and environmental feedbacks on mankind dates at least from the eighteenth century. At this time, the study of high urban disease rates pinpointed the role played by air and water in spreading diseases[80]. The 1952 London Great Smog and its thousands of casualties set the case for the pioneering 1956 Clean Air Act , to the forebear of air pollution regulation throughout the world (Thorsheim, 2006). Later, in 1972, the Club of Rome's *Limits to Growth* publication on 'the predicament of mankind'[81] acknowledged the fact that '*the major problems facing mankind [were] of such complexity and [were] so interrelated that traditional institutions and policies [were] no longer able to cope with them, nor even to come to grips with their full content*' (Meadows et al., 1972). Dennis Meadows and his team inaugurated at that time a systemic approach to mankind's issues that is still being developed today.

Scientific investigation into our global impact became the object of a global cooperation framework with the creation of the International Panel on Climate Change by the UN General Assembly on 6 December 1988. The mission of this scientific entity was to '*prepare a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change; the social and economic impact of climate change, and possible response strategies and elements for inclusion in a possible future international convention on climate'* (IPCC, 2015a). IPCC's First Assessment Report was published in 1990 and served as a main discussion basis for the 1992 Rio Earth Summit (see paragraph B below). Today, the organization compiles and reviews the work of thousands of researchers throughout the world. The IPCC has produced five Assessment Reports (ARs) to date, in 1990, 1995, 2001, 2007 and 2014, along with Special Reports, Methodology Reports, Technical Papers and Supporting Material. The Assessment Reports evaluate potential developments in the climate system and mankind's contribution to climate change; the possible impacts of climate change on human societies and related adaptation options; and political scenarios for the mitigation of human interference with the climate system.

[80] (Kesztenbaum and Rosenthal, 2011; Vedrenne-Villeneuve, 1961; Villermé, 1830)
[81] Cf. Chapter 2, part A.

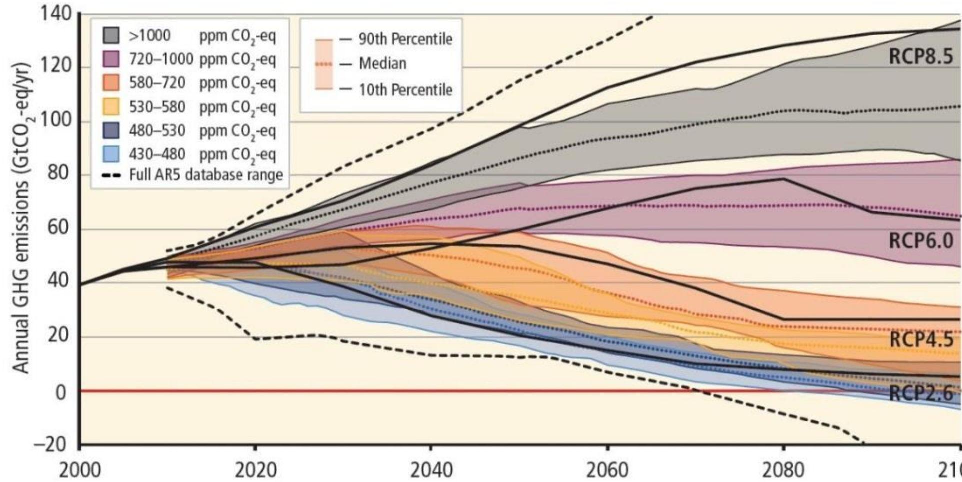

Figure 4-1: IPCC's RCP and assessed policy scenarios. The CO_2-eq concentration refers to 2100 projected values

In addition to reporting that '*human influence on the climate system is clear and recent climate changes have had widespread impacts on human and natural systems*', the Fifth Assessment Report contains gloomy projections for potential futures. Figure 4-1 above depicts the policy scenarios spanned by the AR5 review exercise and their resulting emissions. The broad range of possible outcomes, from negative net global CO_2 emissions to more than a three-fold increase in CO_2 emissions by 2100, reflects the magnitude of uncertainty surrounding future human emissions and mitigation options; yet the data gathered by the fifth phase of the Climate Model Intercomparison Project[82] (Figure 4-2) [83] tends to show that even the least-emission pathway – RCP2.6– translates into substantial temperature and precipitation alteration by 2100 for the whole world, while high-end RCP8.5 leads to up to a 9°C increase in some parts of the world.

[82] The Climate Model Intercomparison Project, Phase 5 (Taylor et al., 2011) is an initiative promoted by the World Climate Research Programme. It coordinates the work of 29 research groups with 62 climate models (CMIP5, 2011) in order to provide climate analysts with an up-to-date dataset on global knowledge about decadal and long-term climate simulations.

[83] Dots indicate that the projected evolution is greater than internal climate variability. On the contrary, dashed zones report weak evolutions compared to internal variability (less than one standard deviation) or poor agreement between climate models.

Climate scenarios: IS92, SRES and RCP

With the growing interest for prospective modeling in climate-related research, the number of emission and climate scenarios has skyrocketed[84]. The Japanese National Institute for Environmental Studies scenario database, which lists climate scenarios used across the world, counted 725 climate scenarios in 2006, according to Crassous (2008); in the 2009 update, this figure had climbed to 1,069. As part of its research coordination work, the IPCC developed three successive reference scenarios sets: the IS92 scenarios (IPCC, 1992), the SRES scenarios (IPCC, 2000) and the RCP scenarios (Meinshausen et al., 2011; Vuuren et al., 2011). IPCC scenarios are described as '*plausible representations of the future development of emissions of substances that are potentially radiatively active, based on an internally consistent set of assumptions about driving forces and their key relationships.'* (IPCC, 2015b)

The Representative Concentration Pathways (RCPs) describe four possible futures up to 2100 for GHG and air pollutant emissions, and land-use (while the IS92 and SRES sets offered 6 scenarios each). Contrary to the SRES and IS92 scenarios, they do not originate from a pre-defined set of techno-economic storylines that would reflect the diversity of the *base assumptions* underlying the global pathways of emissions and concentrations; instead, four scenarios were selected from existing literature, independent of their initial assumptions, to reflect the variety of existing *final projections* of climate change. The climate impact of any independent emission scenario is then derived by choosing the RCP that is closest to the projected emissions and 'bridging the gap' with techniques such as pattern scaling (Moss et al., 2010). The main interest of this approach is to work in parallel on climate evolution and impact assessment, reducing development times which led to inconsistencies in past occasions: by the time the full process of SRES scenarios construction ended, the models had evolved so much that new scenarios were needed. Another main novelty of RCP pathways is that they might be the result of voluntarist policies (and in fact most scenarios nearing RCP2.6 pathway are stringent, including significant net negative emissions), while the IS92 and SRES scenarios presented various futures, yet none of which included a climate policy. As a consequence, RCP pathways span a wider range of outcomes than SRES.

Representative Concentration Pathways are named after their resulting level of radiative forcing in 2100 (in W/m^2). They include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). Usual baseline scenarios lead to pathways ranging from RCP6.0 to RCP8.5. RCP2.6 represents voluntarist policy scenarios that aim to keep global warming below 2°C above pre-industrial temperatures.

Box 4-1: Climate scenarios - IS92, SRES and RCP

[84] For a complete description of the 'prospective' and 'scenario' concepts, refer to Chapter 2, section A.

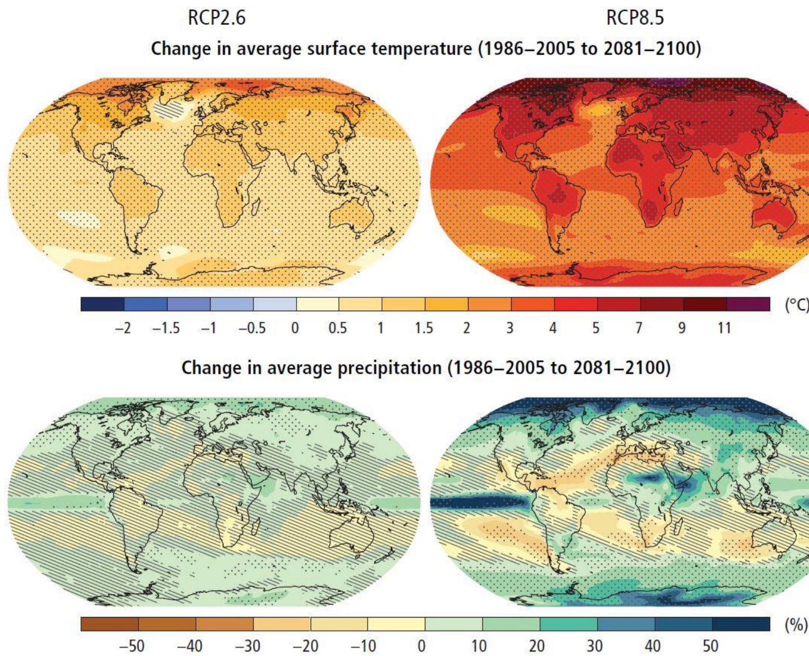

Figure 4-2: Change in temperature and precipitation following RCP2.6 and RCP8.5, averaged over CMIP5 models (IPCC, 2014a)

A.2. Implication of global climate change for South America

Global climate change would impact South America's regional climate in a non-negligible way, as detailed by Table 4-1. The increasing trend for temperature is both regionally consistent and robust across CMIP5 models ('range' rows display the lowest and highest value among all models involved). The precipitation trend is more mixed, yet the annual figures presented here mask deep seasonal differences, with dry seasons becoming drier in most places. Climate change impacts have already been detected in South America with *high confidence*, according to IPCC's uncertainty classification (IPCC, 2014b).

Climate change impacts on the continent are far from negligible: conservative estimations by ECLAC (2014a) expect that climate change will cost the region between 1.5% and 5% of its GDP in case of a 2.5°C world temperature increase. Figure 4-3 presents a summary of the main reported and projected effects of climate change in South America.

			Temperature (°C)			Precipitation (%)		
Region	**RCP**		**2016 2035**	**2045 2065**	**2081 2100**	**2016 2035**	**2045 2065**	**2081 2100**
Central America	RCP2.6	Median	0.7	1	1	0	0	0
		Range	*0.5 / 1.3*	*0.6 / 1.9*	*0.4 / 2.1*	*-6 / 6*	*-9 / 6*	*-15 / 9*
	RCP8.5	Median	0.9	2.1	3.9	-1	-5	-8
		Range	*0.5 / 1.4*	*1.5 / 3*	*2.9 / 5.5*	*-11 / 6*	*-14 / 7*	*-26 / 11*
Caribbean	RCP2.6	Median	0.6	0.8	0.8	-1	0	0
		Range	*0.4 / 1.1*	*0.4 / 1.6*	*-0.1 / 1.7*	*-11 / 7*	*-9 / 0*	*-25 / 4*
	RCP8.5	Median	0.7	1.6	3	-2	-8	-16
		Range	*0.4 / 1.1*	*1.1 / 2.5*	*2.1 / 4.1*	*-14 / 11*	*-19 / 10*	*-50 / 9*
Amazon	RCP2.6	Median	0.8	1.1	1.0	-1	-2	-2
		Range	*0.4 / 1.3*	*0.6 / 2.1*	*0.3 / 2*	*-12 / 11*	*-15 / 15*	*-19 / 20*
	RCP8.5	Median	1.1	2.5	4.3	-1	-1	-2
		Range	*0.5 / 1.9*	*1.4 / 4.1*	*2.4 / 7*	*-12 / 4*	*-23 / 8*	*-33 / 14*
Northeast Brazil	RCP2.6	Median	0.8	1.1	1	-1	-2	-2
		Range	*0.4 / 1.3*	*0.6 / 2.1*	*0.3 / 2*	*-12 / 11*	*-15 / 15*	*-19 / 20*
	RCP8.5	Median	1	2.2	4.1	0	-2	-6
		Range	*0.5 / 1.5*	*1.3 / 3.1*	*2.5 / 5.6*	*-14 / 7*	*-16 / 38*	*-31 / 45*
Western South America	RCP2.6	Median	0.7	1.0	0.9	1	1	2
		Range	*0.4 / 1.2*	*0.6 / 1.7*	*0.3 / 3.2*	*-7 / 5*	*-8 / 5*	*-8 / 6*
	RCP8.5	Median	0.9	2.1	3.8	1	1	1
		Range	*0.5 / 1.4*	*1.5 / 2.9*	*2.8 / 5.1*	*-6 / 5*	*-9 / 8*	*-14 / 11*
Southern South America	RCP2.6	Median	0.6	0.9	0.8	0	1	1
		Range	*0.3 / 1.3*	*0.4 / 1.7*	*0.4 / 1.8*	*-7 / 10*	*-7 / 13*	*-9 / 9*
	RCP8.5	Median	0.8	1.9	3.6	1	3	7
		Range	*0.2 / 1.4*	*1.1 / 3.1*	*1.9 / 5.3*	*-6 / 14*	*-11 / 18*	*-11 / 27*

Table 4-1: Temperature and precipitation compared to 1986-2005 under RCP2.6 and RCP8.5 (Adapted from ECLAC, 2014a)

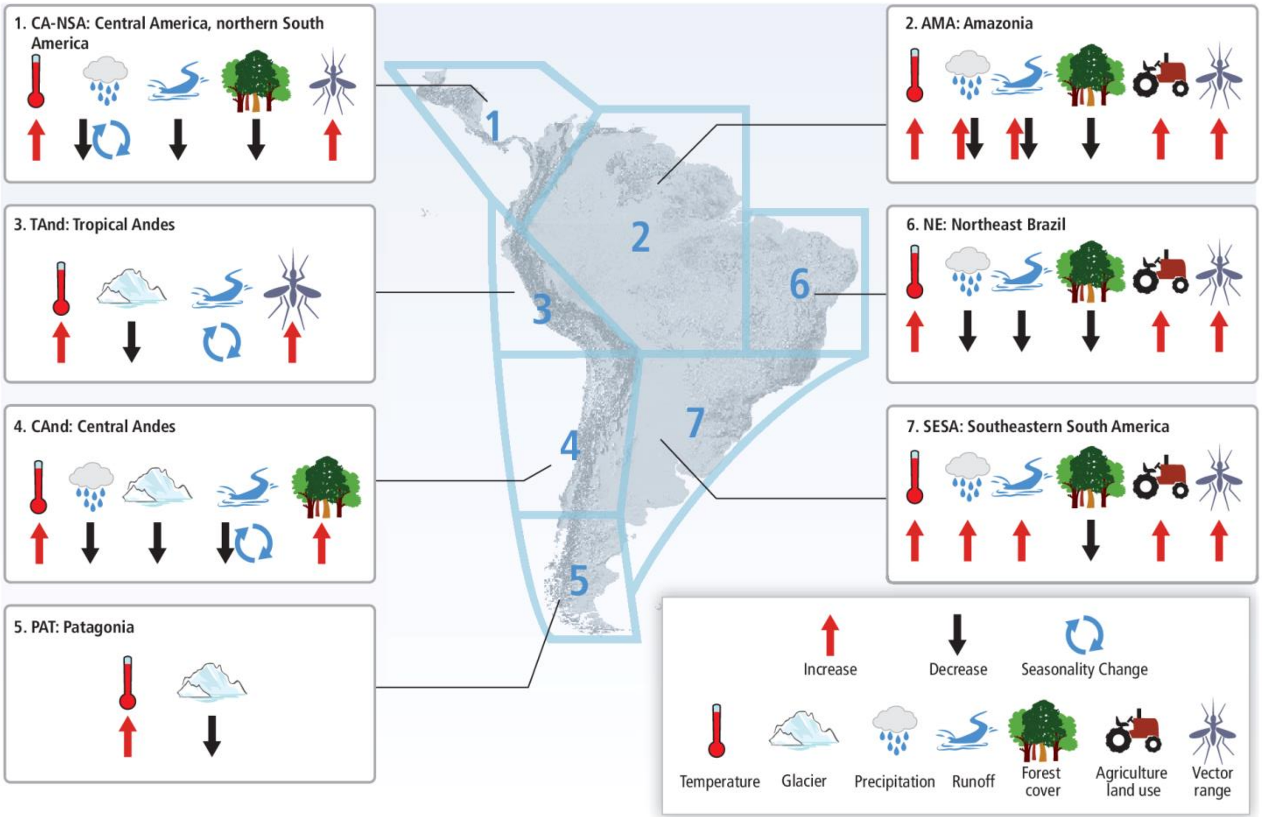

Figure 4-3: Possible impacts of Climate Change in South America (IPCC, 2014b, p. 1543)

Among the most relevant consequences, let us note:

- The hydrological regime will be greatly impacted by a change in the precipitation regime and the retreat of the Andes glaciers, according to (Calvo Cárdenas, 2014; ECLAC, 2014b; Lucena et al., 2009; Vargas, 2012). Glacier retreat is one of the most visible and documented changes in the region (Rabatel et al., 2013). It is estimated that the Andes glaciers lost between 20%-50% surface area in the second half of the 20th century due to climate change (IPCC, 2014b). Together with changes in the precipitation regime and rising temperatures, this phenomenon will provoke significant changes in seasonal streamflow patterns in South American rivers, together with an overall reduction of annual streamflows.
- This evolution would in turn impact hydropower generation and agriculture, in a region where these two sectors are of strategic significance. As already mentioned, hydropower is South America's first source of electricity, yet its potential could be reduced by 10% in some Chilean and Argentine basins (McPhee, 2012; Seoane and López, 2008), by more than 30% in Colombia (Ospina Noreña et al., 2009), or even halved in the most problematic Central American case (Maurer, 2009). The region's potential for agricultural development is key to global future agricultural developments (Nepstad, 2011), yet semi-arid zones, such as the Santiago region in Chile or Northeastern Brazil, already rely on intensive irrigation and are highly vulnerable to a degradation in their hydrological supply due to climate change (ECLAC, 2012a; Hastenrath, 2011; Vicuña et al., 2012). Some crops, like Brazilian coffee, may have to move to other regions (Zullo Jr et al., 2011).

The water cycle : From precipitation to streamflow

Fresh water constitutes only 2.5% of all of the Earth's water. Surface water (lakes, snow, rivers, swamps) amounts to 1.3% of this quantity, the remainder being groundwater (30.1%) and glaciers and ice caps (68.6%). Of the precipitations that do not fall on glaciers and snow caps, a significant share, roughly 75%, returns to the atmosphere by evapotranspiration (See e.g. ECLAC, 2012b; Winter, 1998). For Chile's main hydrological basins, Vargas (2012) calculated evapotranspiration of 35%, due to the basins' high altitude and mountainous conditions (see table below). The rest seeps into the ground (infiltration) or runs over the surface (*runoff*). River discharge, or *streamflow*, is the product of precipitation and glacier melting, through *runoff* aggregation and exchanges with groundwater (Winter, 1998). Miguez-Macho and Fan (2012) showed for 12 Amazon catchments with different climate, topography, vegetation and soil properties that groundwater consistently makes up the bulk of *streamflow*, with a greater relative contribution in the dry season. River discharge is impacted by climate change through changes in precipitation (runoffs and groundwater recharge), evapotranspiration, soil moisture and the glacier melting rate (Döll and Schmied, 2012).

Sub-basin	Total Precipitation	Evapotranspiration	Effective Pp.
Laguna La Invernada	2311	850	1461
Laguna del Maule	2332	850	1482
Embalse Melado	2563	900	1663

An example of evapotranspiration losses on Chile's hydrological basins

Box 4-2: The water cycle

- 78.8% of South America's population live in major cities; together, the biggest urban agglomerations of each South American country total more than 20% of the region's population (ECLAC, 2013). Such oversized concentrations are prone to water, energy and health issues that can be aggravated by climate effects, ranging from water scarcity in Santiago de Chile (Barton, 2013) to floods in Buenos Aires (Nabel et al., 2008) and São Paulo (Marengo et al., 2013). Health issues such as dengue fever outbreaks in Rio de Janeiro (Gomes et al., 2012), malaria, yellow fever and cholera (IPCC, 2014b) are reported to be positively correlated to a temperature increase or sea level rise.
- The sea level rose on an average basis of 3.3 mm/yr on South America's coasts in the 20th century (De Miguel et al., 2011). Together with ocean warming and acidification, this evolution threatens Caribbean coral reefs and South American mangroves (Mora, 2008), puts maritime facilities at risk and increases flood pressure on coastal ecosystems (ECLAC, 2012c). Allison et al. (2009) found that climate change impacts could severely damage the Colombian and Peruvian national economies, given the size and configuration of their fish industry.
- Biodiversity loss: South America is home to 57% of the world's primary forest (FAO, 2011). At the same time, the region harbors 7 of the 20 countries with the most endangered vegetal species in the world (UNEP, 2010). Of the 34 "biodiversity hotspots" identified by Mittermeier et al. (2005) around the world, 6 are located in South America,

namely Mesoamerica, Western Ecuador, Tropical Andes, Central Chile, Brazilian Atlantic forest and the Brazilian Cerrado. Natural species are endangered by quick changes in their habitat, due to human stress factors and climate change.

- The frequency and strength of extreme climate events may increase: the number of hurricanes in the Caribbean rose from 24 between 1980 and 1999 (20 years) to 39 between 2000 and 2009 (10 years)[85]. In 1998, Hurricane Mitch alone cost an estimated 8 billion dollars (ECLAC, 2010). Together with urban floods, glacier lake outburst floods in the Andes, exceptional heat waves and droughts in Northern Brazil and Chile are risk situations created or enhanced by climate change (IPCC, 2014b).

A first set of strategies and policies aimed at minimizing regional climate change impacts focuses on adaptation to climate change, and may take place at a local, regional, national or continental level.

Designing adaptation actions and measures, forecasting their cost and efficiency and reporting their actual effects is a complicated task since most adaptation actions also pursue other economic goals and would be implemented in the absence of climate change; and conversely, some policies that are primarily aimed at economic or social development may prove highly effective in countering climate change effects. To complicate matters further, adaptation to climate change is a relatively new focus of academic interest and policy design, and so literature assessing the efficiency and cost of adaptation measures is scarce (IPCC, 2014b). That said, development and climate institutions such as the World Bank (2010a, 2010b), UNFCCC[86] (2007), OECD (2008), IDB (2013) and ECLAC (2014a) have made economic assessments of regional adaptation costs in South America. They conclude that these costs are likely to range from 0.2% to 5% of regional GDP by 2050 and that adaptation measures should focus on water management, agriculture and coastal protection, with a detailed list of potential adaptation strategies in (ECLAC, 2014a, p. 66).

The IPCC (2014b), in turn, points to the importance of water management initiatives in South America, highlighting emergency responses to droughts and sudden floods in semi-arid regions such as central Chile (Debels et al., 2008; Young et al., 2009), North-Eastern Brazil (Campos and de Carvalho Studart, 2008; Tompkins et al., 2008) and Southern Peru (Warner and Oré, 2006). Other adaptation strategies in the area of water management include institutional evolution (Hantke Domas, 2011) and technological measures such as groundwater pumping (Nadal et al., 2013) or fog water collection (Klemm et al., 2012). Hydropower, which will suffer from concurrent water uses and increased seasonality of flows, needs improved cross-sector management of water and cautious infrastructure planning to anticipate global warming effects (Condom et al., 2012). South American adaptation strategies also rely on community management and indigenous knowledge for ecosystem protection and restoration (Montagnini and Finney, 2011) and food production adaptation (Altieri and Koohafkan, 2008). Genetic engineering and land-use planning improvement (Urcola et al., 2010), improved access to climate forecasts in arid rural areas (Moran et al., 2006) and improved agronomic practices (Quiroga and Gaggioli, 2010) will also contribute to food production adaptation in the South American context.

[85] (UNEP and ECLAC, 2010).
[86] See next paragraph (B).

Bioenergy production will suffer from food crop competition and needs to move from first to second and third generation biofuels, according to Azadi et al. (2012). Urban settlements are working on improved emergency response (Sayago et al., 2010) and preventive urban planning, mainly to anticipate and avoid landslides and floods (Rodríguez Laredo, 2011). For coastal systems, adaptation measures mainly rely on Marine Protected Areas (MPA), which should be further developed (Guarderas et al., 2008). Along with MPAs, the main adaptation measures implemented today in the South American context concern community fishery management (Moura et al., 2009), mangrove replanting and prevention of coastal erosion (Lacambra and Zahedi, 2011).

South America's climate

South America is the fourth largest continent after Asia, Africa and North America. Including the Caribbean, the region runs from 23° North of the Ecuador (Havana) to 56° South (Drake's Passage) between two major oceans, while the Andes Mountains cut the continent in two from Colombia to the Darwin Cordillera in Tierra del Fuego, and act as a 'climatic wall'. Such a physical layout is bound to generate a large variety of climates.

Up towards the North of the continent, precipitations are much higher East of the Andes than West of them. As a consequence, Chile, Peru and Bolivia feature one of the most arid places on Earth, the Atacama Desert, while the Amazon is the biggest freshwater basin in the world. This trend reverses towards the South, making Argentine Patagonia one of the driest regions of South America, while Southern Chile is home to '*selva frías*' (cold jungles) and ice fields that run for hundreds of kilometers. Coastal Northeastern Brazil's precipitation is only a third of inland values, as a consequence of Brazil's Northeastern 'plateau' influence on atmospheric circulation patterns. The average temperature in the tropical band (20°N to 20°S) is quite uniform, around 20°C. It decreases towards the South, nearing 0°C at the Southern end of the continent, yet this average hides marked differences: in the Argentine Patagonia, average temperature differences between summer and winter can reach 12°C.

Climate to the North of the continent is dominated by the Inter Tropical Convergence Zone (ITCZ), also known as the Trade winds, a constant West-bound flow of air that dominates the climate in the Caribbean and Central America climate, as well as in Colombia, Venezuela and North of Brazil. This circulation brings heavy precipitations and moves northward during the austral winter (June-July-August) and southward during summer (December-January-February), in what is known as the South American Monsoon System (SAMS). This monsoon-like pattern (Garreaud et al., 2009) involves a strong complementarity between hydrological conditions in e.g. Colombia and Brazil. Its effect is especially marked during summer, with intense precipitations on the Amazon basin, all the way to Northern Argentina. Precipitation events are so intense that average summer temperatures in the Southern Amazon basin are paradoxically slightly lower than winter ones, due to the cloud coverage and soil moisture. South of 40°S, the trend reverses and atmospheric circulation gets dominated by West-to-East winds that are famous in sailing literature (Moitessier, 2003).

A critical feature of South America's climate is its inter-annual variability. The most relevant component of this variability is known as El Niño and the Southern Oscillation (ENSO). The phenomenon associates an unusual warming of the Tropical Pacific surface temperature (El Niño) with weak trade winds (Southern Oscillation). Both phenomena have been known, independent of each other, for a long time: El Niño, a familiar feature in Peru and Ecuador, owes its name '*The Child*' – God's Child – to the fact that it strikes before Christmas. Their relationship was first postulated by Bjerknes (1966), and then much studied after the devastating El Niño episode of 1997-1998 (Diaz and Markgraf, 2000). El Niño (ocean warming) and its counterpart La Niña (ocean cooling) occur every 2 to 7 years. The ENSO warm phase (El Niño) brings below-average precipitations over tropical South America, above-average ones over Southeastern South America and central Chile and above-average temperatures over tropical and subtropical CSA. La Niña has the opposite consequences. This event is considered the most important climatic event on Earth, with repercussions on all the Southern hemisphere and Southern United States (McPhaden et al., 2006). In South America, El Niño episodes occasion high socio-economic losses and bring the most feared manifestation of extreme climate events (MMAyA, 2009; Moran et al., 2006; Warner and Oré, 2006).

