**KTH Industrial Engineering
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Power investment outlook for Chile to 2040

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Abstract

This study aims to build a medium-term (2019-2040) model for the Chilean electricity generation system in the OSeMOSYS software, a linear cost optimisation model, in light of the most recent developments in government policy and targets. In 2019, the Chilean government committed to decommissioning all coal plants by 2040 at the latest, and set out a non-binding target to be carbon neutral by 2050. The carbon neutrality target could be enshrined in the climate change law, which has yet to be ratified. In this thesis, a focus was put on the upfront capital cost of the system, and the emissions attributable to Chile's GHG Inventory (called the SNI GHG in Chile) from operating the system.

Three scenarios are developed within the thesis, in line with three paths the power system may follow: a BAU scenario including current power purchase agreements, a scenario in which power purchase agreements for fossil fuels are bought out and the free market then takes over, and a non-conventional renewable energy (NCRE) scenario in which certain renewable technologies account for 68% of production in 2040. The model is validated against the results from 2019 and a broadly similar model developed in the private sector.

Sensitivity analysis scenarios were conducted for the input parameters: price of natural gas, price of coal, capital cost of solar PV, capital cost of wind, capital cost of wind & solar, and the capacity factor of hydropower. The sensitivity analyses show the most sensitive input parameters are the price of natural gas and capital cost of wind with respect to the outputs of capital cost, NCRE production ratio such as the share of all solar, wind, and certain hydro technologies as a percentage of total electricity production and GHG emissions.

Abstrakt

Denna studie syftar till att bygga en medelfristig (2019-2040) modell för det chilenska elproduktionssystemet i programvaran OSeMOSYS, en linjär kostnadsoptimeringsmodell, mot bakgrund av den senaste utvecklingen i regeringens politik och mål. År 2019 åtog sig den chilenska regeringen att stänga av alla kolanläggningar senast 2040 och fastställde ett icke-bindande mål att vara koldioxidneutralt år 2050. Målet om koldioxidneutralitet kan fastställas i lagen om klimatförändringar, som ännu inte har ratificeras. Detta arbete fokuserar på systemets kapitalkostnad i förväg och de utsläpp som kan hänföras till Chiles GHG-inventering, kallad SNI GHG i Chile, från drift av systemet.

Tre scenarier utvecklas inom avhandlingen, i linje med tre scenarier som kraftsystemet kan följa: ett BAU-scenario inklusive nuvarande kraftköpsavtal, ett scenario där kraftköpsavtal för fossila bränslen köps ut och den fria marknaden sedan tar över, och ett scenario med icke-konventionell förnybar energi (NCRE) där vissa förnybara tekniker står för 68% av produktionen 2040. Modellen valideras mot resultaten från 2019 och en i stort sett liknande modell utvecklad i den privata sektorn.

Känslighetsanalysscenarier genomfördes för ingångsparametrarna: pris på naturgas, kol på pris, kapitalkostnad för solceller, vindkraft, kapitalkostnad för vind & sol och kapacitetsfaktor för vattenkraft. Känslighetsanalyserna visar att de mest känsliga ingångsparametrarna är priset på naturgas och kapitalkostnad för vind med avseende på kapacitetskostnadens produktion, NCRE-produktionskvoten, till exempel andelen av alla sol-, vind- och vissa hydroteknologier i procent total elproduktion) och växthusgasutsläpp.

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1 Introduction

1.1 Background

In order to achieve the Paris Agreement's long-term temperature goal to hold the global average temperature increase to well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5°C, governments around the world need to raise ambition, beyond that which is currently seen globally [1]. Looking at a sample of 31 countries found in the Climate Action Tracker, just two are Paris Agreement compatible, and just a further five are 2C compatible. Therefore, as things stand, the global effort to reduce greenhouse gas (GHG) emissions is insufficient [2,3].

The production of electricity is both the primary cause of climate change and the primary means of mitigation [4]. Whilst all sectors must contribute to achieving the goal set forth in the Paris Agreement, the electricity sector can and has to move faster as low-carbon electricity provision is a key enabler for the decarbonisation of other sectors [5]. However, whilst the operation of the electricity sector transcends simple market transactions, and is impacted by governance and institutional arrangements, I will focus on the energy policy that Chile has set out and its international commitments [6].

Therefore, fundamental to reducing GHG emissions in the electricity sector is the deployment of renewable energy technology [7]. To model future energy systems and predict emissions pathways based on policy scenarios, there are now many competing techno-economic models which provide policy makers and academics with a view of the economic implications of filling the gaps in technology which many current climate policies around the world are targeting. Such models include TIMES/MARKAL, LEAP, POLES, PROSPECTS+ and OSeMOSYS [8–11].

The electricity sector is often the highest emitting sector in a country, even in countries where the economy relies on production from sectors such as agriculture [12,13]. However, despite major advancements in some countries, globally efforts to decarbonise the energy supply has largely failed, with the carbon emissions intensity average remaining largely the same from 1990-2013 [14–16].

In this regard, Chile is of great interest. Chile's contribution to global emissions is just 0.2%, but the emissions for the electricity sector grew by 101% between 1990-2010 whilst the energy generation from non-conventional renewable energy (NCRE) grew from 5% to 22% between 2014 and 2019 [17,18]. Chile has set a very ambitious goal of net-zero emissions by 2050, but has not published a concrete electricity sector

plan for the next 20 years to achieve this target, let alone an accountable, specific economy wide plan. In fact, even the planned decommissions for coal power plants only goes up to 2025 [19]. As such, there is a need for a model which will lay out a plan which will enable the country to stick to its commitments, of special importance given that there is an 84% gap in capacity between the current installed low-emission technologies and the needed capacity. The SAMBA model captured elements of the Chilean electricity sector in 2015, but had a Brazilian focus and now has outdated data sources [20]. A 2012 paper performed a scenario assessment using MESSAGE for just Chile, but this assessment has two limitations: first, 2012 data is outdated and second the assessment was conducted before the grid interconnection of 2017 between SIC and SING [21]. Furthermore, MESSAGE is not free to use in all cases, unlike OSeMOSYS. As such, I used OSeMOSYS to assess the Chilean electricity sector and mitigation potential with current data and policies. It is particularly relevant because this will be the first Chile centred OSeMOSYS model.

1.2 Aims, scope objective

The overall objective of this thesis is to determine the cost for the electricity sector of Chile's coal phase out plan, and the 2050 net zero emissions commitment, and to calculate the resultant model period emissions. The GHG emissions results are then benchmark compared to international commitments to the UNFCCC, including their Biennial Update Reports and the draft updated National Determined Contribution.

The purpose of the research then is to evaluate the potential for 100% renewable energy deployment in a country case for Chile, and then quantify the annual point of use emissions for the sector if national goals are reached. As such, the primary research question is: *"What will be the GHG emissions and investment costs for the electricity sector if Chile achieves its goal to be coal free by 2040?"*. Following on from this, a sub-research question is *"What will be the GHG emissions and investment costs for the modelling period of 2019-2040 if Chile achieves its goal of carbon neutrality by 2050?"*

This study constructed an OSeMOSYS model to develop a pathway for the current 2050 net-zero plan using available data sources, for the medium term 2019-2040 using 2018 as a base year. Three scenarios were constructed: a business as usual scenario, a scenario with no power purchase agreements, and a non-conventional renewable energy scenario. The scenario rationale can be found in the Methodology (Section 3).

The scope of this thesis encompasses renewable energy generation in Chile from 2019-2040. Whilst Chile currently has the absolute transmission and distribution networks

to transport electricity, this may not be the case region to region. As official government figures for data from 2017 onwards are given for the combined region Sistema Electrico Nacional (SEN), and not Sistema Interconectado (SIC) or Sistema Interconectado del Norte Grande (SING), this thesis does not model granular inter-regional transmission and distribution. Furthermore, this thesis covers three types of emissions: methane, carbon dioxide and NO_x. Emissions sources and values can be found in the Emissions Factor section of the Methodology. This thesis does not cover yet other co-emitted air pollutants such as $PM_{2.5}$. As the emissions penalty for NO_x is locally based (sometimes to within 100km^2), it was not possible to include this penalty for the Chile region as a whole.

1.3 Thesis structure

This thesis contains 8 chapters in total.

Chapter 1 covers the background and motivations of the project before moving to a literature review covering: policy for energy investment and GHG emissions; power system modelling tools in a global context; and power system modelling tools in the Chilean context.

Chapter 2 presents the current state of affairs in Chile, looking at the history of the economy of the state before examining the existing power system infrastructure, management of the system (both generation and transmission & distribution), the potential for renewable energy generation in the country, and the overarching institutional structures and laws which have had a profound impact on the generation mix over the past decade.

Chapter 3 presents the methodology, providing the key data sources and reasoning behind assumptions.

Chapter 4 presents the results for the capital cost, GHG emissions and NCRE share for the three scenarios.

Chapter 5 is the discussion and analysis of results, which is followed by the conclusion in Chapter 6. Chapter 7 provides ideas and rationale for further areas of research, and Chapter 8 contains the Annex with additional information.

1.4 Literature review

1.4.1 Policy for renewable energy investment and GHG emission

First this study will look at the effect of (climate) policy on investments in renewable energy. The first and most direct policy instrument available to a government is the variety of pricing and incentive mechanisms. If able to set variable pricing, a country may wish to choose between flat pricing and peak pricing, and Kök et al found that flat pricing can lead to substantially lower carbon emissions (through renewable energy investment) in the majority of scenarios they explore [22]. The other pricing mechanism which more and more countries are choosing to employ is subsidies on renewable energy investment and carbon emissions. Two common subsidies are direct subsidies in the form of tax credits, and indirect subsidies in the form of taxes [22]. A study by Emodi et al using a LEAP-OSeMOSYS model found that a carbon tax in Australia would reap economic benefit, resource savings and lower environmental externalities by 2050 [23]. A carbon tax can, however, also have the adverse effect on renewable energy investment if the emission intensity of conventional energy sources is sufficiently low (such as in the case of a well performing carbon capture storage system) [22]. Polzin et al found similar results in that taxes (generally) could have a negative impact on further capacity additions in renewables, although solar might buck the trend by seeing increased investment [24]. Cansino et all found that a Pigouvian tax in the form of a Fossil Fuel Levy (directly penalizing fossil fuels) was effective at encouraging renewable energy investment, whereas Polzin found that tax reductions for renewables tended to increase overall capacity in renewables [24,25]. However, despite the ambivalence of taxes' effects on renewable energy investment in the literature (i.e. taxes can help or harm investment depending on the broader situation and other variables), carbon taxes have a multilateral positive effect on GHG emissions reductions throughout the economy, even when they are only levied in the electricity sector [26]. Finally, Renewable Portfolio Standards (RPS) are perhaps the most forceful directive a government can give to those who run the generation system, and by nature ensures increased investment in renewables by creating a minimum renewable energy capacity – such a programme is used in Chile with the Renewable Energy Law 20.257 [27]. However, although RPS are a heavy handed directive from the government to increase renewable energy investment, such standard introduce uncertainty for those running the system by complicating investment decisions, and can have delays of 5-10 years between policy implementation and project completion [28].

1.4.2 Power system modelling tools

There are two main types of energy model: techno-economic models which are bottom-up models that start with the individual power facilities and technologies that fall under the field of Process Systems Engineering (PSE), and macroeconomic models which attempt to project the corresponding economic, power infrastructure or employment net costs and impacts caused by certain policies through a top-down approach, falling under the field of Energy Economics [29]. Energy system models in PSE typically operate at the unit operation, processing plant or supply chain scale, each representing a different level of aggregation [30]. Energy economics approaches use models with a high level of aggregation which based on economic theory such as the laws of supply, demand and market equilibrium [30]. These two different models are often used by different interest groups for different purposes, as each tends to lend itself to specific results. Macro-economic models are often cited by trade associations, energy intensive (supply) companies and conservative policy makers, whereas as pro-climate groups tend to opt for bottom up models as they provide greater granularity to the full consequences of different technologies. In essence, the differences between the two types of models relate to the level of aggregation and the scope of assumptions that one makes when taking one of the two approaches. There is obviously a desire to unify the two approaches and whilst economic theory does provide a unifying concept for both approaches, models mostly formulate problems as a system of linear equations which can be relatively easily solved [31]. Yet, to this day, the simplicity of using one system or another lends to energy modellers adopting one software or another.

There are several different bottom up models which serve a similar purpose, such as TIMES/MARKAL (of which PRIMES and NEMS are in the same family), LEAP, POLES, PROSPECTS+ and OSeMOSYS.

MARKAL/TIMES is a family of energy/economic/environmental models designed under the IEA's Energy Technology Systems Analysis Programme which began in 1978. TIMES is now the primary model and receives update support every few months. The source code is free of charge after signing an agreement to not distribute the code to third parties, after which a shell – usually ANSWER or VEDA – is used to manage the system. However, MARKAL/TIMES is written in GAMS, a commercial software, and due to the nature of the source code a license for the software is needed, which can cost up to US$20,000, which is a major barrier to most interested parties [8].

PRIMES (Price-Induced Market Equilibrium System) model was developed at the National Technical University of Athens in a project co-financed by the European Commission. PRIMES was designed to focus on market-related mechanisms and explicitly project prices influencing the evolution of energy demand/supply and technology development. Evidently the electricity sector has developed a great deal between the project kick off in 1993 and 2019, so the model has received continued support and updates as well as peer reviews in the European Commission framework in 1997 and 2011 [32]. As PRIMES is a mature energy modelling system, researchers have expanded it in several different sectors (such as the transport sector with PRIMES TREMOVE) and sub-sectors (such as the Gas supply sector in a country).

POLES is a recursive simulation model of the world energy system which includes an equilibrium of the energy markets. The model facilitates the assessment of energy demand and supply options through the lens of certain policies, such as GHG mitigation policies. The model does not allow for projections based on assumed technological improvements in the future, nor does it account for unintended consequences that may derive from the utilisation of any given technology, such as food shortages if the model recommends ramping up biomass. In this sense, whilst the model can match energy needs accurately, it somewhat struggles with providing an accurate long term view, and may be better suited to 10-15 year projections [33].

Also from the MARKAL/TIMES family of models is NEMS (the National Energy Modelling System), another energy-economy model, this time from the U.S. used to project production, imports, conversion, consumption and prices of energy. NEMS is a fairly rare case of a modelling system devised by and used by a government agency, in this case the U.S. Department of Energy [34].

In this thesis, OSeMOSYS (a bottom-up approach) is used. OSeMOSYS has been used extensively to cover energy systems in Africa using the TEMBA model, South America in the SAMBA model and even on a global scale in the OSeMOSYS based translation GENeSYS-MOD which was cited in the IPCC special 1.5C report [20,35–37]. The TEMBA model represents each continental African country's electricity supply system and transmission links between them, allowing for continent wide dialogue amongst all members and comprehensive energy planning. SAMBA focuses on the electricity supply infrastructure of South America with a focus on hydropower, and is dominated by Brazil. Notably, however, a little granularity is lost as the scale of the models increase, and at the same time new data and policies are always being released in country specific scenarios. Such is the case with the SAMBA

model, which focuses on Brazil and hydropower but also includes information and model capabilities for Chile.

1.4.3 Power system models in the global context

On the subject of cost optimization power modelling in the global context, there is a plethora. The following is a short section of highlights. Tailor made code can be used to provide highly customizable optimization problems. Although they take longer to set up initially, the design allows for custom inputs, such as the results of global climate models (CGM). This has been used to quantify the impacts of climate change on energy systems [38]. OSeMOSYS has been used to model the power system infrastructure of entire continents in the case of TEMBA and SAMBA [20,36]. Following from this, LEAP-OSeMOSYS hybrid models has been used to examine the effectiveness of emission reduction policies under climate change for optimization analysis, including tax policies and clean energy substitution models [23]. Syri et al used PRIMES to develop low-CO_2 energy pathways and regional air pollution models in Europe examining a variety of pollutants [39]. POLES has been used to inform policy decision-makers on mitigation strategies and energy technology learning rates to forecast future lower prices [40]. Finally, the mitigation action plan scenarios (MAPS) Chile project claims to have used scientific modelling techniques to plan mitigation scenarios and energy planning (with a focus on low carbon development, rather than cost optimization). However, the data is outdated (from 2013) and information is very scarce on the actual tools used, and it is not easily available to academics [41]. Therefore, there is a lack of energy planning literature for Chile, never mind with a focus on investment costs and emissions reductions.

1.4.4 Power system and related models in Chile

Below is a summary of the literature that does exist for Chile, which look at emissions, climate effects or have Chile as part of a global model which focuses on pure energy planning, rather than both investment planning and emissions planning.

The power infrastructure in Chile has been in a rapid state of change over the last four years with the introduction of Energy 2050 policy document [42]. On top of these developments, Law 20.257/08 on non-conventional renewable energy, which stated 5% of generation for medium-large producers needed to be from non-conventional renewable energy (NCRE) sources in 2010-2014, started an incremental progression of requirements for producers in the country [27].

However, despite this, no cost optimization power modelling exercises have been to match demand to supply in light of the future NCRE.

Raugei et al developed a life cycle analysis (LCA) and net energy analysis (NEA) to evaluate existing data against data extrapolations to predict the future demand and supply in the year 2035 [43]. This approach sought to evaluate the energy system without being fixed to cost restraints. Whilst a valuable study to determine feasibility, economic parameters need to be included as this is what a government must do when conducting planning exercises. Bergen et al created their own mixed-integer linear stochastic optimization model to create a scenario based evaluation of the effect of environmental policy decisions on the energy mix and transmission investments required, but did not specifically focus on emissions [28]. Benavides et al used the GEM-E3 model, calibrated with projections from the PRIMES model, to produce a hybrid approach which evaluated how various carbon tax values above the existing $5/ton would impact the energy system [18]. Pereira et al focused more on GHG emissions when developing their own linear optimization model to link emissions to carbon tax levels, including 155 transmission lines and 9 candidate lines linking 46 buses with up to 10 different generation technologies. This was modelled hourly for two representative days over summer/winter, but for a relatively short period from 2020-2029 [44]. O'Ryan et al created a simplified link between the ECOGEM Chile CGE model and a bottom-up type energy model built by the Chilean Energy Ministry (based on the Long-Range Energy Alternatives Planning System (LEAP)) by incorporating the share of different technologies into the CGE model, set at the same for each year [17]. This takes advantage of the strengths of both models, yet also compensating for the disadvantages of each. Gómez et al constructed an energy matrix from a system dynamics approach to focus on long-term energy policies [45]. From a less model based approach, Ana Pueyo looked at technology transfer and enabling frameworks for low-carbon technology transfer, defining technological inputs, technological transfer channels and technology spillover effects to attain a final, direct objective to the technology transfer process using ten case studies in Chile [46].

Löffler et al first created a global OSeMOSYS model for all countries up until 2050, and then included a 100% renewable target for 2050 [35,47]. However, as the model includes countries from around the world till 2050, it lacks the granularity and up to date information that is required for a Chile focused model, especially in light of the recent transformations in the transmission grid and renewable technology capacity. Moura and Howells created a model which included more information and depth for Chile in their South American SAMBA model, but took a Brazilian perspective in

the paper using 2014 data which would thus not capture the current situation for Chile given the developments of 2019 [20].

Therefore, as described above there is a gap in the literature. There are no energy planning models for Chile which provide analysis on investment costs, and the emissions implications of such investments. This thesis will contribute to the literature by providing an up to date scenario analysis of the future of Chile's power system infrastructure, focusing on the investment costs and GHG emissions reductions that may be achieved. The thesis will use OSeMOSYS as a modelling tool, providing a power infrastructure model for the medium term (2019-2040) focusing on Chile.

2 State of Affairs in Chile

2.1 Country Context

2.1.1 History

Chile is a was one of Latin America's fastest growing economies over the past decade, and has reduced the population living under the poverty line from 30% in 200 to just 6,4% in 2017. Much of this growth could be attributed to the performance of copper mining in the country, with 32.8% of the GDP originating in the industrial sector [48]. However, after growing by 4% in 2018, GDP growth fell to 1.8% in H1 2019 due to difficult external circumstances, poor climatic conditions and a delay in some Government reforms – this was exacerbated by the 2019 cost of living protests and subsequent cancellation of COP25 [49,50].

The twelve-month rolling central government deficit remained at just 1.7% of GDP in the first half of 2019, yet despite the GDP growth slowdown, electricity demand is expected to continue to grow as the population is more wealthy [51]. Although Chile is still recovering from the effects of copper prices bottoming out, greening the electricity sector is strong opportunity for the Chilean economy [52].

In 2018, Chile's energy production was 13 Mtoe, whereas the total primary energy supply was 39 Mtoe, covering a final consumption of 76.99 TWh [53]. To cover demand, Chile is currently reliant on commodity imports, importing 45,875,000 TJ of natural gas and 825,000 Mtoe of coal in 2017 [53]. Despite some low-grade coal deposits in the country, extraction costs are too high and Chile imports up to 85% of the coal it uses [54]. Chile also imports all the natural gas it uses, and the diplomatic crisis of the mid 2000s between Argentina and Chile severely curtailed electricity production from natural gas in Chile [55]. When trade restarted in 2018, it was seen as lifeline for Chile to wean itself off coal as renewable energy was installed in the following decade [56].

As the electricity sector is privately owned, investment must come from private sources. The introduction of the renewable energy law (Law 20.257) saw an increase in investment with a spike of USD$2 billion in 2012 to meet the requirements of the Law. However, given the considerable potential of NCRE in Chile, convincing financial institutions to provide loans for the high initial cost projects was difficult, despite the significant positive and negative impacts on economic output and CO_2 emissions respectively [57]. Insufficient financing schemes and system integration barriers were again identified as a key barrier to implementation of the approved

projects, as well as volatile energy prices, insufficient local products, and regulatory barriers [58]. However, by the end of the decade, $14.8B had been invested in renewable energy, with the majority of that after 2014 [59]. Although much of the country is state owned land, the Ministry of State Assets is actively looking to hand out concessions for renewable energy projects to facilitate NCRE deployment [60].

2.1.2 Electricity Sector Profile

The electrical system is privately owned. Before 2017, the grid was split into 4 regions, with the SIC and SING grids accounting for the vast majority of demand. In 2017 Chile connected the SING and SIC grids to form Sistema Electricidad Nacional (SEN). The main transmission grid operator is Transelect, whilst the main distributors are ENEL Distribución, Companía general de Electricidad Distribution, Sociedad Austral de Electricidad, and Chilquinta Energy [61]. A more complete list of the main operators can be found below in Table 1. The electricity market is divided in three: regulated customers (clientes regulados), unregulated customers (free customers), and the spot market [62]. As such, the investment is, in the end, fronted by the private sector, who bid at auctions for contracts (see below Figure 1).

Key companies	*Generation*
	Enel Generación **(6531 MW)**
	AES Gener **(4148 MW)**
	Colbún **(3884 MW)**
	Engie **(1971 MW)**
	Transmission
	Transelec *(9648 KM | 16321 MVA)*
	Compañía General de Electricidad *(3670 KM | 8661 MVA)*
	SAESA *(1602 KM | 2379 MVA)*
	Enel Distribución *(361 KM | 8386 MVA)*
	Celeoredes *(710 KM | 5164 MVA)*
	Chilquinta *(849 KM | 1764 MVA)*
	Distribution
	Compañía General de Electricidad *(70294 KM | 8090 MVA)*
	Enel Distribución *(16507 KM | 4660 MVA)*
	Chilquinta *(16459 KM | 1890 MVA)*
	SAESA *(59559 KM | 987 MVA)*

Table 1 Key companies involved in the generation, transmission and distribution of electricity in Chile [63].

