A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science

Feasibility of renewable electricity targets in Latin America: are we on track?

Laura HURTADO VERAZAÍN

June, 2021

Budapest

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfillment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

(3) For bibliographic and reference purposes this thesis should be referred to as:

Hurtado Verazaín, L. 2021. Feasibility of renewable electricity targets in Latin America: are we on track?. Master of Science thesis, Central European University, Budapest.

Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Laura HURTADO VERAZAÍN

CENTRAL EUROPEAN UNIVERSITY

ABSTRACT OF THESIS submitted by:
Laura HURTADO VERAZAIN
for the degree of Master of Science and entitled: Feasibility of renewable electricity targets in Latin America: are we on track?

Month and Year of submission: June, 2021.

Concerns about climate change call for joint efforts to reduce greenhouse gases emission. The transition to low-carbon energy sources provides a vital opportunity to advance in this reduction, with global objectives framed within the Paris Agreement. The expansion of wind and solar technologies emerges as a priority in this endeavor, and countries have established targets for their increased development. In this dissertation, I evaluate historical trends of wind and solar deployment to assess if Latin American countries are on track to meet their renewable targets. For this purpose, I use a method proposed by Cherp *et al.* (forthcoming) to fit growth models to historical trajectories of wind and solar power to estimate the path of future growth, assuming that it follows an S-shaped curve of technology diffusion. I find the maximum annual growth rates achieved in the region and compare them to the rates required to fulfill their targets. With these observations, it is evidenced that Latin American countries will experience difficulty to achieve their targets unless they ensure actions that sustain the pace of renewables growth constant for a longer time. Latin America is a region characterized by already having the least carbon-intensive electricity mix in the world and enormous potential for wind and solar development, so policies should prioritize the expansion of these technologies.

Keywords: renewable energy, wind, solar, renewable targets, Latin America.

Acknowledgements

This dissertation is the culmination of a long-awaited dream and hopefully the beginning of many more.

I am extremely grateful to the MESPOM family: the professors, coordinators, friends, and especially my supervisor Aleh, whose guidance made this process an even more gratifying and inspiring experience.

I want to thank my classmates for all the moments we shared and the strong bonds we created that no pandemic circumstance can take away from us. A special thanks goes to my dear friends Caro, Dani, Tolga, and Rupal, that saw me at my best and worst and never stopped their support and love. Our memories are always in my heart!

Finally, I want to thank God, my parents, my brother, and my family and friends at home, who are the living proof that no distance is long when you are guided by love.

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1. Introduction

Since the beginning of the Industrial Revolution and the accelerated economic development it entailed, humans have engaged in a never-ending overexploitation of natural resources, with dire consequences for the planet.

Particularly serious have been the effects on the climate caused by CO_2 emissions, often referred to as the climate crisis, and have attracted the attention of scientists, national governments, intergovernmental bodies and the general public. In this regard, several agreements and commitments have been made worldwide, of which the Paris Agreement, adopted by 197 countries in 2015, represents the most ambitious of the Parties committed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN 2016). Following the Paris Agreement, countries have submitted their *Nationally Determined Contributions* (NDC), establishing their own targets to reduce greenhouse gases (GHG) emissions by 2050.

In this context, the energy sector has a pivotal role since it is responsible for around three-quarters of global GHG emissions from the combustion of fossil fuels (Climate Watch 2018), with electricity/heating accounting for about 30% of global GHG emissions or 15.590 $MtCO_2eq$ in 2018 (Climate Watch 2018). Thus, the decarbonization of electricity generation is a priority in our efforts to slow down global warming. Moreover, renewable electricity (electricity generated from renewable sources, such as hydro, wind, solar or biomass) can be regarded as one of the most promising means to mitigate GHGs emissions and meet other sustainability goals (IRENA 2020)

This dissertation explores the feasibility of attaining such decarbonization of the energy system through renewable electricity in Latin America. This region is particularly interesting since it is characterized by already having a significantly large share of renewables in its electricity mix. Historically, the abundance of natural resources, both fossil and renewables, has enabled the region to have hydroelectric plants producing on average more than half of its total power generation (BP 2020; IRENA 2016), as observed in Figure 1. However, wind and solar have taken off at an impressive rate in recent years (IRENA 2016), with countries like Chile, Brazil, Argentina and Mexico among the most attractive destinations for renewable energy investments in the world (EY 2020).

The expected economic expansion (the GDP per capita is expected to grow from 7.8 thousand USD in 2015 to 24.7 in 2050 according to IRENA's 2020 Outlook) alongside the promotion of renewable energy policies has enabled this rapid deployment of wind and solar, and countries have set ambitious renewable electricity targets to fulfill their environmental commitments based on these projections. Thereupon, this dissertation aims to analyze the feasibility of such renewable targets in order to assess if Latin American countries are on track to meet their goals, based on their historical growth trajectories.

However, assessing the feasibility of renewable electricity expansion is not scientifically straightforward. This is because the methods of determining feasibility of energy transitions are only currently emerging in the existing scientific literature. In particular, Jewell *et al.* (2019) and Jewell and Cherp (2020) proposed to assess the feasibility of climate targets by comparing the required developments with historical precedents. Historical observations were also used by Wilson *et al.* (2013) and Napp *et al.* (2017) for assessing the consistency of climate mitigation scenarios. However, such methods have not been applied to renewable electricity because there is a lack of historical precedents of their deployment. In a recently published publication Cherp *et al.* (forthcoming) have proposed to overcome this problem by fitting different growth models to existing data on solar and wind power use in specific countries, regions and globally. They applied this method to assess global climate mitigation pathways, but did not look at the national targets.