Inter-annual climate variability is also impacted, to a lesser extent, by the Pacific Decadal Oscillation, with effects similar to El Niño but less marked, and the Antarctic Oscillation, which alters precipitations in Southern Chile and part of South America's East coast (Garreaud et al., 2009).

Box 4-3: South America's climate

B South America in the global climate negotiations

Adaptation measures as listed above are not sufficient to offset all climate change effects, some of which are irreversible. The other set of climate actions attempts to mitigate climate change by reducing its anthropogenic component through international coordination. This part presents the history of global climate negotiations, the current state of these negotiations, and the contribution of Latin America.

B.1. An overview of climate mitigation negotiations

In 1972, the year that *Limits to Growth* was published, the United Nations answered a 1968 call from Sweden and met in Stockholm for the UN Conference on the Human Environment, laying the foundations for global consideration of environment and climate issues and creating the United Nations Environment Program – UNEP. Fifteen years later, the *Our Common Future* report headed by former Norwegian Prime Minister G. H. Brundtland[87] highlighted once again the fact that human development and economic growth can only take place in a finite environment, and defined for the first time *sustainable development* as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. This report, in turn, laid the foundations for what is probably the most important conference on the environment to date, the UN Conference on Environment and Development, also known as the Rio Earth Summit in June 1992. This conference, still one of the most inclusive UN conferences ever, welcomed representatives from 172 countries, and 108 Heads of State. It was hosted by Brazil as an expression of its early commitment to environmental and sustainability issues. It gave birth to the famous Agenda 21 for Sustainable Development (United Nations, 1992), the Rio Declaration on Environment and Sustainable Development, the Statement of Forest Principles, and the three Rio Conventions on Biological Diversity, Combating Desertification, and Climate Change (Dodds et al., 2012).

Now adopted by 195 countries in the world, the central aim of the United Nations Framework Convention on Climate Change is to *'stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system, in a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner'*. Developed countries, listed in the Annex I to the Convention, are expected to provide the bulk of this effort, based on the new concept of Common but Differentiated Responsibility (see Box 4-1). The UNFCCC also set a comprehensive collaboration framework for all Convention Parties, requesting them to report their advances in mitigation of, and adaptation to, climate change through regular, extensive National Communications and calling for regular Conferences of the Parties to the UNFCCC. The first Conference of the Parties (COP1) was held in Berlin in 1995, three years after the UNFCCC was opened to signature. The frequency then increased to yearly meetings.

[87] (World Commission on Environment and Development, 1987)

UNFCCC and the Common But Differentiated Responsibility (CBDR) concept

Article 3 of the United Nations Framework Convention on Climate Change states that the '*Parties should protect the climate system […] in accordance with their common but differentiated responsibility and respective capabilities.*' This concept of 'common but differentiated responsibility' is a cornerstone of climate negotiations. It stresses the fact that the Earth's climate is a common good shared by all countries; all will be impacted by any climate disturbance, and every nation is requested to take part in climate mitigation and adaptation. On the other hand, it acknowledges that developed countries have historically contributed more than developing ones to global anthropogenic emissions, built their wealth on highly emissive development paths, and possess a greater ability to mitigate their emissions and adapt to climate change effects, thanks to this past development. As a consequence, the Convention distinguishes between 'Annex I' and 'Non-Annex I' countries. Annex I countries include all OECD countries (as of 1992) plus Russia, Ukraine and the Baltic States. All South American countries are non-Annex I. Annex I countries are requested to make a greater mitigation effort than non-Annex I countries, and to assist them in their struggle for virtuous development with financial and technological transfers.

The Kyoto Protocol implemented this concept of common but differentiated responsibility by binding Annex I countries to quantitative emission reduction commitments below historical (1990) rates, while Non-Annex I refused any new commitment under the Protocol. They were however involved through the Clean Development Mechanism (CDM) which allowed developed countries to gain emissions certificates by supporting clean development projects in developing countries. The REDD+ mechanism, aimed at fighting deforestation in developing countries, is inherited from the CDM spirit although the aims of the two tools are slightly different.

The gap between Annex I and non-Annex I countries closed a little with the Copenhagen Accord (2009), which included the option for developing countries to select *Nationally Appropriate Mitigation Actions* (NAMAs) and pledge them to the UNFCCC on a voluntary basis, specifying which actions would be accomplished without any exterior help, and which depended on international support for their fulfillment. In South America and the Caribbean, the countries that pledged voluntary NAMAs with quantitative targets are Brazil, Chile, Colombia, Peru, Costa Rica and Antigua and Barbuda. Argentina and Dominica stated that they were implementing national mitigation actions, but did not make any pledges at a sectorial or national level.

The Paris Conference (COP21) in December 2015 will be an opportunity to make effective a new kind of harmonized, although differentiated, contribution: Intended Nationally Determined Contributions (INDCs) close the gap a little further between Annex I and Non-Annex I countries, by bringing together NAMAs and Kyoto-like mitigation pledges under a common framework. They answer criticism from developed countries like the United States of the traditional Annex I / Non-Annex I distinction which allows big polluters such as China to escape any kind of commitment. At the same time, they respond to objections like the ones voiced by Bolivia, stressing that climate in not a merchant good; and that market mechanisms and performance-based pay schemes are not fair and exclude a number of parameters (e.g. the social service of including indigenous communities) from decision criteria. At COP20 in Lima, one year before the Paris conference, Brazil started campaigning for a new kind of framework including a dynamic setting, presented as the 'concentric differentiation' scheme, whereby any

Party to the new agreement would be compelled to evolve toward ever more stringent and more comprehensive commitments, but at its own pace.

Box 4-4: UNFCCC and the CBDR concept

The third Conference of the Parties, in Kyoto in 1997, saw the emergence of the first international agreement with quantified, binding emission reduction targets for greenhouse gases (GHG): the Kyoto Protocol. The Protocol was opened to ratification in 2001 with the Marrakesh Accords and came into force in 2005, binding 37 countries during its first phase (2008-2012). Besides overall GHG emission reductions, the Protocol opened the door to developing countries' involvement through the Clean Development Mechanism (CDM), which allows developed countries to invest in emission-reduction projects in developing countries in exchange for emission reductions credits.

The next step towards formal developing countries' involvement in climate change mitigation was taken at COP13 in Bali and COP15 in Copenhagen, with the Bali Action Plan and the Copenhagen Accord, which defined the concept of 'Nationally Appropriate Mitigation Actions' (NAMAs). NAMAs provide a flexible framework within which non-Annex I countries can pledge voluntary actions at an economy-wide or sectorial level, aimed at deviating from *Business-As-Usual* (BAU) emissions (Sharma and Desgain, 2014).

COP17, in Durban in 2011, launched a new negotiation cycle which should end at the 21st Conference of the Parties in Paris in 2015 with a new climate agreement. This new global framework will be based on Intended Nationally Determined Contributions (INDC), a concept that unites developed and developing countries' targets under a single definition that does not include implementation steps (Boos et al., 2014). To date, the process of gathering and reviewing INDCs from all participants to COP21 is still underway.

B.2. South American intended contribution to global climate effort

Latin America represents a relevant share of global GHG emissions. Without Mexico, the region emitted 3,742 $MtCO_2eq$ of GHG in 2010; that is, 8.5% of the world's emissions for the same year (World Resources Institute, 2015), almost exactly corresponding to its share of the world's population (8.6% in 2010, according to UN Population Data). A high increase in GHG emissions can be anticipated in the years to come throughout the region on a *business-as-usual* basis, given the increase in energy demand highlighted in Chapter 1 (Carvallo et al., 2014; Fundación Bariloche, 2008; van Ruijven et al., 2015). Logically, the region has a relevant role to play in mitigating global emissions.

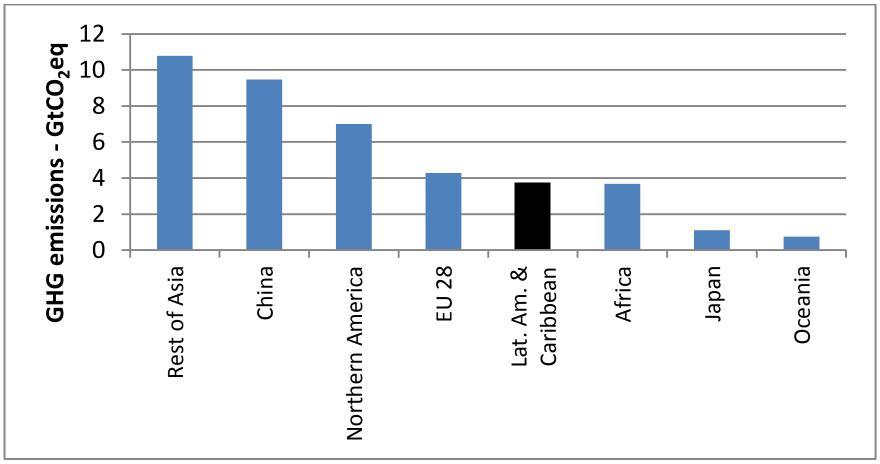

Figure 4-4: World GHG emissions in 2010, by region, including AFOLU (World Resources Institute, 2015)

No South American countries are included in Annex I of the United Nations Framework Convention on Climate Change (UNFCCC) and as such, they are not bound to any quantified GHG emission reduction to date. However, the region is no stranger to international climate negotiations; as mentioned above, Brazil hosted the first Earth Summit in 1992. Apart from the Rio+20 summit (2012) on sustainable development, three more Conferences of the Parties to the UNFCCC (COP) were hosted by Latin American countries, in 1998 (*COP4, Buenos Aires – Argentina*), 2004 (*COP10, Buenos Aires – Argentina*) and 2014 (*COP20, Lima – Peru*).

South American nations first participated in the UNFCCC framework as co-implementers for CDM projects[88], and then various countries submitted Nationally Appropriate Mitigation Actions following the Copenhagen Accord in 2009; as a prelude to the 2015 Paris Conference, most South American countries presented Intended Nationally Determined Contributions (INDCs) to serve as a basis for negotiating a new global climate treaty. The region's tentative contributions vary considerably across the continent, reflecting the profound divergences between South American countries over climate change issues (Edwards and Roberts, 2015). The next two paragraphs reviews these contributions.

B.2.1. Nationally Adapted Mitigation Actions

As mentioned above, NAMAs generally refers to pledges on national *actions*, not on *emission reductions*. However, Brazil, Chile and Antigua and Barbuda had indeed committed economy-wide emission reductions under the NAMA framework:

- **Chile** had pledged emission reductions of 20% by 2020, compared to a 2009 *Business-As-Usual* scenario; its engagement letter included little description regarding how to meet this target and no quantified measure. Energy efficiency, renewable energies and AFOLU (*Agriculture, Forestry and Other Land-Use*) were specified as the main action sectors for these reductions.

[88] Clean Development Mechanism. See Box 4-4.

- **Brazil** based most of its NAMAs on quantified emission reductions in the field of deforestation and more generally the AFOLU sector. Sectorial reductions were then aggregated into an estimated national target of 36.6% to 38.9% emission reductions below a national baseline by 2020.
- **Antigua and Bermuda** pledged 25% reduction of its greenhouse gas emissions below 1990 levels, calling for international collaboration to help fulfill this pledge.

Two more countries, namely Colombia and Peru, pledged national action aimed at renewable energy generation, and reducing deforestation:

- **Colombia** committed to including 77% renewables in its installed electricity production capacity by 2020, 20% biofuels in overall fuel consumption, and to reducing deforestation to zero in the Colombian Amazon rainforest by 2020.
- **Peru** pledged 0% net deforestation by 2021, as well as a minimum of 33% renewable energy in all energy consumed in the country, and non-quantified measures for waste emissions reduction.

The rest of the continent did not make pledges to the UNFCCC. However, national communications emphasized national measures and strategies in e.g.

- **Argentina**: energy efficiency programs, renewable energy including biofuels and hydrogen, forest management, solid waste management;
- **Ecuador**: by 2020,
    - 82% of oil in primary energy, down from 92% in 2011;
    - At least 90% renewable electricity, 80% from hydropower;
- **Uruguay**: the *National Plan to 2015* aimed at over 15% electricity from unconventional renewable sources;
- **Paraguay**: the country set reforestation targets and expressed its intention to expand energy-crop cultures.

B.2.2. Intended Nationally Determined Contributions

Contrary to NAMAs, most INDCs consider *emission reduction targets* instead of *sectorial actions*. National commitments can take the form of absolute emission reductions compared to historical rates; reductions below BAU projected levels; or carbon intensity reductions[89].

- Reducing emissions by a certain amount below historical rates is similar to ‘Annex I’ commitments; in South America, it was taken only by Brazil, Dominica, Dominican Republic and Grenada.
- Reducing emissions below BAU is the preferred method for South American countries. It uses a ‘no-climate-policies’ scenario as a reference for ‘maximal’ emissions at a certain

[89] For an exhaustive compilation of these pledges, see http://www4.unfccc.int/submissions/indc.

point in time (generally 2030), then emissions pledges are taken with respect to this 'worst case configuration'.

- Reducing emission intensity is the solution privileged by Chile[90] and Uruguay. No absolute reduction is pledged; instead, the amount of emission reductions is correlated with economic growth. The number of tons of CO_2eq emitted by unit of GDP generated is the preferred indicator for these pledges.

The year chosen for emission commitments also varies across countries (2025 or 2030), as well as the actual quantitative target and sectorial coverage of each commitment: for example, Brazil's commitment covers all national emissions, while Ecuador focuses on the energy sector only. We summarize below the main South American INDCs as submitted to the UNFCCC:

- **Brazil** pledged *absolute emission reductions* below *2005 levels*, of 37% in 2025 and *43% in 2030*. According to national INDC submission, the country would then emit 1,300 $MtCO_2$eq/year in 2025 and 1,200 $MtCO_2$eq/year in 2030.
- **Argentina** pledged to reduce national emissions by *15% below BAU levels* in *2030*. If international financing is available, these reductions could climb to 30%. Under BAU conditions, Argentina estimates that it would emit 670 $MtCO_2$eq/year in 2030. As a consequence, national absolute emissions under climate effort yet without international support would reach 569.5 $MtCO_2$eq/year; with international support they would drop to 469 $MtCO_2$eq/year.
- **Colombia** committed to unilateral emission reductions of *20% below BAU levels in 2030*. The country projects BAU emissions of 335 $MtCO_2$eq/year in 2030; its commitment thus translates into a 268 $MtCO_2$eq/year target for 2030. If international financing is available, emissions could be reduced by 30%, bringing 2030 emission target to 234.5 $MtCO_2$eq/year.
- **Ecuador** pledged *25%* emission reductions *below BAU levels* by *2025* (in its *energy sector only*). If supported by international financing, these reductions could rise to 45.8% below BAU levels. Ecuador's main focus is on electricity, of which 90% should be hydro-sourced by 2017.
- **Paraguay** proposed to reduce its emissions by *10% below BAU levels* by *2030*. With help of the international community, this effort could ascend to 20%. With 416 $MtCO_2$eq GHG emissions projected in 2030 under BAU conditions, Paraguay would thus limit its 2030 absolute emissions to 374 $MtCO_2$eq/year and 332 $MtCO_2$eq/year, respectively.
- **Peru** offered to reduce its emissions *below BAU levels* by *20%* by *2030* unilaterally –30% with international support. The country would thus emit 238.6 $MtCO_2$eq annually in the first case, 208.8 $MtCO_2$eq/year in the second.

[90] Chile thus moved from a commitment to absolute reductions below BAU levels in its NAMA pledge, to a carbon intensity offer in its tentative INDC contribution.

- **Chile** pledged to reduce its *carbon intensity* relative to GDP by *30%* by *2030*, provided that the country's development follows minimal growth requirements[91]. If international financing is available, this intensity reduction could reach 35% to 45%. The country also pledged to restore 100,000 hectares of endangered forest (0.13% of its national territory), thus storing an additional 0.6 $MtCO_2eq$ each year. National emissions in 2010 (excluding CO_2 sinks) amounted to 91.6 $MtCO_2eq$. In 2030, if the country's carbon intensity does not decline, they should climb to 226.3 $MtCO_2eq/yr$.
- **Uruguay** also proposed *carbon intensity* objectives for *2030*, yet quantified targets depend on the gas considered, the economy sector and international support, going from 25% reduction for energy without international support, to 68% for waste in the case of international financing.

Central and South American NAMA and INDC pledges are gathered for comparison in Table 4-2 at the end of this chapter. Encouragingly, fifteen countries that did not engage formally on NAMAs with the UNFCCC proposed national contributions under the INDC scheme. Brazil, Colombia and Peru moved from sectorial targets to economy-wide absolute emission reductions; only Chile changed back from economy-wide emission reductions to sectorial climate targets. Parallel to these commitments, some South American countries have played and still play an active part in global climate talks, promoting global agreement, or defending alternative cooperation options:

- Brazil, which hosted the Rio Earth Summit in 1992 and the Rio+20 Conference in 2012, has a long tradition of involvement in defining global targets. The country played a crucial role in the design of the UNFCCC in the first place, as well as the Kyoto Protocol –above all, the Clean Development Mechanism (Edwards et al., 2015). Paradoxically, it is both the fourth contributor in the world to global warming (Matthews et al., 2014), and a world leader in biofuels, hydroelectricity (Lucena et al., 2009) and the fight against deforestation (Nepstad et al., 2009). Lately, Brazil made one of the most ambitious pledges on the continent, along with interesting contributions to the current talks, including a call to adopt new metrics –the Global Temperature Potential– to account for greenhouse gases, on the basis that Global Warming Potential overestimates the role of short-lived gases such as methane; and the proposal for 'concentric differentiation' at the Paris Agreement, which adds a dynamic dimension to static INDCs and promotes ever-growing commitment to climate mitigation.
- Bolivia, under Evo Morales' government, chaired the G77+China block in 2014 and issued the declaration '*for a new world order for living well*' (Group of 77 and China, 2014), including an extensive climate section, pushing the concepts of nature rights, state property of natural resources and common but differentiated responsibility. Bolivia

[91] Chile will abide by its commitment if its growth path allows the country to '*reach in 2030 a development similar to the one reached by Francia, the United Kingdom and Canada in 2014*'.

furthermore organized the World People's Conference on Climate Change in 2010, as an answer to the perceived failure of COP15 in Copenhagen; introduced the concept of 'Climate Debt' incurred by developed countries towards least developed ones, a debt that would need to be paid not only by differentiated burden sharing for climate change mitigation, but also through extensive technology transfer from developed to developing countries (MMAyA, 2009); and advocates a scheme that competes with REDD+ for tackling deforestation, namely the Joint Mitigation and Adaptation Approach for the Integral and sustainable management of forests (JMA).

- In 2007 Ecuador, an OPEC country which boasts being the first in the world to include Nature's rights in its Constitution (MAE, 2011), came up with a groundbreaking initiative for climate change co-financing: if the international community were to provide Ecuador with at least half of the estimated profits of exploiting the petroleum in Yasuní National Park, the oil would stay in the ground forever. This represent at least one fifth of the country's oil reserves, in one of the most ecologically diverse zones in the world (Espinosa, 2013; Finer et al., 2010). Due to domestic complications and low international participation, however, the project was abandoned in 2013.
- Costa Rica, together with Papua New Guinea, originated the REDD (*Reducing Emissions from Deforestation and forest degradation in Developing countries*) framework at the 11th Conference of the Parties in Montreal. REDD+ (Angelsen, 2012), institutionalized at COP19 in Warsaw, in 2013, offset 24.7 MtCO_2eq in the same year (Goldstein and Gonzalez, 2014), although its performance-based paradigm is subject to debate today (Buizer et al., 2014).

Greenhouse gases and global warming potential

The 'greenhouse effect', first conceptualized by J. Fourier in 1824, refers to gases in the atmosphere that absorb the Earth's infrared radiations and send part of it back to the ground, a phenomenon also fostered by the glass of a greenhouse. As a consequence, part of the energy received from the Sun in the form of visible light is actually trapped, and the atmosphere heats up[92]. The greenhouse effect is a natural process without which life as we know it would not exist on Earth, since the average temperature would be an estimated -18°C instead of the current 15°C.

In volume, dry air is made up of nitrogen (78.08%), oxygen (20.95%) and argon (0.93%), which do not participate in the greenhouse effect. Of the remaining 0.4%, CO_2 represents more than 93% of the volume composition and is responsible for 64% of the energy retained by the atmosphere through radiative forcing. Together with CO_2, the gases responsible for the greenhouse effect are mainly methane (CH_4, 18%), nitrous oxide (N_2O, 6%) and fluorinated

[92] This description is an extreme simplification of climate dynamics and excludes, most of all, the albedo effects of clouds and ice caps and heat exchanges with the ocean leading to a sea level rise. It is estimated that so far, oceans have stored more than 90% of human-induced energy retention, dramatically slowing the atmosphere's warming.

gases. To give an idea of the orders of magnitude, the current content of CO_2 in the atmosphere (~400 ppm) represents around 3,100 Gt of CO_2, while human activities in 2010 emitted 37.2 Gt of this gas, according to (IPCC, 2014c). These emissions do not lead to an actual increase of 37 Gt of atmospheric carbon dioxide; a considerable proportion is captured by trees, oceans, etc. as part of the carbon cycle, yet atmospheric CO_2 concentration increased by 40% between 1750 and 2011, and the average increase in the 2002-2011 period is 2 ppm.yr^{-1} (IPCC, 2014a).

Calculating the effect of greenhouse gases on the atmosphere is not straightforward, since their action depends on molecules' ability to trap heat and transfer it to other atmosphere components during their lifetime. It also depends on what impact is measured, e.g. sea level rise, atmospheric temperature increase, radiative forcing, etc. and the measurement perimeter (an augmented radiative forcing induces a carbon-emission feedback). The Global Warming Potential is one metrics for comparing the various greenhouse gases in order to facilitate the formulation of emission mitigation pledges and progress reports. It measures the total contribution of a given molecule to radiative forcing over a given period of time, expressed in CO_2-equivalent (by definition, the GWP of CO_2 is 1). IPCC Assessment Reports contain state-of-the-art values for global warming potentials, which evolve slightly as the understanding of each species' full action on the Earth's atmosphere increases. This measure, however, is necessarily biased by the time horizon considered for calculating the action of a molecule, since the lifetime of a molecule is described by a statistical decay function rather than a fixed duration. Current values for the main three gases are given by (IPCC, 2014a). The metrics used for Kyoto pledges is the GWP_{100}, calculated over a 100-year time horizon.

Gas	Lifetime (years)	GWP_{20}	GWP_{100}
CH_4	12.4	86	34
HFC-134a	13.4	3790	1550
CFC-11	45.0	7020	5350
N_2O	121.0	268	298
CF_4	50,000.0	4950	7350

Main GHG gas and their GWP potential, according to two metrics

Box 4-5: Greenhouse gases and global warming potential

Country	NAMAs	INDC
Antigua & Barbuda	**Economy-wide, absolute** reductions. *Target year* = **2020**. *Reference emissions*: **historical** (1990). *Target*: **-25% GHG** emissions.	**Sectorial policies**. *Target years* = **2020, 2030**. *Reference indicators*: not applicable *Conditional policies*: • Construction of a WTE plant. • 50 MW additional RNW ELC capacity (current ~100MW). • Transport efficiency standards. • Protected Areas Policy.
Argentina	**No NAMA pledged to the UNFCCC.** National voluntary measures in biofuels, energy efficiency, urban waste, wind energy, national parks.	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: national **BAU.** *Unilateral target*: **-15% GHG** emissions. *Conditional target*: **-30% GHG** emissions.
Barbados	**No NAMA pledged to the UNFCCC.**	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: **Historical** (2008) *Unilateral target*: **-23% GHG** emissions
Belize	**No NAMA pledged to the UNFCCC.**	**Sectorial targets**. *Target year* = **2033**. *Reference indicators*: national **BAU.** *Unilateral targets*: • Energy: **-62% GHG** emissions. • Transport fuels: **-20% consumption** per year. • Solid Waste Management. • Reforestation, Protected Areas Policy.
Bolivia	**No NAMA pledged to the UNFCCC.**	**Sectorial targets**. *Target year* = **2030**. *Unilateral targets*: • **79% renewable electricity** by 2030. • **+720% capacity** for electricity production. • **+445%** for sustainable wood management. *Conditional*: • **81% renewable electricity** by 2030. • **+840% capacity** for electricity production. • **+890%** for sustainable wood management.
Brazil	**Sectorial targets, with estimated economy-wide results**. *Target year* = **2020.** *Reference emissions*: National **BAU.** *Economy-wide estimate:* **-38% GHG** emissions.	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: **Historical** (2005). *Unilateral target*: **-43% GHG** emissions. *Total resulting emissions*: 1,200 $MtCO_2eq$.

Country	NAMAs	INDC
Chile	**Economy-wide, absolute** reductions. *Target year* = **2020**. *Reference emissions*: National **BAU.** *Target*:**-20% GHG** emissions.	**Sectorial targets**. *Target year* = **2030**. *Reference emissions*: national **BAU**. *Unilateral targets*: • All save AFOLU: **-30% carbon intensity** • AFOLU: **1,5 $MtCO_2eq/yr$** stored *Conditional target*: • All save AFOLU: **-35% to -45% carbon intensity** • AFOLU: **1,5 $MtCO_2eq/yr$** stored
Colombia	**Sectorial targets.** *Target year* = **2020.** *Targets:* • **77% of electric capacity renewable.** • **20% of national fuels bio-sourced**.	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: national **BAU**. *Unilateral target*: **-20% GHG** emissions. *Conditional target*: **-30% GHG** emissions.
Costa Rica	**Economy-wide, absolute** reductions. *Target year* = **2021**. *Reference emissions*: **historical** (2005). *Target*: **+0% GHG** emissions ('carbon neutrality').	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: **historical** (2012). *Unilateral target*: **-25% GHG** emissions.
Dominica	**No NAMA pledged to the UNFCCC.** National voluntary strategies to develop geothermal, solar, wind, hydropower.	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: **historical** (2014). *Unilateral target*: **-44.7% GHG** emissions.
Dominican Republic	**No NAMA pledged to the UNFCCC.**	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: **historical** (2010). *Conditional target*: **-25% GHG** emissions.
Ecuador	**No NAMA pledged to the UNFCCC.** National voluntary targets: • 82% oil in primary energy[93]. • 80% of hydropower in national electricity. • 90% renewable Elec. *Target year* = **2020**.	**Sectorial targets**. *Target year* = **2025**. *Reference indicators*: national **BAU**. *Unilateral targets*: • **-25% GHG from energy**. • **Reforestation of 1,300,000 hectares**. *Conditional targets*: • **-37.5% to -45.8% GHG from energy**. • **Reforestation of 1,300,000 hectares.**
Grenada	**No NAMA pledged to the UNFCCC.**	**Economy-wide, absolute** reductions. *Target year* = **2025**. *Reference emissions*: **historical** (2010). *Unilateral target*: **-30% GHG** emissions. *Indicative target*: **-40% GHG** emissions by 2030.
Guatemala	**No NAMA pledged to the UNFCCC.**	**Economy-wide, absolute** reductions. *Target year* = **2030**. *Reference emissions*: national **BAU**. *Unilateral targets*: **-11.2% GHG** emissions. *Conditional target*: **-22.6% GHG** emissions.