In 2018, installed capacity was 23.315 GW, and end demand was 69.323 GWh, made up 49% of regulated customers and 51% free customers.
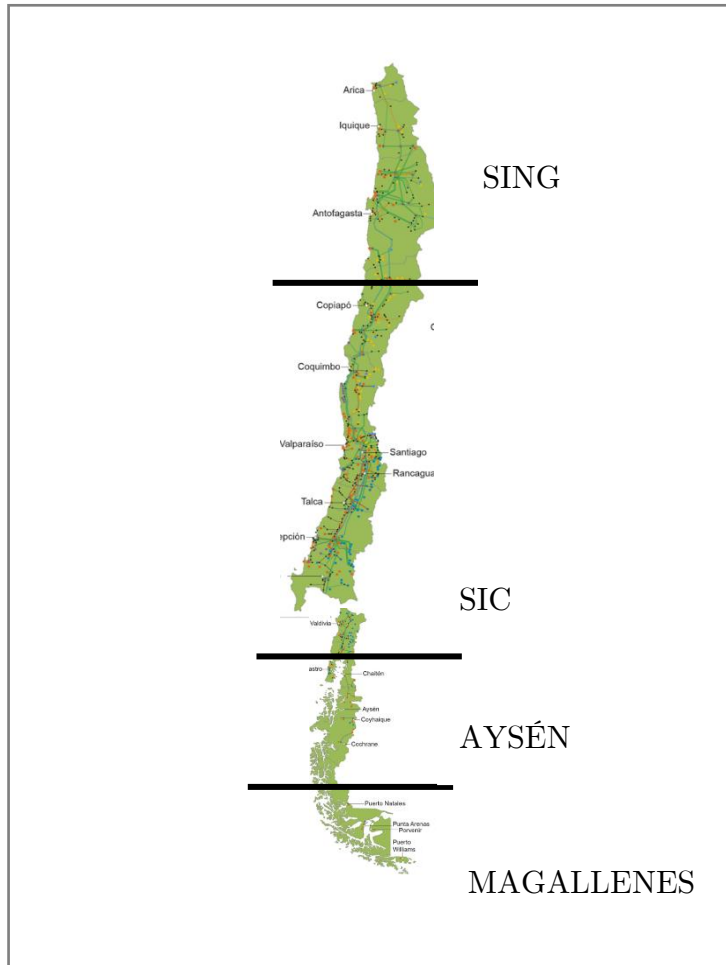
Figure 1 Breakdown of the old electrical system in Chile. SIC and SING have since been connected to form the SEN. Map icon retrieved from [136]

Compared to just 5% a few years ago, NCRE (excluding large hydropower) now accounts for 20.8% of the country's energy supply [64]. This success was in part due to the energy auction system in Chile. The full generation mix is seen in Figure 2 [65]. Before 2005, prices were regulated by the CNE. In 2005, an auction system was created in which potential suppliers would bid to supply energy at a certain price, and the technology for the supply would not be revealed in the bid; most recently, the 2019 auction saw bids for supplying up to 5.6 TWh for the years 2026-2040 [66].

If energy auctions do not meet renewable targets, separate renewable auctions may be held, although in the last 4 years renewable energy has dominated auctions [62].

Compared to other South American countries, Chile has a few unique features. In Brazil, energy auctions are, for example, A-3 or A-5 as they must begin operation within 3 or 5 years [67], and from these PPA are determined and signed by the
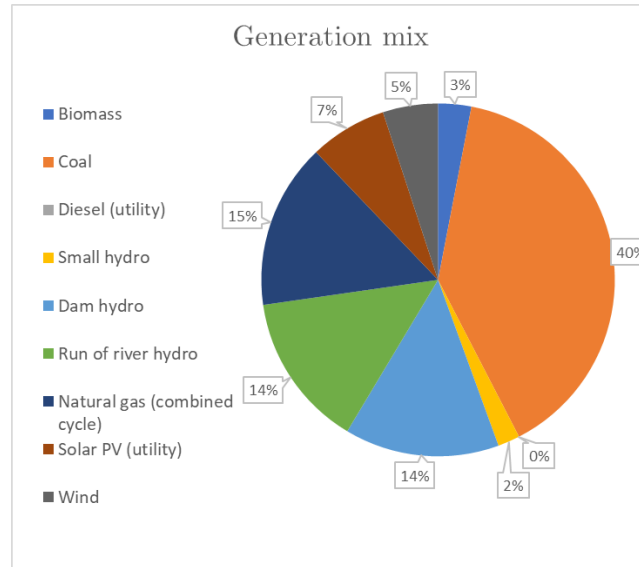
Figure 2 Authors own graphic of the generation mix in Chile in 2018 presented in the Anuario Estadístico [65].

respective parties, normally for 20 years for wind and solar and 30 years for hydropower. Peru has technology-specific pay-as-bid sealed-bid auctions, so renewables have their own auctions [67].

Chile has similar auctions, yet the main differences are that Chile has no start date deadline, and Chile has time block based auctions as well to allow NCRE to be more competitive, allowing, say, solar to provide power just in the daytime [66]. This was revolutionary in the rise of NCRE in Chile, and was instituted in 2014. The situation in Argentina is different. Auctions are held specifically for renewable energy in the RenovAr energy auction, where up to 400 MW of capacity is auctioned at a time in Mini-rounds and more in larger rounds (although for 400 MW opened up in 2018, 269 MW was won) [68,69]. Three rounds have been completed, and the fourth is due to come live soon.

Due to geographical limitations imposed by the Andes mountain range, Chile has limited power connections with other countries in the region. Currently there is a 700 MW interconnection with Argentina, and a planned 300 MW interconnection with Peru from 2021/22. However, in December 2011 Argentina revoked the electricity export license for Salta (the border town) so there is currently no trade [63]. The cost of production for electricity in Chile is higher than in Peru, so it is likely that in the near term Chile would be a net importer of electricity from Peru [70].

2.1.3 Potential

Chile has excellent solar resources, especially in the Atacama desert which receives unusually high levels of solar irradiation equivalent to 2400 kWh/kWp per year [71]. Although PV technology will likely continue dominating investments in the region in

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the coming years, and makes up roughly 1/7 of all projects in the global project pipeline, Chile has the highest number of CSP projects in the project pipeline in the world, with an estimated 5500 MW in the pipeline [72]. The most notable current examples are the SolarReserve Tamarugal Solar Plant, a 450 MW project approved and to be operated by USA company SolarReserve, and Cerro Dominador at 110 MW. Chile also has a considerable project pipeline for wind energy, ranking 4th globally for wind capacity under development at approximately 8.4 GW of on-shore capacity [73].

Chile's raw potential to electricity from renewable energy sources (rather than NCRE) stands at 12 GW for hydroelectric, 1 TW for solar, 40 GW for wind and 16 GW for geothermal [74].

Overall then, Chile has favourable geographic conditions for renewable energy, political conviction backing industry and an attractive regulatory environment, with just a few barriers impeding the deployment.

2.2 Institutional Environment

Table 2 below provides a summary of the institutional environment in Chile with key institutions, plans & strategies, pledges and targets, laws and regulations. Below Table 2 is a deeper dive into how the institutions are relevant for the research topics of this paper, as well as supporting evidence for the analysis that has been conducted on the institutional environment. *It is important to evaluate the institutional environment* for two reasons. First, renewable energy introduction in Chile was heavily influenced by legislation, and this trend looks to continue. Second, the results of the thesis are compared to the NDC for Chile, a policy document which is a result of the collaboration of all aspects of Chilean society.

National level

National Climate Change Cabinet (GNCC) [Gabinete Nacional de Cambio Climático]
The National Climate Change Cabinet brings together national public bodies involved in climate policies, under the orbit of the Cabinet of Ministers. It seeks to reorient public policies, ensure coordinated responses and generate mitigation and adaptation actions.

Key Institutions

Electricity sector level

Ministry of Energy (MdE) [Ministerio de Energía]
Hosts the Division of Environment and Climate Change [División Ambiental and Cambio Climático], the Division of Energy Markets [División de Mercados Energéticos] and the Division of Sustainable Enrergy [División de Energías Sostenibles]. As of 2nd August 2019, the Ministry was led by *Juan Carlos Jobet* [75].

National Energy Commission (CNE) [Comisión Nacional de Energía]
The Commission id a public and decentralised entity, with its own authority and capacity to acquire and exercise rights and obligations for the President of the republic as an intermediary for the Ministry of Energy. As a technical organisation, the Commission analyses prices, tariffs and technical laws related to companies related to the production, generation, transport and distribution of energy [76].

Superintendence of Electricity and Combustibles (SEC) [Superintendcia de Electricidad y Combustibles]

In charge of safety and quality of the operation of the electricity, gas and fuel services in Chile [77].

Key Plans & Strategies

National level

National Climate Change Action Plan 2017-2022 [Plan de Acción de Cambio Climático 2017-2022]
The National Climate Change Action Plan is an economy wide action plan for climate change mititgation and adaptation, with pillars of action in the transport, electricity, agriculture and industrial sectors [78].

Electricity sectoral level

Energy 2050: Chile's Energy Policy, 2016
A medium-long term policy planning document outlining strategic and technological aspects that will define the energy matrix in Chile to 2050. The document is sustained by four pillars: Quality and Security of Supply; Energy as a Driver of Energy; Environmentally-friendly energy; and Energy Efficiency and Energy Education [42].

Mitigation Plan for GHG for the Energy Sector [Plan de mitigación de gases de efecto invernadero para el sector energía], 2017
The plan, produced by the Ministry of Energy, is a public policy instrument, examining mitigation policy on various axes including cost-efficiency, equality, flexibility and the contribution to emissions reduction [79].

Energy Route 2018-2022 [Ruta Energética 2018-2022], 2018
A seven-step plan to a modern, low emission system energy system for Chile. The short term plan to complement Energy 2050 [80].

Pledges & Targets

National level

Draft Second Nationally Determined Contribution (NDC)
Unconditional: Economy-wide emissions capped at 1110-1175 $MtCO_2e$ incl. LULUCF between 2020 & 2030, and 97 $MtCO_2e$ in 2030.
Conditional: Not supplied in the draft

Electricity sectoral level

Energy 2050: Chile's Energy Policy, Ministry of Energy Statement
The government plans for 70-100% NCRE by 2050 [42,81].

Key Laws & Regulations	**Draft Climate Change Law, 2019** The draft law would introduce sweeping measures and enshrine NDC targets in law, strengthening the ability of the government to ensure climate targets are met [82] **Law 20.571 on environmental taxation, 2014** Implementation of an annual tax on emissions from fixed sources of thermal power great than or equal to 50 MW [83]. **Law 27.780 tax reform implementing a green tax, 2014** Implantation of a green tax on fixed sources of pollutants, including CO2, starting in 2017 [84]. **Law 19.657 on Geothermal Energy and its Regulation by Decree 114, 2010** Establishment of a special system for granting concessions for the exploration and development of geothermal energy [85] **Law 20.571 regulating the payment of electricity tariffs of residential generators, 2012** Allows final users to inject electricity from renewable installations up to 100kW into the distribution grid [83]. **Law 20.365 on tax exemption for solar thermal systems, 2010 & Law 20.897 amending Law on tax exemption for solar thermal systems** Grants tax deductions equivalent to the cost of the installation of new solar thermal systems. Later amended [86]. **Law 20.257 on Non-Conventional Renewable Energy, 2008 & Law 20.698 on the Modification of Electrical services, 2014** Mandates that a certain percentage of power solar by electricity companies, operating at more than 200 MW, must be produced from NCRE. The perctage was later raised, and now amounts to 20% by 2025 [27] **Law 19.940 modifying the general electrical services Law from 1982, 2004** Changed several aspects of the energy generation market in Chile, facilitating the rise of small power producers [87]. **Law 20.936 on new power transmission systems, 2016** Establishes new power transmissions Systems and an independent coordinating body for the national power system to ensure transmission system is not a barrier to NCRE deployment [88]. **Law 20.928 on equity mechanisms in electrical service rates, 2016** Amends the price mechanism, including for regulated customers by adjusting the discount on price according to the power demand [89].

Table 2 Institutional summary surrounding electricity production. Format of table developed with NewClimate Institute [90]

According to the NDC the intended emissions shall not exceed 1175 MtCO$_{2eq}$ cumulative between the years 2020 and 2030, and intend to reach a peak of in the year 2027 (excluding the LULUCF sector) [91]. This sets a definitive metric of comparison for the GHG emissions results of each scenario.

The Minister of Energy, Juan Carlos Jobet, is the head of the main policy decision maker in the company, and is committed to sectoral mitigation with his steadfast backing of Energía Zero Carbon, Chile's plan to be carbon neutral by 2050, stating "the main mandate is to facilitate the development of clean generation capacity and a balanced matrix that serves the people" [92]. The focal point for the Ministry of Energy for climate change and renewable energy is the head of the Sustainable Development and Climate Change Division, at a mid-seniority level [42,93].

Recently, the sector has given priority to climate mitigation and renewable energy installation through various plans and measures: the Council for Minister for Sustainability adopted the "Mitigation Plan for the Energy Sector" to align sector plans with the NDC, whilst on June 05th the Ministry announced a radical decarbonisation plan that would see coal completely removed from the matrix by 2040. This accompanied the rapid uptake of renewable energy by electricity providers after the introduction of the Energy Agenda 2050 and the Chilean auction structure [94]. Priority was also given to climate mitigation in Energía 2050, Ruta Energética, Estrategía Nacional de Electromobilidad, and Guía Chile Energía.

Ministry of Energy uses the 2050 carbon neutral long-term target and feeds this into short-term policy implementation. The 2018-2022 Energy Pathway is structured into 7 axes, the fourth of which details low-emission energy, and uses this policy document to realise the (at the time) target of 70% renewables by 2050. Distinct short-term planning based on long-term targets are seen elsewhere in policy too, such as in the National Energy Policy which is split into three time frames: short-term (to 2022), medium term (to 2035) and long-term (to 2050) [80,95].

The Chilean electricity and heating sector's GHG emissions are covered in the national inventory, and other transparency framework measures are reviewed on an individual basis and presented in the BUR, major policy documents such as the National Energy Policy, and on individual websites. The most prominent of review mechanisms seems to be "MRV de politicas y acciones de mitigación del sector energía" [MRV of mitigation policies and actions in the energy sector] [96].

Overall, the institutional environment shows strong support to the deployment of non-conventional renewable energy (solar, wind, small hydro, biomass), and there are both regulatory organisation ensuring targets are met, and laws to guarantee that Chile's energy mix moves to a great NCRE share [27,75,76,82,85].

3 Methodology

The purpose of modelling energy systems is typically to gain insight into future performance of the system based on historical data to aid decision making [97]. This is not just for accounting though; it also aids in the optimisation of energy resources, and can also be conducted with limited historical data if sound scientific assumptions are made. This thesis uses OSeMOSYS to model the system.

3.1 Scenario and Modelling Approach: Open Source Energy Modelling System (OSeMOSYS)

3.1.1 Origins of the OSeMOSYS model

OSeMOSYS is of the family of bottom-up, or techno-economic, models designed for long-term energy planning. Unlike other models, such as MARKAL/TIMES, OSeMOSYS is completely free to use as the code is written in GNU MathProg or Python (both open source), and uses the free solver GLPK to calculate results, whilst MoManI (Model Management Infrastructure) is used as an interface [11]. Furthermore, the model allows the user to include the existing capital stock and its remaining lifespan. However, the model faces several weaknesses including operational requirements, governmental regulations/institutional conditions and socioeconomic situations, broader economic context and external shocks (such as the 2008 financial crisis).

In order to define the optimal pathways, the model uses the given technologies for production and necessary associated fuels to match the demand given to the model over the relevant time period, all of which is given as an input. The model allows for users to add constraints to the system, and with these three-broad categories of inputs, creates and solves a system of linear equations. The original design of the system was in "blocks" of functionality to allow for users to update and modify the system easily to their own requirements. The seven original blocks were: objective (function); costs; storage; capacity adequacy; energy balance; constraints; and emissions [98]. The overall structure can be seen in Figure 3, whilst a detailed description can be found in the Annex for how the blocks interlink to minimise the objective function.
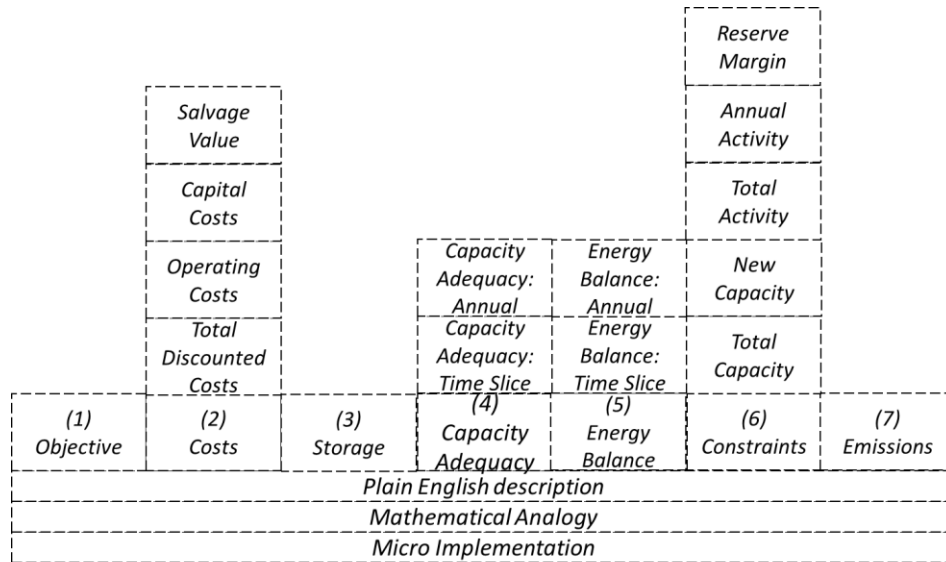
3.1.2 Techno-economic parameters used in the model

There are two distinct sets of data in the model: time dependent, and time independent.

Time independent

is the data which is constant across the modelling period, but may vary for each technology. Table 3 below describes the time independent parameters, as well as their units [99].

Year Split	Duration of a modelled time slice expressed as a fraction of the year. The sum of all entries equals 1.	
Discount Rate	Region specific value for the discount rate used across all technologies, expressed as decimal (not a percentage).	Percentage
Depreciation method	Binary parameter defining the type of depreciation: 1 for sinking fund, 2 for straight-line depreciation.	0 or 1
Capacity to Activity Unit	Conversion factor relating the energy that would be produced when one unit of capacity is fully used in one year (GW -> PJ).	Unitless
Operational Life	Useful lifetime of the technology in years.	Years
Input Activity Ratio	Rate of commodity use by a technology, as a ration of the rate of activity.	Unitless
Output Activity Ratio	Rate of output of a commodity from a technology, as a ratio of the rate of activity.	Unitless

Table 3 Time independent parameters used in the model [99]

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This data may vary for both technology, year and time period. Table 4 below describes the time dependent parameters, as well as their units [99].

Specified Annual Demand	Total demand for the year, linked to a time of use during the year	PJ
Specified Demand Profile	Annual fraction of energy service or commodity demand by time slice. Sum of all time slices equals 1.	0 oto 1
Capacity Factor	Capacity available in each time slice expressed as a *fraction of the total installed capacity*, from 0 to 1. Allows for forced outages.	0 to 1
Availability Factor	Maximum time a technology can run in the whole year, *as a fraction of the year* from 0 to 1. Allows for planned outages.	0 to 1
Residual Capacity	Remaining capacity available from before the modelling period. Must be manually phased out at end of lifetime.	GW
Capital Cost	Capital investment cost of a technology, per unit of capacity.	M$/GW
Variable Cost	Cost of a technology per given mode of operation (variable O&M), per unit of activity.	M$/PJ
Fixed Cost	Fixed O&M of a technology per unit of capacity.	M$/GW
Total Annual Max Capacity	Total maximum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.	GW
Total Annual Min Capacity	Total minimum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.	GW
Total Annual Max Capacity Investment	Maximum capacity of a technology expressed in power units.	GW
Total Technology Annual Activity Upper Limit	Total maximum level of activity allowed for a technology in one year.	PJ
Total Technology Annual Activity Lower Limit	Total minimum level of activity allowed for a technology in one year.	PJ
Reserve Margin	Minimum level of reserve margin required that the tagged technologies must provide for the tagged commodities.	PJ
Reserve Margin Tag Fuel	Binary parameter. Tags the fuels to which the reserve margin applies.	0 or 1
Reserve Margin Technology	Binary Parameter. Tags the technologies which may contribute to the reserve margin.	0 or 1
RE Tag Technology	Binary parameter. Tags the renewable technologies that may contribute to the RE minimum production target.	0 or 1
RE Min Production Target	Minimum production target for the tagged technologies. Fraction from 0 to 1.	0 to 1
Emissions Activity Ratio	Emissions factor of a technology per unit of activity, per mode of operation.	Mton/PJ
Emissions Penalty	Monetary penalty per unit of emission.	M$/Mton
Annual Emissions Limit	Emissions limit for the given year.	Mton
Model Period Emission Limit	Emissions limit for the modelling period.	Mton

Table 4 Time dependent parameters used in the model [99].

3.1.3 Designing a Reference Energy System for Chile

A Reference Energy System (RES) is a graphic of the particular energy system to be modelled. As standard, technologies are depicted as blocks whilst services (such as fuels) are depicted as lines [98]. This allows the designer to have a clear visual representation with which to model their system, and also allows those analysing the results to see the model set up without having to go into the code or interface itself.
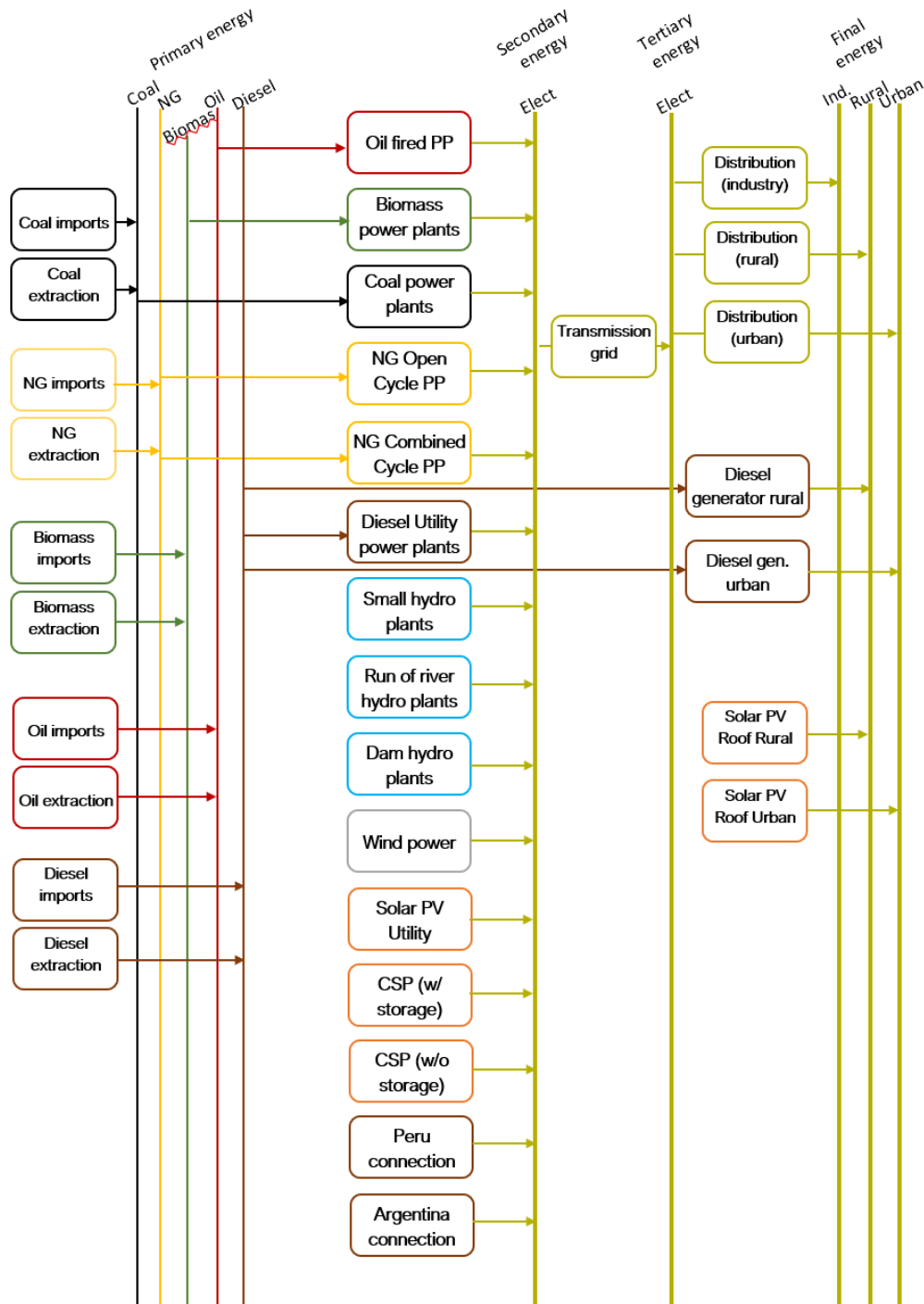
Figure 4 The reference energy system for used to design the OSeMOSYS model for Chile

3.1.4 Scenarios

Chile has committed to removing coal from the energy matrix by 2040, and to be carbon neutral by 2050 [81]. In order to answer the research question, *"What will be the GHG emissions and investment costs if Chile achieves its goal to be coal free by 2040?"*, this thesis used three scenarios. First was a (1) Business as Usual scenario, including just the 2040 coal plant decommissions. This scenario includes power purchase agreements (PPAs) up to 2026 which includes coal and natural gas production. The volume of the production from coal and natural gas was taken from historical production, as seen in the Anuario Estadistica [65].

Definition: **PPA**	A **Power Purchase Agreement** (PPA) is a **long-term electricity supply agreement** between two parties, usually between a power producer and a customer. The PPA defines the conditions of the agreement, such as the amount of electricity to be supplied, negotiated prices, accounting, and penalties for non-compliance. Since it is a **bilateral agreement**, a PPA can take many forms and is usually tailored to the specific application. In this thesis, a PPA refers to both corporate deals and the government auction agreements for simplicity [137].

Second, a (2) null PPA scenario modelled the case where current PPAs are bought out, and instead open market conditions are allowed to play out.

It is possible that, despite PPAs, Chile may switch these contracts to renewable energy. There is precedent for this already in Chile, as the mining company BHP announced that it would be switching to renewable energy supply and had set aside US$780M to cover the costs of buying out PPAs for coal [100]. This is after Miner Anglo American made the same renewable energy pledge [101]. Thus a scenario to model the least net present cost pathway in such a scenario was needed.

Then, a (3) non-conventional renewable energy (NCRE) was created. Chile has set a 2050 carbon neutrality target. As described earlier, the generation of electricity is both the primary cause of climate change and the primary means of mitigation [4]. As such, if Chile is to reach its neutrality goal by 2050, the electricity sector will have to reach net zero emissions by 2050 at the latest. Chile defines non-conventional renewable energy as solar, wind, biomass, ocean, and hydraulic (less than 20 MW) power.

Therefore, the NCRE used a 100% NCRE penetration ratio for 2050 to simulate Chile meeting the carbon neutrality target, which corresponds to a 2040 target of 68%.

3.2 Assumptions and data sources

Instead, data was collected from various government documents and academic journals. For some variables, standard numbers were used. In the OseMOSYS model, there are two distinct types of data: time dependent data which depends on the year, and time independent data which is fixed across the 22 years for which the model runs.

3.2.1 Global assumptions

Base year

The analysis throughout the paper focuses on generation and demand with a baseline year of 2018 (the latest year for which complete statistical information on electricity generation and demand was available at the time of writing).

Mode of operation

Modes of operation allow the model to simulate different outputs; for example, a combined heat and power plant would have two modes of operation, one for power and one for heat. In this model CHP plays a minor role in production, and when forcing fossil fuel-based energy production within Annual Activity Lower Limit, coal and natural gas produced in mode 2, which does not correlate to anything for coal. As such, the model was simplified to use one mode.

Discount rate

The discount rate of 8.16% was calculated using NERA Consulting's reference to the Department for Energy and Climate Change (DECC) Hurdle Rates. Each technology has an individual hurdle rate, so a weighted average was calculated based on the installed capacity in the country [102].

Table 5 Individual technology discount rates from 2013 DECC figures, as reported in 2015 NERA paper [102]

Solar	5.3%
Biomass CHP	13.6%
Wind	7.1%
Hydropower	5.8%
Geothermal	22.0%
CCGT	7.5%
OCGT	7.5%
Nuclear	9.5%
Coal (carbon capture storage)	13.5%
Weighted average	8.16%

Monetary Unit

The monetary unit for the model was set to the US$ with a base year of 2018.

Modelling Period

Following typical medium-term plans, this model runs from 2019-2040, with 2018 used as a base year (as this was the latest data from most sources).

Year Split

Each year is split into two primary seasons (summer/winter), and each day is split into two time periods (day/night). This is an aggregation of demand and supply data: capacity factors were found for day and night for most technologies at a high aggregation level, whilst the demand profile was given for an example day, and for each month [103]. The sunset/sun rise time was taken to be the delimiter for day and night, and from this the capacity factor, specified annual demand and other hour dependent data were calculated for summer/winter day/night. Without additional data for local breakdowns, further time splits would have yielded false positive accuracy for the model: for just one example, the capacity factor of hydropower cannot be assigned for multiple months, and is instead better presented as the included SD/SN/WD/WN.

Electricity generation technologies

Electricity generation technologies were mostly taken from the "Cost of generation" report by the CNE [104]. From this, CSP was split into two, with thermal salt storage and without. In addition to this, rooftop solar was added to the model, with and without storage, to provide the model the option of installing rooftop solar panels for residential demand. Thus the electricity generation technologies are: biomass CHP, coal power, diesel (utility), diesel generator (industry), diesel generator (urban), diesel generator (rural), trade links (Argentina, Peru), small hydropower, dam hydropower, run of the river hydropower, oil fired gas turbines, natural gas (open/single cycle), natural gas (combined cycle), CSP (with storage), CSP (without storage), solar PV (utility), rooftop solar PV (with/without storage & rural/urban), wind power. Chile has no nuclear generation capacity and does not plan on utilising nuclear. In addition, the commodity/fuel technologies are: biomass import/extraction, coal import/extraction, natural gas import/extraction, oil import/extraction, solar potential.

3.2.2 Specific data sources and assumptions

Capital cost, fixed cost, variable cost

The majority of cost figures were sourced from "Informe de Costos de Tecnologías de Generación", released by Comisión Nacional de Energía in 2019. This provided information on the current capital costs, fixed costs and non-fuel related variable costs for each technology [104].

Technology	Reference investment cost (US\$/kW)	Fixed costs (% of investment)	Non-fuel variable costs (US\$/MWh)
Thermal carbon	3000	1%-2%	2
Thermal natural gas (open cycle)	800	1%-2%	3.5
Thermal natural gas (combined cycle)	1048	1%	3.5
Thermal diesel (dual gas turbine + motor generator)	687	1%-2%	3.5-10
Wind	1361	3%-4%	-
Solar PV	970	1%-2%	-
Solar thermal (CSP)	6055	1%-2%	-
Hydropower (dam)	2180	1%	1.3
Run of river hydro (>20MW)	4050	1%	1.3
Small hydro	3565	1%	1.3
Thermal biomass	3100	3%-4%	9.3
Geothermal	5870	4%-5%	-

Table 6 Reference investment (capital, fixed costs and non-fuel variable costs as laid out by the Comisón Nacional de Energía (CNE) using 2018 values [104].. Some figures are provided in the government report as a range. This thesis uses the middle value of the range.

However, rooftop solar was not covered by the Anuario Estadistico or the CNE Cost Report, and was instead garnered from a CEPAL report on the economics of rooftop solar in Chile which is endorsed by the Comisión Económica para América Latina y el Caribe (CEPAL), which gave an estimate of \$2260/kW [105].

However, several technologies are still in the early stages of commercial viability, such as solar PV, CSP, geothermal and to some extent wind power. For these technologies, the learning curve was plotted in excel using data from IRENA and IEA. A power trendline was added to graph and then the equation for this displayed on the graph. This equation was then used to calculate the future costs of these nascent technologies, with the starting point for the series taken as the first

commercially viable power plant in the world. As such, solar is predicted to reach a lower final capital cost than wind, for example, as it is a newer technology and thus has some way to fall down the learning curve still. This corresponds with various literature predictions. Fossil fuel technologies (including natural gas) are assumed to be mature enough to have a stable capital cost, as is hydropower. Furthermore, due to the elongated nature of the geography, the country spans a great length from South to North, and as such covers many different biomes. Climate change and varying water levels are not taken into account in the model, as seasonal rain patterns in the north of Chile vary to those in the south. As such, availability factors are assumed to be constant throughout the year, and capacity factors are presumed to not change between night/day. The trend for biomass capital costs was plotted from IRENA's renewable energy power generation costs, which showed that prices had slightly decreased in the last 10 years [106].

Fuel costs

Fuel costs (the other component of variable costs) were calculated using a combined method. First, the World Bank Pink sheets market outlook from April 2019 provide an outlook until 2030 of major commodity prices such as coal, natural gas and oil [107].

Commodity	Unity	2016	2017	2018	Forecasts					
					2019	2020	2021	2022	2025	2030
Coal, Aus	$/mt	66.1	88.5	107.0	94.0	90.0	86.4	83.0	73.5	60.0
Crude oil, avg	$/bbl	42.8	52.8	68.3	65.0	65.5	66.0	66.0	67.5	70.0
Natural Gas, Euro	$/mmbtu	4.6	5.7	7.7	6.0	6.0	6.1	6.2	6.5	7.0
Natural Gas, U.S.	$/mmbtu	2.5	3.0	3.2	2.8	2.9	3.0	3.1	3.4	4.0
Natural Gas, Japan	$/mmbtu	7.4	8.6	10.7	7.4	7.5	7.6	7.7	8.0	8.5

Table 7 Global values for the commodity price forecasts from the World Bank Pinksheets, compared with the World Outlook 2017 [107]. These values are then converted to Chile using a conversion factor based on the 2019 values.

Then these world values were converted to Chile specific prices by looking at the current prices of commodities in the country in the Anuario Estadistico de Energía and applying this ratio through all years [65]. For example, in 2018 coal was $130.50/mt compared to $107.00 in the World Bank figures. This factor was then applied throughout the modelling period. Finally, the trend for 2018-2030 was extrapolated to 2040.

The Cost Report provides a specific consumption in MMBtu/GWh, with which the cost per MMBtu is converted to $/PJ, specific to technology and market conditions Chile.

Technology	Specific consumption	Unit
Thermal carbon	0.385	(ton/MWh)
Thermal natural gas (open cycle)	9.000	(MMBtu/MWh)
Thermal natural gas (combined cycle)	6.500	(MMBtu/MWh)
Thermal diesel (dual gas turbine – utility)	0.250	(m³/MWh)
Thermal diesel (motor generators)	0.270	(m³/MWh)

Table 8 Specific consumption of fossil fuel technologies in Chile, as an average [104].

Finding an accurate base cost for wood chips & pellets which feed biomass power plants was more difficult. A 2013 analysis for Danish prices of $1.5M/PJ was used with the assumption that, because the technology is more mature in Denmark, the prices in 2013 would be more similar to that of todays [108]. Furthermore, IEA projections show that biomass prices are likely to remain largely the same lest a food crisis hit.

Residual Capacity

Residual capacity and planned builds which had already been funded were also taken from the Anuario Estadistisco [65]. Residual capacity is in the report as single numbers for each technology, but in order to put the planned capacity in for each year, the planned constructions were put into Excel with the project name, the capacity and the year of project completion. This was then filtered into year by year, technology by technology tables of installed capacity to be fed into the main database sheet which was directly transferred to Momani.

Furthermore, whilst OSeMOSYS has a built-in function, plant lifetime, to decommission capacity beyond its technical lifetime, this does not apply to the residual capacity in the model. As a consequence, existing residual capacity is reduced by 2% a year (assuming a 50-year average lifetime for the current technologies of dam hydro, natural gas, diesel, and run of the river hydro). This

applies even for hydropower plants which would typically get upgraded and retrofitted in the same location, to simulate the refurbishment costs.

For existing renewable energy capacity, a phase out of 4% a year was used due to the generally shorter life time of solar and on shore wind generation. This is however a technical number: often, power plants are run past their technical lifetimes if no breakdown occurs and there are no safety risks.

Chile has a commitment to phase out coal by 2040, with a number of the older plants scheduled to be phased out by 2025. The plants which already have a decommission date were put into the model, and then coal capacity was linearly phased out between 2025 and 2040 for the unknown coal plants.

Table 9. Capacity expansion (in MW) for currently under construction projects

Technology (MW)	2018	2019	2020	2021	2022	2023	2024
Biomass	0	1	0	0	0	0	0
Coal	375	0	0	0	0	0	0
CSP	0	110	0	0	0	0	0
Hydro dam	16	0	0	0	0	0	0
Diesel	27	333	50	0	0	0	0
Mini hydro	46	31	20	0	0	0	0
Natural gas	127	132	0	0	0	0	0
Solar PV	229	153	70	0	0	0	0
Run of river	0	0	682	0	136	0	170
Wind	80	547	204	0	0	0	0

Note: data is put together from the extensive project list in the Anuario Estadistico [65].

Emissions Penalty

The emissions penalties in Chile covers particulate matter (such as PM2.5), NOx, SO_2 and CO_2. The price for CO_2 is US$5/ton [109]. Currently, the only global pollutant covered by the green tax is CO_2, which is thus set to $5 in this model. As NOx is a local pollutant, the government has a formula for calculating the cost based on social costs and the affected population for a fixed source. As the value varies across the country, it is not incorporated in this model.

Availability and Capacity Factor

The availability and capacity factors provide similar indications of the technology.

The availability factor is the maximum amount of time that the power technology was able to produce electricity over the year long time period, as a fraction of the year, allowing for forced outages. The capacity factor is the electrical output in a given time slice over the maximum electrical output.

Availability factors were taken from government documents and relevant Chilean literature. Capacity factors were available for most technologies from company websites, and in the case of PV the assumption was made that without storage it would have a capacity factor of 0 during the two night time slices.

Many wind farms in the south of Chile which are part of the second generation of wind farms in the country, such as Las Peñas farm achieve consistent capacity factors of close to or more than 40% [110]. PV systems in the country are reported to reach capacity factors of 26%, whilst the singular JAMA solar PV project has systems which can reach 45% [111]. This thesis uses the more representative number of 26%. Using the company SolarReserve's CSP technology, a conservative estimate puts the capacity factor at 50%, modelled in the Atacama desert [112]. The solar collector trough at Cerro Dominador (currently the only CSP system in Chile) maintains heat once the sun goes down, so the capacity factor for summer night is 10% and winter night is 8%. A 2015 report produced by GIZ and funded by the German Ministry for the Environment, Protection of Nature and Nuclear Security found that capacity factors of 20% can be expected for rooftop solar, and have had government support over the last 3 years through the Distributed Distribution Law [113]. However, due to the geography of the country which runs north to south and is very thin, this is a quite a large generalisation for rooftop solar. Taking the TEMBA paper has a proxy for rooftop systems in similar climatic conditions, night time capacity factors of 11% and 13% for one and two hour storage respectively can be expected [36]. For more mature fossil fuel technologies, established availability factors from 2014 could be used. Chile has capacity factors of 78%, 62%, and 50% for coal, combined cycle natural gas and open (single) cycle natural gas production respectively [114]. Existing biomass facilities in Chile have capacity factors of 55%, although biomass CHP plants can reach capacity factors higher than this [115]. A 2015 report by Centro UC gave indicative availability factors of 90% for both fuel oil and diesel power plants, whereas the capacity factor can be as low as 30-60% [116].

Finally, a 2016 report by the University of Chile (Universidad de Chile) provided a full update of the capacity factors for all hydropower plants in the country [117]. However, as hydropower is such a geography and climatically dependent power source, the results themselves vary widely. As such, indicative figures for capacity factors of 0.65, 0.75 and 0.6 were chosen for run of river, small hydro and dam hydro plants respectively, based upon the spread of data available in the Universidad de Chile report.

Emissions Factor

Quantifying emissions is difficult, not only because data for emissions for technologies within Chile itself is not publicly available, but because the emissions from every power plant varies. Furthermore, there is the issue of whether the lifecycle of emissions should be counted, including construction (which would show PV and hydropower to perform significantly more poorly). However, following the Greenhouse Gas Protocol, the operational boundary for construction would normally preclude these emissions from inventories unless produced in the country – this is difficult to know and thus excluded [118]. *As such, emissions are point of production/operation emissions only.* Therefore, emission factors were first taken from the EPA values which the U.S. uses for the GHG Inventory, and assumed to be largely consistent across the Americas [119]. This was compared to the Japanese Joint Crediting Mechanism (JCM) calculation of Chile's emission factors for solar as a sense check. The ratio between the EPA values and the JCM values is consistently 1:2, but is important to remember that the JCM values include the entire grid emissions, and the emissions reductions calculation benefit Japan by allowing them to offset their own emissions [120]. Furthemore, the JCM values might also include heat production from CHP technologies. Nonetheless it provides a satisfactory benchmark and validation of emissions factors used in this study. For emissions from NCRE sources, Pehl et al's 2050 values were used, which give an estimate of the emissions on operation and environmental impact, including future advances in technology. Notably, this also includes methane emissions from reservoirs used for dam hydro generation, an often overlooked emission – here set at 1.765 g kWh-1 [121]. Methane is produced from the degradation of plants and organic matter, as well as flooded soils, leading to methane release at the water surface, turbines, spillways and downstream [122]. Values for wind, CSP and solar were given as CO_2eq only, and as such the emission factor was modelled as just CO_2. The figures in Pehl's study are somewhat lower than the proposed numbers by the IPCC: this is

because they were calculated to include technological innovation, and just encompass operation [123].

Table 10 Lifetime operation emission factors for both NCRE and biogenic sources for Solar PV, Wind Power, CSP, dam hydropower, factoring in technological improvements in the next 30 years as new technologies and processes for production are evermore efficient [121]

Technology	Emission factor
Solar PV	0.01389 $ktCO_2eq\ PJ^{-1}$
Wind power	0.1389 $ktCO_2eq\ PJ^{-1}$
CSP	0.2778 $ktCO_2eq\ PJ^{-1}$
Hydropower (biogenic CH_4)	0.4903 $ktCH_4PJ^{-1}$

Note: Dam hydropower does not have operational emissions.

Table 11 Emissions factors used in the model for Chile based on EPA values

Technology	CO_2 factor (kg/mmbtu)	CH_4 factor (g/mmbtu)	N_2O factor (g/mmbtu)
Biomass CHP plant	107.330	25.800	16.200
Coal power plant	95.520	11.000	1.600
Diesel power plants (all)	73.25	3.000	0.600
Oil fired gas turbine	73.250	3.000	0.600
Natural gas (combined cycle)	53.060	1.000	0.100
Natural gas (open cycle)	53.060	1.000	0.100

Note: These values were converted to Mt/PJ in the model, with original figure from [119]. Import is not calculated as an emissions source as the accounting would go to the country which extracted the commodity.

Reserve margin

Chile has had troubles since Argentina cut off the supply of gas, and as such there is no defined target for the country, although it has recently been 20%. The reserve margin was chosen to be 1.2 for fuels, forcing 20% reserve stock. Normally reserve margins are kept for reasons such as a natural disaster or (geo)political conflict, such as that seen in Venezuela, a country well-endowed with oil but unable to extract it [124].