[93] Down from 92% in 2010

Country	NAMAs	INDC
Guyana	**No NAMA pledged to the UNFCCC.**	**Sectorial targets**. Target year = **2025**. No reference emissions. Conditional targets: • Forestry: net removal of **52 $MtCO_2eq/yr$.** • Energy: **20% renewable electricity** in national supply.
Haiti	**No NAMA pledged to the UNFCCC.**	**Sectorial, absolute** reductions. Target year = **2030**. Reference emissions: national **BAU.** Unilateral targets: **-5% GHG** emissions in energy, AFOLU, waste Conditional targets: **-25% GHG** emissions in energy, AFOLU, waste
Honduras	**No NAMA pledged to the UNFCCC.**	**Sectorial, absolute** reductions. Target year = **2030**. Reference emissions: national **BAU**. Unilateral targets: • **-15% GHG** emissions in energy, industry, AFOLU, waste. • Reforestation of 1 million hectares.
Panama	**No NAMA pledged to the UNFCCC.**	**No INDC pledged to the UNFCCC (03 November, 2015)**
Paraguay	**No NAMA pledged to the UNFCCC.** National voluntary targets in reforestation.	**Economy-wide, absolute** reductions. Target year = **2030**. Reference emissions: national **BAU**. Unilateral target: **-10% GHG** emissions. Conditional target: **-20% GHG** emissions.
Peru	**Sectorial targets**. Target year = **2021.** Targets: • **0% net deforestation**. • **33% of final energy from renewables.**	**Economy-wide, absolute** reductions. Target year = **2030**. Reference emissions: national **BAU** (updatable until 2020). Unilateral target: **-20% GHG** emissions. Conditional target: **-30% GHG** emissions.
Trinidad and Tobago	**No NAMA pledged to the UNFCCC.**	**Economy-wide, absolute** reductions. Target year = **2030**. Reference emissions: national **BAU**. Conditional target: **-15% GHG** emissions.
Suriname	**No NAMA pledged to the UNFCCC.**	**Sectorial measures and policies**. Target year = **2025.** Reference indicators: national **BAU.** Unilateral targets: • Reduce deforestation, extend protected areas. • Establish an Energy sector plan and an Energy authority. Conditional targets: • Participation to REDD+ at national level. • At least **25%** renewable energy in 2025.

Country	NAMAs	INDC
Uruguay[94]	**No NAMA pledged to the UNFCCC.** *Voluntary actions in National Plan 2015*: • 300 MW additional wind. • 200 MW additional biomass. • 50 MW additional small hydro. • 15% of electricity from non-hydro renewables • 30% of waste used for Elec.	**Sectorial, gas-specific targets**. *Target year* = **2030**. *Unilateral targets*: • Forestry: **Store 13,200 GgCO_2/yr**. • **-25% CO_2 intensity** (energy). • **-33%** (meat), **-40%** (waste/other) **CH_4, N_2O intensity**. *Conditional targets*: • Forestry: **Store 19,200 Gg CO_2/yr**. • **-40% CO_2 intensity** (energy). • **-43%** (meat), **-60%** (waste/other) **CH_4, N_2O intensity**.
Venezuela	**No NAMA pledged to the UNFCCC.**	**No INDC pledged to the UNFCCC (03 November, 2015)**

Table 4-2: Summary of NAMAs and INDCs submissions by South America to the UNFCCC

[94] Uruguay's INDC is simplified here for readability. The full contribution can be found on UNFCCC's portal.

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Chapter 5: Energy sector contribution to regional climate action – Modeling and results

What is the use of having developed a science well enough to make predictions if, in the end, all we are willing to do is stand around and wait for them to come true?

– Dr. F. Sherwood Rowland

Chapter 5: Energy sector contribution to regional climate action – Modeling and results 175

As stated in the previous chapter, South America represents a significant share of global GHG emissions (8.5% in 2010). At the same time, the effects of global climate change could cost the region up to 5% of its annual GDP by 2050, in case of a slight temperature increase (2.5°C). The long time scales involved in climate-energy interactions make the issue an ideal case study for regional prospective modeling, all the more since energy offers a large panel of mitigation and adaptation options. After proposing Nationally Appropriate Mitigation Actions (NAMAs) following the Copenhagen Accord, South American countries are now submitting their Intended Nationally Determined Contributions (INDCs) in view of the Paris Climate Conference (December 2015). These pledges were described at length in the previous chapter; this chapter assesses their impacts on the regions' energy sectors and conversely, the contribution of South America's energy to fulfilling regional emission targets. I start by presenting the mitigation options and adaptation threats identified for South America's energy sector, with respect to climate change. I describe then the way in which NAMAs and INDCs are implemented in T−ALyC, followed by a description of GHG emissions, capture and storage in the model. T-ALyC acknowledges the relevance of Agriculture, Forestry and Land-Use (AFOLU) emissions in South America by including non-energy emissions and mitigation options. Our model's *business-as-usual* emissions are validated by comparing them with national BAU projections as per INDC communications. The third, and last, part of this chapter is dedicated to comparing the relevance of NAMAs versus INDCs in decarbonizing South America's economy, and analyzing more specifically their impact on electricity production and primary energy supply at regional scale.

A Mitigation options and adaptation threats for South America's energy sector

South America's energy sector takes its fair share of the climate burden, from two complementary prospects: it is highly vulnerable to climate change effects, and closely involved in mitigation strategies. Following the region's economic development, South America's total primary energy supply increased by 32% between 2000 and 2010; this is 5% above the world's average. The region, however, was second only to the OECD for the decrease in its carbon intensity (IPCC, 2014, p. 521), despite the fact that no South American country features in Annex I of the UNFCCC, which frees them from any contractual emission reduction.

Beyond this encouraging self-decarbonizing trend, dedicated mitigation strategies can still achieve substantial emission reductions in most Latin American countries:

- In **Chile**, the ECLAC (2012a) estimates that energy emissions will increase by 281% between 2010 and 2030 if no action is taken. Authors such as Carvallo (2014) consider that these BAU emissions could be halved with a very small added cost (3%) above the BAU configuration. This view is reinforced by Chile's flagship research project on mitigation actions, MAPS-Chile (*Mitigation Action Plans and Scenarios for Chile*), whose results confirm that the energy sector should provide the bulk of Chile's intended emission reductions, both in absolute terms and relative to sectorial emissions (MAPS Chile, 2014);

- In **Brazil**, Margulis et al. (2011) come to the conclusion that energy-specific mitigation measures alone could avoid the emission of 1.8 $GtCO_2eq$ between 2010 and 2030; that is, more than the country's overall CO_2 emissions in 2005 (MCT, 2010);
- In **Argentina**, the energy sector accounts for more than 80% of all historic and projected GHG emission reductions between 1990 and 2100, according to the national study on climate change economics (ECLAC, 2014);
- In **Uruguay**, business-as-usual energy emissions can be cut by 43%, at the very low cost of 12.3 dollars per tCO_2eq on average (ECLAC, 2010). Such a reduction represents 55% of the total mitigation effort proposed by the country in its most virtuous scenario;
- It is considered that Ecuador could reduce its end-use energy demand by 12%, cutting its energy-related emissions by 33% (ECLAC, 2013);
- Preliminary research for **Colombia** in the framework of the MAPS collaboration found that energy is one of the sectors that respond most readily to non-discriminative policy instruments such as a carbon tax (Delgado et al., 2014) ;
- The **Dominican Republic** considers that it could reduce its primary energy consumption by 16% and that such a reduction would abate national emissions by 23% (SEMARENA, 2009).

As a consequence, energy-related mitigation often collects a considerable share of a country's mitigation efforts:

- In **Honduras**, more than 50% of the projects eligible for Clean Development Mechanism credits in 2010 were related to the energy sector (PNUD and SNV, 2010; SERNA, 2010) ;
- In **Peru**, of 26 national initiatives or laws to promote climate change mitigation between 2001 and 2009, 15 were explicitly aimed at the energy sector (MINAM, 2010). 84% of the CDM portfolio was made up of energy projects, and the national Climate Change Plan (PlanCC, 2014) dedicates nearly half of its prospective climate investments (48%) to the energy sector;
- **Ecuador** included renewable energy development and energy efficiency in its national priorities, by writing them in the country's Constitution itself, in articles 15 and 413 (MAE, 2011, p. 125);
- In 2010, **Uruguay** declared that it intended to install 300 MW and 200 MW of wind and biomass production capacity respectively, over a 10-year-long horizon (MVOTMA, 2010). This would mean a 20% increase in the country's installed capacity in 2009, which was 2.5 GW (CIER, 2011), and a potential 15% of Uruguayan electricity from renewable origin (MVOTMA, 2010). As we will see below, this target has been considerably increased with the result of the first wind tenders;

- In **Colombia**, Cadena et al. (2008) estimate that wind power, geothermal energy and micro-hydroelectricity together could represent between 700 and 1,400 MW of new installed capacity, mitigating 45 $MtCO_2eq$ over 20 years.

A minority of countries in the region seems to escape this rule. In Bolivia for example, energy-related mitigation accounts for only 2.33% of estimated GHG emission reduction, according to (MMAyA, 2009); yet this pattern is more than uncertain since Bolivia's electricity demand is likely to multiply by 17 by 2100, while Andean glaciers are melting faster than anywhere in the world (BID and CEPAL, 2014).

The mitigation measures listed here do not account for adaptation to climate change consequences, which may well prove more expensive than mitigation itself: in Brazil for example Margulis et al. (2011) estimate that climate change adaptation would call for an additional 25% to 31% electricity production capacity, compared to 2008 values. The following paragraphs look at specific country-wise vulnerability and mitigation options, at a sub-sectorial level. Since the scale of the region and the scope makes any exhaustive inventory tedious and nearly unfeasible, I attempt to give a representative overview of the stakes, current situations and state-of-the art projections for the energy-climate nexus in Central and South America and the Caribbean, excluding Mexico.

A.1. Hydropower

Hydropower is probably the main option for emission mitigation in South America. The Amazon River alone accounts for 18% of global freshwater inputs into the world's oceans (Magrin et al., 2007). Hydropower accounts for 84% of **Brazil**'s electricity production, yet nearly 65% of the country's potential remained untapped in 2010 (MCT, 2010), leaving plenty of options for low-carbon growth based on this renewable energy (Herreras Martínez et al., 2015). In **Colombia**, untapped hydro potential amounts to 79 GW, excluding protected areas. This is enough to cover the maximum forecasted electricity demand in 2030 (140,000 GWh) four times over when considering an availability factor of 80% for these new plants (UPME, 2010). 66% of **Peru**'s Clean Development Mechanism portfolio is made up of hydro projects, and national mitigation priorities include a target of 65% hydropower in all of the electricity feeding into the National Interconnected Electric System, up from 52% in 2012 (CIER, 2013; MINAM, 2010). **Ecuador** has committed itself to move from 43% to 80% of hydropower in its electricity mix by 2020 (MAE, 2011). As part of its planned capacity expansion, in 2009 **Bolivia** projected to build 3.29 GW of new hydroelectric power plants in ten years (MMAyA, 2009) – that is, roughly 2.3 times its overall 2009 generation capacity (CIER, 2011).

On the other hand, hydropower is among the sectors most impacted by climate change. Reduced annual streamflows and increased seasonality put electricity production under pressure; on a continent where hydropower provided nearly 60% of the electricity produced in 2010 (CIER, 2013), more than half of the countries will experience a drop in their hydro potential by 2050

(Byman Hamududu, 2012). Water scarcity increases the competition between industrial, agricultural and energy uses, while increased precipitations, glacial lake outbursts and extreme climate events put structures and settlements at risk.

The vast majority of South American countries expect scarcity issues for their hydropower production. In **Chile**, water use in the Aconcagua basin could be restricted up to 65% (ECLAC, 2012a), while the Maule and Laja basins, which provide 25% of the country's electricity, could see their production drop by 20%. The adaptation strategy considered by (McPhee, 2012) is to replace all hydropower generation by coal-based electricity, leading to an annual 3 $MtCO_2eq$ emission. Using the same approach, yet basing its fuel switch strategy on natural gas, **Bolivia** estimates that reduced precipitations could cost the country 0.8% of its GDP each year by 2100 (BID and CEPAL, 2014). In **Central America**, the report prepared by F. López for (ECLAC, 2012b) states that electricity generation from the Chixoy and Cerrón Grande power plants would drop by more than 40% as early as 2050 under the SRES-A2 scenario (stringent climate change). The Chixoy plant, which provides 30% of Guatemala's electricity, could see its output reduced by 80% by the end of the century. There is concern for **Colombia**'s future endowment, both on annual averages and from a seasonal point of view, due to an increase in the El Niño phenomenon (MAVDT, 2010; Nakaegawa and Vergara, 2010; Ospina Noreña et al., 2009). **Argentina** considers that 20% of its hydroelectric production (that is, nearly 10% of its national electricity production) is threatened by climate change (SAyDS, 2007). **Ecuador**, Colombia's close neighbor, also expects a decrease in annual streamflow from 21% to 25% in three major hydrological basins (MAE, 2011). However, compared to Colombia, the Ecuadorian case is complicated by a severe depletion of the country's tropical glaciers, leading to an increased seasonality of flows. **Venezuela**, which depended on hydropower for 64% of its electricity production in 2012 (CIER, 2013), will see its agricultural and energy sectors strongly impacted by precipitation reductions in the case of climate change. In its 2005 communication to the UNFCCC, the country was considering the option of a 'price of water' to arbitrate between agricultural and electricity production end-uses (MARN, 2005). **Saint Vincent and the Grenadines** presents the typical situation of a Small Island Developing State, where water availability is limited by the island's size, and rampant deforestation increases runoffs at the expense of underground water. The hydric stress due to usage competition between domestic uses, irrigation and electricity generation is projected to grow as climate change puts these three competing sectors under pressure (NEAB, 2000). Last, but probably most prominent, **Brazil** is highly prone to hydrological changes. The Northeast region hosts 28% of Brazil's population (IBGE, 2010), yet only 3% of its water resources (Montenegro and Ragab, 2012). It has been affected by severe droughts in the past (de Assis de Souza Filho and Brown, 2009), causing up to 500,000 fatalities in one single event in 1877; and this situation is not improving with climate change, since groundwater recharge is found to decrease by more than 70% in all four SRES scenarios (Kundzweicz et al., 2007). Brazil's Northeast region has been identified as one of the most vulnerable to climate change for its hydroelectricity production (Lucena et al., 2009; Pereira

Villar, 2013), yet the 2001, 2002, 2014 and 2015 droughts in São Paulo proved that the Northeast is not the only potential victim of climate change.

Moreover, greater environmental concerns lead to a predominance of 'run-of-river' dams in new plants, which feature small reservoirs if any at all (Nogueira et al., 2014a). Although more environmentally friendly, these plants lack the inter-season storage capacity, a major benefit of dams for network operation.

The infrastructure risks are mostly linked to the El Niño – Southern Oscillation (ENSO) phenomenon, and its future developments. Although they are by nature difficult to predict, **Bolivia** has estimated that past El Niño phenomena in 1982, 1997, 2006 translated into losses as high as 7% of national GDP (MMAyA, 2009), while **Ecuador** estimated that future climate damage on electrical infrastructure (generation and transmission) could cost the country 1.2 billion dollars, or 60% of all identified infrastructure damage in case of a climate event (ECLAC, 2013). Without stating a figure for infrastructure damage, **Uruguay** (MVOTMA, 2010) and **Argentina** (ECLAC, 2014) have also identified floods as a main concern for human settlements and infrastructure, including energy works.

A.2. Biofuels and biomass

When it comes to biofuels, **Brazil** is a world-class leader: biomass, both liquid (biofuels) and solid (sugarcane bagasse for industrial heat) is the second energy source in the country behind oil, and before hydropower. The Brazilian national bio-ethanol program Proalcool (Puerto Rico et al., 2010), started in 1975 and based on sugarcane valorization, is still a role model in the world. It has been driven since 2002 by a legal minimum share of 20% bioethanol in car gasoline. It has allegedly avoided 600 $MtCO_2eq$ GHG emissions since its creation in 1975 (MCT, 2010) and put Brazil behind only the US for bioethanol production, with 26% of the world's annual output (IPCC, 2014). Margulis et al. (2011) consider that up to 19 million hectares could still be added to cultivated land, respecting sustainability considerations, without competing with other land uses. Moreira et al. (2014) even show that this option could prove more cost-effective than tapping the country's offshore oil located in the so-called 'pre-salt' fields. As a consequence, bioethanol production could climb to 65 billion liters/year, meaning a 123 $MtCO_2eq$ annual GHG abatement[95] for Brazil. Biodiesel is not forgotten either: the Pro-Biodiesel program led to 1.6 billion liters of biodiesel produced in 2009 and Margulis et al. (2011) estimate that domestic demand could climb to 9 billion liters in 2030, if reasonable incorporation rates were applied. Considering that biodiesel represents an emission reduction of 2.0-2.6 tCO_2/t_{Diesel} (MCT, 2010), the resulting reductions in 2030 could reach 20.6 $MtC0_2eq/yr$[96]. **Argentine** law N° 26.093/06 on biofuels sets a mandatory threshold for biofuels in all liquid fuels, starting at 5% in 2010. Argentina's Secretary for Environment and Sustainable Development (SAyDS, 2007) states that

[95] According to Brazil's National Communication, ethanol's CO_2 abatement rate is 1.9 tCO_2/m^3
[96] Considering a specific mass of 880 kg/m3 for Brazilian biodiesel – based on the 2012 Brazilian Energy Balance figures.

this threshold should eventually rise to 20%, but there is no legal record of this final target so far. However, the total production capacity for biodiesel was already estimated at 2.4 billion liters in 2009 (Sorda et al., 2010), and the economic potential of soy biodiesel and switchgrass bioethanol, avoiding indirect Land-Use Change, could reach 368 PJ and 1,100 PJ respectively, according to (Diogo et al., 2014). Based on (MCT, 2010) figures for induced GHG mitigation and (MME, 2012) for heating values, this translates into potential abatements of 24 $MtCO_2$/yr and 89 $MtCO_2$/yr respectively[97]. Other biofuel-based mitigation strategies in South America include **Chile**, which considers that promoting biofuels in transport could reduce GHG emissions by 23 MtCO2eq between 2010 and 2030 (Poch, 2010); the **Dominican Republic**, with an estimated 100 million BTU ethanol production potential, which considers exporting future production to the Caribbean and the US (SEMARENA, 2009); and **Paraguay**, where biofuel incentives have been identified as the mitigation strategy best adapted to national institutions and with relatively low barriers to implementation (SEAM, 2011).

As for hydropower, biofuels, and more generally biomass production, may be severely impacted by climate change; as an agricultural product, it suffers from all agriculture-related plagues; and as a non-subsistence product, competition with food products magnifies climate change impacts on bioenergy. Edenhofer et al. (2012) pointed out these weaknesses from a global point of view, insisting that a shift to second generation biofuels was necessary to limit competition with food production, while Persson et al. (2009) studied the effects of El Niño (negative) and La Niña (positive) on the energetic yield of maize in the Southern United States. Lucena et al. (2009), Schaeffer et al. (2012) and Ebinger and Vergara (2011) focused on the Brazilian case, stressing the impacts of reduced land-use availability, increased temperature and degraded hydrological conditions, most of all in the Northeast region, while Podestá et al. (2009) also forecast a strong decline of productivity in the Argentine Pampa in case of reduced precipitations. In addition to drought-related losses, Uruguay's National Communication (MVOTMA, 2010) points to the impact of drought- and flood-related diseases in plants and animals, yet does not come up with any consolidated figure at this stage for agricultural production as a whole, let alone dedicated energy crops.

A.3. Other renewable energies

Among so-called 'non-conventional renewable energy sources', the most promising for electricity production are wind, solar, and geothermal. A plus point for these energies is that climate change will impact them little if at all. In the case of wind energy, Brazil has even forecasted a positive trend in electricity production in most common climate scenarios (Lucena et al., 2010)

[97] These figures should be considered as orders of magnitude only, since Brazilian figures do not perfectly correspond to the Argentine context. In particular, the CO_2 abatement efficiency of Brazilian bioethanol is based on sugarcane features, while Argentine bioethanol is mostly generated from switchgrass, with a somewhat lower yield.

- **Costa Rica** was still the regional leader for wind energy production in South America in 2011, with an installed capacity over 30 MW. However, **Brazil** turned the tables in 2013, installing 1 GW of new capacity in only one year (Vergara et al., 2013). The giant country's estimated potential is close to 145 GW for winds above 7 m/s (CEPEL, 2001), giving it more than sufficient ground to develop this energy; wind capacity is indeed expected to increase by at least 14 GW in Brazil between 2011 and 2021 (Juárez et al., 2014). It is a particularly interesting option for the windy, semi-arid Northeast region, where 97 TWh of electricity could be generated annually, at a cost below 80$/MWh (Lucena et al., 2010). In **Argentina** wind power is chosen by national planning models as the first mitigation option in the electricity sector, together with nuclear power (Di Sbroiavacca et al., 2015). While this energy would only represent 4% of the power mix (and 1.5 GW of installed capacity) in 2050 under baseline conditions, this figure is tripled under a 20% GHG abatement target. The same stands for **Chile**, where wind power is expected to provide the bulk of renewable electricity production under climate constraints, with an installed capacity of 7 to 8 GW (Carvallo et al., 2014). As already mentioned, **Uruguay**'s initial target, in 2010, was to install 300 MW of wind capacity in ten years. Yet the 2011 and 2012 tenders went well beyond any expectation, providing the country with a total of 853 MW of operating or planned projects. In 2015, Uruguay has 1.2 GW operational wind capacity. Very approximate wind potential estimates by the national energy company (Ferreño and UTE, 2013) give wind potential of 600 GW; as a consequence, updated middle-run targets consider that wind capacity should get close to 3 GW by 2030 and provide at least 30% of the country's electricity, making it the first wind electricity producer in the world in relative terms, with generation costs below 65$/MWh (DNETN-MIEM, 2014). Island states are also well placed when it comes to wind generation: **Dominican Republic** estimates that its potential for wind production with "good or excellent" conditions is close to 10 GW, which is three times higher than its current overall generation capacity (SEMARENA, 2009); **Antigua and Barbuda** claim a 900 MW potential while the maximum generation capacity projected by 2030 on the islands is exceed 200 MW (ED-MHE, 2009); wind farms, together with waste-to-energy measures, have the potential to cut **Saint Lucia**'s emissions by 10% (MPDE, 2011).
- **Chile** stands out as a clear winner for solar potential. Its Northern region, home to most of the country's mines, also boasts some of the highest solar radiation in the world in a cloudless sky, with annual averages for daily Direct Normal Irradiance exceeding 9 kWh/m²/d in parts of the Atacama's desert (del Sol and Sauma, 2013; Escobar et al., 2014). In comparison sake, radiation levels in Germany are between 2.22 – 3.33 kWh/m²/d. As a consequence, the country's feasible potential is estimated at over 1,200 GW, with plant factors greater than 24% (Minenergía and GIZ, 2014). Solar development may be spurred by national targets as is the case for wind, possibly reaching 3 GW installed capacity in 2030 (Carvallo et al., 2014). Chile is home to the first utility-scale

solar farm to be built without an external loan, and selling its energy without subsidies: the 70 MW Salvador Project, which came online in 2014. **Brazil** does not receive such strong radiations: the highest irradiation values (São Francisco Valley, Northeast Brazil) reach 5.7 to 6.1 kWh/m²/d (Pereira et al., 2012). Although technical potential remains high thanks to the huge area available[98], it is not yet economically feasible due to the 'low' energy content of incoming solar radiation, the high cost of the technologies available, and low national generation prices for electricity (Malagueta et al., 2014). Rooftop photovoltaic panels may escape this rule since they are not burdened by high transmission costs; Miranda et al. (2015) consider that 29 million homes could adopt rooftop solar panels by 2026. Nevertheless, except for Chile, literature considers that solar energy is still less interesting than wind or biomass technologies in South America.

- Geothermal power is already an effective and implemented option for GHG mitigation in Central America, with more than 500 MW operating between **Costa Rica**, **Salvador**, **Guatemala**, **Honduras** and **Nicaragua** (Vergara et al., 2013). Yet it is far from its full potential. In the **Dominican Republic**, 60% of the new capacity installed under climate constraints could be based on geothermal (ECU, 2012). The reference report by Battocletti (1999) estimates that geothermal-based electric production potential could be higher than 2 GW in **Argentina**, **Bolivia**, **Chile**, **Peru**, **Colombia**, **Costa Rica**, **El Salvador**, **Guatemala**, **Nicaragua**, **Guadeloupe**, **Martinique** and the **Netherland Antilles**. A recent update by Vieira and Hamza (2014) placed **Argentina** and **Chile** on the two first podium steps for recoverable heat, followed by Venezuela, Bolivia, Ecuador and Colombia; **Chile**'s potential alone could reach 16 GW for electric generation, according to Lahsen (1985; 2015). Chile's National Communication to the UNFCCC presents geothermal power as the mitigation measure with the biggest emission reduction potential (MMA, 2011, p. 176), an information backed by the work of Carvallo et al. (2014). The weakness of this energy source lies with the risks of geothermal exploration, which will continue to discourage private investment in geothermal energy unless governments set up risk-sharing schemes.

A.4. Fossil fuels and carbon storage

Fossil fuels are all sources of CO_2 emissions, yet they provide room for mitigation, mainly by shifting from fuel to gas burners. Long-term mitigation scenarios for **Jamaica** identify the introduction of natural gas as 'the major mitigation measure' for the island, which has run of fuel so far (MWH, 2011), while **Costa Rica**'s target of reaching carbon neutrality by 2021 involves an 80% to 90% reduction in fossil fuel sector emissions (MINAET, 2009). Like Jamaica, **Colombia** considers that replacing 50% of its industrial coal heaters by gas-fired ones is the most effective option for carbon emission reduction, with 75 $MtCO_2eq$ abated by 2050 (Cadena et al., 2008). 77% of **Venezuela**'s emissions come from the energy sector, yet 21.7% could be abated without even switching fuels, since they are due to vented gases that could be captured and sold, or burnt

[98] for CSP, this potential could reach 346 GW, according to (Salvi Burgi, 2013).

(MARN, 2005). **Argentina**, **Bolivia** and **Peru** also identify the role of gas for mitigation in transportation, with up to 1.5 million vehicles in Argentina being powered by natural gas (SAyDS, 2007). Fossil fuels could also be combined with Carbon Capture and Storage (CCS) technologies in various South American countries. Herrera Martínez et al. (2015) present CCS technologies as 'one of the most promising low-carbon options for the region', a vision confirmed by Calderón et al. (2015) and Nogueira et al. (2014b) for the **Colombian** and **Brazilian** cases, respectively. However, Lucena et al. (2015) argue that the technical and institutional challenge is very high in Brazil, while Di Sbroiavacca et al. (2015) point out that CCS is a very costly option for Argentina. In both papers, CCS is not used except in the most stringent mitigation scenarios. The conceptual work by Gerlagh and Zwaan (2012) on the very long-term benefits of CCS goes further, showing that Carbon Capture and Storage may at best prove a valid option for some hundreds of years, but that geological leakage reduces its relevance for large time scales (> 1,000 years). Fossil fuels are actually highlighted more for issues related to adaptation to climate change effects. In **Argentina**, gas is expected to be part of the answer to hydrological stress on agriculture (SAyDS, 2007); in **Brazil**, it is expected that air conditioning demand will increase during summer periods, that is, when water availability is low. In **Haiti** and **Chile**, fossil sources are expected to replace lost hydropower capacity, despite higher GHG emissions (McPhee, 2012; MINENV, 2013). Last, **Uruguay** points out the risk that increased extreme events put on its energy supply: its maritime importation terminals are at risk in case of severe weather, while its refineries and refined product storage facilities are highly prone to floods (MVOTMA, 2010).