Specified Annual Demand

The specified annual demand was determined using the Previsión de Demanda, which can be found in the Annex [125]. Due to the change in Law 20.805, Clientes Libres (free customers) are now defined as those whose connected power exceeds 5000 kW [126]. Thus, industry was taken to be the free customers whilst the rest of the demand was taken to be rural and urban demand over the year. The report gives a projection to the year 2038, and the trend line was extrapolated to 2040. The split between rural and urban was taken as the percentage split between the rural and urban population, which does admittedly assume that rural and urban users have the same consumption habits, therefore modelling the geographic separation but not necessarily the societal separation [127]. Demand was modelled for the SEN network, which covers 99% of demand in Chile: the Aysén and Megallenes regions have been excluded from this study, in large part due to availability of data.
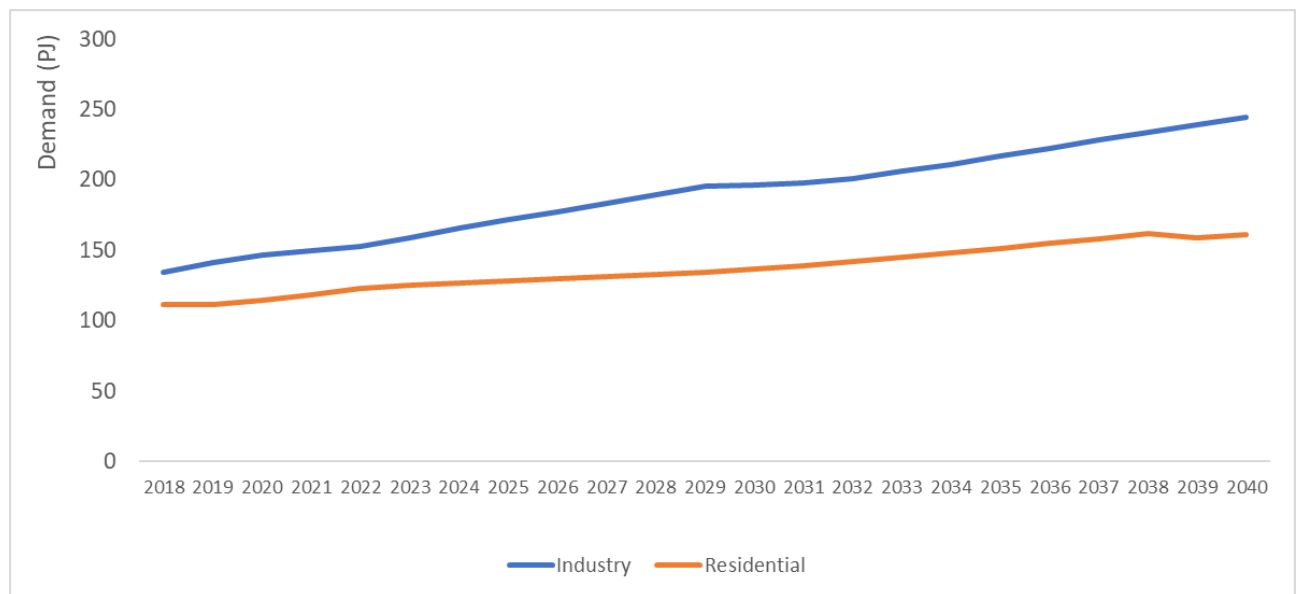
Figure 5 The demand, in PJ, as modelled and predicted by the CNE in Chile [127].
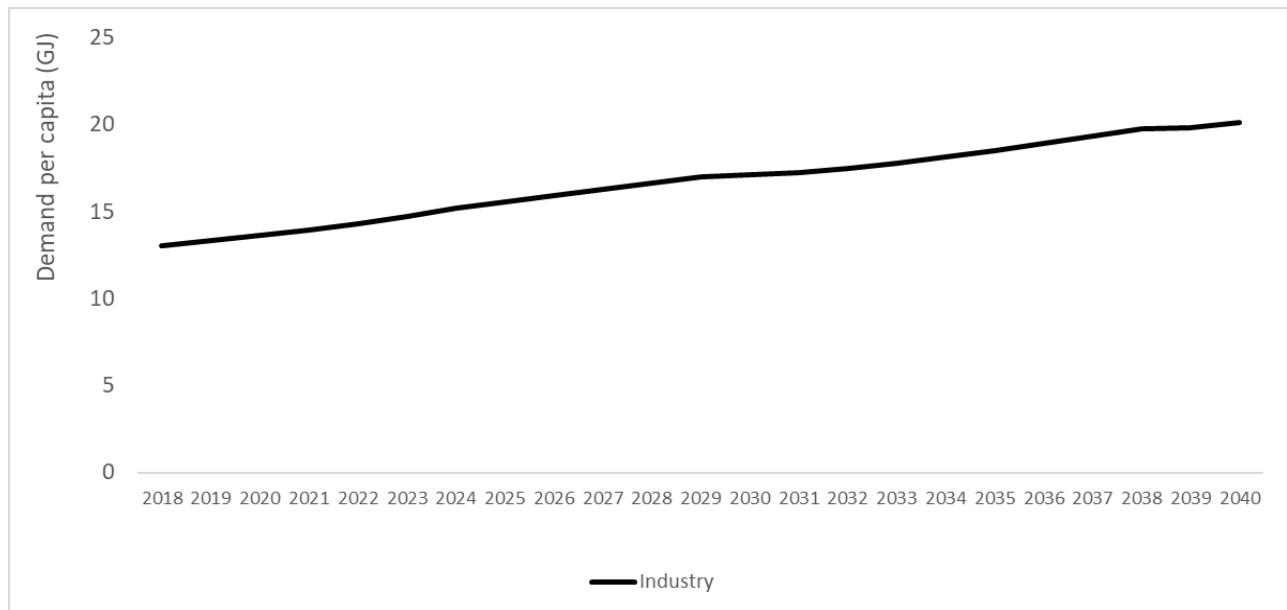
Figure 6 The annual, demand per capita, in GJ. (source: Author's estimation from CNE demand projections and World Bank population projections [125,135,138]

Specified annual demand profile

The specified annual demand profile was taken from a government analysis showing the daily load profile for every month [103]. This was plotted in excel, and taking the sunset and sunrise hours, converted into the specified annual demand profile for summer day/night and winter day/night. The demand profile for rural, urban and industry was taken from CNE data (below). Given that 100% of the Chilean population has access to electricity, the divide between urban and rural is
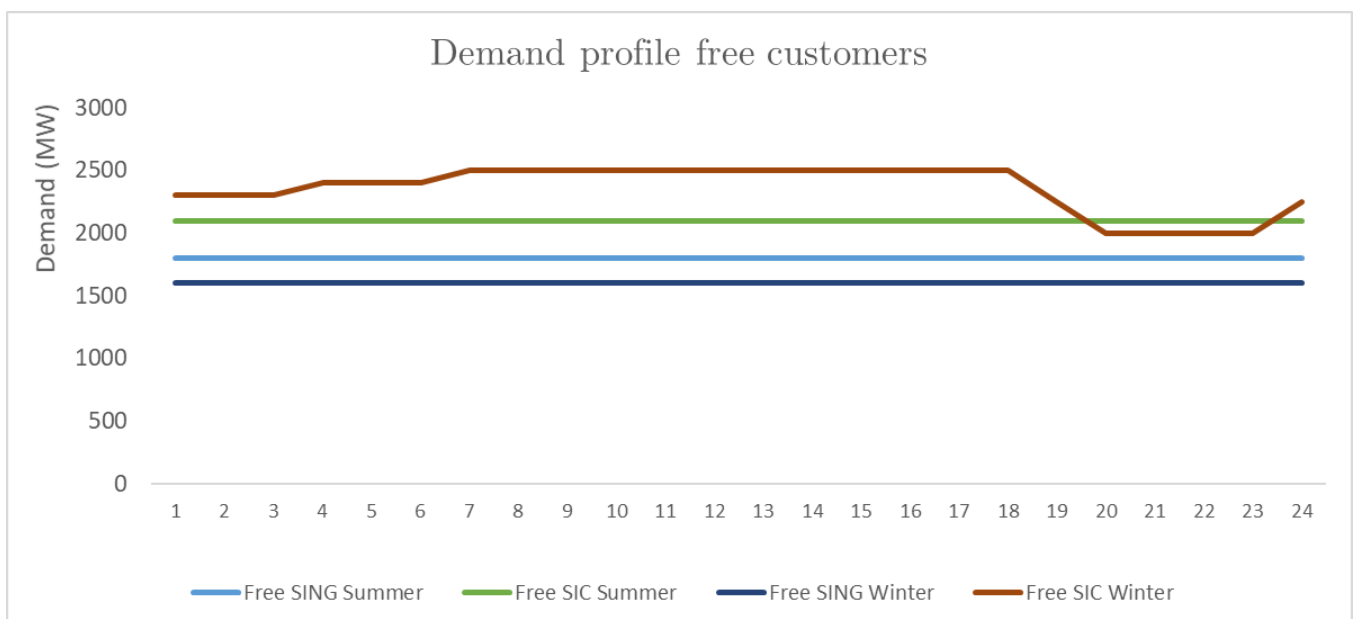
Figure 7 Demand profile for free customers with a demand of more than 5 MW [103].
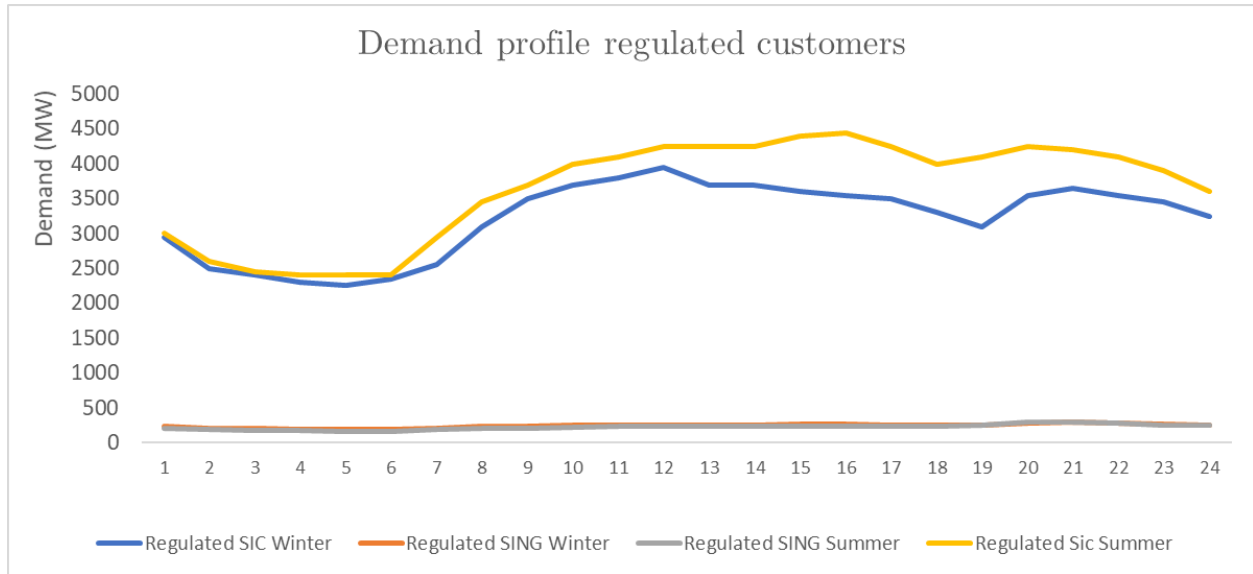
Figure 8 Demand profile of regulated customers with a demand of less than 500 kW, or between 500 kW and 5 MW should they choose to be regulated customers [103].

geographical, set up to allow future modelling of the transmission network and costs [128]. This allows the modeller to see if remote technologies (such as mini-grids) would be more effective, but is not included in this model.

The Total Annual Max/Min Capacity [Investment] were generally set at infinity (99999) and 0 respectively to encourage the model to find the best solution given the real-world constraints, except for where existing construction was already planned, whereby the Min Capacity [Investment] value was merely Residual plus newly installed capacity, and for dam hydro, for which there is only so much existing capacity potential in the country. Solar PV and wind had a limit of 1GW investment for the first 3 years, after which a limit of 1.5 GW each was set to simulate the financial conditions and realities of investing in renewables right now in Chile. The same was done for the Annual Activity Limits, except for extraction technologies which have a low limit as Chile is currently a gross net importer of fossil fuels.

Capacity to activity

Capacity to activity ratio is the conversion factor from the power units used in the model to the energy units: in this case, 31.536. This is taken by multiplying the capacity by hours in a year to obtain 8760 GWh, and converting this into PJ.

3.2.3 Sensitivity Analysis

A sensitivity analysis is key to determining how different parameters within the OSeMOSYS model affect the key outputs, which in this case are the total production by technology, the share of NCRE, the investment costs and the GHG emissions.

In order to keep consistency between results of the sensitivity analysis, changes are applied to the inputs of one scenario. As the business as usual scenario is the scenario which details the likely outcome given current conditions and policy, the BAU was chosen for the sensitivity analysis. For each parameter, three changes on the parameter were selected: an extreme decrease, a possible decrease, and a possible increase. The structure of the sensitivity analysis was inspired by Benavides et al's paper on the green tax in Chile [18].

Based on the results seen in the model, six-key parameters were selected for sensitivity analysis. The values are given as percentages of the original BAU figures:

a) Price of coal as a fuel
   i.   25%
   ii.   50%
   iii. 150%
b) Price of natural gas as a fuel
   i.   25%
   ii.   50%
   iii. 150%
c) Capital cost of wind
   i.   50%
   ii.   125%
   iii. 150%
d) Capital cost of solar
   i.   50%
   ii.   125%
   iii. 150%
e) Capacity factor of hydropower (in light of climate change)
   i.   -0.10
   ii.   -0.05
   iii. +0.05
f) Capital cost of both wind and utility scale PV
   i.   50%
   ii.   125%
   iii. 150%

Again, the sensitivity analysis was applied to the BAU case.

4   Results

In this chapter, results for each of the three scenarios are presented, starting with the business as usual scenario, then the null PPA scenario, and finally the NCRE scenario. Results are presented considering the research questions:

A) *"What will be the GHG emissions and investment costs for the electricity sector if Chile achieves its goal to be coal free by 2040?".*

B) *"What will be the GHG emissions and investment costs for the modelling period of 2019-2040 if Chile achieves its goal of carbon neutrality by 2050?"*

Thus, the results are divided into production by technology, capital investment, total annual capacity and annual emissions.

4.1   Scenario 1: Business as Usual Scenario

The pathway with the lowest net present cost for the business as usual scenario involves a total investment of US$42.61B, with US$10.85B invested in 12.18 GW of solar PV and US$17.24B invested in 13.87 GW of wind power. This is due to the low capital and fixed costs of solar and wind in Chile, coupled with the high cost of fossil fuels in the country. The low cost of solar, partly due to the desert, is cause for investment in solar around 2026 when the new auction for 2026 comes into force,
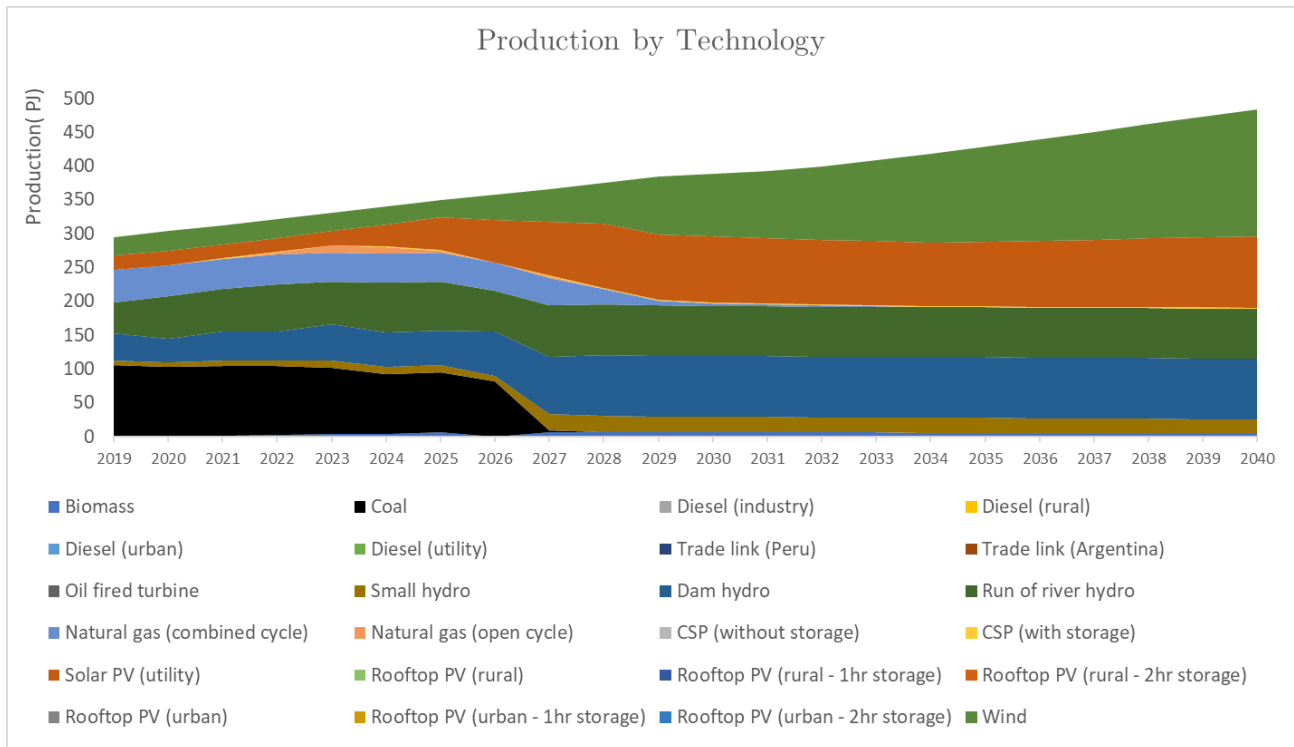
Figure 9 Production by technology, in PJ, for the BAU scenario in the time period 2019-2040
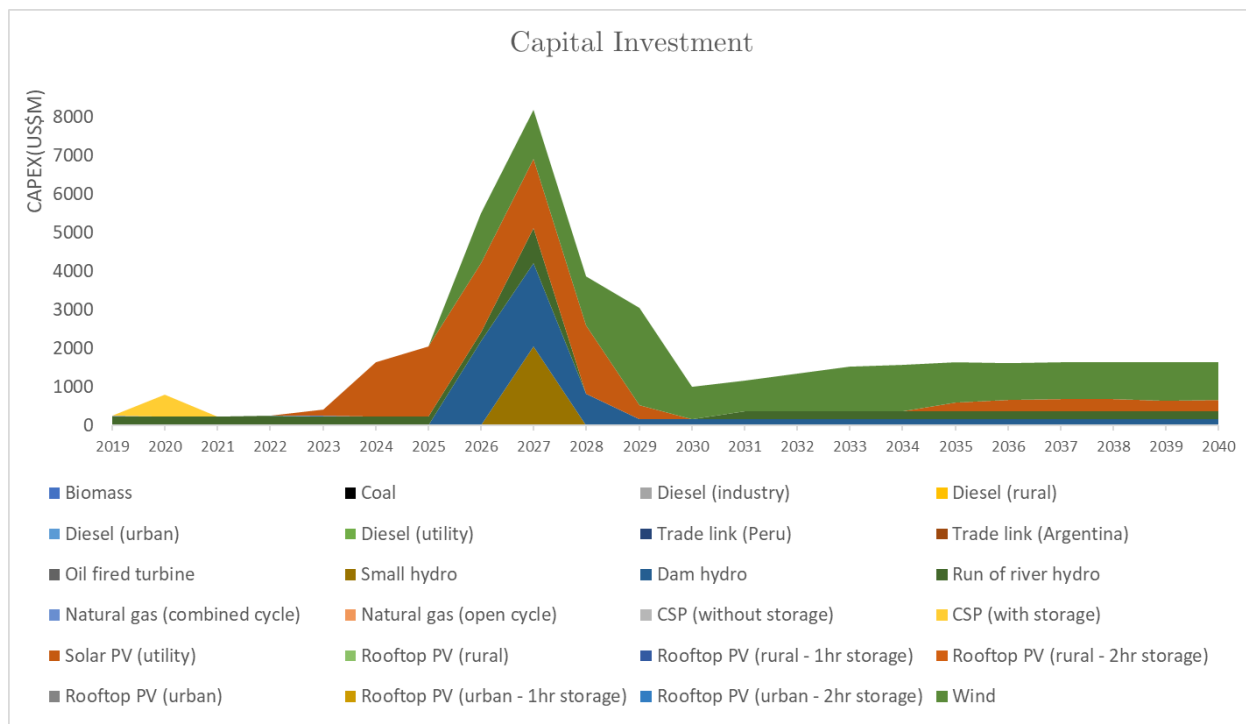
Figure 10 Capital investment, in US$M, for the BAU scenario in the time period 2019-2040

after which the price for wind falls under US$1300M/GW. As wind has a higher capacity factor over the year (and especially at night) as it does not directly depend on solar irradiation, the cost per kWh produced is comparable to solar PV, which has a capital cost of US$900M/GW in 2025. Without suitable large-scale storage solutions in Chile, the model elects to install wind to meet the night time demand. Even in the business as usual scenario, with just a 20% minimum NCRE requirement in 2025, the least NPC pathway is still to not invest in fossil fuels. The reason is twofold: first, coal, natural gas and diesel are expensive in Chile, driving the cost of each kWh high; second, NCRE is already cost competitive in Chile. In 2018, the cheapest technology by capital cost was solar at US$970M/GW, which also had the fourth lowest fixed cost of US$14.55M/GW. Whilst wind had the third highest fixed cost at US$47.6M/GW, the lack of a fuel cost makes it more competitive than fossil-based technologies.

Solar and wind produced 49 PJ in 2019, rising to 293 PJ in 2040, or 16.7% to 60.7% in 2019 and 2040 respectively. Hydropower production increases from 92.7 PJ in 2019 to 184 PJ in 2040, or 31.4% to 38.1% in 2019 and 2040 respectively. CSP continues to produce 1.38 PJ from 2021 to 2040 from the one CSP plant at Cerro Dominador saw a two-year stoppage in construction from 2016 to 2018. The share of production from NCRE increases from 18.7% in 2019 to 65.3% in 2040.
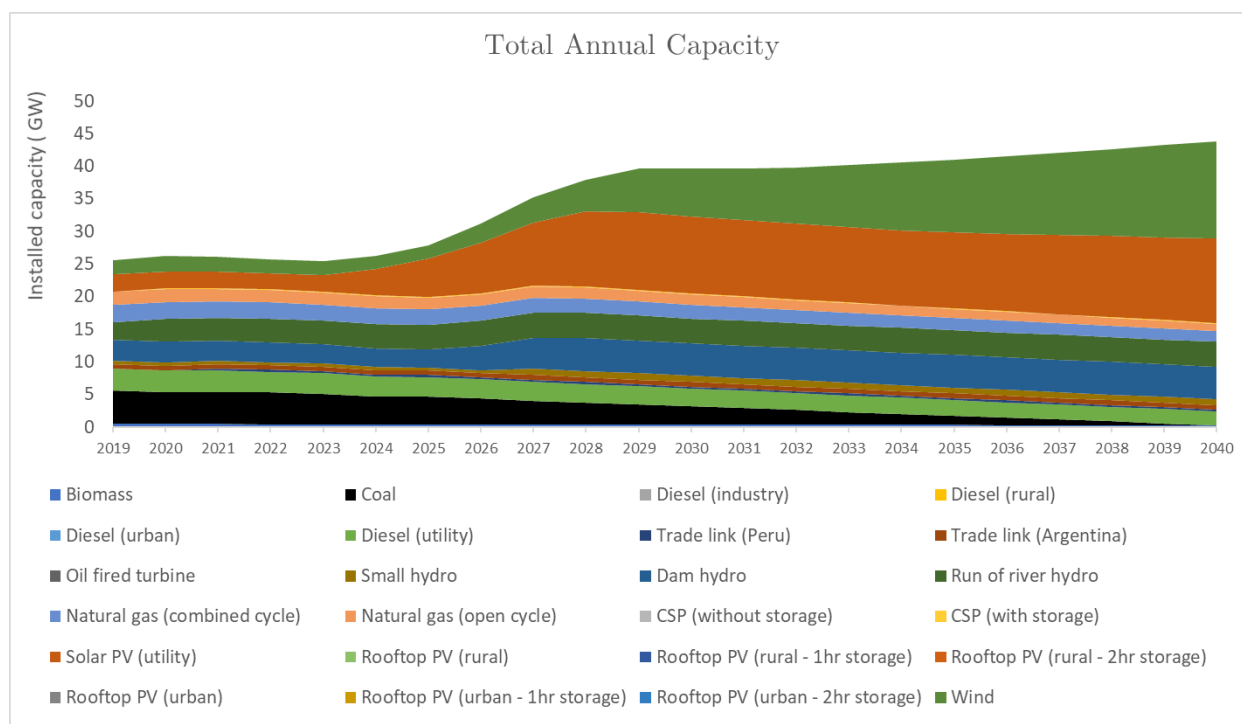
Figure 11 Total annual capacity, in GW, for the BAU scenario for the time period 2019-2040

In the BAU scenario, due to power purchase agreements for mines and supply contracts bought on the Chilean energy auction, coal and natural gas power still provide electricity until 2026, when the next round of the energy auction is due to take place. Between 2019 and 2026 this amounts to around 100 PJ a year for coal, 47 PJ a year for natural gas.
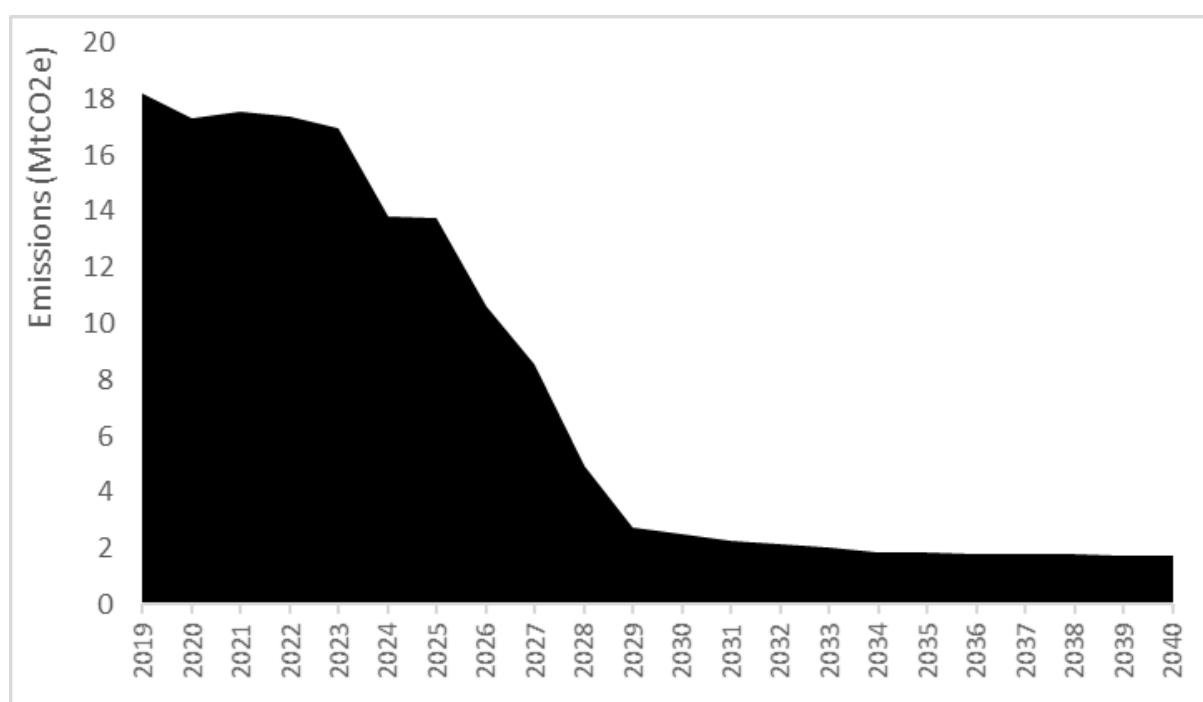
Figure 12 Annual emissions, in Mt, in the BAU scenario in the time period 2019-2040

The model covers three common greenhouse gases: carbon dioxide, methane and nitrogen dioxide. CH4 and NO2 have a global warming potential of 34 and 298 relative to CO_2, although this figure changes depending on the period over which the emissions are evaluated. Following the lowest net present cost pathway laid out by OSeMOSYS, in the year 2030 (a common year of analysis and comparison for NDCs), Chile would emit 0.00011 Mt of NO_x, 1.21 Mt of CO_2 and 0.036 Mt of CH_4. Converted to CO_{2eq} and summed, this gives 2.47 Mt of CO_{2eq} for the year 2030, significantly lower than Chile's targets. Over the model lifetime, this gives 163.2 Mt CO_{2eq} for emissions from the electricity section. However, between 2020-2030, the emissions total 126 Mt CO_{2eq}.

The decreasing trend is largely due to the switch from fossil-based fuels to wind and solar power. Until 2026 there are power purchase agreements which are fulfilled which involves the burning of fossil fuels. After this date, the model switches to NCRE and hydro power, both of which have much lower emission activity ratios. Due to biogenic CH_4 emissions from dam hydro power, CH_4 emissions remain high at 1.23 $MtCO_{2eq}$ in 2040.

4.2 Scenario 2: No Power Purchase Agreements Scenario
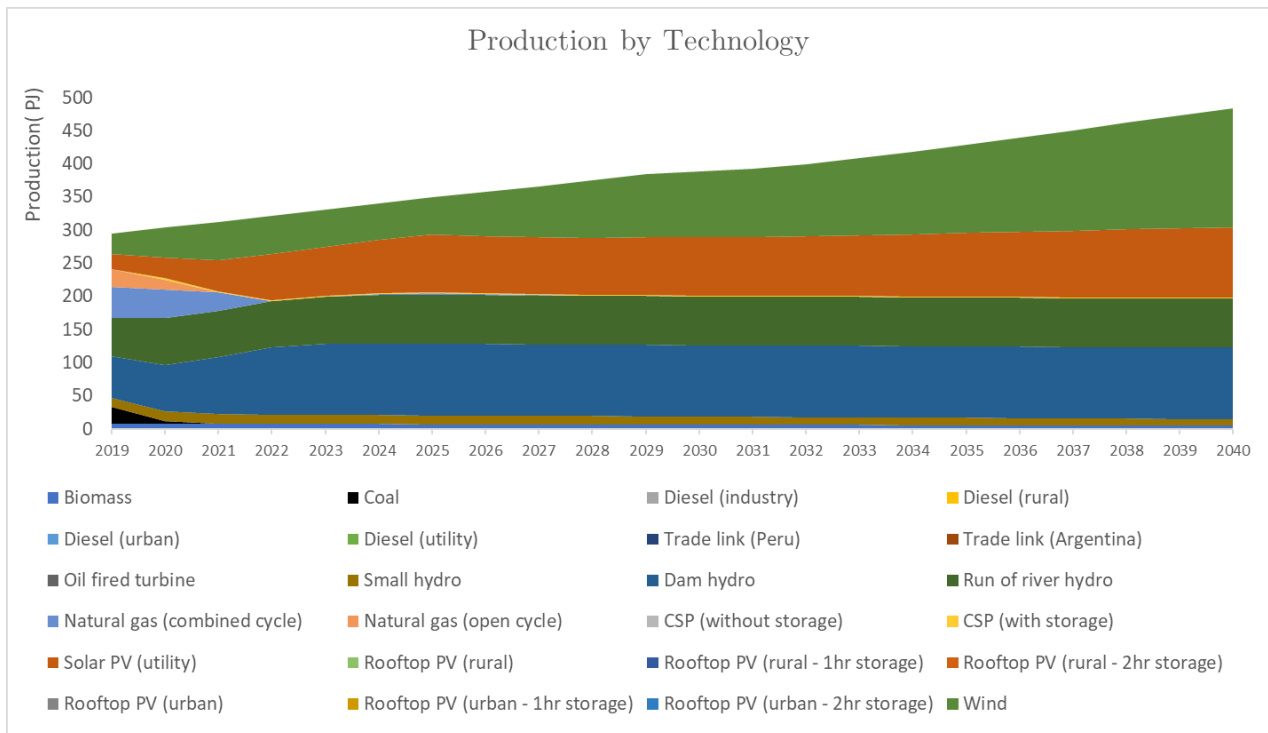
Figure 13 Production by technology, in PJ, for the Null PPA scenario in the time period 2019-2040

In the scenario where power purchase agreements are either paid off (in the case of mines for example) or the voluntary switch of auction purchases from fossil fuels to renewables, there is a marked difference in the use of fossil fuels to power the system. Natural gas covers 73.2 PJ of total production in 2019, with 46.5 PJ of combined cycle production and 26.6 PJ of single cycle production. Combined cycle natural gas continues to produce electricity till 2021, producing 42.5 PJ and 28.3 PJ in 2020 and 2021. Production from wind increase from 36.7 PJ in 2019 to 179.7 in 2040, whilst solar moves from producing 23.5 PJ in 2019 to 106.8 PJ in 2040. CSP provides a constant 1.39 PJ from operation, and biomass starts by providing 7.94 PJ in 2019 and falls to 4.54 PJ in 2040. Hydropower provides the remaining electricity –from 45.7% in 2019 to 39.6% in 2040. Dam hydro provides the bulk of this, rising from 62.2 PJ in 2019 to 107.9 PJ in 2040, whereas run of the river hydro rises from 58.3 PJ in 2019 to 73.7 PJ in 2040.
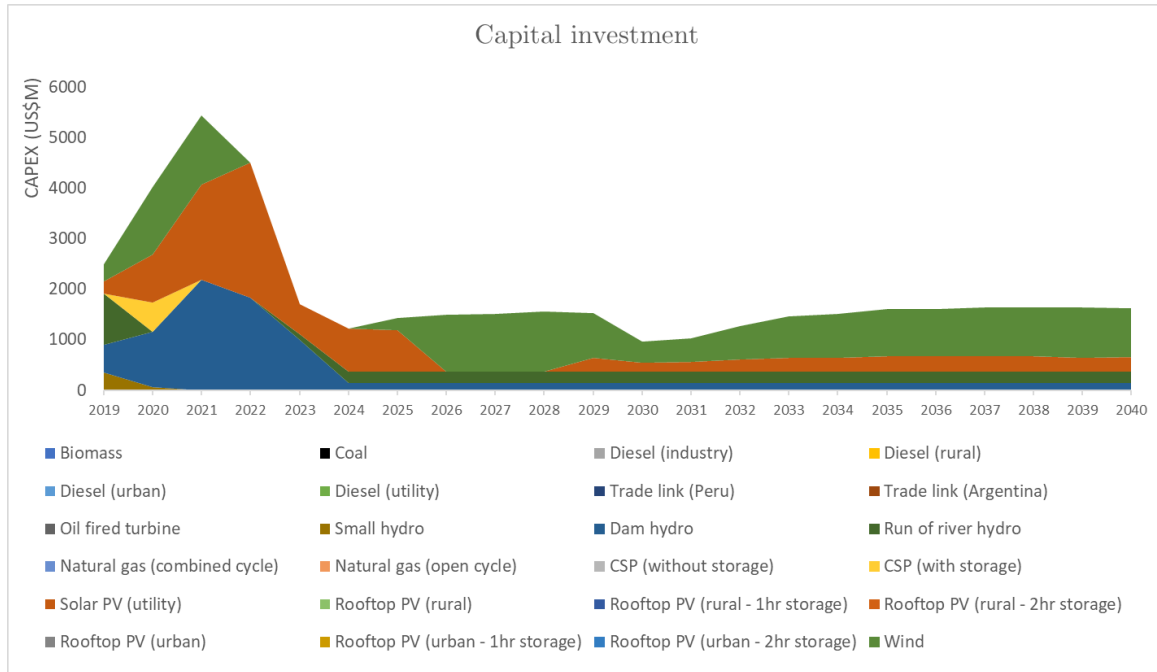
Figure 14 Capital investment, in US$M, for the null PPA scenario in the time period 2019-2040

Capital investment throughout the modelling period totals US$42.80B, $190M more than the BAU scenario. However, the fixed and variable costs are significantly lower, in large part due to the fuel price difference between free wind and solar resources, and fossil fuels. Years 2019 through 2022 include pre-planned construction, as well as significant dam hydro investment which would max out the potential for hydro in Chile. The capex for utility scale PV totals US$11.2B, and US$16.6B giving 12.3 GW and 13.2 GW of additional generation capacity for PV and wind respectively.

Overall, the total installed capacity shows a trend to increased renewables over the modelling period. In 2019, the proportion of NCRE is 23.9%, which increases to 64.2% in 2040. The percentage of installed generation capacity which does not rely upon fossil fuels as a feedstock rises from 48.2% in 2019 to 86.5% in 2040. Installed capacity rises from 26.6 GW in 2019 (including pre-planned projects and model recommendations) to 43.7 GW in 2040. Although the model was presented with 24 technology options, in this scenario it chooses just 13.

In 2030, Chile's emissions 1.94 Mt of CO_{2eq}. Over the model lifetime, emissions are 76.1 $MtCO_2e$.
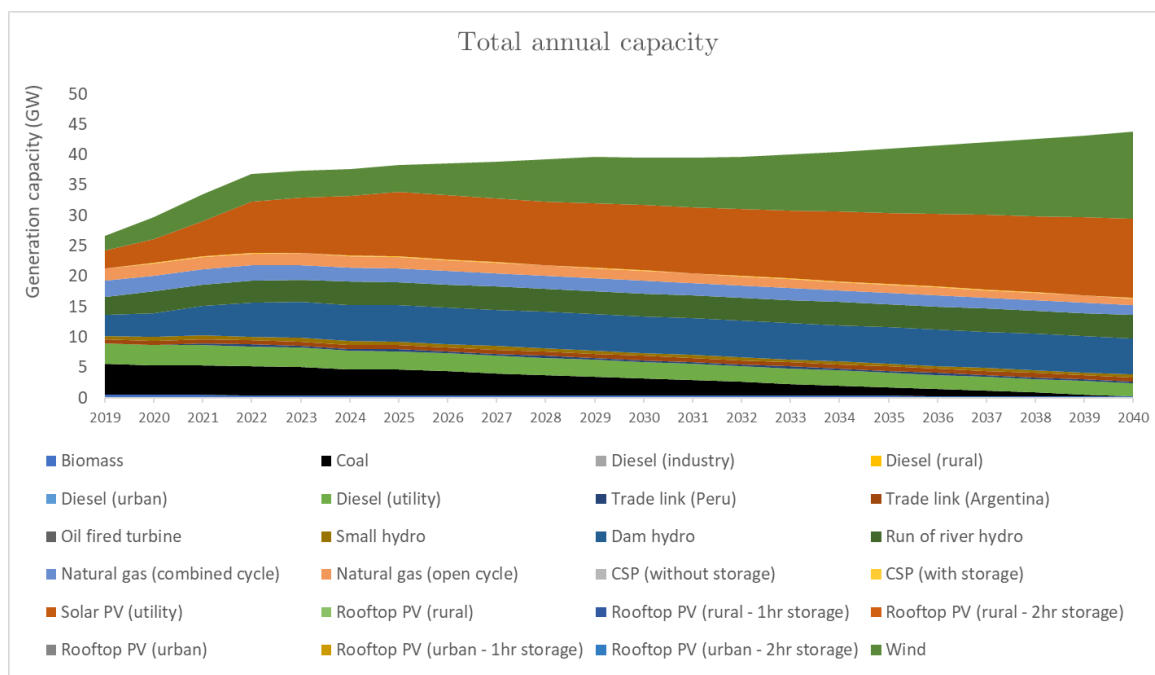
Figure 15 Total annual capacity, in GW, for the null PPA scenario in the time period 2019-2040

In 2019 and 2020, some coal and natural is still used to produce electricity while other technologies are installed. After 2021, the model switches to NCRE and hydro power, both of which have much lower emission activity ratios, and emissions fall significantly. In this scenario, there are biogenic CH_4 emissions from dam hydropower and CH_4 emissions from biomass power plants, so CH_4 emissions are 1.2 $MtCO_{2eq}$ in 2040.
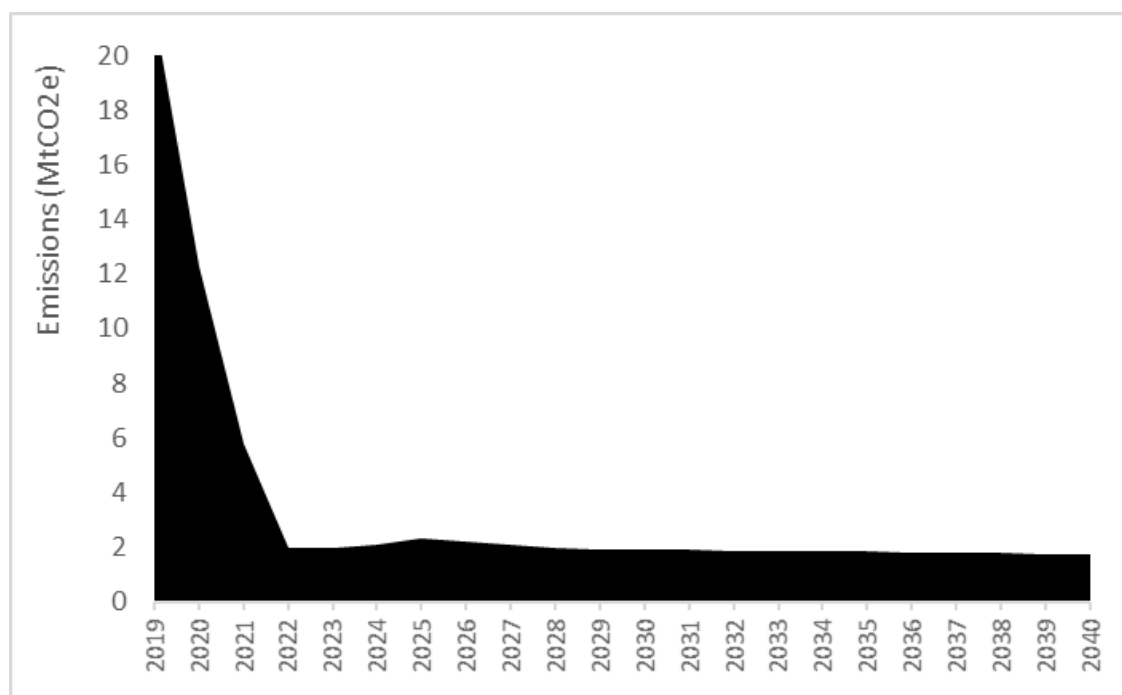
Figure 16 Annual emissions, in Mt, in the no PPA scenario in the time period 2019-2040

4.3 Scenario 3: Non-Conventional Renewable Energy Scenario
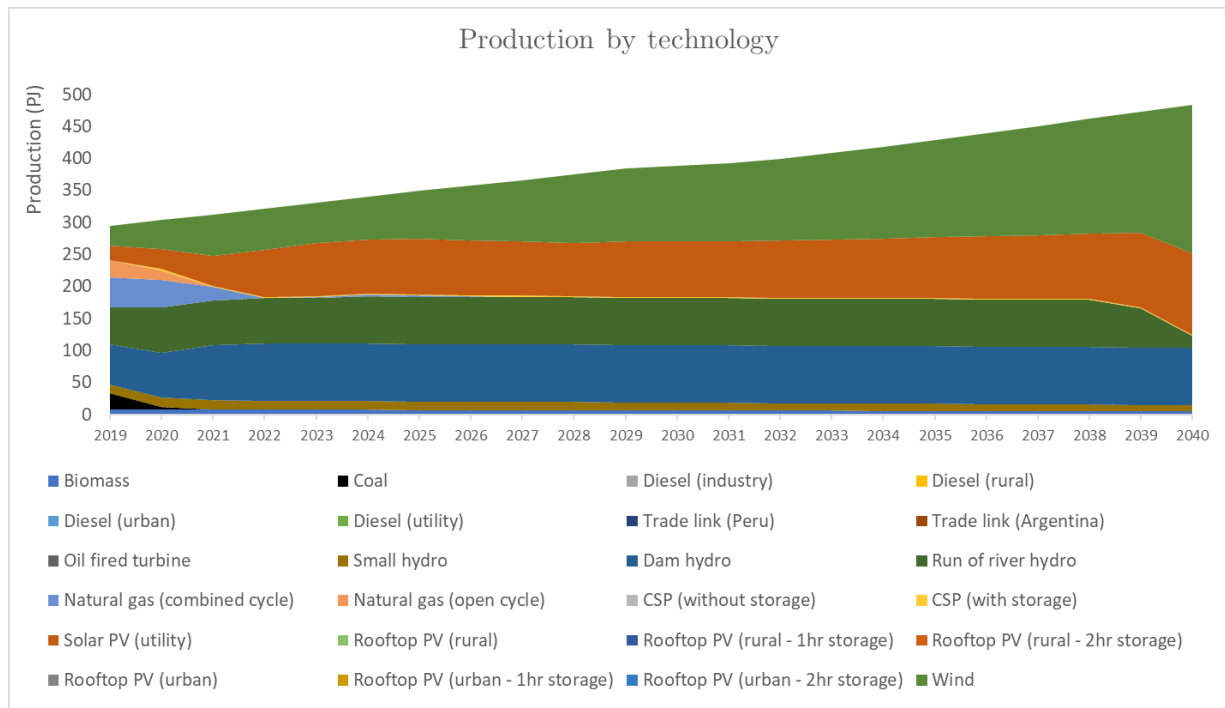
Figure 17 Production by technology, in PJ, for the NCRE scenario in the time period 2019-2040

In this scenario, we see that hydro still plays a large role till 2040 due to relative the cheap capital and operating requirements. Dam hydro generates 62.2 PJ in 2019 and 89.9 PJ 2040, making up the majority of the production which is not NCRE. Run of the river hydro increases from 58.3 PJ in 2019 to 73.7 PJ in 2024, but tapers off to just 18.9 PJ between 2038 and 2040 to fulfil the NCRE requirement. Small hydro, a NCRE, provides 14.2 PJ in 2019 and 10.0 PJ in 2040. Natural gas provides 73.2 PJ in 2019, 58.4 PJ in 2020 and 21.5 PJ in 2021, then provides a cumulative 9.7 PJ per year between 2023 and 2027 whilst renewable generation capacity is installed. Coal provides 28.5 PJ total in 2019 and 2020. The Cerro Dominador CSP plant comes online in 2020 and provides 1.39 PJ per year, but no new CSP generation capacity is installed in the modelling period, likely due to the high capital cost compared to other non-conventional renewable energy technologies. Solar PV production increases over five-fold in the modelling period, starting at 23.5 PJ and finishing at 127.1 PJ. Wind production also increases over five-fold from 30.8 PJ in 2019 to 232.1 PJ in 2040. In the NCRE scenario, the Peru trade link is not used when it comes online in 2021, and the Argentina trade link is not as the export license does not exist. Overall, generation increases from 295 PJ to 484 PJ.

Similar trends are seen for capital investment in the NCRE scenario as were seen in the null PPA scenario. First, 2019 through 2022 see particularly high investments totalling US\$16.3B, as these years not only include historical investments which were

due to come online/finish construction, but also include the necessary investment to meet the NCRE minimum production requirement for the scenario. Compared with the no PPA scenario, more is invested in wind from 2019 to 2021, with a total of US$3.76B as opposed to US$3.04B, which helps to meet the early NCRE minimum production requirements of the scenario. In 2039 to 2040, over twice as much is invested in wind in the NCRE scenario, with a total of US$5.1B compared to US$1.96B in the null PPA scenario. Over the modelling period, US$21.7B is invested in wind, which is 30.7% more than in the null PPA scenario. This allows the system to transition away from conventional hydropower at the end of the modelling period to satisfy the NCRE minimum production. After a large initial expenditure of US$7.1B in utility PV between 2020 and 2023, there is a more uniform investment of US$5.3B between 2029 and 2040.