A.5. Demand-side options

Demand-side mitigation and adaptation options can be implemented in a great variety of ways, yet they are often based on energy efficiency and demand-side management. I list some of them here, according to consumption sectors.

- The most promising sector may be industry. **Brazil** is in the global top five for the production of energy-intensive goods such as iron and concrete (IPCC, 2014) and ranks 9th for paper production (yet 4th for pulp). Its pulp and paper industry employs 130,000 people. Energy efficiency measures, as well as further use of renewable biomass for coal supply in the iron industry (renewable charcoal) could reduce emissions by as much as 1,473 $MtCO_2eq$ over the 2010-2020 period (Henriques Jr. et al., 2010; MCT, 2010). According to Borba et al. (2012), Brazilian industry could provide 55% of the country's emission reductions. In **Chile**, where the mining sector consumes over half of the country's industrial energy (IPCC, 2014), energy efficiency is the main end-use mitigation from a national point of view (UNFCCC, 2013). In **Colombia**, in addition to the industrial heater switch considered above, energy efficiency is the mitigation option most readily adopted by Colombian entrepreneurs, as quoted by (MAVDT, 2010) in the framework of the PROURE program (PROgram for the Rational Use of Energy). In their opinion, energy efficiency makes it possible to reach GHG abatement targets with co-benefits for competitiveness. In **Uruguay**, the main identified co-benefit of energy efficiency as a tool to mitigate emissions is to hedge against energy shortages. The national energy efficiency program is called PEE (*Proyecto de Eficiencia Energética* – Energy Efficiency Project) (MVOTMA, 2010). **Argentina** also features national programs for the rational use of energy: PURE (*Programa para el Uso Racional de Energía*, Program for the Rational Use of Energy) and PUREE (*Programa para el Uso Racional de Energía Eléctrica*, Program for the Rational Use of Electric Energy), which could allegedly yield 0.9 $MtCO_2eq$ annual emission reductions, and not only from industry. In fact, Tanides et al. (2006) warn that in relative terms, mitigation potential in Argentine industry may be much lower than that of the residential and commercial sectors[99]. In addition, inertia is much grater in industry, where equipment lasts longer.

- Transport also offers significant potential for end-use emission mitigation. In **Brazil**, it comes just behind industry in the study by Borba et al. (2012), with 33% of the country's mitigation potential for end-use by 2030. The Brazilian mitigation policy draws heavily on biofuel minima in car gasoline, and on FlexFuel vehicles. These vehicles, which can indifferently consume any share of oil and bioethanol, were launched in 2003. In 2010, they represented more than 90% of sales (MCT, 2010). In **Colombia**, Cadena et al. (2008) note that increasing private vehicles' occupation rates by up to 50% in 2050 could yield nearly 63 $MtCO_2eq$ emission reductions in 40 years, the second most effective measure after switching industrial heaters to gas. Public transportation projects being developed in eight of the country's main cities are expected to reduce national emissions by up to 0.8 $MtCO_2eq$ by year (MAVDT, 2010). In **Ecuador**, a comprehensive transport legislation package (national rules on efficiency and pollution, mandatory renovation of old vehicles, mass transportation, etc.) could achieve a reduction of 0.9 $MtCO_2eq/yr$ in the country's emissions (MAE, 2011).
- Reviewed literature did not offer much information on national mitigation potentials for the residential and commercial sector. However, as already mentioned, Tanides et al. (2006) consider that energy efficiency in these sectors could yield twice as much emission reductions as industry in **Argentina**, mostly from buildings. Argentina's Second National Communication to the UNFCCC (SAyDS, 2007) states a combination of energy-saving light bulbs and building insulation could reduce the country's GHG emissions by 2.3 $MtCO_2eq$ annually. **Brazil** requires its energy companies to spend at least 1% of their income in energy-efficiency measures, with at least 25% of this fund directed at end-use energy efficiency (UNEP SBCI, 2007), in addition to energy-saving labeling on household appliances through its Conpet program. The **Chilean** Agency for Energy Efficiency (ACHEE) sets minimum requirements and labels for the energy consumption of household appliances, while **Paraguay** encourages a move from fuelwood to electricity in

[99] It is still nearly equal in absolute terms to residential and commercial abatement potentials, but only because the industry sector is, or will be, a higher GHG emitter in a no-policy projection.

the home as the easiest way for individuals to help decarbonize end-use consumption (SEAM, 2011).

This review of mitigation options and adaptation issues for South America's energy system to deal with climate change highlights the extreme diversity of these options and issues, both from a geographic and technical point of view. Some intuitive deductions and orders of magnitude can be drawn: hydropower offers the highest techno-economic potential for future clean electricity generation in Brazil, Colombia, Peru, Ecuador and Bolivia, yet future water scarcity and increased seasonality threaten more than half of the continent. Unlike hydropower, biofuels and more generally modern biomass are not restricted to electricity production; their ability to provide e.g. industrial heat and transport services may make them the most important mitigation option for Latin America, with Brazil leading the region's current use of biomass as well as its future prospects. Brazil is also the regional champion for wind turbine installation; however, Uruguay shows very promising potential for final wind share in its national mix and is putting quite significant efforts into developing this potential. As mentioned in Chapter 4, Chile leads the continent by a more than a fair margin for technical solar energy potential, yet current national projections deliver quite a balanced view for the future energy mix of this country, acknowledging the fact that this energy is not yet totally mature. Geothermal energy is already used in Central America, and should develop in the years to come in Chile and Argentina. Fossil fuels are expected to make a significant contribution to climate change mitigation as South American countries shift from oil and coal to gas and Venezuela starts using or selling its vented natural gas. These fuels should also contribute to attenuating climate-change related stresses on end-use demand or energy. Demand-side mitigation should not be neglected and will primarily rely on the industry and transport sectors, which should deliver the highest absolute emission reductions, even though they do not possess the highest relative abatement potential.

This variety of options, the many ways of assessing them, their co-benefits, side effects and potential interactions provide an interesting framework for integrated modeling tools such as T-ALyC, through the analysis of contrasted climate policy scenarios.

B Modeling mitigation

B.1. Pledge scenarios

In order to assess the impact of NAMAs on South America's energy sectors, and the additional modifications introduced by the INDCs, five climate policy scenarios were designed: '*Business-As-Usual'* (BAU), '*Nationally Adapted Mitigation Actions*' (NAMAs), '*Unilateral INDCs, based on national BAUs*' (Uni_Nat), '*Conditional INDCs, based on national BAUs'* (Cond_Nat), and '*Conditional INDCs, based on T-ALyC BAU'* (Cond_TALyC).

The *Business-As-Usual* scenario considers that no climate pledge is taken by any country. It allows presenting the key energy determinants of the continent, and serves as a comparison point for climate pledge scenarios. However, T-ALyC's *Business-as-Usual* emissions can differ substantially from national BAU projections (see section B.2). To account for this discrepancy, the last climate scenario —*Cond_TALyC*— considers conditional national contributions based on T-ALyC's *Business-As-Usual* emissions for all countries that provided BAU-based INDCs. T-ALyC's *Business-As-Usual* scenario is also used to calibrate the *NAMAs* scenario, since most countries did not provide national BAU projections with their NAMA commitments.

The *Nationally Adapted Mitigation Actions* scenario considers that UNFCCC pledges as described in the previous chapter are implemented in Brazil, Chile, Colombia and Peru, plus a 30% deforestation reduction in Ecuador. For Brazil, T-ALyC's target is less stringent than the one actually pledged in 2010, since the original objective was based on national BAU projections. I did not have access to this BAU, and used T-ALyC's instead. However, the fight against deforestation improved dramatically between 2005 and 2010, so I assumed that part of the objective had already been met by 2010[100]. Also, Brazil's constraint is written as an overall cap for the joint emissions of the two-region Brazil, meaning that the choice of where to reduce emissions is left to the model. Both Brazil and Chile's targets are extrapolated to 40% below BAU in 2050. On the other hand, pledges for Colombia, Peru and Ecuador do not become stronger between 2020 and 2050. National voluntary policies that did not lead to a NAMA pledge to the UNFCCC were not included in my modeling hypotheses.

The *Unilateral INDCs, based on national BAUs* scenario considers all national unilateral contributions, i.e. the minimal pledges offered by UNFCCC Parties in the absence of international support. As T-ALyC 10-region disaggregation does not support country-scale modeling, national pledges were aggregated into regional emission bounds, as per Table 5-1. When BAU information was available, these bounds translate BAU-based targets, intensity-based targets and absolute emission reductions into absolute, all-encompassing maximum emissions. The only exception is Brazil, which provided its own absolute target for national emissions. All targets are extrapolated with constant values through 2050, since no information was available past 2030. This more-than-optimistic assumption has the merit of being straightforward and uniform, and of giving an insight on how the continent would react under increasing climate pressure over the 20-year period following the INDC horizon.

The *Conditional INDCs, based on national BAUs* scenario reflects national contributions if international help (financial, technological transfers etc.) is available. It models the optimistic outcome of Paris negotiations. When a country (e.g. Brazil) has not specified a conditional target, this scenario considers its unilateral contribution. As for *Uni_Nat*, 2030 targets are extrapolated as constants until 2050.

The *Conditional INDCs, based on T-ALyC BAU* scenario, deals with the fact that T-ALyC's BAU differs from national projections in some sub-regions of South America, primarily

[100] Brazil's emissions in T-ALyC are calibrated based on updated national GHG inventories, for which 2010 values were already much lower than 2005 values.

Argentina and Chile (see Figure 5-2, p.192). Although this result can be explained in the framework of T-ALyC's assumptions, providing interesting insights on South America's possible energy expansion, it may also distort the effect of national pledges on the energy mix: if emissions are already low in T-ALyC's BAU, an upper bound based on national projections will have less impact in T-ALyC than in real life. On the other hand, if T-ALyC's BAU emissions are higher than national projections, a bound based on national projections could prove unrealistically costly –and at worst, unfeasible– in the model's framework. This scenario allows us to assess the gap between these two acceptations of 'below BAU reductions'. Last, since T-ALyC's BAU is actually less emissive than national projected pathways, *Cond_TALyC* gives us a vision of the potential impacts of stringent reduction pledges in South America. Like the two previous scenarios, *Cond_TALyC* uses constant GHG bounds between 2030 and 2050.

A scenario was also developed using unilateral INDCs calibrated on T-ALyC's BAU, rather than national ones. However, its results fell between the three remaining INDC scenarios (*Uni_Nat*, *Cond_Nat*, *Cond_TALyC*) and is not presented here. Table 5-1 gathers the main emission bounds in our four climate scenarios.

Region	NAMAs	Target Year (INDCs)	Uni_Nat	Cond_Nat	Cond_TALyC
AND	30% RNW in Final NRJ Deforestation drop[101]	2025	333 $MtCO_2eq$	277 $MtCO_2eq$	283 $MtCO_2eq$
ARG	–	2030	570 $MtCO_2eq$	469 $MtCO_2eq$	293 $MtCO_2eq$
BPU	–	2025	310 $MtCO_2eq$	276 $MtCO_2eq$	276 $MtCO_2eq$
BSE-BWC	1,414 $MtCO_2eq$(2020) 1,542 $MtCO_2eq$(2050)	2030	1,200 $MtCO_2eq$	1,200 $MtCO_2eq$	1,200 $MtCO_2eq$
CHL	-20% GHG (2020) -40% GHG (2050)	2030	158 $MtCO_2eq$	124 $MtCO_2eq$	84 $MtCO_2eq$
COL	77% RNW in ELC 20% biofuels in TRA	2030	268 $MtCO_2eq$	235 $MtCO_2eq$	214 $MtCO_2eq$
CYC	–	2030	304 $MtCO_2eq$	270 $MtCO_2eq$	270 $MtCO_2eq$
SUG	–	–	–	–	–
VEN	–	–	–	–	–

Table 5-1: Scenario assumptions for regional emission targets

[101] Deforestation absolute target cumulating the effect of 0% net deforestation in Peru, and 30% reduction of deforestation in Ecuador.

B.2. Greenhouse gas emissions and storage in T-ALyC

The emission structure in South America is quite different from the rest of the world. As mentioned above, Brazil is both the world's fourth contributor to global warming and a world leader in biofuels, hydroelectricity, and the fight against deforestation. The country's national emission inventory reports GHG emissions from the energy sector that amount to only 15% of total national emissions (MCT, 2010). By comparison, energy emissions for the European Union at the same date accounted for 80% of total emissions[102] (European Commission, 2014). This is mainly due to AFOLU emissions: in 2005, AFOLU contributed 1,329 $MtCO_2eq$ to Brazilian emissions, while the same sector in Europe was a net sink for greenhouse gases with 281 $MtCO_2eq$ GHG captured and stored. AFOLU emissions may not be explicitly energy-related, yet they compete with energy emissions through climate pledges: faced with an economy-wide emission-reduction target, planners can spend the money either on emission reductions in the energy-production sector, or on dedicated non-energy measures in e.g. AFOLU or waste. On the other hand, emission reductions can go hand in hand with energy production in the case of e.g. waste-to-energy measures, or sustainable biomass production. Available options in AFOLU include curbing deforestation, reforestation measures (re-establishment of a forest depleted by deforestation) and afforestation (creation of new forest areas). Accurate reporting of non-energy sources and sinks for South America's greenhouse gases is thus a necessary step towards analyzing the specific contribution of the energy sector to regional climate targets.

B.2.1. Non-energy emissions

Non-energy emissions are taken into account in an exogenous fashion through dedicated emission technologies, as described on Figure 5-1 below. The activity of these technologies is calibrated based on national communications to the UNFCCC; model values are presented in Table 5-2. The three main emission sources by far are CO_2 from Land-Use, Land-Use Change and Forestry (LULUCF), N_2O from agriculture (including manure) and CH_4 emissions related to biomass burning and enteric fermentation (cattle ranching). BWC and AND are the main emitters in T-ALyC's regions.

Exogenous emissions	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Solid wastes (landfills)	7E-4	8E-4	2E-4	4E-4	2E-3	2E-4	9E-4	2E-3	6E-6	1E-4
Wastewater	5.3	7.3	1.3	3.5	14.2	0.1	0.6	1.1	0.1	1.0
Agriculture CH_4 - Manure	0.6	1.5	1.5	3.8	15.3	1.7	1.3	1.0	2E-2	0.7
Other CH_4 (Bio burning, enteric ferm.)	19.9	69.4	46.7	60.2	240.7	5.6	41.2	0.7	3E-2	0.5
Agriculture N_2O (incl. manure)	179.2	67.0	23.4	31.1	124.4	8.2	35.9	6.0	0.4	3.8
Industry – Adipic acid production (N_2O)	N/A	N/A	N/A	2.8	12.1	N/A	N/A	N/A	1E-2	0.6
Industry – Nitric acid production (N_2O)	0.2	0.2	N/A	0.3	1.2	N/A	1.0	0.8	1E-3	6E-2
LULUCF – CO_2	280.1	<0	95.3	37.0	350.7	<0	32.4	67.0	10.7	116.4
LULUCF – N_2O	3.1	0.6	6.5	2.2	21.2	1.8	0.4	0.8	0.1	1.4
LULUCF –CH_4	0.3	0.1	0.8	0.2	1.7	0.4	0.0	0.1	0.0	0.1

Table 5-2: exogenous emissions in T-ALyC in 2010 ($MtCO_2eq/yr$)

[102] Excluding AFOLU which is actually a sink rather than a source of CO2 emissions in Europe.

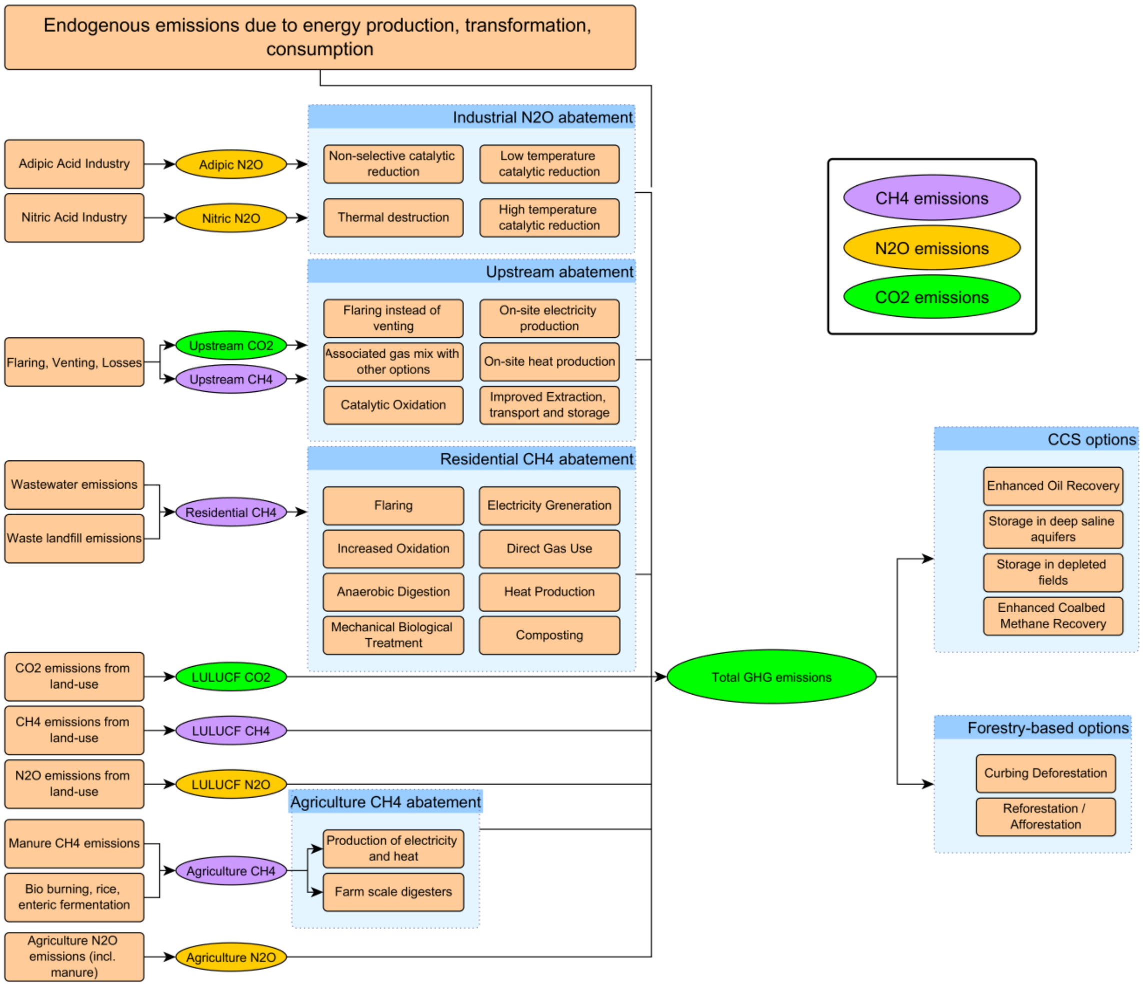

Figure 5-1: Accounting for non-energy GHG sources and sinks in T-ALyC

Resulting GHG emissions in T-ALyC's *business-as-usual* projections are detailed on Figure 5-2 below on a region-by-region basis for the year 2030. These results include both energy and non-energy emissions; they are compared with national estimated projections as provided in 2015 INDC submissions to the UNFCCC, when such projections are available. For Brazil and the Andean region, T-ALyC's BAU is fairly in line with national projections, with less than 5% difference between the two figures; Colombia also presents similar values, with less than 10% difference between national projections and T-ALyC's projections. Chile and Argentina, on the other hand, exhibit very low BAU emissions in T-ALyC's projections, 30% to 40% below national ones. The main reason for this is the quick decarbonization of energy production in T-ALyC in these two regions, as presented on Figure 5-3. Existing fossil-based capacity that finishes its technical life is replaced by renewable energy production sources, mainly hydropower, with very low GHG emissions. Since the relative weight of AFOLU emissions is lower to begin with, this drop in energy emissions drives a strong decrease in the two regions' overall emissions. This decarbonization of energy production in the absence of climate constraints is supposedly not envisioned in national projections, leading to this gap between T-ALyC's BAU and national BAUs. However, as mentioned p.177, Carvallo et al. (2014) showed that a decarbonization scenario for Chile was only very slightly costlier than their highly emissive BAU; as a consequence, a low-emissive BAU in T-ALyC is easily conceivable. As specified in paragraph B.1 above, I capitalized on this BAU difference through the *Cond_TALyC* scenario.

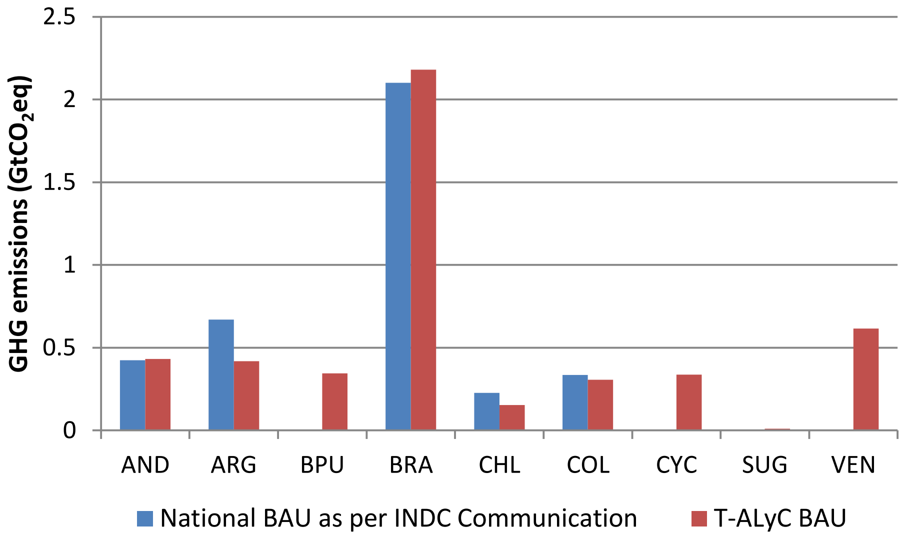

Figure 5-2: BAU emissions in 2030 in T-ALyC and in national projections

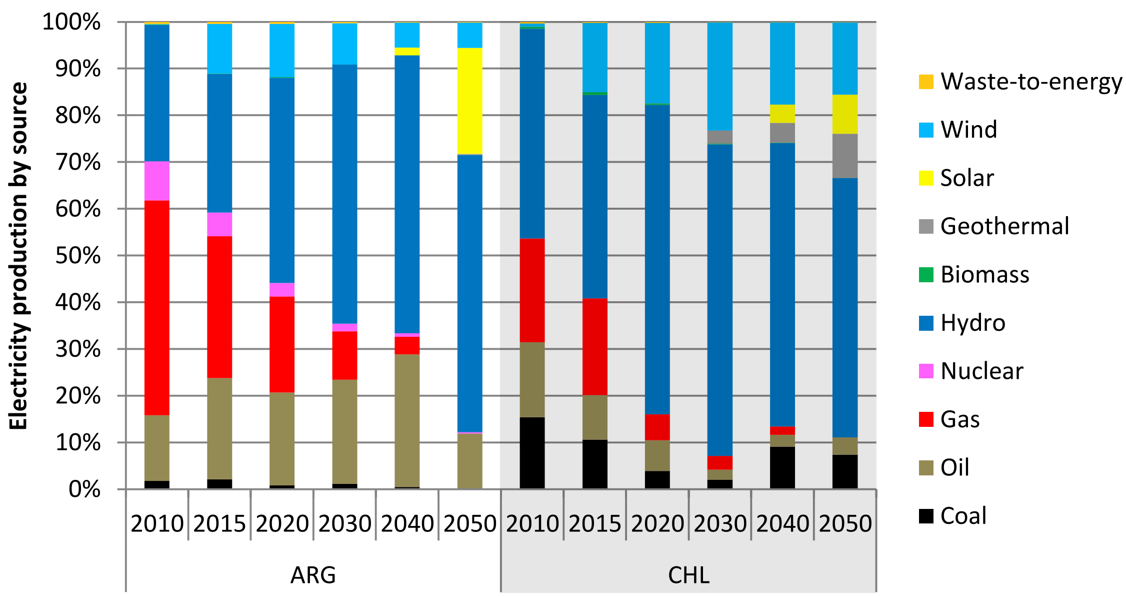

Figure 5-3: Chile and Argentina's power mix under BAU conditions

B.2.2. Non-energy mitigation options

External options for non-energy emission reductions also exist in T-ALyC to account for the competition between energy and non-energy mitigation options.

While some mitigation measures directly reduce GHG emissions (e.g. thermal destruction of N_2O emissions from the Nitric Acid Industry, or the fight against deforestation), some mitigation options are only indirectly related to emission values –e.g. reforestation– or totally unrelated –e.g. deep aquifer storage. In the case of forestry-based options, the potentials and associated costs of emission mitigation and GHG storage were calibrated on external sources[103]. We separate measures related to the fight against deforestation, calibrated on national baseline projections for deforestation, from afforestation-related measures, whose potential is linked to the available surface area. This area depends on the amount of forest-free land, and on the competition between afforestation and agriculture or other productive activities.

[103] See (Asner et al., 2014; Elberg Nielsen et al., 2014; Gonzalez Arenas et al., 2011; MAE, 2011; MCT, 2010; MINAM, 2010; MMAyA, 2009; MVOTMA, 2010; Nepstad et al., 2009; SAyDS, 2007; SEAM, 2011; Smith et al., 2014).

For non-forestry based options, we used TIAM costs and potentials (Ricci and Selosse, 2013) and regionalized the latter based on T-ALyC's sub-regional fossil fuel extraction potentials and surface areas. The potentials and costs of carbon storage technologies are detailed in Table 5-3 and Table 5-4 respectively; carbon capture and storage costs include transportation.

Storage option	AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
Enhanced Oil Recovery	1,629	2,863	1,732	1,593	7,258	778	1,087	762	369	928
Storage in depleted fields	5,341	9,389	5,680	5,224	23,798	2,552	3,564	2,498	1,211	3,044
Enhanced coalbed meth. recov.	171	301	182	168	764	82	114	80	39	98
Deep saline aquifers	2,598	4,566	2,763	2,541	11,574	1,241	1,733	1,215	589	1,480
Curbing deforestation	15,506	1	4,905	1,272	12,053	0	3,764	0	0	0
Afforestation/reforestation	3,299	1,561	756	572	5,424	229	1,258	0	0	0

Table 5-3: Cumulative storage capacity (2010-2050) for T-ALyC carbon storage options (MtCO_2)

Storage option	Cost (\$/tCO_2)
Deep saline aquifers (onshore)	5.7
Deep saline aquifers (offshore)	9.3
Enhanced Oil Recovery and depleted fields injection (onshore)	5.1
Enhanced Oil Recovery and depleted fields injection (offshore)	8.2
Enhanced coalbed methane recovery	4.9
Curbing deforestation – Step 1	3
Curbing deforestation – Step 2	6
Curbing deforestation – Step 3	55
Afforestation – Step 1	10
Afforestation – Step 2	25
Afforestation – Step 3	45

Table 5-4: Cost of carbon storage technologies ($\$_{2000}$/t$CO_2$)

C Results and analysis

We now investigate the results of T-ALyC's calculations. Figure 5-4 offers an overview of South America's main GHG emissions by region and by source, and the impact of national contributions on these emissions. As mentioned in section B.2, AFOLU is the main source for GHG emissions on the continent, followed by upstream and transportation. Brazil is the largest emitter on the continent; its BWC region alone emits more than any other model region due to Amazon deforestation. These emissions are fairly reduced in the *Cond_TALyC* scenario, as shown on the right of Figure 5-4. The overall impacts of South American INDCs and NAMAs are further detailed in section C.1. Section C.2 focuses on the impact of climate pledges on the energy sector, while section C.3 investigates the changes happening to primary energy supply. Last, section C.4 details the role of South America's non-energy emissions and South America's non-energy mitigation options.