Overall, the installed capacity for the renewable energy scenario again shows a trend to increased renewables over the modelling period. In 2019, the share of NCRE is 23.9%, which increases to 70.3% in 2040. The percentage of installed capacity which
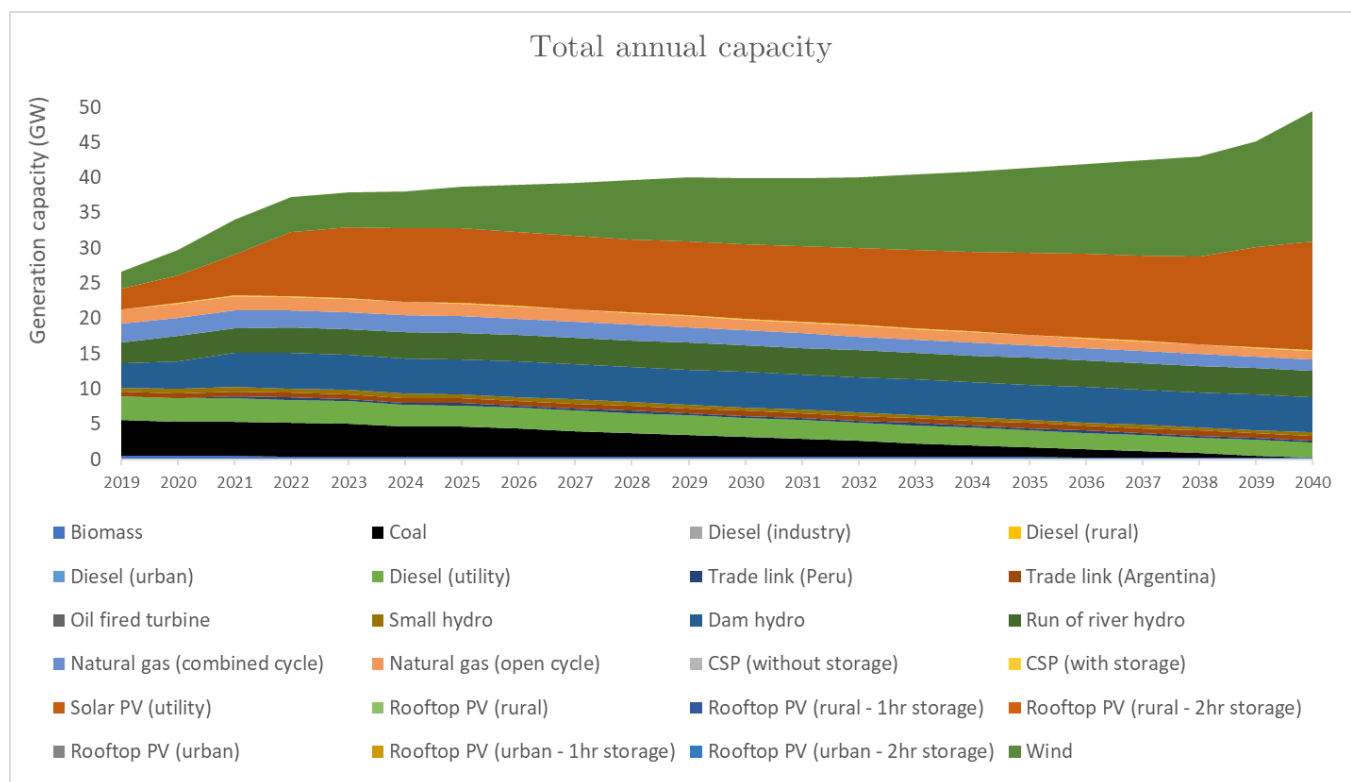
Figure 18 Total annual capacity, in GW, for the NCRE scenario in the time period 2019-2040
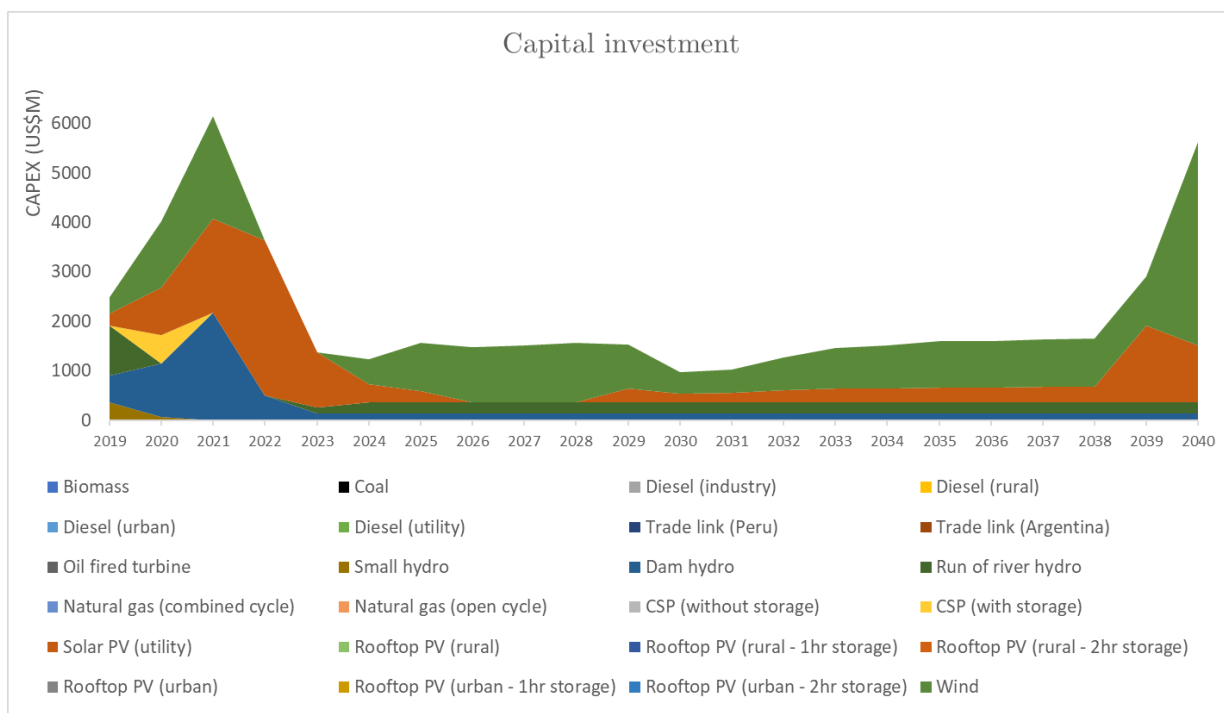
Figure 19 Capital investment, in US$M, for the NCRE scenario in the time period 2019-2040

does not rely upon fossil fuels as a feedstock rises from 48.2% to 88.1%. Installed capacity rises from 26.6 GW in 2019 (including pre-planned projects and model recommendations) to 49.4 GW in 2040.

In 2030, Chile's emissions would be 0.0009 Mt of NO_x, 0.645 Mt of CO_2 and 0.036 Mt of CH_4. Converted to CO_{2eq} and summed, this gives 1.9 Mt of CO_{2eq} for the year
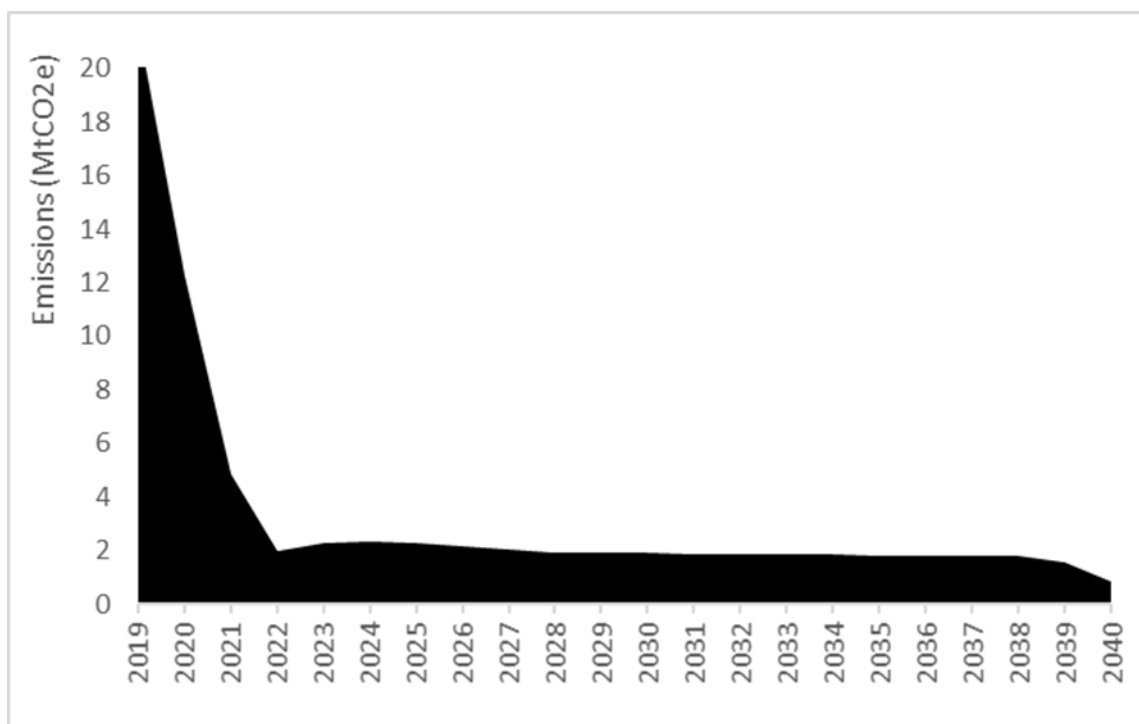
Figure 20 Annual emissions, in Mt, in the NCRE scenario in the time period 2019-2040

2030. Over the model lifetime, emissions are 74.68 Mt CO_{2eq}, 1.9% lower than the null-PPA scenario. However, between 2020-2030, the emissions total 36 Mt CO_{2eq}.

In 2019 and 2020, some coal and natural is, like in the null PPA scenario, still used to produce electricity while other technologies are installed. After 2021, the model switches to NCRE and hydro power, both of which have much lower emission activity ratios, and emissions fall significantly. In this scenario, there are fewer biogenic CH_4 emissions from dam hydro power, so CH_4 emissions are 0.32 $MtCO_2eq$ in 2040.

4.4 Results of sensitivity analysis

The results are presented in Table 12 below, showing that the price of natural gas is the most sensitive parameter.

Sensitivity scenario	Sub-scenario	Δ NCRE production share[1]	Δ% Capital investment[2]	Δ% GHG emissions[3]
a (price of the coal)	i	0.80	-2.23	99.74%
	ii	0.50	-2.18	62.77%
	iii	0.90	0.00	0.37%
b (price of natural gas)	i	-43.00	-36.69	230.94%
	ii	-5.80	-7.67	40.93%
	iii	0.90	0.11	-2.51%
c (capital cost wind)	i	11.30	-32.71	-3.60%
	ii	-0.20	8.07	15.26%
	iii	-2.30	12.16	34.79%
d (capital cost solar PV)	i	-1.70	-17.82	-0.55%
	ii	0.90	6.23	11.95%
	iii	-0.20	9.07	6.31%
e[4] (capacity factor hydropower)	i	8.40	3.33	6.13%
	ii	3.50	3.39	1.96%
	iii	-1.80	-3.49	-1.40%
f (capital cost of wind and solar)	i	12.30	-44.97	-4.13%
	ii	0.80	16.50	4.69%
	iii	0.20	31.53	15.10%

Table 12 Summary table of the sensitivity analysis results. Red text represents an undesirable change with respect to the thesis research and Chile's goals.

As coal has a pre-determined phase out plan, even a drastic fall in coal prices would only change the capital investment needed by 2.23%, and would see a change to the NCRE share of production by 1.23 percentage points. However, whilst coal is still in

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[1] Change in NCRE of production in 2040

[2] For the total required capital investment

[3] For the total model period GHG emissions in $MtCO_2e$

[4] The hydropower sensitivity takes a 10-15% variation in input, whereas the other variables take a 25-75% variation.

operation, the cheap price would see increased uptake and thus a huge increase in GHG emissions.

The most sensitive variable which would affect all three primary outputs is the price of natural gas as a fuel: if natural gas were 50% cheaper to Chile, the share of NCRE in 2040 would be 8.88% less, the required capital investment would be US$3.3B less and the resulting GHG emissions would be 40.93% higher compared with the BAU scenario. A 40.93% increase in model period emissions is equivalent to 17.463 $MtCO_2e$ between 2020 and 2030: compared to Chile's target range of 1110-1175 $MtCO_2e$ economy wide emissions for the same period, it would result in an additional 1.57% of the carbon budget filled. Whilst not insignificant, the figure is still relatively small. This is significant because currently the price of natural gas in Chile is high, even compared to the rest of South America. Argentina, which has sizeable gas fields (such as La Vaca Muerta) likely sees this 50% price for their own gas consumption, and as such it is possible that Chile could see natural gas prices falling in the next 20 years if trade with Argentina increased or if the global prices varied significantly to the figures used in this thesis.

On the other side, the capital cost of wind and solar seems to be less significant variable for emissions and NCRE share. A 25% increase in the capital cost of wind, solar or wind & solar leads to -0.20, 0.90, and 0.80 difference in NCRE respectively (compared with a starting value of 65.3%). This an insignificant value. However, the capital cost increases for these scenarios. Yet this is because even *with* a 25% increase in capital cost, the model calculates that NCRE energy investment is still leads to the cheapest net present cost.

The sensitivity scenarios for hydropower show interesting result. In the BAU scenario, both large dam hydropower and run of the river hydropower provided a significant share of electricity production: together, all three hydropower technologies accounted for around 40% of production in 2040. However, climate change will lead to uncertainty and increased variability in rain fall. If the capacity factor of hydropower technologies were to reduce by 0.05, the overall change would be small (as seen in sensitivity scenario *e ii*). However, if the capacity factor were to fall by 0.1, the share of NCRE would increase 8.40 to cover for hydropower, and emissions would increase to 1800 $MtCO_2e$ as natural gas would also be used to cover for the lack of hydropower.

4.5 Model calibration

In order to determine that results fall within an expected range, it is important to compare them with existing data. In this case, two points of data exist: results from 2019 and the BloombergNEF Chile Power System Outlook [59]. For more details of the BloombergNEF report, please go to Model calibration in the Annex.

In 2019, 0.2 GW of wind was installed in one quarter, giving a total possible range of 0.2-0.8 GW for wind, and there was 1.4 GW of installed solar. Besides the "Minimum New Capacity" from existing projects, the OSeMOSYS model implements no new solar or wind, and just 50 MW of small hydropower from existing projects. Thus, the total new additions for 2019 in the OSeMOSYS perfectly match what was installed.

Then, comparing the results of the OSeMOSYS model to BloombergNEF's results, the trendlines for total emissions in the BAU scenario follows exactly the same shape which can be seen in Figure 27 of BloombergNEF's report.

Figure 26 shows the gross capacity additions and cumulative investments in the BNEF report. There are clearly differences in the way the BNEF model and the model in this thesis have been set up. This thesis' literature review found that batteries on a large scale were not yet considered, and that peaking hydro storage would be considered from 2030 onwards. Furthermore, rooftop solar was not economically viable compared to utility scale PV price wise, but of course residential solar is in the end a choice for the end consumer, not the energy auctions. Furthermore, this thesis divided hydro into three components, as this information allowed small hydro to be pulled into NCRE, and this is how the government itself issues statistics.

The BloombergNEF numbers for emissions are higher than this thesis, for two principle reasons. Firstly, Bloomberg assumes that in both their coal phase out and BAU scenarios, production from coal will only drop below an initial plateau in 2025.

However, current trends in Chile have shown that the rate of coal replacement is higher than this. Furthermore, due to the reopening of the natural gas trade route with Argentina, this thesis has used higher production numbers for natural gas power plants which at one point held long term PPA contracts which were then left in limbo, assuming that power producers such as Enel would elect to use the natural gas instead of coal when possible, and natural gas has lower emissions per unit of electricity output.

Next, the BloombergNEF report estimates that the capital investment cost from 2019-2040 for a coal-phase out scenario would be US$44.4B [59]. This is just US$1.8B or 4.1% out from the result of this thesis for the BAU scenario at US$42.6B. Finally, BloombergNEF's projections show that variable renewable's share of generation, which can be closely approximated to NCRE, is 73% in 2050 or around 70% in 2040. This thesis estimates that value to be 65.3%, which is an approximate 5% difference.

Finally, there is a calibration point to be made for the emissions factors used. A JCM (Joint Crediting Mechanism – A Japanese initiative) non-peer reviewed report for Chile found that the emissions factor for fossil fuel-based technologies for the whole generation system were around 40% higher than even the coal figures for the EPA government values [120]. This would put the results more in line with the BNEF values. However, the JCM figures are for the whole system, not just point of source emissions, and as included earlier, may have bias as the JCM stands to benefit financially through saved emissions through switching to PV through technology transfer, as the saved emissions could also be used for Japanese emissions reduction targets. Without technology specific emissions and no peer review, the values could only be used as a bench mark.

5 Discussion

The research of this thesis was centred around two primary axes presented in the research question: investment cost and GHG emissions. In all three scenarios, it is clear that solar PV at a utility scale and wind power play a large role in the generation mix, making up the majority of NCRE technology, whilst hydropower is also important in all three scenarios during the modelling period. As there is a limited potential for new hydropower capacity, most investment in all three scenarios is in solar PV and wind. This has a positive effect on GHG emissions in all three scenarios, with a negative trend in CO_2e emissions. The negative trend is especially steep in the null-PPA and NCRE scenarios, in which Chile is likely to meet its NDC targets (for both the existing and revised NDC).

The BAU and null-PPA scenarios are of similar cost, as the null-PPA has an investment cost just 0.469% higher than the BAU scenario. This is because in both scenarios, coal plants will be decommissioned, and other generation capacity needs to be installed to cover this. In both cases, NCRE is the cheapest technology to do this, so both scenarios see the same production share from NCRE in 2040, as well as the same investment cost. The only difference is the years in which NCRE is deployed. However, there is a dramatic difference in emissions between the two scenarios, which can be seen in Figure 21.

Between 2019 and 2030, emissions are 87.141 $MtCO_2e$ higher in the BAU scenario. However, in both scenarios coal capacity is phased out. This shows that it is not the coal power capacity that is important for emissions, but the utilisation of this capacity. If PPAs are kept and adhered to, emissions will remain high. However, although the capital investment cost may be lower for the BAU scenario, there is a large discrepancy between the variable operating costs. For coal alone, the variable cost in 2019 is \$3B+ vs \$920M in the null-PPA scenario. This is why there is a large
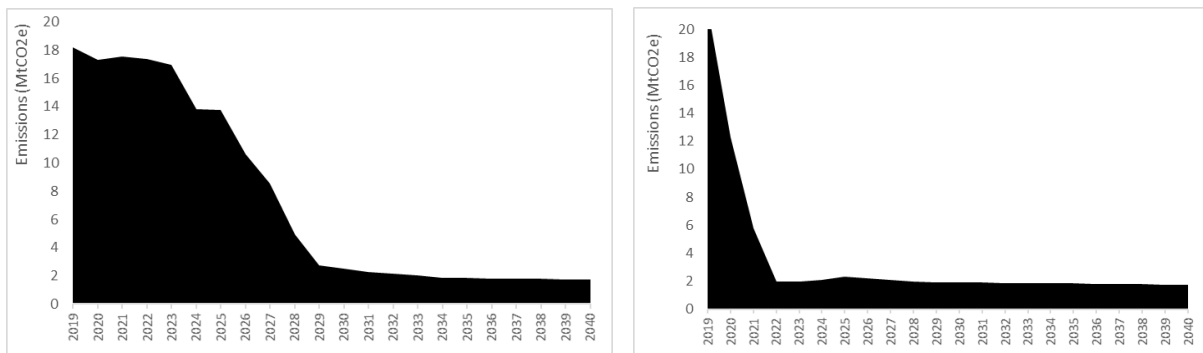
Figure 21 Comparison of emissions between BAU scenario (left) and the null-PPA scenario (right) which have the same investment costs.

difference in NCRE installed capacity in years 2019-2027 between the BAU and null-PPA scenario; although the coal generation capacity is already in place, the variable plus fixed cost of coal is higher than the fixed plus capital cost of wind and solar (as well as the fixed cost of coal which still exists in the null PPA). In purely economic terms, the marginal cost of coal is higher than the levelized cost of energy of soalr and wind. As described in the methodology, a small learning curve was applied to wind, solar PV and CSP. OSeMOSYS optimises the net present cost, which includes all three costs, and the NPC of wind and solar is cheaper. The same is true for natural gas. As such, it is imperative for Chile to find a way to transition existing fossil fuel PPAs to NCRE, or to eliminate PPAs to achieve an enormous reduction in GHG emissions. This is not the only case in which an OSeMOSYS model has shown that investing in renewable energy is a cost effective solution long term whilst removing fossil fuel import decision; a 2017 study by Dhakouani et al found that Tunisia could state invest in renewable energy to reach 30% penetration without significantly increasing system costs.

Although there is a large inherent cost in breaking contracts, BHP (the mining company) has shown that there is some business sense to doing so, likely as NCRE is cheap enough to recoup some of the money back. However, for PPA annulment to be rolled out on a wide scale, the government will need to introduce legislation to facilitate breaking and switching for private PPAs. The ever-increasing pace at which coal power plant owners, such as Enel, are committing to removing coal from the generation mix shows that there is will on the supply side too, for both "free customers" and the government procured "regulated customers". When there is cooperation by state actors with non-state actors on both side of the sale, such a move from Scenario 1 to Scenario 2 is completely feasible. It may not be easy, but the agreements between coal power producers and the government in 2019 shows that the phase out is possible. This is aided by the fact that the power big 5 power producers in Chile (see Table 1) all have a broad portfolio of generation technologies and are able to make the transition, in part due to the introduction of the renewable energy law, Law 20.257.