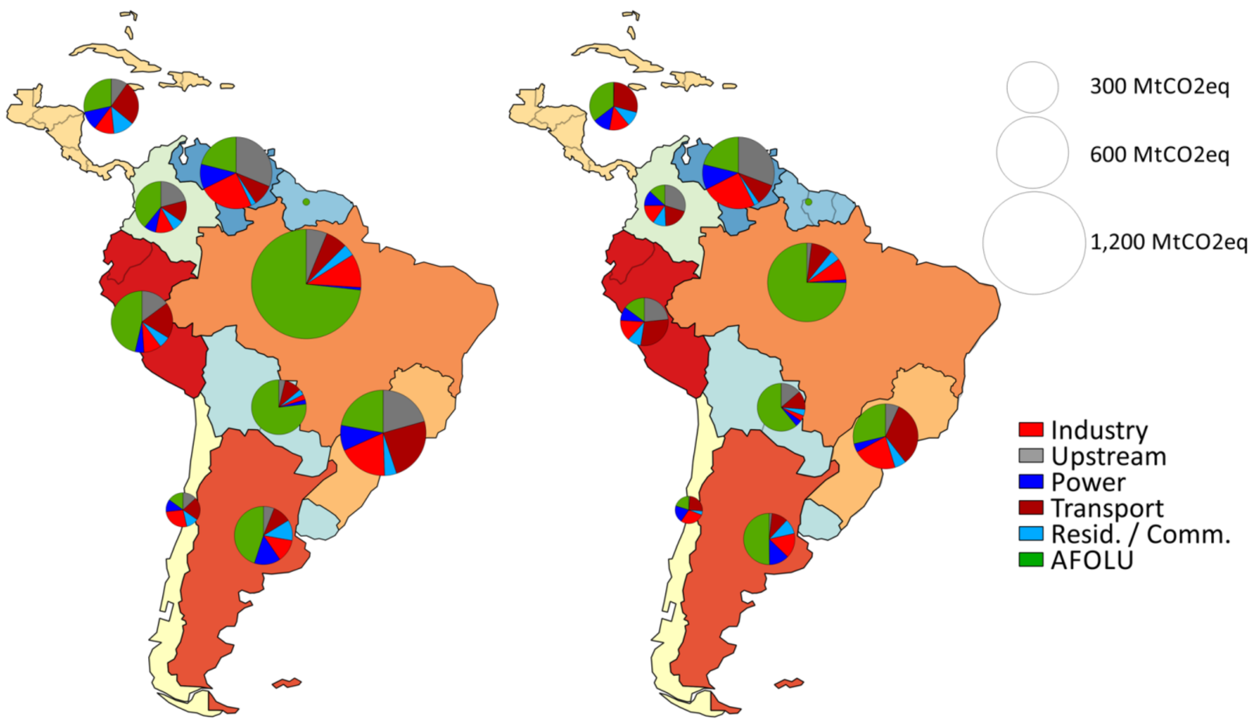

Figure 5-4: Latin American GHG emissions in 2030 under *BAU* (left) and *Cond_TALyC* (right) scenarios

C.1. Impact of climate pledges on the energy sector: NAMAs vs. INDCs

Figure 5-5 shows the regional impact of climate scenarios in terms of emissions reductions. The *NAMAs* scenario results in emissions that are 21.4% below *BAU* levels in 2030 (3.8 $GtCO_2eq$ instead of 4.8), not as good as INDC results (from 24.4% to 32.4% emissions reductions below *BAU*); however, 2050 emissions are still above 2010 figures, and the upward trend is only slightly curbed. On the other hand, 2050 emissions are below 2010 levels in the *Cond_Nat* and *Cond_TALyC* scenarios, with emissions reductions up to 42.8% below BAU levels. Due to constant past-2030 GHG bounds in most model regions, T-ALyC's emissions nearly stop increasing from 2030 on: the year-on-year increase in regional emissions between 2030 and 2050 drops from 51.4 $MtCO_2eq/yr$ in *BAU* down to 4.5 $MtCO_2eq/yr$ in *Cond_TALyC*.

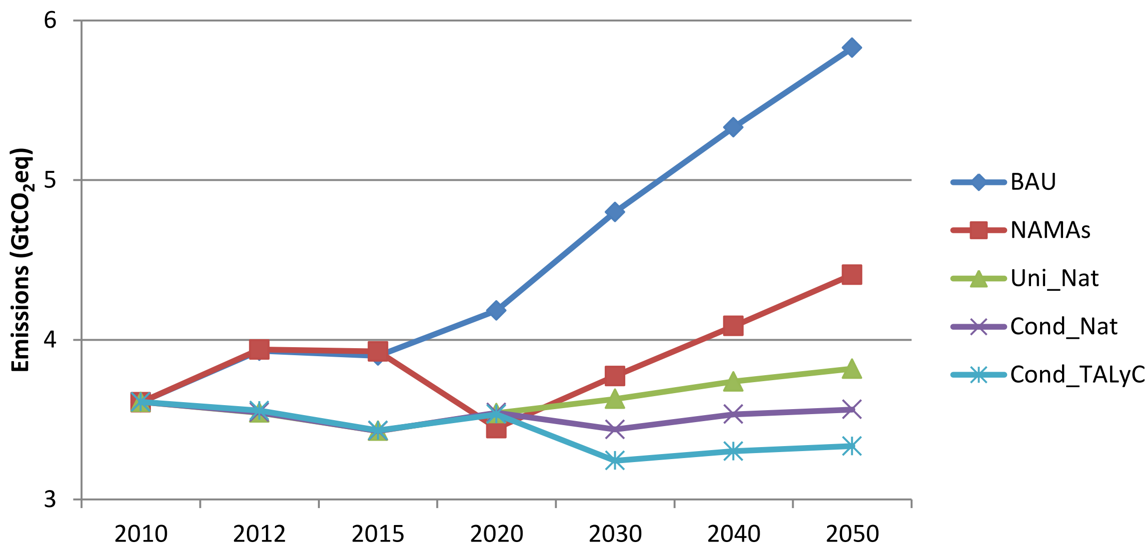

Figure 5-5: GHG emissions in CSA under BAU, NAMAs and INDC conditions

The dynamics presented on Figure 5-5 are far from homogeneous across the continent. Figure 5-6 presents a sub-regional detail for four scenarios, excluding the 'middle' *Cond_Nat* scenario. We can point out some interesting features of this graph:

- In most cases, by 2030 INDC contributions lead to stronger emissions reductions than NAMAs. This difference is noteworthy for Bolivia, Uruguay, Paraguay, for Central America and the Caribbean and Colombia. For Brazil, this drop is less significant in relative terms; however, given the country's size, it still accounts for more than one third of the regional emissions decrease between the *NAMAs* and *Cond_TALyC* scenarios in 2030. The exception is the Andean region: Peru had ambitious NAMAs given its high deforestation rates. The country had not quantified the overall impact of its pledges, but independent academics estimated that the measures should lead to a 41% GHG reduction compared to BAU (Hof et al., 2013). Peru's INDC, however, aims at a 30% emissions reduction below BAU at best, while Ecuador's INDC considers sectorial targets, not economy-wide ones.
- In all regions save BPU, emissions under the *Cond_TALyC* scenario are lower in 2030 than in 2010; and *Uni_Nat* emissions also come close to or drop below 2010 levels. In BPU, however, even the 20% reduction committed to in the *Cond_TALyC* scenario is not sufficient to offset the region's strong growth of *BAU* emissions; we leave aside the case of Venezuela and the SUG region, since these regions had not submitted their INDCs at the time of writing these lines. Although it is a major oil producer, Venezuela has not

submitted any NAMAs or INDCs and its long-term behavior is currently hard to predict, due to domestic political instability.

- Last, the *Uni_Nat* scenario for Argentina deviates very little from *BAU* projections (no pledge is considered in *NAMAs*). The *Cond_Nat* scenario, although not shown on the graph, does not give better results. Only the *Uni_TALyC* (not shown either) and *Cond_TALyC* scenarios result in effective emissions reductions. This means that given high national *BAU* emissions projections, the emissions reductions proposed by Argentina already occur under a no-policy framework in T-ALyC's representation. Chile presents similar results until 2030; however, the country's emissions after 2030 deviate from *BAU* including in the *Uni_Nat* scenario, suggesting that Argentina's national BAU is slacker than Chile's with respect to T-ALyC's projections.

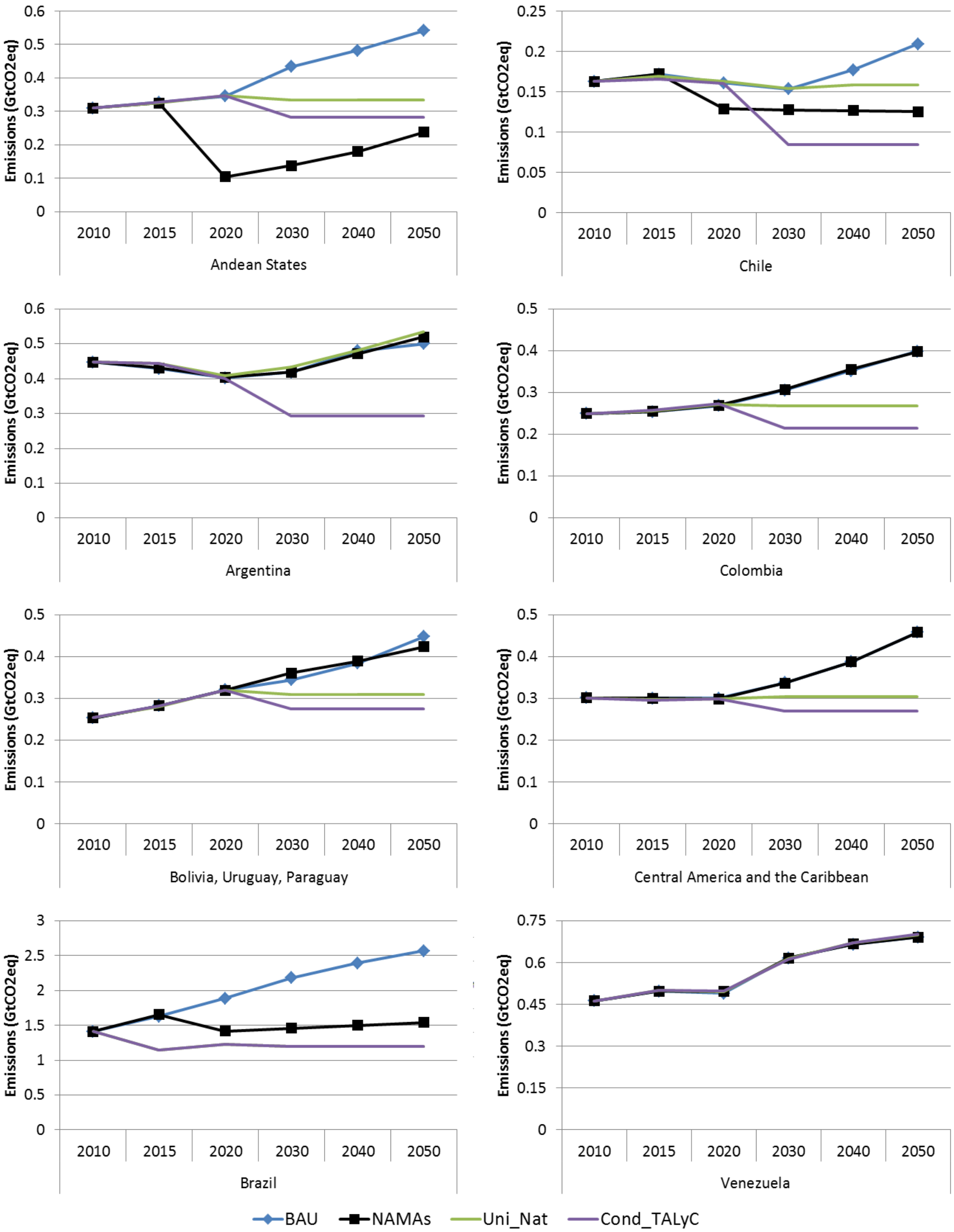

Figure 5-6: GHG emissions by region, under *BAU*, *NAMA* and *INDC* conditions

C.2. Impact of climate pledges on the electricity sector: the weight of Southeast Brazil

In 2012, South America already boasted a highly renewable electricity mix, with more than 60% of hydro-sourced electricity (CIER, 2013). The remaining electricity production was mainly made up of fossil fuels (gas, oil and coal) and nuclear power, leaving some room for improvement. As shown on Figure 5-7, electricity generation is bound to more than double between 2010 and 2050, reflecting the region's forecasted strong growth, and this could in principle increase the share of carbon-emitting electricity sources in the energy mix, if no climate pledge was made. However, this 132% increase in electricity generation goes hand in hand with a sharp drop in the share of fossils and nuclear between 2010 and 2050. Similarly, while hydro production keeps increasing in absolute terms – from 677 TWh in 2010 to 1,552 TWh in 2050, its share stabilizes at around 70% of all electricity production, even dropping slightly from 2030 (from 72.8% in 2030 to 68.1% in 2050). The production gap is filled mainly by wind- and solar-based electricity production.

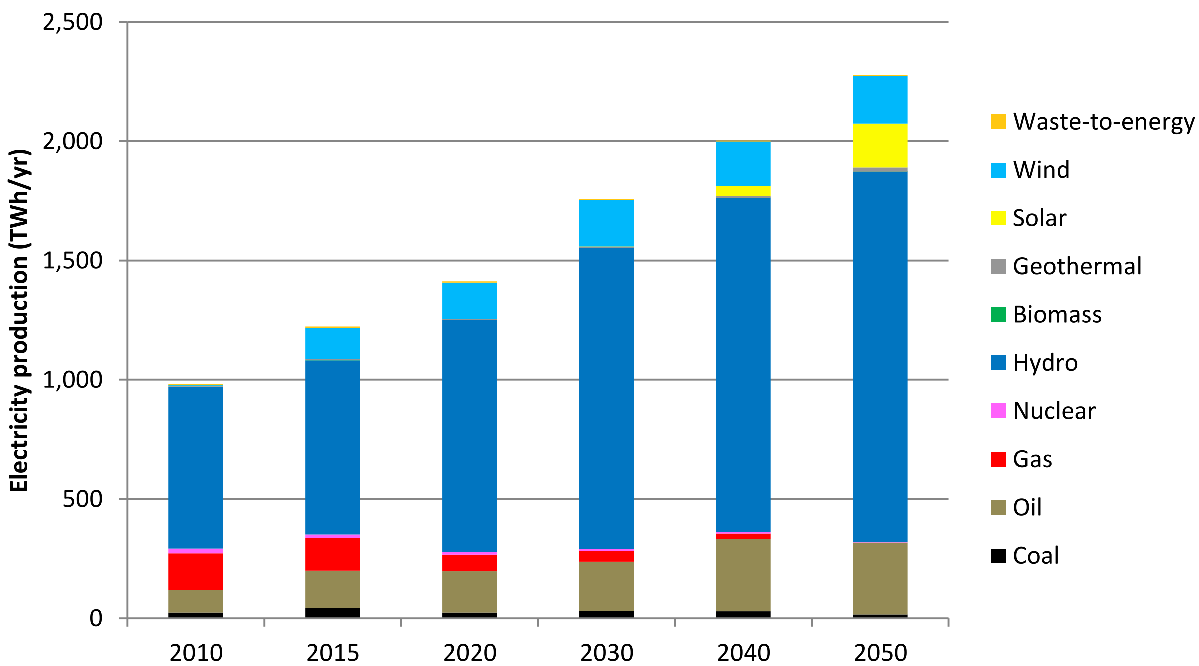

Figure 5-7: Electricity production in South America, 2010-2050 (Business-As-Usual)

The implications of such a result are already highly interesting, and were hinted at by the Argentine and Chilean cases: with no other assumption apart from cost minimization on a long-term horizon, the model already chooses green energies as the most interesting options for electricity production. This is partly due to the fact that this scenario occurs in an ideal world where long-term centralized planning is the rule. In practice, authors such as (Arango and Larsen, 2010) have stressed the fact that market forces and national policies in e.g. Argentina may lead to a carbonization of the electricity mix in the years to come. However, our results imply that moving from a nearly 100% renewable power mix today to a 100% renewable mix tomorrow in

South America is more about social acceptation and economic limitation than its lack of technical or economic potential.

Figure 5-8 details the results shown on Figure 5-7 on a country-by-country basis. 2030 electricity production is already highly renewable across the whole continent, mainly based on wind and hydro energy; solar electricity experiences a dramatic rise on half of the continent in the last decade of our modeling horizon. Together with wind and hydro, it dominates electricity production in 2050 in Colombia, Peru, Ecuador, Venezuela and Argentina. Southeastern Brazil satisfies part of its power supply with decentralized oil-based production; its electricity, together with that of Chile and Argentina, is the most expensive on the continent. However, Argentina resorts to solar energy and Chile to solar, wind and geothermal energy to complement their hydro production capacity; the power mix of these two regions is thus less emissive than BSE's, although Chile retains some coal production capacity and oil-based electricity does not disappear from Argentina's mix. Interestingly, CYC does not tap into its geothermal potential, even though it possesses the biggest resource on the whole continent. This result may seem counter-intuitive, since many Central American countries have been installing pilot projects for geothermal production in the past ten years; however, it is in line with the fact that no Central American INDC mentions geothermal energy as an option for emissions mitigations, save for Grenada's and Dominica's. In fact, according to Dolezal et al. (2013), only Nicaragua considered geothermal development as a priority in its national energy plan. These authors explain this lack of interest by "*high upfront costs for resource assessment and test drilling*", with somewhat less expensive oil imports than Chile's. Venezuela experiences a very interesting and thorough decarbonization of its power mix between 2030 and 2050. However, this solar-driven decarbonization of the country's power mix does not translate into less reliance on oil for the economy as a whole: as will be detailed Figure 5-16 (p.209), the country's primary oil consumption keeps growing all the way to 2050. Last, we can mention than BWC's strong solar production potential (see Chapter 3, Section C.3) is not used, since hydro and wind power together prove sufficient to satisfy the region's electricity needs.

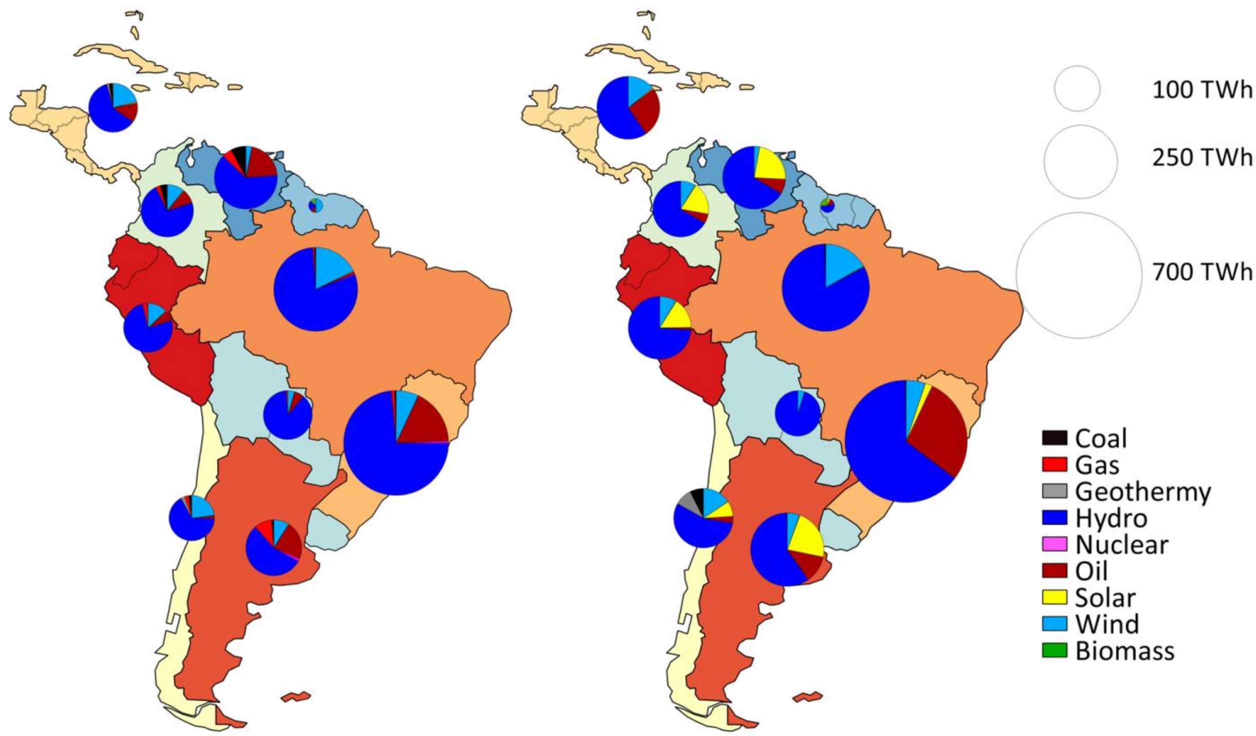

Figure 5-8: BAU electricity production in South America in 2030 (left) and 2050 (right)

Figure 5-9 displays the variations in power generation for our three climate scenarios compared to *BAU*, from the least stringent (*NAMAs*) to the most stringent (*Cond_TALyC*). The impact of climate pledges on the energy sector is clear: the reliance on fossil fuels decreases in the four climate scenarios, increasingly so as time goes by. Hydropower is the main mitigation option chosen by the model, in line with existing literature (see Section A.1, p.179). The second-best option –solar power– is more surprising, since literature tends to consider that wind potential would be tapped first (cf. section A.3); it is mostly due to BSE's strong energy constraints (cf. next paragraph). The amount of electricity generated under emission constraints also increases. While this increase is moderate in *NAMAs* (+0% in 2030, +14% in 2050 over BAU), it is overwhelming in the most stringent climate scenario, *Cond_TALyC*, leading to a more than doubling of regional electricity production towards the end of the period (+15% in 2030, +125% in 2050). Electrification is thus used heavily by the model as a decarbonization option, yet occurs only in the event of strong climate pressure.

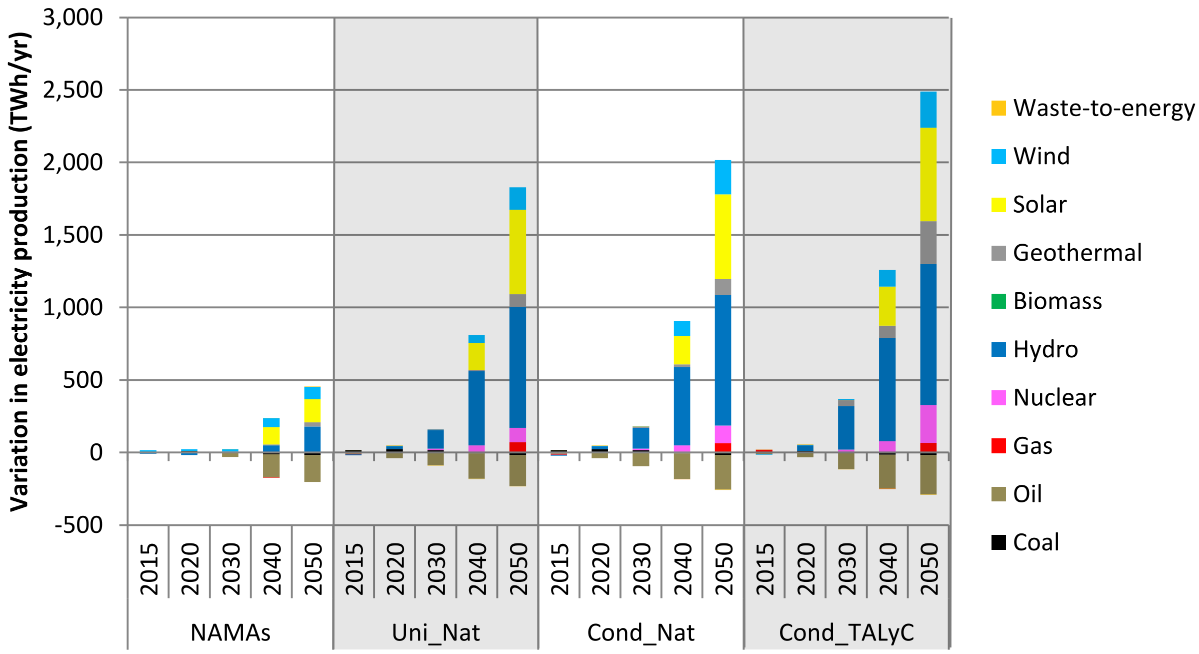

Figure 5-9: Modification of the power mix relative to *BAU* in climate scenarios

Figure 5-10 below details the insights of Figure 5-9 on a country-by-country basis, solely for the *Cond_TALyC* scenario. It appears that massive electrification in response to strong climate constraints is mainly due to Brazil, followed by Argentina and Chile, yet these four regions (BSE, BWC, ARG and CHL) do not rely on the same energy forms. BSE presents the most drastic change from *BAU* to *Cond_TALyC* in 2050. First, the remaining oil production highlighted on Figure 5-8 disappears totally and is replaced by solar electricity generation. This change actually also occurs in the *NAMAs* scenario, although not displayed here. Second, electricity production increases by 122% in 2050, lifted by more solar and wind energy, along with the installation of new nuclear capacity. This behavior is mostly driven by a shift in industrial demand (machine drive power, process heat and steam production, in various industrial sectors) from imported LNG towards electricity. BSE's dependency on imported electricity also increases, driving BWC, BPU and ARG to increase their own electricity production. BWC's noticeable ramp-up, relying almost exclusively on hydropower, supports both the electrification of its own energy system, and increased exports towards BSE. 10% of Argentina's additional electricity production, based on geothermal, nuclear and hydro power, is also siphoned off by BSE. On the other hand, Chile's increased electricity production fuels the electrification of its own industry sector. It relies, among others, on nuclear electricity production, which is a politically unlikely option in the country today, and geothermal energy, which was indeed pointed out by various authors as an interesting option to decarbonize Chile's power mix (cf p.184). The small contribution of AND and BPU is in line with Bolivia's conclusion, mentioned p.179, that energy's potential contribution to GHG mitigation is very small.