Between the null-PPA and NCRE scenario, there is a 1.90% difference in GHG emissions over the modelling period, yet a difference of $4.983B in the capital cost. Figure 24 shows the year on year total spending difference. The pattern is largely the same, although from 2034-2038 the numbers are slightly higher for the NCRE scenario. Most notably, however, is the spending from 2038-2040 which is significantly higher and accounts for most of the difference. This extra spending is to

accommodate for the NCRE requirement (as a NCRE is defined by the Chilean government and Law 20.571 on renewable energy). This difference in investment leads to 51% lower emissions in 2040 for the NCRE scenario compared to the no-PPA scenario. It is also pertinent to look at the capital investment vs GHG emissions as well as the production by technology vs GHG emissions to see how each of these outputs are connected to each other. The comparison graphs below for comparison within each scenario.
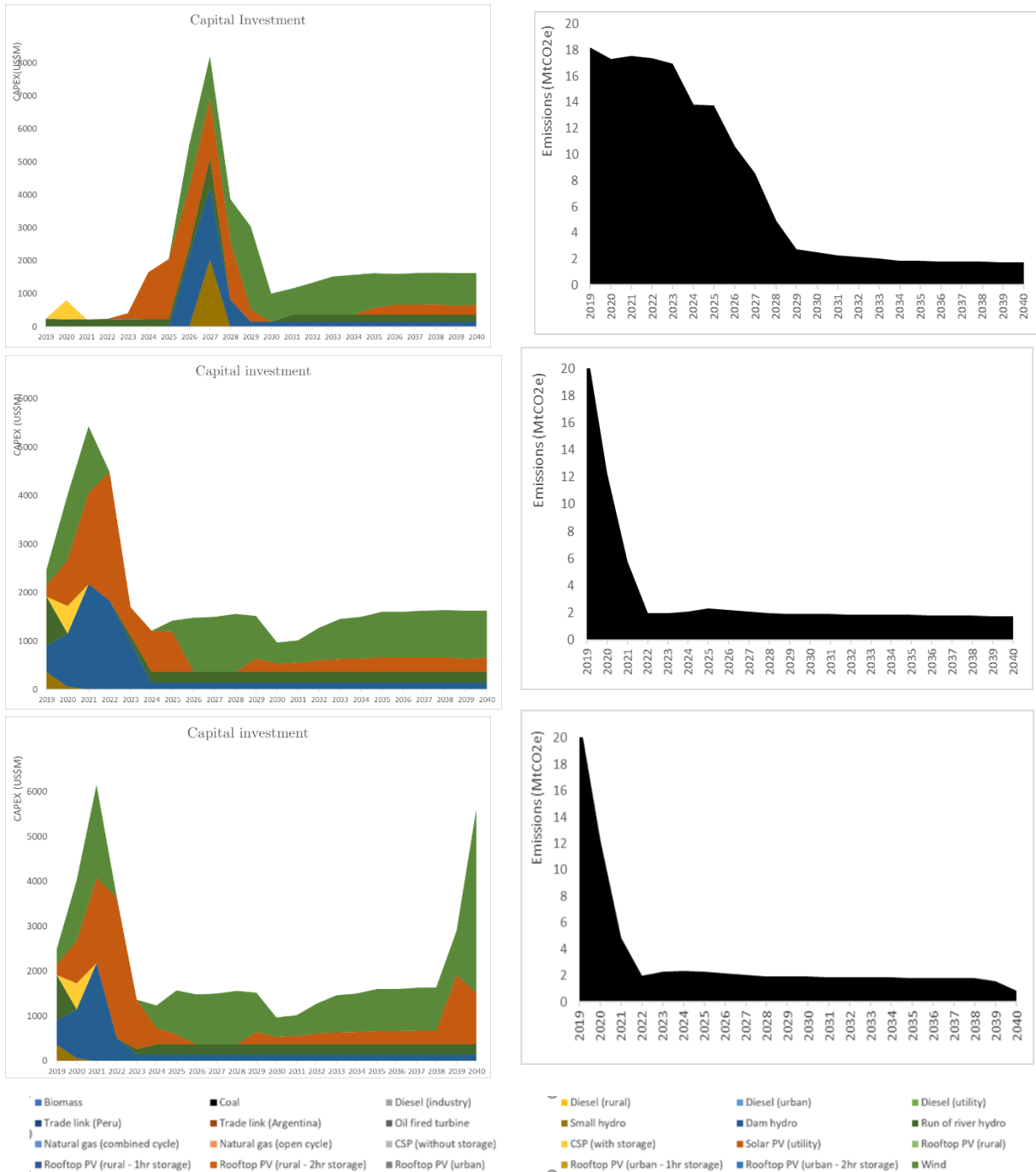
Figure 22 Comparison of the capital investment cost and annual emissions for the BAU (top), null PPA (middle) and NCRE (bottom) scenarios.

By delaying investment in NCRE technologies (in the case of the BAU scenario from 2021 to 2027) there is a significant increase in GHG emissions. As a consequence, the sooner that NCRE investment is deployed, the lower overall emissions will be, and the sooner emissions will peak and fall: from Figure 22 it is clear that the first major peak in investment leads to consistent falling emissions
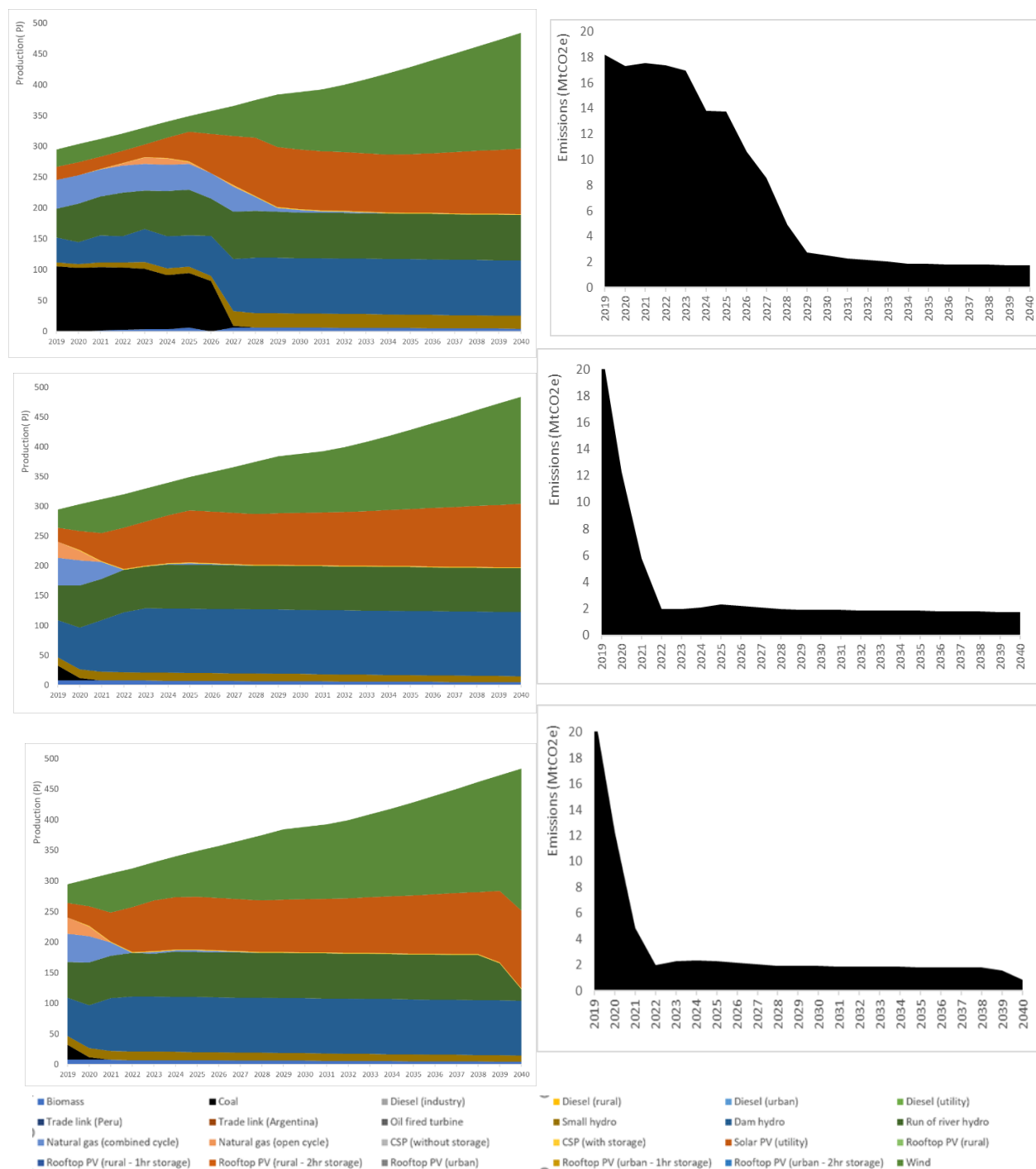
Figure 23 Comparison of the production by technology and emissions for the BAU (top), null-PPA (middle) and NCRE (bottom) scenarios.

From Figure 23, it is clear that production from coal and natural gas are the major drivers of emissions in Chile. As coal and natural gas production are phased out in each scenario, there is a noticeable drop off in emissions. With the natural resources Chile has, it should be a clear strategy to move towards NCRE and hydro production as soon as possible.

Next, these results will be compared against the updated NDC that Chile has released, to see if the various scenarios are in the ball park of complying with the targets. The most recent results, published in both the 3rd BUR and Chile's online National Greenhouse Gas Inventory Portal (SNI Chile), are for 2016, which provide a comprehensive breakdown of emissions for different sectors. In 2016, there were 48.5 $MtCO_2e$ of emissions not related to electricity and heat production, including manufacturing (but not industrial processes) and transport [129]. Whilst this thesis focused on electricity and not centralised heat production, utility scale heat production will be ignored. The Ruta Energética 2018-2022 envisages 20% energy efficiency savings throughout the energy sector outside of electricity production by 2025 [80]. Thus, additional emissions not related to electricity production in the year 2027 (the year in which Chile intends to reach peak emissions) could be approximately 38.8 $MtCO_2e$. All other emissions in the economy (from the agriculture, waste and industrial processes sectors, but excluding LULUCF) in 2016 were 24.55 $MtCO_2e$. Finally, emissions in the industrial sector could be expected to rise by up to 38.6% when factoring in the increased projected industrial demand as well as the 20% energy efficiency targets, which would result in a 2.66 MtCO2e by 2027. Therefore, by using 2016 values for emissions as a crude proxy for the economy in 2027 (whilst including planned policy measures and sectoral growth), estimated emissions for the BAU scenario would be 74.56 $MtCO_2e$. For the no PPA scenario this value is 68.07 $MtCO_2e$, and for the NCRE scenario is 66.65 $MtCO_2e$. These values do not account for heat generation in the energy sector, and does not account for increases or decreases in emissions from the waste, industrial processes, and agriculture sectors. Furthermore, the NDC mentions direct emissions and excludes LULUCF, so would not include the 1.1 $MtCO_2e$ savings expected from Chile's reforestation programme [130]. Furthermore, GHG emission savings by switching to EVs are also not included in these benchmarks. Chile has set out the target of 40% electrification of the private fleet by 2050, and 100% of public transport by 2050

[131]. With EV number in the private fleet set to increase from 900 (0.0167%) to 80000 (1.48%) by 2030, the savings would not be very significant by 2027 [132].

Comparing this to the NDC commitments set out by Chile, it is clear that all three scenarios should be feasible. Chile has set an unconditional target of 97 MtCO$_2$e in 2030, with emissions peaking in 2027 [91]. Chile has set a conditional target of 61-91 MtCO$_2$e for 2030, yet have not made clear what the terms of condition are. Based on the BAU scenario, emissions from heat generation, and potential increases from the waste, industrial processes and agricultural sector would have to over 30 MtCO$_2$e for Chile to not meet its unconditional NDC target.

Although the difference in GHG emissions is only 1.421 MtCO$_2$e (or 1.90%) between no PPA and NCRE scenarios over the modelling period, this does not tell the whole picture. In order to compare the results to Chile's NDC targets, GHG emissions were taken as *operating* emissions, as these are the emissions directly attributable to Chile's GHG Inventory. However, GHG emissions from construction are equally as important, but in some cases would not count towards Chile's GHG inventory. One example of this would be if Chile uses PV panels produced in China for its PV arrays; the emissions would be attributed to China's manufacturing sector.
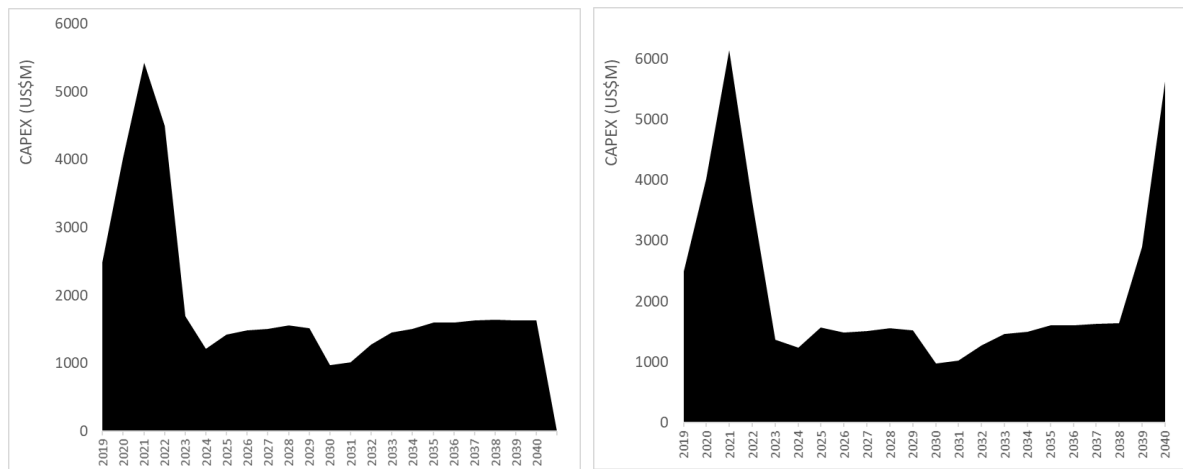
Figure 24 Comparison of investment (capital) costs between the null-PPA (left) and NCRE (right) scenarios

This difference is important. Pehl et al provide the following estimates for emissions from construction for NCRE, which is compared to the operating emissions in Table 13. As can be seen, dam hydro has lifetime emissions 18x larger than PV, 9x larger than CSP and 21x larger wind.

Although the operating emissions between the null-PPA and NCRE scenarios are 1.421 MtCO$_2$e (or 1.90%) different, in order to be truly carbon neutral by 2050 Chile needs to have an electricity sector which predominantly relies on NCRE, and this is

where the additional \$4.983B of spending in the NCRE is important. There is a difference of 0.9 MtCO₂e between the null PPA and NCRE scenarios in 2040, so the move to NCRE technologies does lead to a significant reduction in emissions. If the NCRE target was modelled till 2050, the difference would become more evident as biogenic CH_4 emissions from hydro amount to around 1 MtCO₂e, or the same as proposed reforestation measures in Chile. Furthermore, rain fall shows a negative trend in Chile in the coming decades, whereas solar irradiance is likely to remain the same [133]. For these reasons, a move away from hydropower is in the best of interests of Chile.

Technology	Operating emissions (gCO_2e kWh^{-1})	Construction emissions (gCO_2e kWh^{-1})
PV	0.1	4
Wind	1	2.5
Dam hydro	55	18
CSP	1	7

Table 13 Comparison of operating and construction emissions for NCRE and dam hydro

Although not the focus of this study, cross border trade of electricity is nonetheless an import component of a generation mix, and was included in this study. However, the geography of the regions surrounding Chile plays a limiting factor in cross border trade and leads to a lack of trade connections. Chile only currently has one interconnection, with Argentina. Between the regions of demand in Chile (to the north and in Santiago) lies the Andes mountain range which provides a significant physical barrier to interconnections, driving up the costs. To the north, a 300 MW connection is planned with Peru, which would only come online in 2021. Along with the 2011 suspension of the license for trade of electricity between Argentina and Chile, Chile is left with few options for regional trade. When the 300 MW interconnection with Peru does come online, it is likely that Chile will be a net importer of electricity (assuming Peru runs a net surplus), as Peru's marginal cost is significantly lowers than Chile's – although this disparity could diminish as cheap renewables take a larger share of the generation mix in Chile [70]. As such, this is one of the most interesting variables which can't be modelled with accuracy in the OseMOSYS model, and provides some uncertainty to the question of NCRE share of the generation mix, as the model currently assumes that the Argentina interconnection will continue to lay dormant, when in reality this is unlikely to be the case for 22 years. Nonetheless, given the small proportion of the generation capacity it represents for Chile (1 GW out of 42+ GW by 2040) it is not the most

important issue to focus in on given the study examines phasing out coal and deploying NCRE.

With the figures of $42.6-47.8B for investment costs, comparing these values with historical investments is a useful exercise to determine feasibility. Between 2010 and the end of 2019 $14.8B was invested in renewable energy capacity, with the majority of this investment from 2014 onwards [59]. That would put a rough average of about $2-2.5B invested each year once the full effects of Law 20.257 on renewable energy began to result in investment. Over the 22 year modelling period, this equates to $44-55B. Therefore, all the scenarios' required investment costs fall within this range, assuming that the investment trend seen from 2014-2019 is indicative of possible future investment trends. However, it is most certainly a large mobilisation of capital. Furthermore, the investment would be largely private, and this introduces conflicting motivations. The private sector which runs the electricity generation sub-sector is motivated, first and foremost, by profit. *This* is where the renewable energy law becomes so important: although NCRE is currently the most viable option, there is nothing to say that a novel natural gas technology or huge natural gas fields won't drive down the cost of electricity from natural gas. An example of this kind of price drive down is La Vaca Muerta fossil basin in Argentina, discovered in 2010 and still influencing the global commodity market in 2019 [134]. In this way, Scenario 3 ensures that private investment is funnelled into NCRE.

Whilst still an issue today, before 2017 transmission limitations were a critical issue. One potential limiting factor of this paper is that Chile was modelled as one region due to a lack of data for demand projections for SIC and SING. The official demand projections from the CNE are given for the entire SEN network. This was chosen as the best compromise given the data available for Chile, including the cost data which is also given by the government at a SEN aggregated level. However, an important factor in Chile is the location of generation technologies and generation potential (namely the Atacama desert) and the location of demand (in the case of residential urban demand, in the southern SIC network). As a consequence, although the OSeMOSYS model gives data for the required system wide capacity additions that are needed for the transmission and distribution networks, it does not account for the bottleneck at the transmission connection between the SIC and SING networks. Although this connection has plans to be further fortified, a future study could use the data from solar PV utility capacity recommendations to see how much further the SIC-SING connection needs to be upgraded, as utility scale PV and CSP potential, as well as a significant proportion of wind potential, lies to the north. This

would allow for another limitation to be overcome: due to different weather conditions, attrition rates on transmission lines, and overall capacity factor, is different in the north (SING) compared to the south (SIC). The transmission lines in the SING network would have a lower capacity factor as the weather is significantly warmer, which would in turn change the required capacity for the system: a lower capacity factor for the transmission requires more generation from generation technologies to meet a fixed demand. Therefore, it is likely that a higher investment in NCRE technologies would be needed, and the investment cost to reach NCRE targets in the third scenario would be higher. However, it is not likely that this additional cost would change the result for technologies that should require investment for any of the scenarios; a 1-3% difference in transmission grid capacity factor in the north would equate to about 250-750 MW extra capacity for renewables in the north. Compared to the costs of fossil fuels, this is relatively small: in one reference scenario completed in this study to check, coal needs to be roughly 25% of
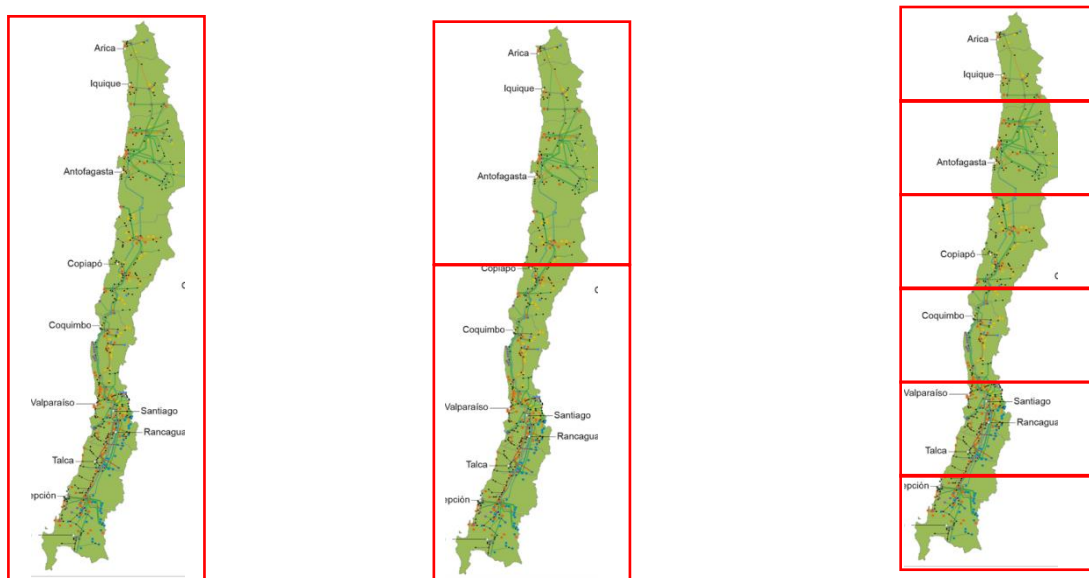
Figure 25 Different options for regional splits within the OSeMOSYS model, each with specific advantages and disadvantages. Left: current implementation of one SEN region, middle: two region model for SIC and SING with accurate demand projections for each to model the transmission upgrades needed, right: smaller regions [136].

the actual forecast price to be a viable option till 2040 [135]. The other piece of data which is collected from government sources is the capital, non-fossil variable and fixed cost for generation technologies, is given as a SEN wide average. Adding more regions to the model would provide more accurate data for capacity factors for technologies in each region at the cost of assumptions which would be made for costs in each region. Figure 25 provides a visual representation of the different regional splits that could be chosen when modelling Chile. Although the capacity factor of transmission lines cannot account for the actual distances between generation and

demand, this paper overall provides a good compromise. If more regions were implemented (such as the far right example in Figure 25), more assumptions would need to be made to split determine the costs for each region. The only way to account for the losses due to distances travelled between generation source and demand would be to model very small regions within Chile, then lower the efficiency/capacity factor of the inter-regional transmission lines, which would give a detailed insight into transmission losses, but this would entail a high level assumption based analysis of investment costs and demand projections, which would not provide satisfactory answers to the research questions posed in this study.

Demand (both specified annual and the demand profile) is one of the most important parameters used in this study. The figures used come from the CNE. Demand in Chile is typically dominated by industry [51]. In 2019, the share of free customers to regulated customers was 54.7%. This is expected to grow to 59.1% by 2038 [51]. This has several impacts on the overall power generation mix. First, Figure 3 regarding the demand profile shows that SIC has a greater demand for industry than SING, although most of the copper mines are in the SING grid. The SING region covers the Atacama desert, and this demand is forecasted by the CNE to grow. During the winter time bracket, SIC sees a fall in demand after 1800 and as such solar is well suited to match the demand profile, especially during the winter months. However, for the rest of demand, a night time base load is required, which is fulfilled by a combination of dam hydro and wind. Both of these resources have intermittency issues: wind is dependent upon the wind blowing, but has a capacity factor of 40% throughout the day, whereas dam hydro is dependent upon rainfall (which is predicted to decrease overall) but currently has a capacity factor of 60%.

As can be seen in Figure 7 and Figure 8, free customers (industrial demand) tends to have a uniform demand profile over the day, whilst regulated customers (rural/urban demand) exhibit a noticeable fall in demand from the hours of 0200-0600. Free customers have a year round average of 4000MW power demand, whereas regulated demand peaks at 4500MW at 1600, and falls to just 2500MW at night. Currently, there is no storage built into the system, and as such there must be a generation technology to match the industrial demand at night. This is why so much wind is installed in the three scenarios (especially the NCRE scenario in which hydro cannot be fully relied upon), despite being more expensive than solar PV. On the flip side, solar PV is able to meet the peak demand of rural/urban demand, and is especially valuable for this side of the demand, even if the region of highest solar potential is not next to the demand. Although one of the CSP technologies has storage built into

the model through modified capacity factors at night (for the thermal salt), the investment cost is too high to be viable for the model to include future investments in CSP over solar PV and wind.