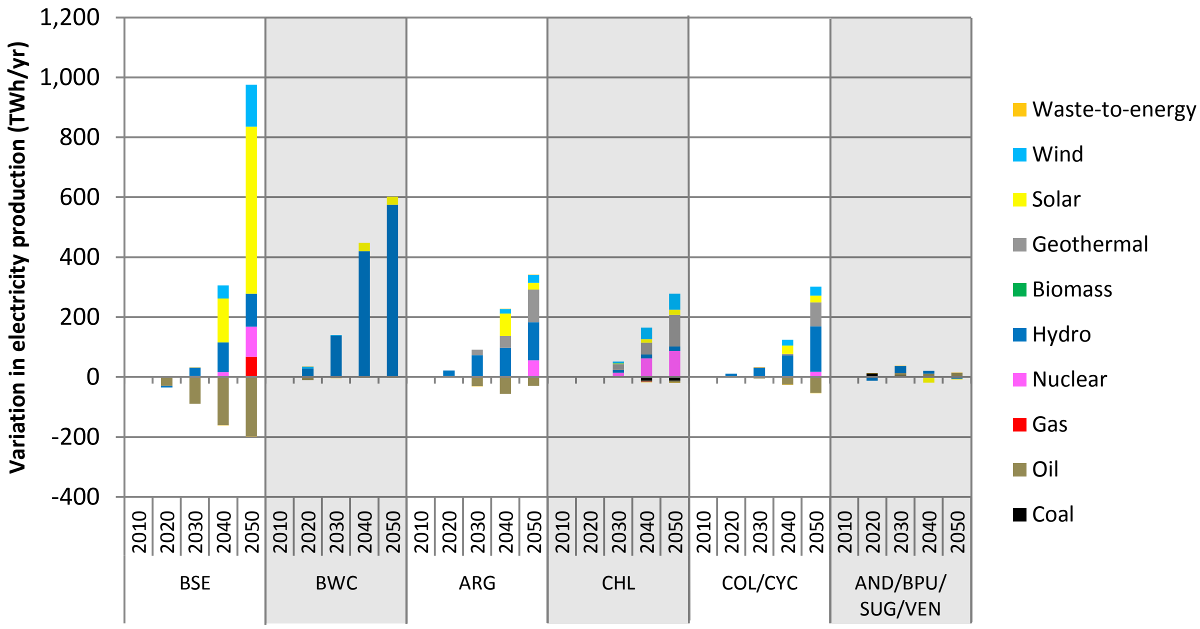

Figure 5-10: Modification of the power mix relative to *BAU* in *COND_TALyC* (sub-regional detail)

South America's electricity mix thus contributes to regional emission targets by two means:

- First, by lowering the carbon intensity of the electricity produced: the reliance on fossil fuels falls to 2% in 2050 under the most stringent climate scenario, compared to BAU projection. Together with the return of nuclear production, 92% of the continent's total electricity generation in 2050 is assured by green technologies, from a situation in which the electricity matrix was already quite virtuous.
- Second, by increasing the absolute amount of electricity produced, by up to 125% in 2050. Clean electricity competes here with other forms of energy to provide end-use energy services, mainly gas in the industry sector. This electrification is strongly driven by BSE, whose very high electricity needs trigger exports from all of its neighbors.

While the relevance of INDCs and their impact on South America's power mix is certain, the impact of NAMAs is more mixed. On the one hand, Chile and Brazil's NAMAs, based on BAU projections, incontestably bring down regional emissions compared with a BAU pathway. On the other hand, NAMAs by AND and COL have little impact on the continent's energy mix, for two main reasons: first, the two regions together represent 11% of the electricity generated in South America in 2010 (15% in 2050); and second, the electricity targets registered as NAMAs for COL and AND are already partially met under *BAU* conditions.

C.3. Primary energy consumption decarbonizes mainly through electrification

C.3.1. The relevance of oil exports

When taking export-bound oil production into account, fossil fuels dominate primary energy production, constantly accounting for more than 75% of total production (Figure 5-11). In 2030, fossil fuels represent nearly 86% of Latin American primary production; oil alone makes up 71% of this production with 971 Mtoe.

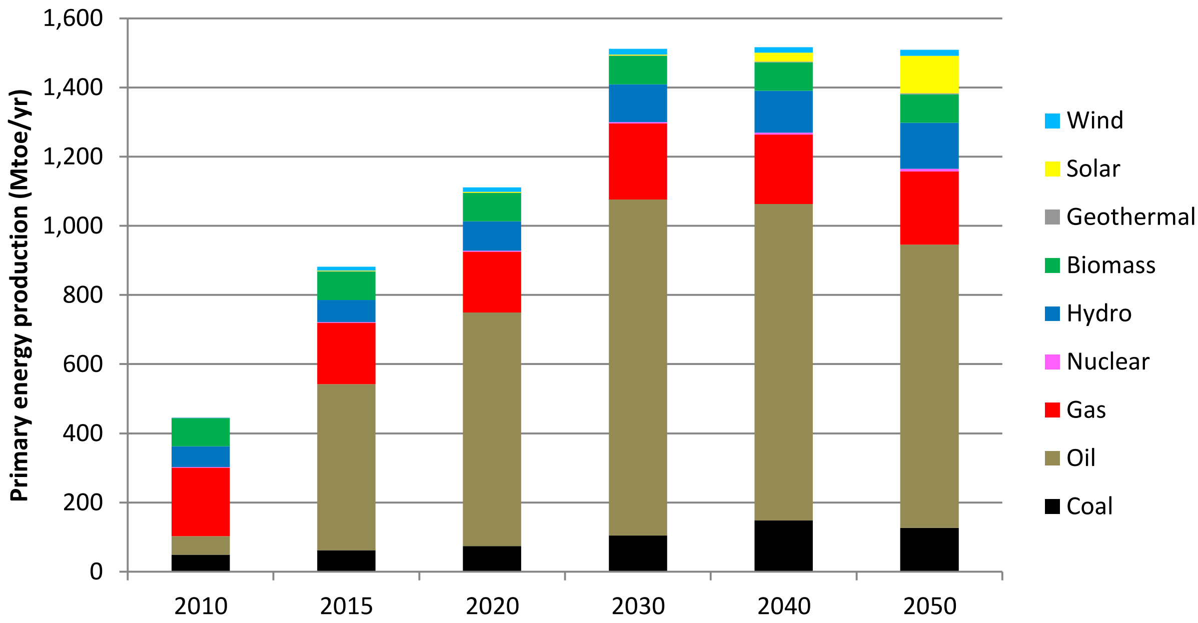

Figure 5-11: Primary energy production under BAU assumptions

The decrease in oil production after 2030 can be explained by two factors (see Figure 5-12). First, Venezuelan crude oil exports, which make up the bulk of South American exports, are capped in our model at 24 PJ/year (approx. 573 Mtoe/yr) to avoid over-unrealistic export volumes, since global oil prices are static in this version of T-ALyC. Due to capacity expansion inertia, this threshold is reached in 2030, marking a clear break in the upward trend. Second, after two decades of oil bounty, exporting towards its neighbors and the rest of the world, Brazil starts importing oil itself, dragging Argentina and Uruguay along with it. The conjunction of those factors starts a downward trend for oil production in 2030. In the 2030-2050 period however, the rise of solar energy in the primary mix offsets this trend, leading to almost stationary primary energy consumption between 2030 and 2050. However, primary solar energy as considered here is incoming solar radiation before conversion into electricity[104]. As a consequence, the contribution of both biomass and solar energy to primary energy consumption is significantly higher than their actual output in terms of electricity/fuel/heat production.

[104] That is, without the energy losses incurred by solar panels/connecting lines. As specified in Chapter 3, Section C.3, more than 75% of this primary energy is lost in the conversion process.

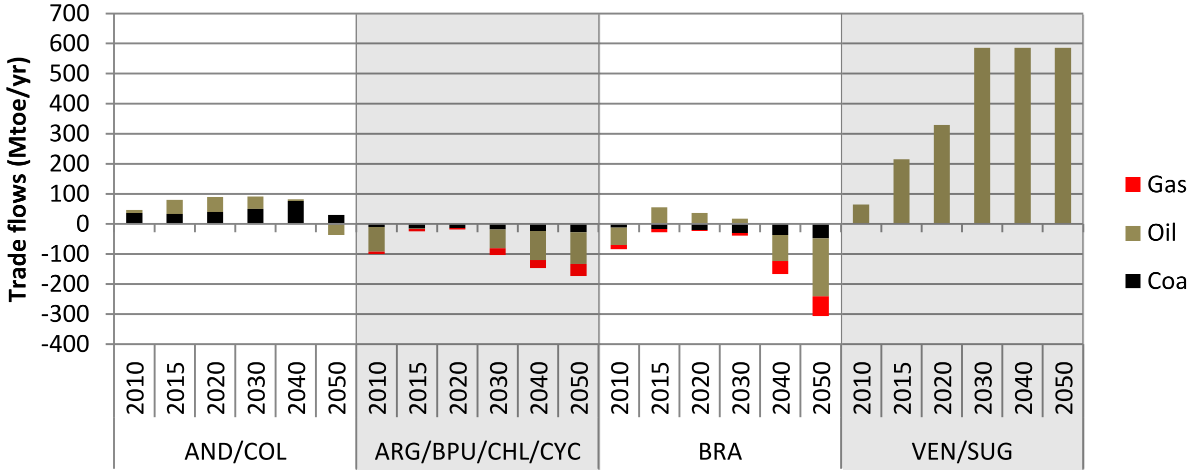

Figure 5-12: Latin America's fossil fuel trade with the rest of world (BAU)

The overwhelming majority of exported oil is crude, with few associated emissions[105]. Nevertheless, climate pledges could still impact oil trade in South America, in three main ways:

- Regardless of decisions and pledges from other world regions, penalizing the regional consumption of fossil fuels (through taxes, subsidies on green fuels, etc.) would indeed make them less competitive on the internal market, but would not impact exports' competitiveness. We can thus expect that the decrease in primary fossil energy production will at best be limited, with a shift from internal consumption to exports. Financing a green subsidy policy could even lead to an increase in oil production when the takeoff of renewables is bound to the redistribution of an oil rent, as studied by Goldemberg et al. (2014).
- Export volumes can be voluntarily reduced as part of a political volition to reduce the continent's contribution to global emissions. The Yasuni-ITT initiative, although unsuccessful, established an interesting case for this type of new cooperation framework (see e.g. Pellegrini et al., 2014; Vallejo et al., 2015).
- Export volumes can also drop as a result of international climate pledges, through their impact on global oil prices. The idea here is that international pledges would push renewable energy production and reduce global oil demand, thus bringing down oil prices. Venezuela produces heavy oil at relatively high costs (breakeven price estimated at USD 30, compared to USD 10 for Saudi Arabian wells) and would be among the first impacted by such a slowdown (its budget breakeven is considered by most analysts to be around USD 120). This assumption is confirmed by authors such as Labriet et al. (2015). Another option could be a global border tax system, which would place oil exports on a level field with internal oil consumption (see e.g. Keen and Kotsogiannis, 2014) but have a detrimental effect on national industries.

[105] Venezuela's refinery capacity is way below the domestic production capacity.

The risk inherent to such a scenario would be that the no-longer-exported oil could be consumed within Latin America itself, replacing other renewable forms of energy production, starting with biofuels. As a first approximation of this issue, Figure 5-13 presents the evolution of the primary energy mix (net of trade) in a global context with oil prices 40% lower than their current TIAM value: solar energy all but disappears from the energy mix. Coal consumption is also reduced, yet the increase of oil and gas consumption more than offsets this slight improvement.

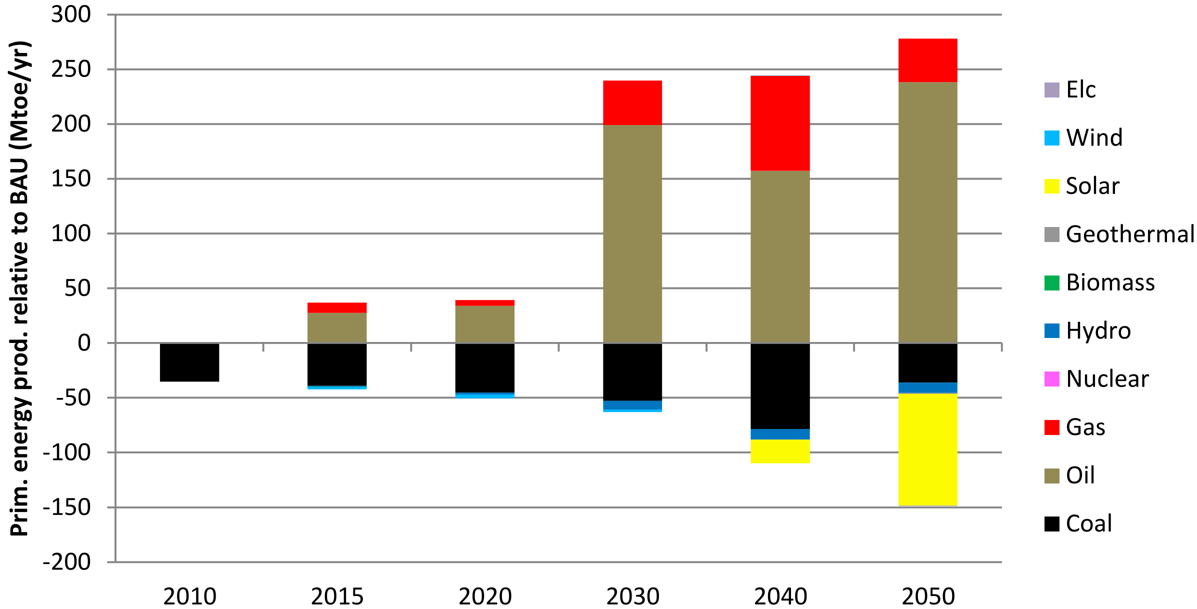

Figure 5-13: Change in primary energy consumption in CSA, in the case of low global oil prices

C.3.2. Transport and industry drive regional energy decarbonization

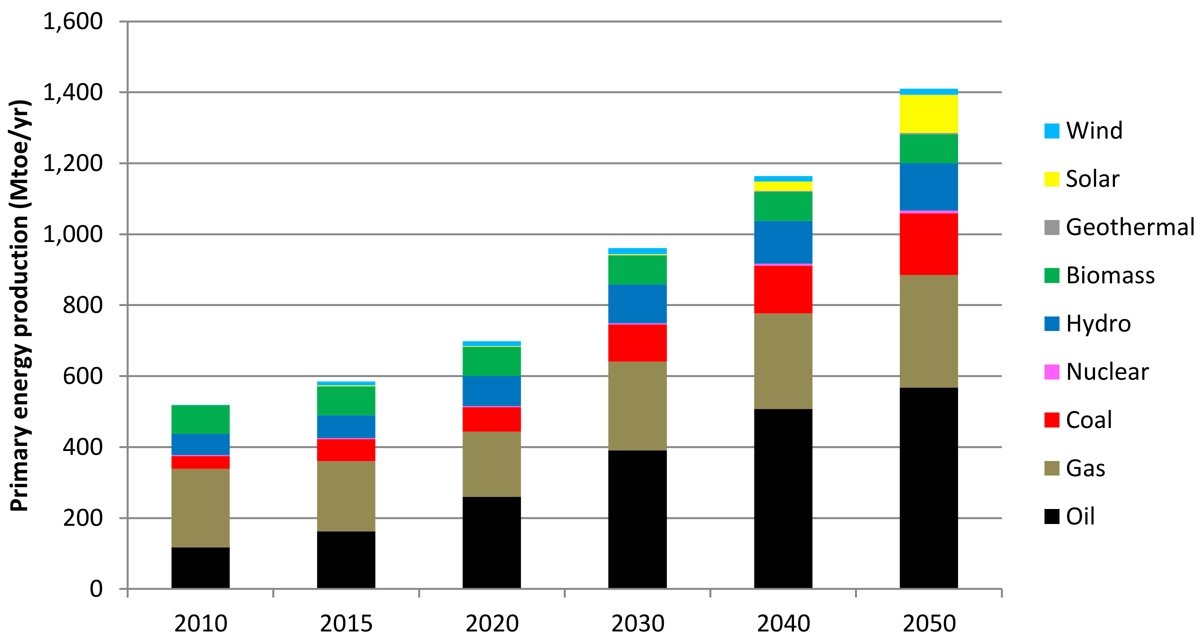

Figure 5-14: Primary energy consumption in BAU case, 2010-2050 – Net of trade

Figure 5-14 shows primary energy production in Latin America minus net energy trade. Total primary energy supply increases by 172% between 2010 and 2050. The share of oil is considerably reduced compared to Figure 5-11 and, conversely, the share of gas increases, mainly due to net gas imports in Brazil and Chile. The overall fossil fuel share remains above 70% of total primary consumption during the whole period; South America's primary energy mix is thus quite heavily fossil-fuel based, despite clean electricity generation and even without accounting for oil exports. Oil, natural gas and coal all increase their absolute contribution to South America's total primary energy supply between 2010 and 2050; despite promising potential and encouraging prospects as reviewed Chapter 1[106], biomass energy does not increase its participation to South America's energy mix in the absence of climate constraints. As shown on Figure 5-15, the power sector is the first consumer in 2010; however, its dependence on fossil fuels decreases with time as renewable production increases and fossil production efficiency improves. On the other hand, fossil fuel consumption increases dramatically in the industry and transport sectors, reflecting the strong regional economic growth: +186% for transport between 2010 and 2050, +263% for industry. Quite logically, while industrial demand is met by all three fossil fuels (oil, coal and natural gas), the transport sector relies nearly exclusively on oil-based fuels, despite an interesting incursion into natural gas in the last decade.

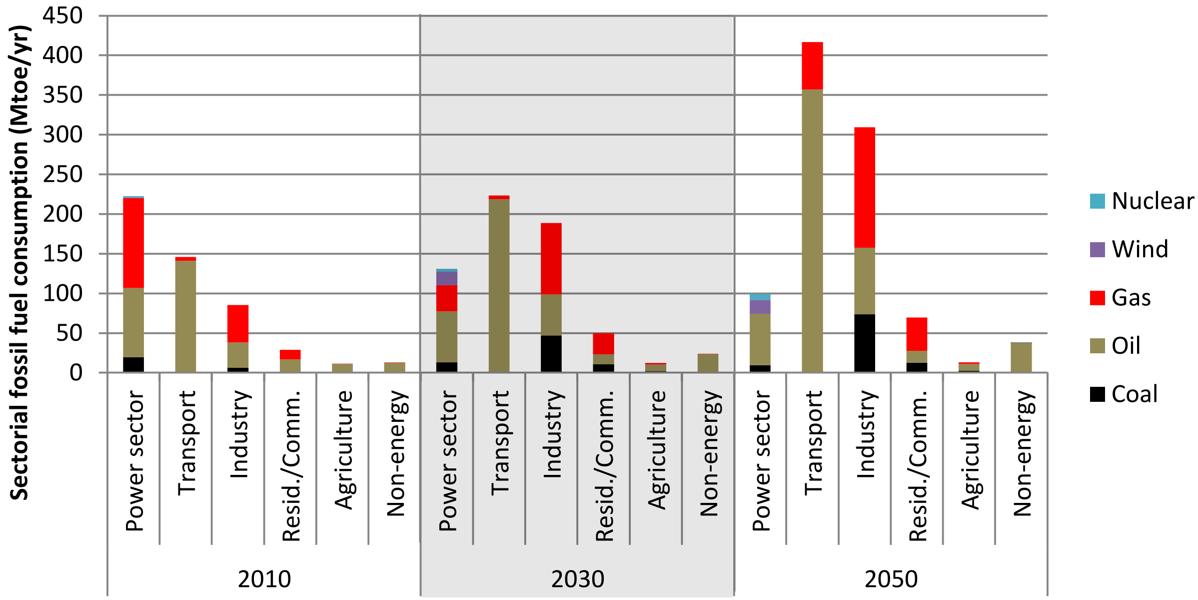

Figure 5-15: Fossil fuel consumption in 2010, 2030 and 2050 (BAU)

Figure 5-16 extends the results of Figure 5-14 on a country-by-country basis. Unsurprisingly, Brazil is still the continent's main energy consumer in 2050, far ahead of its three main followers (Venezuela, Argentina and Colombia). Although oil dependency tends to decrease in BSE, this drop is nearly offset by the corresponding increase in BWC's oil consumption. Coal is used in

[106] Among them, the works of Margulis et al. (2011) and Moreira et al. (2014) are quite optimistic about biomass options for Brazil's energy future.

nearly all T-ALyC regions to different degrees, yet only Colombia is a relevant producer, exporting towards VEN, AND, BWC and outside South America. BSE also produces some lower-quality coal; however, most of its consumption is satisfied by coal imports from the rest of the world. Brazilian coal is mainly consumed by non-energy petrochemical feedstocks, industrial heat and steam; Argentina's coal, also imported, is used in non-energy petrochemical feedstocks and electricity production, before industrial uses. Chilean coal imports mainly serve its industrial (mining) sector and electricity production. Natural gas is present in all model regions in 2030 and 2050 yet only AND, BPU and VEN meet their energy needs without external imports throughout the period. By 2050, CHL, BSE, and CYC rely almost entirely on imported gas (mostly LNG) for their domestic consumption; BWC imports half of its consumption from BPU, and even ARG complements its domestic production through LNG imports, despite large shale gas reserves. Argentine gas is used mainly for industrial applications, followed by residential uses. Venezuela increases its use of natural gas, mainly to fuel its upstream sector (followed, fairly closely, by industry); this is mostly owed to a better use of the country's flared and vented gas, as highlighted p.187. The country's oil is mainly used for export rather than domestic consumption. The rest of the continent, including Brazil, consumes most of its gas for industrial purposes, the second use being transport.

Apart from petrochemical feedstocks, coal and gas can be substituted by renewable energy carriers for their main uses (industrial heat and steam, residential heat). Transport uses, both for oil and gas, are less substitutable, since only biofuels could be expected to fill the gap in the short term. Dedicated energy crops are already used to their full potential in Brazil and Argentina in our *BAU* scenario, for ethanol (Brazilian sugarcane) and biodiesel (Argentine soy) production, confirming the good potential identified in section A.2; however, other solid biomass sources are used little under business-as-usual conditions. Chile and Central America also tap into their energy crop production potential, yet the resource is directed more towards industrial and residential uses.

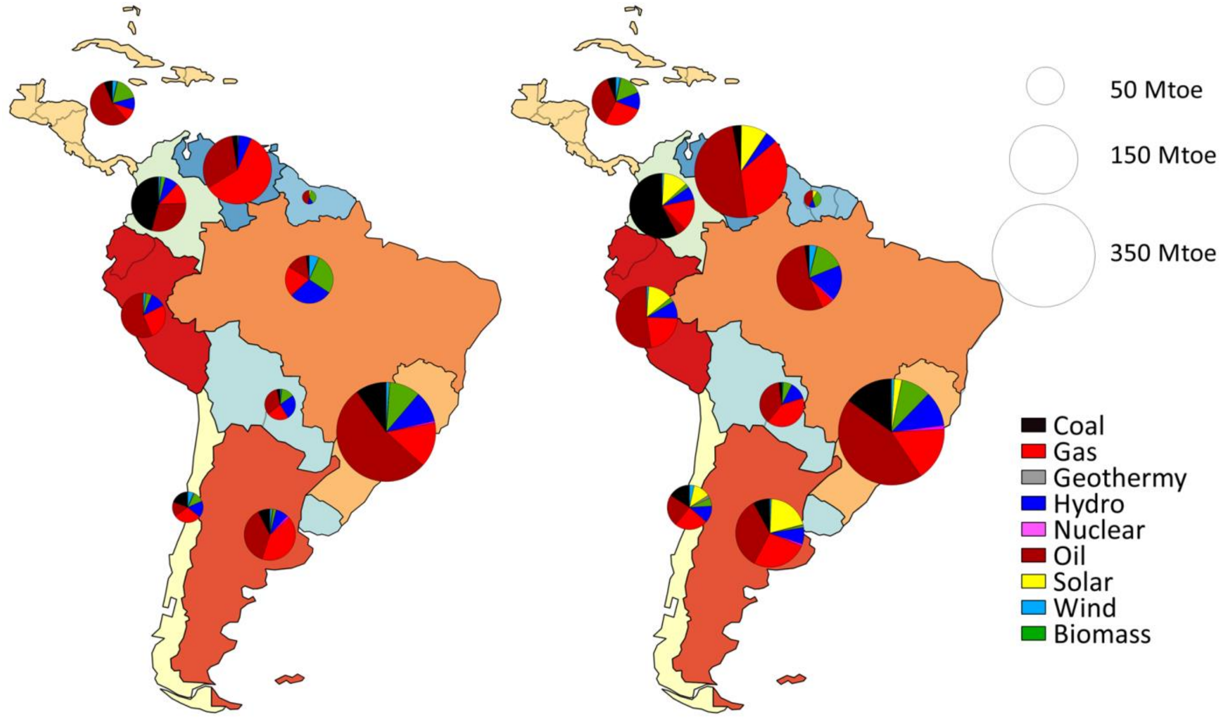

Figure 5-16: BAU primary consumption in South America in 2030 (left) and 2050 (right)

Figure 5-17 displays the variations in primary energy consumption (net of trade) for the four climate scenarios compared to BAU, from the least stringent (*NAMAs*) to the most stringent (*Cond_TALyC*). As for electricity, the decline in fossil fuels is noteworthy. The rise of electricity as a privileged clean energy carrier in INDC scenarios appears clearly from 2030 onwards. As shown on Figure 5-18, electrification is preferred to energy efficiency across all economy sectors save transport: the amount of energy consumed by each sector does not vary much, only its composition changes. Residential energy consumption is even seen to increase, but this is a reporting artifact: this increase is due to decentralized rooftop solar heating, which displaces gas for residential applications. As solar resource use is reported in primary energy units, its contribution is artificially increased.

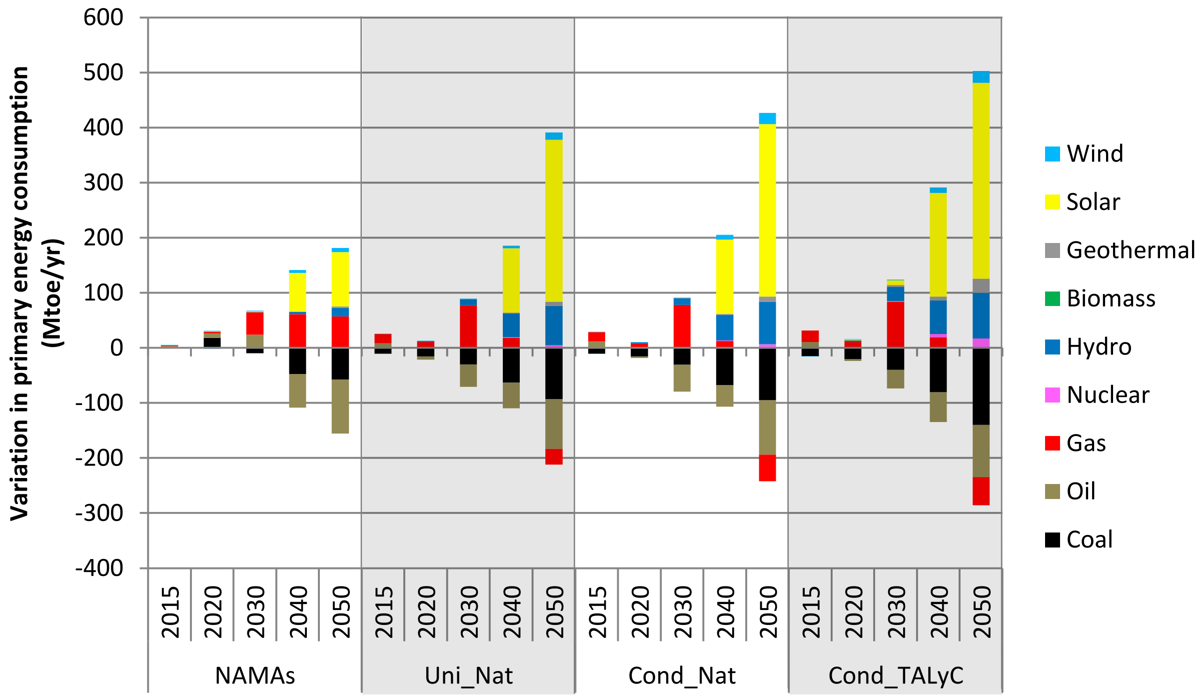

Figure 5-17: Modification of primary energy consumption relative to *BAU* in climate scenarios

Ultimately, the two main sectors for energy decarbonization are industry and transport, through electrification and energy efficiency measures, respectively. Residential energy consumption is also strongly decarbonized, through electrification and decentralized solar heat generation; however, this sector's share of overall energy consumption is small, leading to a reduced sectorial contribution to emissions reductions. In particular, T-ALyC's results for Argentina[107] are similar to those of Tanides et al. (2006), mentioned p.186: despite a high contribution of the residential and commercial sectors in relative terms (these sectors use 90% and 65% of electricity and renewables in 2050 respectively in the *Cond_TALyC* scenario, against 20% and 50% in *BAU*), the absolute mitigation provided by Argentine industry is still larger, given the size of this sector in terms of GHG emissions.

[107] See Annex **¡Error! No se encuentra el origen de la referencia.**, p.230.

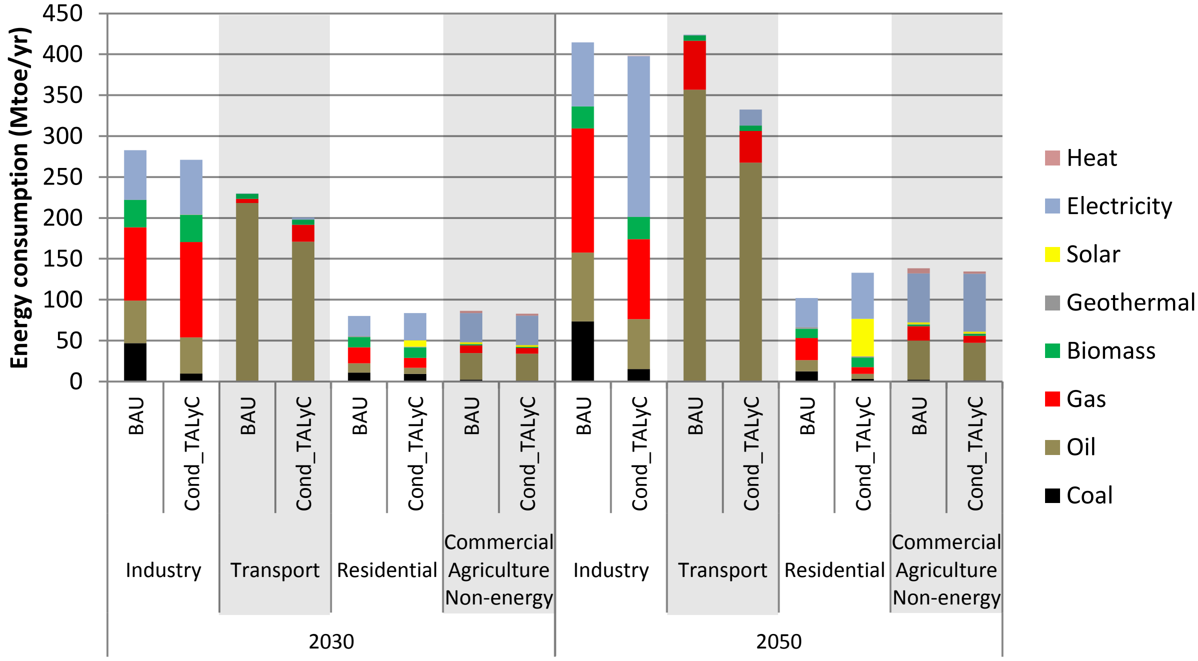

Figure 5-18: End-use energy consumption according to consumptions sectors, in BAU and Cond_TALyC scenarios

C.4. Non-energy emissions

Although weakly emissive, South American energy production offers valuable emission mitigation options, mainly through further electrification of the energy system. However, from the map presented Figure 5-4 in the introduction of this part (p.195), we can assume that the energy sector may not have the highest emissions reduction potential in South America, due to the weight of forestry and agriculture in the continent's emissions. In this last paragraph, we review the various non-energy mitigation options modeled in T-ALyC and their contribution to GHG emissions reduction, to contextualize the energy sector's contribution to fulfilling regional climate commitments. Figure 5-19 shows GHG emissions, sector by sector, under the *BAU*, *NAMAs* and *Cond_TALyC* pledge scenarios, for the whole region. Figure 5-20 details GHG abatement in the *Cond_TALyC* scenario.

AFOLU is the most emitting sector, totaling 46% of regional emissions in 2030 in the *BAU* scenario (2.2 $GtCO_2eq$ out of 4.8 $GtCO_2eq$ total emissions). The industry and transport sectors together account for 28% of GHG emissions; the energy sector (oil refining and electricity production) comes third with 21% of total emissions. The share of transport and industry increases to 40% in 2050, yet AFOLU still represents 41% of the continent's emissions. This sector also accounts for 57% of total GHG abatement in 2030 and 43% in 2050 under the *Cond_TALyC* scenario. It is worth noting that due to the virtuous trend highlighted in paragraph C.2, energy emissions already decrease in *Business-as-Usual* conditions, and energy is the only sector showing this downward trend.

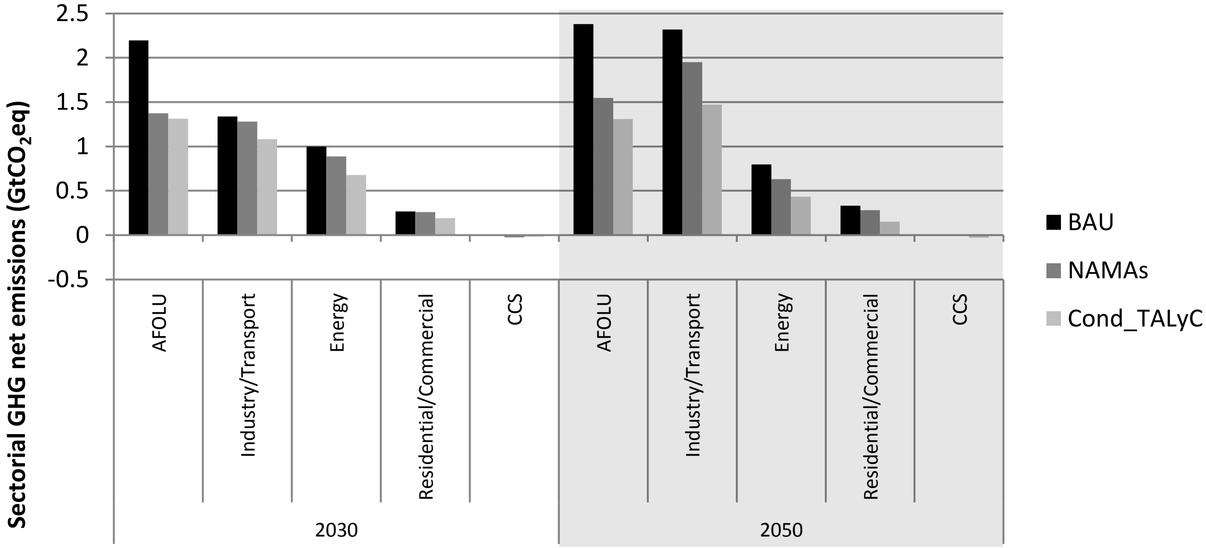

Figure 5-19: GHG net emissions by sector, under *BAU, NAMAs* and *Cond_TALyC* scenarios

Figure 5-20 focuses specifically on emissions absorption. The gray shading concerns absorption in the energy sector, green shows forestry options and red indicates GHG abatement options deployed in end-use sectors. GHG mitigation as displayed here only relates to specific abatement technologies, i.e. it does not consider emission reductions through e.g. fuel shift, demand reduction or efficiency improvements. As a consequence, the origin of emissions reduction in the transport and industry sectors is not captured well. However, AFOLU appears clearly as the main contributor to GHG emissions abatement by a huge margin, with 876 $MtCO_2eq$ emissions avoided by combating deforestation and promoting reforestation (in 2030, in *Cond_TALyC*). Carbon storage, although less visible than AFOLU, provides also a valuable contribution to emissions mitigation: together, enhanced Oil & Gas Recovery and Storage in depleted fields account in *Cond_TALyC* for 40 $MtCO_2eq$ of emission reductions, i.e. around 12% of all energy-bound emission reductions in 2030. Proper handling of flared gases adds another 29 $MtCO_2eq$ (9%); the remaining 79% of energy-related reductions are due to the rise of carbon-free energies such as wind, solar and hydropower.

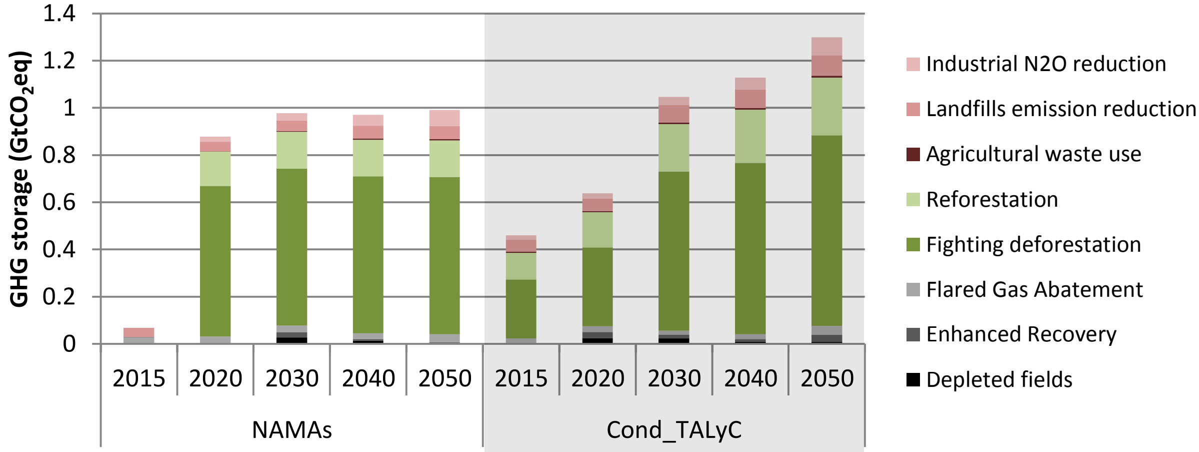

Figure 5-20: GHG capture and storage by sector (Red4All scenario)

Concluding remarks

This chapter analyzed the energy sector's contribution to GHG emissions reduction in the UNFCCC framework. We outlined South America's energy sector potential for GHG abatement and the evolutions required to realize this potential. We compared five scenarios based on NAMAs and INDCs communications to the UNFCCC: a *Business-As-Usual* case; a *NAMAs* scenario including all communicated NAMAs; a *Uni_Nat* scenario considering all unilateral (minimum) national contributions as communicated to the UNFCCC, based on national BAU estimates; a *Cond_Nat* scenario considering the maximum effort envisioned by South American countries with international help, based on their own national BAU; and a *Cond_TALyC* scenario considering conditional (maximum) pledges, but based on T-ALyC BAU estimates instead of national projections.

In Central and South America, our modeling confirms the existence of a significant emissions mitigation potential in the energy sector, which was individually identified by various countries as a valuable lever towards decarbonization (see the Introduction of Part A). The main energy mitigation option identified is to increase the share of electricity in end-use demand satisfaction, making use of the significant existing potential for renewable electricity production through hydropower, solar and wind. However, due to the overwhelming weight of AFOLU emissions, energy may not be the least expensive or most efficient tool to reduce GHG emissions, and is definitely not sufficient to tackle GHG emissions alone; in our projections, energy accounts for 21% of total emissions in 2030 in the most stringent (*Cond_TALyC*) scenario, with AFOLU providing 46% of these emissions. This result confirms that South American emission reduction patterns are radically different from the situation in Europe, where energy is considered to be the main contributor to emissions reduction by 2050 (European Commission, 2011). The present work tends to confirm that South America's AFOLU sectors is a long-run carbon sink or 'low-hanging fruit' in the fight against climate change (Stern, 2007), (Buizer et al., 2014).

We also showed that under business-as-usual conditions, long-term economic optimization already leads to a decarbonization of the electricity sector. Further decarbonization can be achieved by shifting to electricity for some energy demands, especially in the industry and transport sectors; however, these first results suggest that heavy subsidies on fossil fuels such as those that exist in Venezuela, Argentina and Peru, may not move in the direction of economic optimality, in addition to their environmental inefficiency. In the same line, a sustained drop in international oil prices due to e.g. an international climate agreement, could negatively impact the continent's emissions if South America did not commit to such an agreement, as oil exports would be redirected towards internal consumption and displace renewable energy sources. It is worth noting that such a drop would also have dramatic consequences on the Venezuelan economy, which relies quite heavily on oil exports.

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General concluding remarks

‘South American energy’ is a topic as vast as a continent. A fragmented, heterogeneous continent with a complex history and strong social, political and physical disparities, in which bringing out common features and regional drivers is an arduous task. A continent also bound by close languages and cultures, where issues such as climate change are better treated at regional scale, where regional cooperation on energy assets could improve everyone’s prosperity yet remains a distant goal.

This work was a first attempt at capturing South America’s energy complexity into a decision-support tool, oriented towards regional long-term energy prospective. I used the 40-years’ experience of bottom-up energy systems optimization embedded in the TIMES paradigm, and the global modeling experience with the TIMES Integrated Assessment Model, to translate my understanding of South America’s energy into an actual prospective model, namely the *TIMES-América Latina y el Caribe* model (T-ALyC), which describes the regional resources, energy demands, and conversion technologies. Although this regional description remains much more aggregated than national ones, due to limitations in computational resources and my own capabilities, it is a useful extension to national considerations, and a definite improvement over the 1-region description existing so far in TIAM.

Climate change negotiations provided me with a very interesting case study, for two main reasons: first, it represents a real regional (even global) challenge, with a strong value added in getting a regional picture rather than national ones. Comparing pledges between neighbors, assessing the regional consequences of national pledges, most of all by regional giant such as Brazil, is an interesting work for which T-ALyC is quite well adapted. Second, climate change issues underline quite well the structural specificities of South America’s energy mix, which make it so different from the rest of the world: its high renewable potential, quite unequally distributed, the near-absence of coal resources, the unique position of Venezuela as an oil giant in a continent without oil, the sustainability issues arising from deforestation… Energy in South America is different from the European vision, not only because resources and demands are different, but also because the entire social, environmental, economic context in which energy is embedded, is very different from Europe. Such a finding questions the relevance of global, ‘one-size-fits-all’ models, in which climate-energy issues are described according to a Western (European, American) vision of energy and –more importantly– the surrounding society. Adapting the resources, demands, and non-energy emissions of TIAM was only the very first step towards a truly representative South American energy prospective model. Describing better agriculture, cattle ranching, mining, biomass crops and transport, geothermal energy, are only some of the improvements which will prove necessary in the short term for this model.

The conclusions of this first assessment, however, are quite optimistic: most South American countries submitted national contributions which represent a real improvement beyond business-as-usual trajectories, and also beyond their previous NAMA commitment. Increasing the role of electricity leads to significant emission reductions by 2030, and even allows fulfilling stringent climate targets by 2050. While the need for public incentives has not been quantified here, some countries even decarbonize their energy mix in the absence of climate targets, i.e. on a pure economic optimization basis. However, AFOLU remains the main source of emission reductions for the region, which points to one limitation of our study: although we considered energy production and transformation in a very detailed way, our representation is more limited when it comes to AFOLU, due to the weak link between energy and e.g. reforestation. Further investigation of energy and AFOLU interactions in a climate context would require a better description of the latter, especially in its interaction with energy (energy crops, agricultural residues, firewood and logging).

While the application presented here focused on climate change mitigation, another interesting aspect of the climate-energy nexus is adaptation: as we have seen, South America relies strongly on hydropower and biomass for its energy production, and the reliance on hydro, at least, should still grow. Moreover, its agriculture and mining sectors consume a lot of water, potentially conflicting with energy generation. Climate change will probably worsen this situation, by decreasing annual streamflows while increasing their seasonality. However, the magnitude of these changes is not known; it depends on global emissions trajectories which are not known yet, and on climate response which is not totally understood so far. In this uncertain context, it is of crucial importance to understand which decisions can avoid lock-in situations, with three main options in the case of hydropower: investing in over-capacity for energy production, making the most of regional complementarities through enhanced electric connections or turning to other energy sources – renewable, or not.

Energy integration is actually a topic in itself. Although this issue proved to be complex, it is still the focus of active research by countries and regional organisms such as ECLAC (UN Economic Commission for Latin America and the Caribbean) or CAF (the regional development bank). Giving insights into the costs and consequences of gas and electricity integration with or without climate pressure, based on the existing project portfolio, is a topic which is currently investigated although not presented here.

Ultimately, a topic of interest regarding South American energy is the region's integration in the global economy and energy trade. A first approach was developed here, through a static coupling with TIAM-FR (cf. chapter 3). However, developing a dynamic coupling would provide a more realistic representation of South America's exchanges with the rest of the word and allow for a better comprehension of trade dynamics, mainly for Venezuela and Brazil's oil and Colombia's coal exports, and Chile and Argentina's fossil fuel imports.

Appendix

D Demand in South America: drivers

Table 0-1 presents the growth of demand drivers for South America by sub-region, taking 2010 as the reference year. Base-year energy consumption is calibrated after IEA's *World Energy Statistics* (2014) for base-year energy consumptions.

		AND	ARG	BPU	BSE	BWC	CHL	COL	CYC	SUG	VEN
GDP	2015	1.53	1.03	1.63	1.09	1.09	1.11	1.43	1.35	1.37	1.18
	2020	2.18	1.03	2.35	1.45	1.45	1.35	1.96	1.81	2.02	1.33
	2030	3.41	1.75	4.06	2.25	2.25	1.98	2.95	2.76	3.94	1.83
	2050	6.50	4.37	10.28	4.21	4.21	3.73	6.53	5.78	11.61	3.50
Population	2015	1.06	1.05	1.07	1.04	1.04	1.05	1.07	1.07	1.03	1.07
	2020	1.12	1.09	1.14	1.07	1.07	1.09	1.13	1.14	1.05	1.15
	2030	1.22	1.16	1.26	1.11	1.11	1.15	1.24	1.26	1.10	1.27
	2050	1.34	1.25	1.43	1.12	1.12	1.21	1.36	1.41	1.08	1.43
GDP per capita	2015	1.45	0.98	1.52	1.05	1.05	1.24	1.34	1.26	1.33	1.09
	2020	1.95	0.94	2.06	1.36	1.36	1.59	1.73	1.59	1.92	1.17
	2030	3.18	1.33	3.21	2.03	2.03	2.33	2.39	2.19	3.60	1.44
	2050	7.24	2.35	7.19	3.77	3.77	4.21	4.81	4.09	10.79	2.46
Number of households	2015	1.13	1.09	1.11	1.14	1.14	1.15	1.15	1.12	1.09	1.15
	2020	1.28	1.18	1.25	1.31	1.31	1.29	1.32	1.25	1.23	1.31
	2030	1.63	1.37	1.54	1.67	1.67	1.57	1.70	1.58	1.51	1.68
	2050	2.32	1.82	2.27	2.16	2.16	1.93	2.37	2.28	1.81	2.43
GDP per household	2015	1.35	0.95	1.46	0.96	0.96	1.13	1.24	1.21	1.26	1.02
	2020	1.70	0.87	1.89	1.11	1.11	1.34	1.48	1.44	1.64	1.02
	2030	2.38	1.13	2.63	1.35	1.35	1.72	1.73	1.75	2.62	1.09
	2050	4.16	1.62	4.53	1.95	1.95	2.62	2.76	2.54	6.43	1.44
Agricultural activity	2015	1.10	1.07	1.28	1.13	1.13	1.07	1.06	1.09	1.06	1.06
	2020	1.19	1.23	1.44	1.25	1.25	1.15	1.05	1.20	1.05	1.05
	2030	1.40	1.30	1.52	1.28	1.28	1.24	1.05	1.25	1.05	1.05
	2050	1.52	1.41	1.64	1.39	1.39	1.34	1.14	1.35	1.14	1.14
Chemical production	2015	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
	2020	1.31	1.31	1.31	1.35	1.35	1.31	1.31	1.31	1.31	1.31
	2030	1.79	1.79	1.79	1.92	1.92	1.79	1.79	1.79	1.79	1.79
	2050	3.38	3.38	3.38	4.27	4.27	3.38	3.38	3.38	3.38	3.38
Steel & non-ferrous production	2015	1.31	1.22	1.16	1.21	1.21	1.09	1.16	1.16	1.00	1.05
	2020	2.63	1.79	2.33	1.74	1.74	1.25	1.87	1.87	1.00	1.22
	2030	4.00	2.91	4.50	3.04	3.04	1.59	3.34	3.34	1.00	2.51
	2050	6.40	4.65	6.52	4.85	4.85	2.37	4.49	4.49	1.00	3.82
Other energy intensive industries	2015	1.53	1.03	1.63	1.09	1.09	1.11	1.43	1.35	1.37	1.18
	2020	2.18	1.03	2.35	1.45	1.45	1.35	1.96	1.81	2.02	1.33
	2030	3.41	1.75	4.06	2.25	2.25	1.98	2.95	2.76	3.94	1.83
	2050	6.50	4.37	10.28	4.21	4.21	3.73	6.53	5.78	11.61	3.50
Other industries	2015	1.53	1.03	1.63	1.28	1.28	1.34	1.43	1.35	1.37	1.18
	2020	2.18	1.03	2.35	1.63	1.63	2.10	1.76	1.63	1.82	1.20
	2030	3.07	1.57	3.25	2.41	2.41	2.66	2.51	2.34	3.35	1.55
	2050	3.90	3.50	6.68	3.76	3.76	5.28	4.25	3.75	7.54	2.27
Services	2015	1.53	1.13	1.63	1.15	1.15	1.16	1.43	1.35	1.37	1.18
	2020	2.39	1.23	2.35	1.60	1.60	1.48	2.15	1.99	2.22	1.47
	2030	4.10	2.19	4.67	2.59	2.59	2.28	3.54	3.31	4.73	2.19

2050	8.77	5.68	14.40	5.69	5.69	5.04	8.82	7.80	15.67	4.72

Table 0-1: Selected T-ALyC drivers, from 2015 to 2050, respective to 2010

E Trade

Table 0-2 details the distances considered in T-ALyC for international commodity trade.

Region	Commodity	Foreign port	Local port	Distance (thousand km)
AND	Coal	**Australia** *(Newcastle, Hay Point, Gladstone)*	Lima (Callao)	13.4
	Oil	**United States** *(Houston)*	Lima, Quito	6
	Gas	**Japan, Mexico**		17.2
ARG	Coal	**South Africa** *(Richards Bay)*	Buenos Aires	8.6
	Oil	**Nigeria** *(Port Harcourt)*	Buenos Aires	8.5
	Gas	**Qatar**	Bahia Blanca	16.5
BPU	Coal	**South Africa** *(Richards Bay)*	Montevideo	8.6
	Oil	**Nigeria** *(Port Harcourt)*	Montevideo	8.5
	Gas	Only internal	Only internal	
BSE	Coal	**United States** *(New Orleans)*	Rio de Janeiro	15
	Oil	**United States** *(Houston)*	Rio de Janeiro	11
	Gas	**Nigeria, Qatar, Spain, Trin. & Tobago**	Guanabara Bay, TRB	6
BWC	Coal	Only internal	Only internal	
	Oil	**United States** *(Houston)*	Fortaleza	7
	Gas	**Nigeria, Qatar, Spain, Trin. & Tobago**	Pecem	5
CHL	Coal	**Australia** *(Newcastle, Hay Point, Gladstone)*	San Antonio	6
	Oil	**United States** *(Houston)*	San Antonio	8
	Gas	**Indonesia, Qatar**	Mejillones, Quintero	20
COL	Coal	**Europe, internal**	Baranquilla	7.5
	Oil	**United States** *(Houston)*	Baranquilla	3
	Gas	Only internal	Only internal	
CYC	Coal	**Mexico**	Managua	1.5
	Oil	**Mexico**	Managua	1.5
	Gas	**Mexico** *(Salinas Cruz)*	Tapachula	0.4
SUG	Coal	**South Africa** *(Richards Bay)*	Paramaribo	11
	Oil	**United States** *(Houston)*	Paramaribo	5
	Gas	Only internal	Only internal	
VEN	Coal	Only internal	Only internal	
	Oil	**United States** *(Houston)*	Caracas	3.7
	Gas	**Europe** *(Fos-sur-Mer)*	Caracas	8.3

Table 0-2: International energy trade distances in T-ALyC

F Cogeneration : from TIAM to T-ALyC

This Annex describes one structural evolution from TIAM to T-ALyC, related to the efficiency of Combined Heat and Power (CHP) units.

In TIMES-VEDA, a refinery can be described by 6 coefficients: EFF, CHPR~FX, CEH, Cap2Act, AF, RESID.