When analysing the demand and supply constraints of the model, it is important to consider additional constraints that could be imposed on the system. The most likely of which is the electrification of the transport system; by 2050, 40% of private and 100% of public transport will be electrified, and as such this will impose an additional constraint on the system [131]. Peak demand in the system is currently around 10 GW, with overhead capacity thus at 13 GW. But by 2040, 5 GW of coal will be decommissioned and a larger amount of NCRE invested. This is a situation in which storage will start to play a role. The electrification targets are for 2050, and thus from the years 2040-2050 there will be a need for investment in energy storage solutions such as pumped hydro and utility scale battery to meet the peak demand without resorting to fossil fuels.

Finally, the initial research question was, "*What will be the GHG emissions and investment costs for the electricity sector if Chile achieves its goal to be coal free by 2040?*", and the sub-research question was *What will be the GHG emissions and investment costs for the electricity sector in the modelling period of 2019-2040 if Chile achieves its goal of carbon neutrality by 2050?*".

The BAU answers the initial research question: the investment cost would be $42.606B and would result in 163.2 $MtCO_2e$ total emissions from electricity generation. The null-PPA scenario explores the scenario in which PPAs are nullified, which would result in a reduction of 87.1 $MtCO_2e$ of GHG emissions compared to the BAU, at an extra cost of just $200M. The NCRE scenario provides the answer to the sub research question, showing that the investment cost would be $47.789B, and would result in 74.7 $MtCO_2e$ of operating emissions. Table 14 is a summary of results.

Scenario	NCRE share of production 2019	NCRE share of production 2040	Investment cost ($B)	Cumulative Emissions ($MtCO_2eq$)
BAU	18.7%	65.3%	42.606	163.2
Null-PPA	23.9%	64.2%	42.806	76.1
NCRE	23.9%	70.3%	47.789	74.7

Table 14 Comparison between the production by NCRE, total investment cost and emissions across the three scenarios in 2019 and 2040

6 Conclusion

This study sought to answer the research questions:

A) *"What will be the GHG emissions and investment costs for the electricity sector if Chile achieves its goal to be coal free by 2040?".*

B) *"What will be the GHG emissions and investment costs for the modelling period of 2019-2040 if Chile achieves its goal of carbon neutrality by 2050?"*

To do this, I presented a method to quantify the investment costs and GHG emissions that resulted in two related policy decisions taken in Chile in 2019: first, that Chile would phase coal out till 2040, and the second that Chile intended to be a carbon neutral economy by 2050. To do this, OSeMOSYS was used to model the power system infrastructure. The majority of the required data was found in two government reports: the "Anuario Estadistico", and "Informe de Costes de Generación". The remaining data was collected from Ministry websites and scholarly literature. This fulfilled the objective of modelling the electricity generation system for Chile in light of the policy developments described above.

Using this information, a business as usual scenario was built, which included power purchase agreements till 2026. The next scenario modelled the result of power purchase agreements being nullified, and the final scenario modelled the result of a 100% non-conventional renewable energy penetration target for 2050.

In all three scenarios, hydropower continues to play an important role in the energy mix. The investment cost of solar and wind is competitive, and as a consequence the share of NCRE greatly increases in all three scenarios.

Notably, the share of production of NCRE in the Null-PPA scenario is 64.2% in 2040. From an economic stand point, the lowest net present cost would result in a scenario in which the NCRE share of production falls just 5.8% short of the requirement in the NCRE scenario. In the business as usual scenario, the NCRE of production is 1.1% higher than the Null-PPA scenario. This shows that NCRE are market competitive in Chile.

In the business as usual scenario, the investment cost associated with removing coal as a production technology by 2040 is $42.606B, and this pathway would result in 163.2 MtCO$_2$eq of emissions over the model period.

If all PPAs are nullified, the total investment cost would be \$42.806B, resulting in 76.1 $MtCO_2eq$ over the model period. Compared to the BAU scenario, this is a 53.4% decrease in emissions.

In order to meet the 2050 carbon neutrality goal, which, as the government currently defines their plans, would see a 68% NCRE minimum production target in 2040, a total investment of \$47.789B which results in 74.68 $MtCO_2eq$ of emissions over the model period.

Despite the small difference between emissions for the null-PPA and NCRE scenarios, there are other benefits to NCRE technologies which make it a priority for the government, such as producing electricity closer to industrial demand and mitigating the effects of variable rain fall on hydro production.

There are several trends throughout the results which are of note. Firstly, rooftop production is not used in any of the scenarios. Compared with utility scale NCRE, it is simply too expensive.

Across each of the scenarios, it is clear that hydro resources are among the most promising, with dam hydro set to provide up to 25% of supply in all scenarios. In 2017 and 2018 Chile had 31 MW and 17 MW of dam hydro in construction, although almost 3 GW has at one point held an environmental license. Although the potential is there, mega projects have in the past failed to pass the public vote and had their license revoked. Therefore, although the costs of large hydropower are some of the most competitive, they face significant social barriers. This is on top of the risk climate change poses to water levels throughout the world, including Chile.

Therefore, in order to ensure the greatest reduction in emissions, Chile needs to move away from fossil fuel generation technologies as soon as possible, and follow the lead of mining companies to quickly move away from both coal and natural gas.

7 Further research

There are limitations with this study. As discussed earlier, there is a limitation of demand data, and it was not possible to model intra-regional transmission and distribution networks. Moving forward, with demand data from 2018 for both SIC and SING, the model could be split into two regions: SIC and SING. As the demand profile data is for both SIC and SING, specified demand projection for SING and SIC separately would allow for demand to be more accurately matched to supply—for example, the demand of mines could be more accurately modelled to potential NCRE investments, as the model would instead model transmission between SIC and SING as trade, and future grid investments needed to overcome historical grid connection issues would be highlighted.

Furthermore, this model used historical data for hydropower capacity factors. With climate change, increasingly variable water levels are expected, which would affect the production capability of hydropower. Weather forecast data could be used to evaluate future capacity factors for hydropower by creating each hydropower station as a separate technology, and using weather forecasts to apply individual capacity factors.

The model does not make use of the storage code equations of OSeMOSYS as currently there is very limited planned storage solutions in the country. Instead, the thermal salt storage for the Cerro Dominador CSP plant was modelled by providing a capacity factor for the night instead. If Chile were to come out with policies which incentivised storage solutions, then including OSeMOSYS's built in storage parameters may become pertinent, and would add a valuable extra layer to the model. This would be relevant to the research focus of this paper (unlike the transmission grid modelling trade-offs analysis seen in the discussion).

Finally, the lifecycle emissions have not been calculated in this study, but have been mentioned in the discussion. A further study could additionally calculate the life cyle emissions for better comparison between technologies and the 2050 carbon neutrality target.

As this study stands, there is no discernible difference between rural and urban demand: Chile has a 100% electrification rate and as such rural demand does not require different sources of electricity. However, by including rural as a specific demand, future research could use the existing model and some of the data, and then take the multi-region approach seen to the right of Figure 25 would then be able to

model the most suitable new generation capacity investments based on geographical challenges and costs of reaching remote communities, which allow the paper to analyse microgrids, for example. However, as the research focus of this paper was the investment costs and consequent GHG emissions of the governments climate policy plans for the electricity sector, this approach would not have been suitable for this study.

8 Annex

8.1 How OSeMOSYS works

In OSeMOSYS, as in other linear programmes, contains parameters and variables which are used in the governing equations to solve for the dependent variables which are output as results.

As seen in Figure 3, the OSeMOSYS code is broken down into blocks of equations which, overall, comprises one objective function, several equations and several constraints. The objective function is:

$$minimum\ cost: \sum_{r,y=1}^{r,y} C_{ry}$$

Where C is the total discounted cost for the year y in region r.

Following, several equations are generated. The first is the rate of demand, generated from the user defined Specified Annual Demand and Specified Demand Profile for each commodity (in the case of this thesis, coal, natural gas, oil, primary/secondary/tertiary electricity).

$$RoD(r,l,f,y) = \frac{SpecifiedAnnualDemand(r,f,y)\ .\ SpecifiedDemandProfile(r,f,l,y)}{YearSplit(l,y)}$$

Next, Capacity Adequacy A is calculated. This is done by taking the Residual Capacity from before 2019, adding this to the Accumulated New Capacity, and then adding the incremental New Capacity. This capacity is compared to the Rate of Total Activity in each Time Slice and Year, for each technology and the respective commodity.

Capacity Adequacy B ensures that the capacity of technologies can meet the average annual demand.

There are two sets of Energy Balance equation. Energy Balance A ensures that the demand for each commodity (such as coal, natural gas, electricity 1/2/3 etc. is met in every Time Slice (summer/winter day/night). Energy Balance B ensures that the demand for each commodity is met in each year (2019-2040).

There are further equations used in OSeMOSYS which are explained further in the manual: Accounting Technology Production/Use equations are used to generate

specific intermediate variables such as Production by Technology. There are no storage equations or constraints in the model used in this thesis.

After this, the capital costs set of equations calculates the total discounted capital cost expenditure for technology (one equation for the undiscounted capital investment, and one to calculate the discounted value from the undiscounted).

Salvage value is calculated using straight line depreciation to give a value of the recoverable value of assets. The operating costs set of equations calculates the total variable and fixed operating costs for each technology, in each year.

Finally, the Total Discounted Costs equations calculate the total discounted system cost over the modelling period to give Total Discounted Cost, which is minimized in the objective function.

Next are the constraints. Total Capacity Constraints ensures that the total capacity of each technology in each year is great than the used generated Total Annual Min Capacity Investment and less than the user generated Total Annual Max Capacity Investment.

New Capacity Constraints ensures that the new capacity for each technology installed is greater than Total Annual Min Capacity Investment, but less than Total Annual Max Capacity Investment – these parameters are used in the model to ensure unfeasible early model period investments are not made.

The Annual Activity Constraints ensure that the total activity of each technology is great than or less than the parameters Total Technology Annual Activity Lower Limit and Total Technology Annual Activity Upper Limit, respectively. These parameters are used in the BAU scenarios to ensure that coal and natural gas production mandated by PPAs is carried out.

There are several further constraints which can be read in the manual, but here I will disclose one more. RE Production Target ensures that the production from technologies tagged as renewable energy technologies is greater than or equal to the user-defined renewable energy target.

Finally, the Emissions Accounting accounting calculates the annual and model period emissions from each technology for each emission gas, as well as the associated emission penalties (for CO_2 in this thesis). OSeMOSYS is run in two versions: long and shore code equations. This thesis used the short code equations.

8.2 Model calibration

Currently there is only one other fully disclosed model for just Chile which has been constructed in the last year, by BloombergNEF. This serves as a source for two points of calibration: first, the results of the generation capacity mix and emissions for 2019, and second a comparison for capital investment, emissions and generation mix share all the way up to 2040 [59]. Below are figures relevant for cross-examination and are mentioned in the calibration section of the Results.

Figure 43: Gross capacity additions & retirements: coal phase-out

Figure 44: Cumulative investments in new capacity ($bn, real 2018): coal phase-out

Source: BloombergNEF
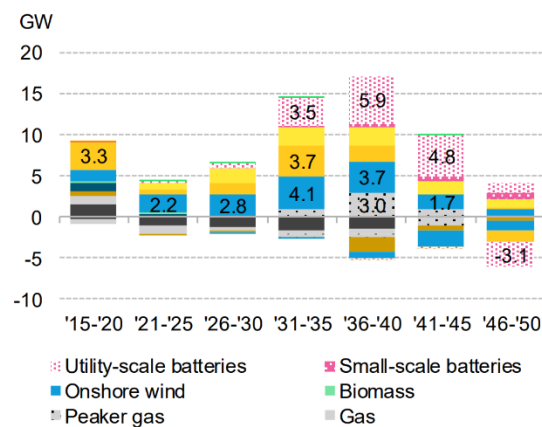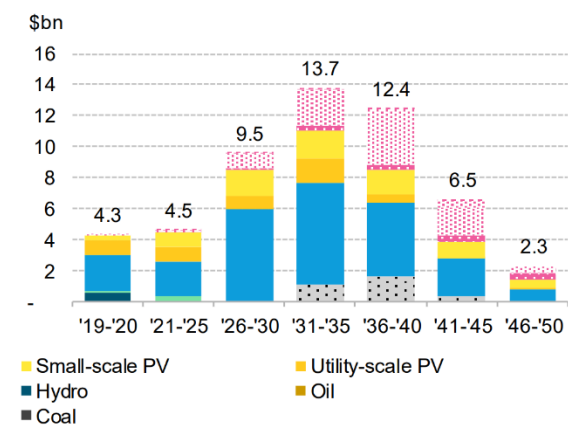
Source: BloombergNEF

Figure 26 Gross capacity additions and cumulative investments from BloombergNEF Chile Power System Outlook, for the coal-phase out scenario. Both figures and results are completely produced by BloombergNEF [59].

Figure 26 shows the gross capacity additions and cumulative investments. There are clearly differences in the way the model and the model in this thesis has been set up. This thesis' literature review found that batteries on a large scale were not yet considered, and that peaking hydro storage would be considered from 2030 onwards. Furthermore, rooftop solar was not economically viable compared to utility scale PV price wise, but of course residential solar is in the end a choice for the end consumer, not the energy auctions. Furthermore, this thesis divided hydro into three components, as this information allowed small hydro to be pulled into NCRE, and this is how the government itself issues statistics.

MtCO2

Figure 27 The annual emissions for the coal-phase out scenario from BloombergNEF Chile Power System Outlook, for the coal-phase out scenario. Both figures and results are completely produced by BloombergNEF [59].

Figure 27 shows that the overall trajectory for emissions between the BloombergNEF Chile Power System Outlook and this thesis are largely the same. The Bloomberg paper does not include emissions from biomass or exogenic CH4 emissions from dam hydropower, which would raise the results seen above.

Demand Projections (PJ)			
Year	Regulated customers	Free customers	Total
2018	111	134	246
2019	112	141	253
2020	114	146	261
2021	118	150	268
2022	123	153	275
2023	125	159	284
2024	126	165	292
2025	128	172	300
2026	129	177	307
2027	131	183	314
2028	133	189	322
2029	135	195	330
2030	137	197	333
2031	139	198	337
2032	142	201	343
2033	145	206	351
2034	148	211	359
2035	151	217	368
2036	155	222	377
2037	158	228	387
2038	162	234	396

Table 15 Demand projection by the CNE for the years 2018-2038 for regulated and free customers [51]

Technology	Coal	Natural gas (CC)	Natural gas (OC)	Diesel (utility)
Availability Factor	0.85	0.909	0.909	0.889
Capacity factor (SD)	0.78	0.62	0.5	0.9
Capacity factor (SN)	0.78	0.62	0.5	0.9
Capacity factor (WD)	0.78	0.62	0.5	0.9
Capacity factor (WN)	0.78	0.62	0.5	0.9
Emissions activity ratio (NO_x) [Mt/PJ]	1.52	0.09	0.09	0.57
Emissions activity ratio (CO_2) [Mt/PJ]	90.54	50.29	50.29	69.43
Emissions activity ratio (CH_4) [Mt/PJ]	10.43	0.95	0.95	2.84
Capital cost [M$/GW]	3000	1048	800	687
Fixed cost [M$/GW]	45	10.48	12	10.305
Variable cost [M$/PJ]	*5	*1	*1	*1
Input activity ratio	2.703	2.083	3.33	2.857
Output activity ratio	1	1	1	1
Residual capacity [GW]	*6	*2	*2	*2

Table 16 Parameters for conventional fossil based energy sources [104,119,135]

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[5] Please see Table 18 for variable cost, which includes fuel prices
[6] Please see Table 17 for residual capacity

Tech	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Biomass	0.458	0.449	0.439	0.430	0.421	0.411	0.402	0.393	0.383	0.374	0.365	0.356	0.346	0.337	0.327	0.318	0.309	0.299	0.290	0.281	0.271	0.261
Coal power	5.100	4.942	4.942	4.828	4.700	4.224	4.224	3.943	3.661	3.379	3.098	2.816	2.534	2.253	1.971	1.690	1.408	1.126	0.845	0.563	0.282	0
Diesel (ind)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (rur)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (urb)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (util)	3.058	3.330	3.320	3.259	3.198	3.138	3.077	3.017	2.956	2.895	2.835	2.774	2.714	2.653	2.592	2.532	2.471	2.410	2.350	2.289	2.229	2.168
Trans	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178	71.178
Dist (ind)	39.776	39.956	39.824	39.469	39.829	40.362	40.826	41.146	41.486	41.858	42.137	41.993	41.776	41.736	41.800	41.861	41.931	41.973	41.973	41.973	41.973	41.973
Dist (rur)	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878	3.878
Dist (urb)	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	28.435	71.178	71.178	71.178	71.178	71.178	71.178
Arg trade	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Peru trade	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Oil power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Small hyd	0.503	0.514	0.484	0.475	0.466	0.456	0.447	0.438	0.428	0.419	0.410	0.400	0.391	0.382	0.372	0.363	0.354	0.344	0.335	0.326	0.316	0.307
Dam hyd	3.215	3.150	3.084	3.019	2.954	2.888	2.823	2.758	2.693	2.627	2.562	2.497	2.431	2.366	2.301	2.236	2.170	2.105	2.040	1.974	1.909	1.844
River Hyd	2.686	3.368	3.368	3.504	3.504	3.674	3.562	3.450	3.338	3.226	3.114	3.002	2.891	2.779	2.667	2.555	2.443	2.331	2.219	2.107	1.995	1.883
Nat Gas (CC)	2.617	2.569	2.521	2.473	2.424	2.376	2.328	2.280	2.232	2.184	2.136	2.088	2.039	1.991	1.943	1.895	1.847	1.799	1.751	1.703	1.654	1.606
Nat Gas (OC)	2.052	2.010	1.968	1.926	1.885	1.843	1.801	1.759	1.717	1.675	1.633	1.591	1.550	1.508	1.466	1.424	1.382	1.340	1.298	1.256	1.215	1.173
CSP (no storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CSP (storage)	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
PV (utility)	2.620	2.597	2.504	2.410	2.317	2.224	2.131	2.037	1.944	1.851	1.758	1.664	1.571	1.478	1.385	1.291	1.198	1.105	1.012	0.918	0.825	0.732
Roof PV urb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roof PV urb(storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rooftop rur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rooftop rur (storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind	2.194	2.332	2.267	2.202	2.137	2.071	2.006	1.941	1.876	1.810	1.745	1.680	1.614	1.549	1.484	1.419	1.353	1.288	1.223	1.157	1.092	1.027

Table 17 Residual capacity, in GW [65]

Tech	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Biomass	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05	3.05
Coal power	14.51	12.82	12.29	11.82	11.38	10.97	10.56	10.14	9.79	9.44	9.09	8.73	8.38	8.25	8.12	7.99	7.86	7.73	7.60	7.47	7.34	7.21
Diesel (ind)	57.78	55.90	55.09	55.49	55.90	56.31	56.72	57.13	57.53	57.94	58.35	58.76	59.16	58.89	59.15	59.41	59.67	59.93	60.18	60.44	60.70	60.96
Diesel (rur)	57.78	55.90	55.09	55.49	55.90	56.31	56.72	57.13	57.53	57.94	58.35	58.76	59.16	58.89	59.15	59.41	59.67	59.93	60.18	60.44	60.70	60.96
Diesel (urb)	57.78	55.90	55.09	55.49	55.90	56.31	56.72	57.13	57.53	57.94	58.35	58.76	59.16	58.89	59.15	59.41	59.67	59.93	60.18	60.44	60.70	60.96
Diesel (util)	57.78	55.90	55.09	55.49	55.90	56.31	56.72	57.13	57.53	57.94	58.35	58.76	59.16	58.89	59.15	59.41	59.67	59.93	60.18	60.44	60.70	60.96
Trans	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Dist (ind)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Dist (rur)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Dist (urb)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Arg trade	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Peru trade	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Oil power	55.69	53.82	53.00	53.41	53.82	54.23	54.63	55.04	55.45	55.86	56.27	56.67	57.08	56.81	57.07	57.32	57.58	57.84	58.10	58.36	58.62	58.88
Small hyd	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Dam hyd	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
River Hyd	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Nat Gas (CC)	6.97	6.22	6.41	6.60	6.78	6.97	7.16	7.34	7.57	7.79	8.02	8.24	8.47	8.47	8.64	8.81	8.98	9.15	9.32	9.50	9.67	9.84
Nat Gas (OC)	9.28	8.24	8.50	8.76	9.02	9.28	9.54	9.80	10.11	10.42	10.73	11.04	11.35	11.35	11.59	11.83	12.06	12.30	12.54	12.77	13.01	13.25
CSP (no storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CSP (storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PV (utility)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roof PV urb	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roof PV urb(storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rooftop rur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rooftop rur (storage)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 18 Variable cost, in US$M, for each year of the modelling period, displayed in the top row (i.e. 19=2019)

Tech	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Coal imp.	220	220	220	220	220	220	220	220	220	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal extr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal power	106	103	103	101	98	88	88	82	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel imp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel extr.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (ind)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (rur)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (urb)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel (util)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil import	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil extrac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NG imp.	110	110	110	110	110	110	110	110	110	0	0	0	0	0	0	0	0	0	0	0	0	0
NG extrac	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat Gas (CC)	110	110	110	110	110	110	110	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nat Gas (OC)	47	46	44	44	43	42	42	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 19 Total annual minimum activity constraint used for the BAU scenario. Author's calculations based on [65]

REmin target	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Min Prod.	0.14	0.15	0.16	0.17	0.18	0.19	0.2	0.232	0.264	0.296	0.328	0.36	0.392	0.424	0.456	0.488	0.52	0.552	0.584	0.616	0.648	0.68

Table 20 Minimum renewable energy production target for tagged commodities, as used in the NCRE scenario. Own calculations

Tech	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Biomass	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Coal power	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (ind)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (rur)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (urb)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (util)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Trans	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (ind)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (rur)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (urb)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Arg trade	0	0	0	0	0	0	0	0	0	0	0	0	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Peru trade	0.3	0.3	0.3	0.3	0	0	0	0	0	0	0	0	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Oil power	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Small hyd	0.1	0.1	0.1	0.25	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dam hyd	0.25	0.5	1	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
River Hyd	0.25	0.5	1	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Nat Gas (CC)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Nat Gas (OC)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
CSP (no storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
CSP (storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
PV (utility)	0.25	1	2	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Roof PV urb	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Roof PV urb(storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Rooftop rur	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Rooftop rur (storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Wind	0.25	1	2	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999

Table 21 Total annual max capacity investment constraint (in units of GW)

Tech	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Biomass	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Coal power	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (ind)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (rur)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (urb)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Diesel (util)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Trans	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (ind)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (rur)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Dist (urb)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Arg trade	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Peru trade	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Oil power	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Small hyd	1	1	1	1	1	1	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Dam hyd	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
River Hyd	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Nat Gas (CC)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Nat Gas (OC)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
CSP (no storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
CSP (storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
PV (utility)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Roof PV urb	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Roof PV urb(storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Rooftop rur	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Rooftop rur (storage)	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999
Wind	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999	99999

Table 22 Total annual max capacity constraint used in all scenarios. Small hydropower has environmental licenses for 1 GW up to 2025. It is assumed that, because it is an NCRE technology, there will be no limit on this afterwards. Dam hydropower and run of the river hydropower both have limited environmental licenses, and max potential used up.

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