- **EFF** is the efficiency of the refinery, based on its *electric output*[108] :

$$EFF = \frac{Output_{ELC}}{Input}$$

- **CHPR~FX** is the « CHP ratio » determining the heat-to-electricity ratio of outputs[109].

$$CHPR{\sim}FX = \frac{Output_{HET}}{Output_{ELC}}$$

- **CEH** determines the nature of the activity and the capacity of the plant: If it is zero, activity and capacity are linked to plant's electric output. If it is 1, activity and capacity are linked to the total output.
- **Cap2Act is the conversion coefficient** from plant activity (in PJ, for each period) to capacity (in GW, or PJ/yr):

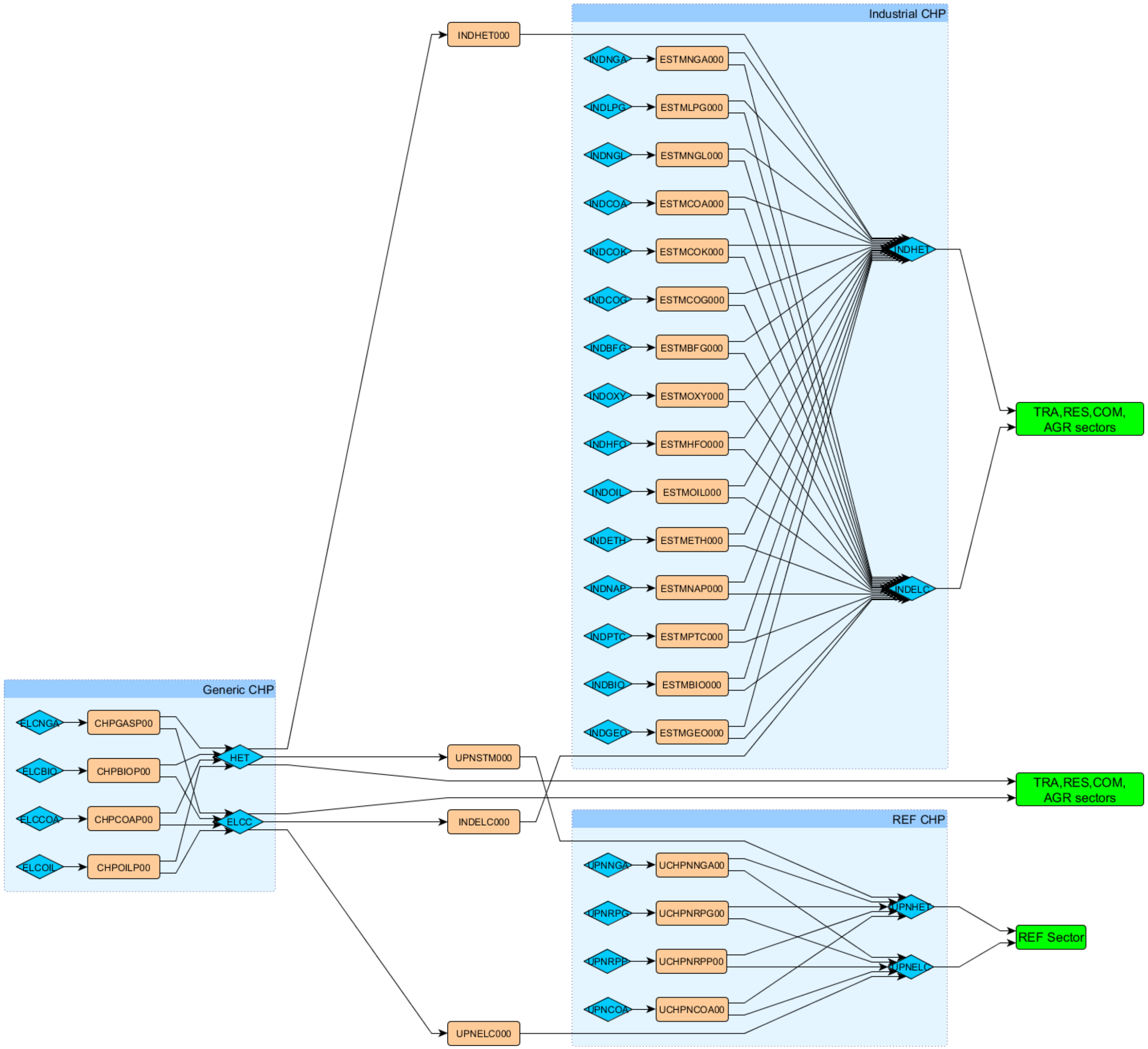
$$ACT = Cap2Act * CAP$$ [110]

- **AF is the availability coefficient** of the plant: a plant with a 1GW capacity that can actually work only 80% of the time will produce at most 0.8*31.356 PJ per year.
- **RESID is the total installed capacity** at base year. It is calculated from IEA statistics of production over one year (activity) according to the following formula:

$$RESID = \frac{ACT}{Cap2Act * AF} = \frac{Output_{Elc}}{Cap2Act * AF}$$

Where $Output_{Elc}$ is the electricity produced by CHP technologies, as provided in IEA statistics.

[108] Since CEH=0 here. For CEH=1, it would take into account *total production*. See (Kanudia and Lehtilä, Antti, 2013).
[109] The ratio here is a fixed one (back pressure plant). For other options, see (Gargiulo, 2009).
[110] When capacity is in GW and activity in PJ, then, Cap2Act=31.536 PJ/GW. When capacity is in PJ/yr, Cap2Act=1PJ/PJ.yr^{-1}



Industrial CHP
INDHET000
INDNGA
ESTMNGA000
INDLPG
ESTMLPG000
INDNGL
ESTMNGL000
INDCOA
ESTMCOA000
INDCOK
ESTMCOK000
INDCOG
ESTMCOG000
INDBFG
ESTMBFG000
INDOXY
ESTMOXY000
INDHFO
ESTMHFO000
INDOIL
ESTMOIL000
INDETH
ESTMETH000
INDNAP
ESTMNAP000
INDPTC
ESTMPTC000
INDBIO
ESTMBIO000
INDGEO
ESTMGEO000
INDHET
INDELC
TRA,RES,COM, AGR sectors
Generic CHP
ELCNGA
CHPGASP00
ELCBIO
CHPBIOP00
ELCCOA
CHPCOAP00
ELCOIL
CHPOILP00
HET
ELCC
UPNSTM000
INDELC000
UPNELC000
TRA,RES,COM, AGR sectors
REF CHP
UPNNGA
UCHPNNGA00
UPNRPG
UCHPNRPG00
UPNRPP
UCHPNRPP00
UPNCOA
UCHPNCOA00
UPNHET
UPNELC
REF Sector

Figure 0-1: CHP representation in T-ALyC

In TIAM, the cogeneration units that work for refineries are modeled in the UPS sector while those operated by industrial auto producers are modeled in the IND sector. Last, CHP plants that produce electricity and sell it on the network are modeled in ELC and IND sectors.

TIAM (or T-ALyC) does not differentiate the electricity (resp. heat) that is sold, and the electricity (resp. heat) that is consumed on-site[111]. IEA statistics, on the other hand, account separately for the electricity consumed on-site ("*autoproducers*") and sold ("*main activity producers*") and do not account at all for the heat consumed on-site by e.g. blast furnaces. We then need to disaggregate IEA's production and consumption of CHP plants in three categories[112]:

- "generic" CHP, producing for all sectors,
- "Upstream" CHP, linked to refineries,
- "Industry" CHP that represent the auto production of big industrial consumers.

Such a disaggregation involves re-constructing the full energy input of the plant from incomplete statistics. In turn, this re-construction is based on assumptions on the thermal efficiency of the plant[113] and its electricity-to-heat ratio. First, we choose a refinery ratio RR_{CHP} that represents the share of CHP units that belong to the refinery sector[114].

F.1. TIAM version

TIAM parameters for CHP in the refinery sector are as follows:

$$\boldsymbol{EFF_{th} = 0.80}$$

For thermal efficiency

$$\boldsymbol{CHPR{\sim}FX = 1/1.5}$$

That is, a CHP unit produces 1.5x more electricity than heat

$$\boldsymbol{CEH = 0}$$

$$\boldsymbol{Cap2Act = 31,536}$$

$$\boldsymbol{AF = 0,7}$$

Those parameters describe CHP processes in TIAM, based on exogenous assumption. Then, the calculations are as follows:

---

[111] Electricity might indeed be produced through technologies labeled as 'autoproducer', but it is then mixed with electricity from ELC sector before being consumed.

[112] In Figure 0-1 the electricity (resp. heat) produced by CHP plants blends with generic one, and is then consumed by IND and UPS plants. However, it does not matter that electrons might be virtually exchanged between IND and RES sector as long as the consumption of CHP plants is still well defined.

[113] See IEA's *Energy Statistics Manual* or any introduction to CHP description for the definition of the thermal efficiency of a CHP plant.

[114] Actually, this ratio describes the share of all inputs to CHP plants that are consumed by the refinery sector. It may be different for each commodity (natural gas, oil, etc.). In practice, its value in TIAM is either 0% or 10%.

$$EFF = \frac{Eff_{total}}{1 + \frac{1}{CHPR}}$$

With

$$Eff_{total} = \frac{Output^{TIAM}_{ELC,REF} + \overbrace{Output^{TIAM}_{ELC,REF} * CHPR_2}^{Output^{TIAM}_{HET,REF}}}{Input^{TIAM}_{TOT,REF}} = \frac{\overbrace{Output^{TIAM}_{ELC,REF} * (1 + CHPR_2)}^{Output^{TIAM}_{TOT,REF}}}{Input^{TIAM}_{TOT,REF}}$$

Where

- $\boldsymbol{Output^{TIAM}_{ELC,REF} = Output^{IEA}_{ELC,CHP} * RR_{CHP}}$ is the electricity output for CHP plants belonging to the refinery sector, as calculated in TIAM, while $Output^{IEA}_{ELC,CHP}$ is the electricity output for all CHP plants, as provided by IEA.
- $\boldsymbol{CHPR_2 = 1/REH = 2,6}$ (REH is a constant, also exogenously set).
- $\boldsymbol{Output^{TIAM}_{HET,REF} = Output^{TIAM}_{ELC,REF} * CHPR_2}$ is the total heat output, based on the electrical output (IEA statistics) and the $CHPR_2$ ratio (assumption).
- $\boldsymbol{Input^{TIAM}_{TOT,REF} = \underbrace{\frac{Output^{TIAM}_{HET,REF}}{EFF_{th}}}_{Input^{TIAM}_{HET,REF}} + Input^{IEA}_{TOT,CHP} * RR_{CHP}}$ represents in TIAM the total input of CHP processes in the refinery sector.

However, in the last expression, ***the input corresponding to the heat sold is counted twice:***

- Once in the $Input^{TIAM}_{HET,REF}$ term that represents the input dedicated to heat production (virtual decomposition between input that goes to electricity, and the one that goes to heat) is calculated based on *all the heat output*[115],
- And once in the $Input^{IEA}_{TOT,CHP} * RR_{CHP}$ term that takes into account the input for *all electricity, plus the heat that is sold*.

Also, according to these calculations, CHP processes are described in TIAM by a CHP ratio $CHPR = 1/1.5$, but their inputs and outputs are extrapolated from IEA data using another CHP ratio $CHPR_2 = 2.6$. This need for a *second* CHP ratio, $CHPR_2$, is questionable. The only explanation would be to consider that $CHPR_2$ is not an actual CHP ratio but the ratio between the heat that is produced *for local use*, and electricity. But then we should have $CHPR_2 = \frac{HET_{local}}{ELC_{total}} < \frac{HET_{total}}{ELC_{total}} = CHPR$, which is not the case:

$$CHPR_2 = 2.6 > CHPR = 1.5$$

So, in the end,

[115] Unless EFF_{th}links the total heat output with the extra input necessary to produce auto-consumed heat. But since the relation between this extra input and the total output is probably non-linear, this does not seem possible…

$$\boldsymbol{EFF = \frac{Output_{ELC,REF}^{TIAM} * (1 + CHPR_2)}{\left(1 + \frac{1}{CHPR}\right) * Input_{TOT,REF}^{TIAM}} = \left(CHPR * \frac{Output_{ELC,REF}^{TIAM}}{Input_{TOT,REF}^{TIAM}} * \frac{1 + CHPR_2}{1 + CHPR}\right)}$$

With a double counting for sold heat in $t_{TOT,REF}^{TIAM}$.

And the expression for the RESID coefficient[116] is

$$RESID = \frac{Input_{TOT,CHP}^{IEA}.RR_{CHP}.Eff_{total}.CHPR}{Cap2Act.AF.(1 + CHPR)} = \frac{RR_{CHP}.Input_{TOT,CHP}^{IEA}}{Input_{TOT,REF}^{TIAM}}.\frac{1 + CHPR_2}{1 + CHPR}.\frac{Output_{Elc,REF}^{TIAM}.CHPR}{Cap2Act.AF}$$

Which is also

$$\boldsymbol{RESID = \frac{EFF_{th}.Output_{Elc,CHP}^{TIAM}.RR_{CHP}}{EFF_{th} + CHPR_2.Eff_{Elc}} * \frac{1 + CHPR_2}{1 + CHPR} * \frac{CHPR}{Cap2Act.AF}}$$

Where we used the notation $f_{Elc} = \frac{Output_{Elc,CHP}^{IEA}}{Input_{TOT,CHP}^{IEA}}$.

This formula also integrates two different CHPR coefficients.

F.2. T-ALyC version

T-ALyC's parameters for modeling CHP in refineries are based on TIAM, yet the subsequent calculations are different:

$$\boldsymbol{EFF_{th} = 0.80}$$

For thermal efficiency

$$\boldsymbol{CHPR{\sim}FX = CHPR_2 = 1/1.5}$$

That is, a CHP unit produces 1.5x more electricity than heat

$$\boldsymbol{CEH = 0}$$

$$\boldsymbol{Cap2Act = 31,536}$$

$$\boldsymbol{AF = 0,7}$$

The overall efficiency of the technology is defined as

$$EFF = \frac{Output_{ELC}}{Input_{total}} = \frac{Output_{total}}{Input_{total}} * \frac{1}{1 + CHPR}$$

With

[116] As a reminder, the RESID coefficient represents the actual installed capacity at base year.

$$\frac{1}{1+CHPR} = \frac{1}{1+\frac{Output_{HET}}{Output_{ELC}}} = \frac{Output_{ELC}}{Output_{total}}$$

Note that the $\frac{1}{1+\frac{1}{CHPR}}$ coefficient from TIAM is now $\frac{1}{1+CHPR}$ in T-ALyC.

We defineEff_{total}:

$$Eff_{total} = \frac{Output_{ELC,CHP}^{IEA} * RR_{CHP} + Output_{HET,sold}^{TIAM} + Output_{HET,Auto}^{TIAM}}{Input_{TOT,REF}^{TIAM}}$$

With

$$Output_{HET,sold}^{TIAM} = Output_{HET,sold}^{IEA} * RR_{CHP}$$

And

$$Output_{HET,Aut}^{TIAM} = \underbrace{Output_{ELC,REF}^{TIAM}.CHPR}_{Output_{HET,total}^{TIAM}} - Output_{HET,sold}^{TIAM}$$

$$= RR_{CHP}\left(\underbrace{Output_{ELC,CHP}^{IEA}.CHPR}_{Output_{HET,total}^{TIAM}} - Output_{HET,CHP}^{IEA}\right)$$

We obtain the total input by adding the consumption due to on-site heat consumption:

$$Input_{TOT,REF}^{TIAM} = Input_{TOT,CHP}^{IEA}.RR_{CHP} + \frac{Output_{HET,Aut}^{TIAM}}{EFF_{th}}$$ [117]

Thus

$$Eff_{total} = \frac{EFF_{th}.Output_{ELC,CHP}^{IEA}}{EFF_{th} * Input_{TOT,CHP}^{IEA} + CHPR.Output_{ELC,CHP}^{IEA} - Output_{HET,CHP}^{IEA}}.(1+CHPR)$$

Which is

$$\boldsymbol{EFF = \frac{EFF_{th} * Output_{ELC,CHP}^{IEA}}{EFF_{th} * Input_{TOT,CHP}^{IEA} + CHPR * Output_{ELC,CHP}^{IEA} - Output_{HET,CHP}^{IEA}}}$$

This formula is still far from simple and it still relies on a hypothesis on the plant's thermal efficiency (EFF_{th}). However, it is in my view better than TIAM one for at least two reasons:

- It does not need any hypothesis on a second CHPR coefficient;

[117] Here $Input_{TOT,CHP}^{IEA}$ is the total input to CHP plants *as reported in IEA statistics* (i.e., input linked with on-site heat consumption is missing).

- It counts the heat sold only once.

The formula for the base-year residual capacity in T-ALyC is in turn:

$$\boldsymbol{RESID = \frac{Output_{ELC,REF}^{TIAM}}{AF * Cap2Act} = RR_{CHP} * \left(\frac{Output_{ELC,CHP}^{IEA}}{AF * Cap2Act}\right)}$$

G Translations and acronyms for Chapter 2

We gather here the Spanish and Portuguese original names corresponding to the translations used in the manuscript. To make name research and matching more convenient, we follow the structure of the manuscript instead of ordering them chronologically, or alphabetically.

English translation	Original name	Acronym
C.1. 1930-1980: The early ages of planning and prospective in South America		
Economic Commission for Latin America and the Caribbean	*Comisión Económica para América Latina y el Caribe*	ECLAC / CEPAL
Charter of Punta del Este	*Carta de Punta del Este*	
Alliance for Progress	*Alianza para el Progreso*	
Regional Energy Integration Committee	*Comisión de Integracíon Energética Regional*	CIER
Andean Community	*Comunidad Andina*	CAN
Development Bank of Latin America	*Banco de Desarrollo de América Latina*	CAF
Bariloche Foundation	*Fundación Bariloche*	FB
C.1.1. Argentina		
Economy Action Plan	*Plan de Acción Económica*	
Quinquennial Plan	*Plano Quinquenal*	
Secretary for Strategic Planning	*Secretaría de Planeamiento Estratégico*	
post-War Council	*Consejo de Postguerra*	
National Development Council	*Consejo Nacional de Desarrollo*	
National Development Plan 1965-1969	*Plan Nacional de Desarrollo 1965-1969*	
National Planning System	*Sistema Nacional de Planeamiento*	
C.1.2 Brazil		
Special Plan for Public Works and the Preparation of National Defense	*Plano Especial de Obras Públicas e Aparelhamento da Defesa Nacional*	
National Steel Company	*Companhia Siderúrgica Nacional*	
Health, Alimentation, Transport and Energy	*Saúde, Alimentação, Transporte, Energía*	SALTE
Council for Development	*Consejo do Desenvolvimento*	
Objectives' Program	*Programa de Metas*	
Planning Ministry	*Ministerio do planejamento*	
Program for Governmental Economic Action	*The Programa de Ação Econômica do Governo*	PAEG
Decennial Plan	*Plano Decenal*	PED
National Development Plans	*Plano Nacional de Desenvolvimento*	PND
Geoscience Institute	*Instituto de Geociências*	

Science and Technology Policy Department	*Departamento de Política Científica e Tecnológica*	
Campinas' State University	*Universidad Estadual de Campinas*	
Energy Planning Program	*Programa de Planejamento Energético*	PPE
Rio de Janeiro's Federal University	*Universidade Federal do Rio de Janeiro*	UFRJ
C.1.3. Chile		
National Development Agency	*Corporación Nacional de Fomento*	Corfo
Department for Planning and upstream Studies	*Departamento de Planificación y Estudios*	
National Program for the Economic Development 1961-1970	*Programa Nacional de Desarrollo Económico 1961-1970*	
Planning Bureau	*Oficina de Planificación*	Odeplan
C.1.4. Colombia		
National Planning Department	*Departamento Nacional de Planeación*	
Colombian Fund for Scientific Investigation and Special Projects	*Fondo Colombiano de Investigaciones Científicas y Proyectos Especiales*	Colciencias
National Council for Science and Technology	*Consejo Nacional de Ciencia y Tecnología*	
Operation Development	*Operación Desarrollo*	
Colombia's Group of the Year 2000	*Grupo Colombia Año 2000*	
C.1.5. Costa Rica		
National Planning Office	*Oficina de Planificación Nacional*	Ofiplan
National Planning System	*Sistema Nacional de Planificación*	
Secretary for sub-sectorial energy planning	*Secretaría de Planificación Subsectorial de Energía*	
National Energy Plan: 1986-2005	*Plan Nacional de Energía 1986-2005*	
C.1.6. Cuba		
Perspective Plan	*Plan Perspectivo*	
C.1.7. Peru		
National Planning Institute	*Instituto Nacional de Planificación*	INP
National Development Plan	*Plan Nacional de Desarrollo*	
National Strategy for Long-Term Development	*Estrategia Nacional de Desarrollo de Largo Plazo*	
Latin American Energy Organization	*Organización Latinoamericana de Energía*	OLADE
Office for Coordination and Planning	*Oficina de Coordinación y Planificación*	Cordiplan
Venezuelan Corporation for Guyana	*Corporación Venezolana de Guyana*	CVG
C.2. 1980-1995 : The neo-liberal		

wave		
Technology Prospective for Latin America	*Prospectiva Tecnológica para América Latina*	PTAL
High Technology for Latin America 2000	*Alta Tecnología América Latina 2000*	ATAL 2000
Project of Regionalized Scenarios for Latin America	*Proyecto de Escenarios Regionalizados de América Latina*	
C.2.1. Argentina		
Planning Secretary	*Secretaría de Planeamiento*	
Energy Secretary	*Secretaría de Energía*	
Prospective for the Electric Sector	*Prospectiva del Sector Eléctrico*	
C.2.2. Brazil		
National Environment Policy	*Política Nacional de Meio Ambiente*	
Brazilian Economy Scenarios	*Cenários para a economia brasileira*	
National Development Bank	*Banco de Desenvolvimento Econômico e Social*	BNDES
National Plan for Electric Energy 1987-2010	*Plano Nacional de Energia Elétrica 1987-2010*	
Strategic Plan for the Petrobras System 1990-2000	*Plano Estratégico do Sistema Petrobras*	
C.2.3. Chile		
Pontifical Catholic University	*Pontificia Universidad Católica*	
Center for the Study of National Planning	*Centro de Estudios de Planificación Nacional*	
C.2.4. Colombia		
National Development Plan	*Plan Nacional de Desarrollo*	
Calí Valley in 2000	*El Valle 2000*	
National Prospective Program 1986-2000	*Programa Nacional de Prospectiva 1986-2000*	
C.3. 1990-Today: Emergence of dedicated climate-energy prospective		
Latin American Network for Prospective and Technology watch	*Red Iberoamericana de Prospectiva y Vigilancia Tecnológica*	RIAP
Latin American Program for Development-aimed Science and Technology	*Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo*	CYTED
Latin American Network for Prospective Studies	*Red Latinoamericana de Estudios Prospectivos*	
C.3.1. Argentina		
Ministry for Federal Planning, Public Investment and Services	*Ministerio de Planificación Federal, Inversión Pública y Servicios*	

Energy Secretary	*Secretaría de Energía*	
Prospective 2002	*Prospectiva 2002*	
Prospective for the Electricity Sector	*Prospectiva del Sector Eléctrico*	
Center for Advanced Studies	*Centro de Estudios Avanzados*	
Center for Future Studies	*Centro de Estudios del Futuro*	
University of Buenos Aires	*Universidad de Buenos Aires*	
C.3.2. Bolivia		
Indicative plan for rural electrification	*Plan indicativo de electrificación rural*	
Cartagena Agreement	*Junta del Acuerdo de Cartagena*	JUNAC
Ministry for the planning of Development	*Ministerio de Planificación del Desarrollo*	
National Plan for Development	*Plan Nacional de Desarrollo*	
Viceministry of Energy Development	*Viceministerio de Desarrollo Energético*	VMDE
Bolivian Strategy for Hydrocarbons	*Estrategia Boliviana de hidrocarburos*	
Plan for the Energy Development 2008-2027	*Plan de Desarrollo Energético 2008-2027*	
Optimal expansion plan for the National Interconnected System	*Plan óptimo de expansion del Sistema Interconectado Nacional*	
National Energy Plan	*Plan Energético Nacional*	
Institute for Advanced Development Studies	*Instituto de Estudios Avanzados en Desarrollo*	Inesad
C.3.3. Brazil		
Secretary of Strategic Affairs	*Secretaria de Assuntos Estratégicos*	SAE
Pluri-annual Plan	*Plano Plurianual*	PPA
Department of Strategic Affairs	*Núcleo de Assuntos Estratégicos*	NAE
Energy Investigations Company	*Empresa de Pesquisa Energética*	EPE
General Bureau of Energy Information	*Coordenação-geral de Informações Energéticas*	
Decennial Plan for Energy Expansion	*Plano Decenal de Expansão de Energia*	
National Energy Plan 2030	*Plano Nacional de Energia 2030*	
C.3.4. Chile		
Planning Ministry	*Ministerio de Planificación*	Mideplan
Ministry of the Presidency's General Secretary	*Ministerio Secretaría General de la Presidencia*	SegPres
Direction for Energy Prospective and Energy Policy	*Dirección de Prospectiva y Política Energética*	
Energy Center	*Centro de Energía*	
Chile's University	*Universidad de Chile*	
C.3.5. Colombia		

Colombia's Revolutionary Army	*Fuerzas Armadas Revolucionarias de Colombia*	FARC
Destination Colombia	*Destino Colombia*	
Mining and Energy Planning Division	*Unidad de Planeamiento Minero Energético*	UPME
Ministry of Mines and Energy	*Ministerio de Minas y Energía*	
Reference Plan for the Expansion of Generation and Transmission	*Plan de Expansión de Referencia Generación – Transmisión*	
Vision for the 2nd Centenary of Colombia: 2019	*Visión Colombia II Centenario: 2019*	
Colombia: Energy Principles 2050	*Colombia: Ideario Energético 2050*	
C.3.6. Costa Rica		
Sectorial Direction for Energy	*Dirección Sectorial de Energía*	DSE
6th National Energy Plan	*VI Plan Nacional de Energía*	
Costa Rican Institute for Electricity	*Instituto Costarricense de Electricidad*	ICE
Plan for the Expansion of Electricity Generation	*Plan de Expansión de Generación Eléctrica*	
C.3.7. Peru		
Multisectorial Commission for Industrial Technology Prospective	*Comisión Multisectorial de Prospectiva Tecnológica Industrial*	
National Division of Strategic Planning	*Centro Nacional de Planeamiento Estratégico*	Ceplan
Strategic Plan for National Development – Plan Peru 2021	*Plan Estratégico de Desarrollo Nacional – Plan Perú 2021*	
Energy Plan 2002-2005	*Plan Energético 2002-2005*	
Reference Electricity Plan 2008-2017	*Plan Referencial de Electricidad 2008-2017*	
Strategy for the Development of Peru's Energy Sector	*Estrategia para el Desarrollo del Sector Energético del Perú*	
General Direction for Energy Efficiency	*Dirección General de Eficiencia Energética*	DGEE
National Energy Policy 2010-2040	*Política Energética Nacional 2010-2040*	
National Energy Plan 2014-2025	*Plan Energético Nacional 2014-2025*	
C.3.8. Venezuela		
Planning Ministry	*Ministerio de Planificación*	
Ministry of People's Power for Planning	*Ministerio del Poder Popular de Planificación*	MPPPF
National Planning System	*Sistema Nacional de Planificación*	
Simon Bolivar Project– First Socialist Plan	*Proyecto Simón Bolivar – Primer plan socialista*	
Ministry for Electric Energy	*Ministerio de Energía Eléctrica*	

C.3.9. Other		
Ministry of Economy and Planning	*Ministerio de Economía y Planificación*	
Cuban Observatory of Science and Technology	*Observatorio Cubano de Ciencia y Tecnología*	
Center for the Management of Information and Development of Energy	*Centro de Gestión de la Información y Desarrollo de la Energía*	CUBAENERGÍA
National Electricity Council	*Consejo Nacional de Electricidad*	CONELEC
Ministry for the Coordination of Strategic Sectors	*Ministerio Coordinador de Sectores Estratégicos*	MICSE
Planning General Division	*Secretaría General de Planificación*	SEGEPLAN
K'atun: Our Guatemala 2032	*K'atun: Nuestra Guatemala 2032*	
National Energy Secretary	*Secretaría Nacional de Energía*	
Technical Division for Planning	*Secretaría Técnica de Planificación*	STP
Strategic Plan for the Electric Sector	*Plan Estratégico del Sector Eléctrico*	
National Electricity Administration	*Administración Nacional de Electricidad*	
Viceministerio de Minas y Energía	*Vice Ministry of Mines and Energy*	
National Development Plan	*Plan Nacional de Desarrollo*	
Planning and Budget Office	*Oficina de Planeamiento y Presupuesto*	OPP
Ministry of Industry, Energy and Mines	*Ministerio de Industria, Energía y Minas*	MIEM
Energy Prospective Study 2014	*Estudio de Prospectiva Energética 2014*	
National Administration for Fuels, Alcools and Cement	*Administración Nacional de Combustibles, Alcohol y Pórtland*	ANCAP
Energy Prospective 2030	*Prospectiva energética 2030*	
Uruguay's Infrastructure 2030	*Infraestructura Uruguay 2030*	

Table 0-3: Translations and acronyms used in Chapter 2