For this thesis, I will use Cherp's and his colleagues' method for estimating feasible future developments in wind and solar power in Latin American countries. In this manner, the objective of this dissertation is to answer two interrelated questions:

RQ1) Will Latin American countries achieve their renewable electricity goals for wind and solar with their current growth rates?

RQ2) If the first answer is no, what are the growth rates required to achieve these targets? How should the deployment curves look like? Have these been achieved in other countries in the world?

Answering these questions can equip policy-makers, expert advisors, and consultants with a better understanding of the attainability of low-carbon electricity goals, in order to adjust over-optimistic targets in the envisioned scenarios for sustainable energy transitions.

To anticipate the main findings that I present in the empirical results section, I have found that the selected countries are not on track to meet their targets based on their current renewables growth rates, assuming that the forecasted deployment follows an S-curve shape estimated by the two most widespread models. This is especially the case for solar power in Brazil, which is ambitiously expected to contribute to 4% of total electricity generation by 2050 according to the long-term national energy development plan ("Plano Nacional de Energia 2050" 2020), but will fail to do so if keeping the current growth trends. The results were more favorable for wind power, as countries were closer to reach their established targets, especially in the case of Mexico, which has set gradually increasing targets for 2021, 2024, 2030 and 2050.

Scope and Limitations

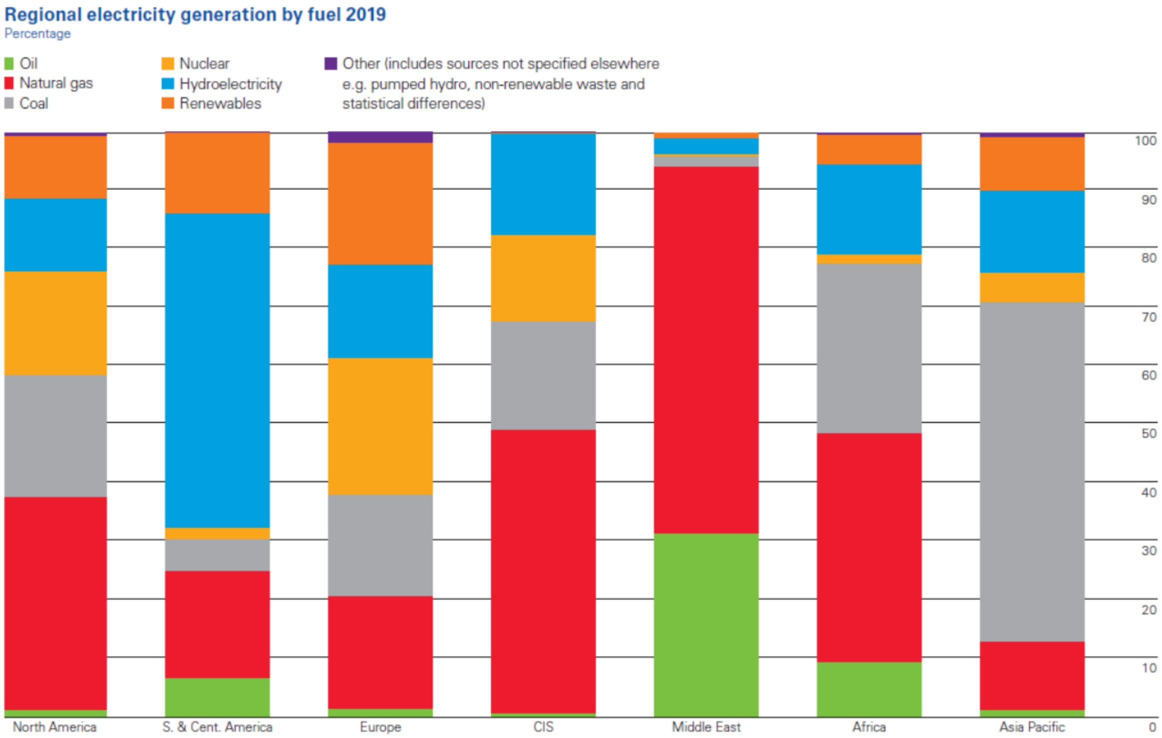
The empirical base of this dissertation is historical electricity generation from wind and solar sources in Brazil, Chile, and Mexico, because these three countries have reached stable growth levels in renewables production that can provide sufficient data points for accurate forecasting. Specifically, I fit S-curves growth models on these data points to calculate the necessary parameters to predict the curve's trajectory and calculate the variable G (maximum yearly growth rate) for comparison of historical vs. required performance, as proposed by Cherp and co-authors. In the case of wind, I focused on Brazil, Chile, and Mexico, and for solar data I concentrated on Brazil and Chile, since this technology has only been recently adopted in Mexico and is still growing at an accelerated rate, therefore making it impossible to provide a reliable forecast.

This thesis focuses solely on wind and solar sources for electricity generation, as these technologies have developed massively around the world, thanks to the increase in their technical and economic potential. As we advance in their learning curves, costs for these technologies have significantly fallen in the last decade compared to fossil fuels, which has allowed their vast adoption (Carbon Tracker 2021), representing around 8% of the global electricity supply in 2020 (Enerdata 2020). Globally, wind and solar represent 91% of the increase in installed capacity, since countries continue to invest in renewable energy infrastructure to accelerate capacity additions (IEA 2020a).

Structure

The rest of this dissertation will be structured as follows: in section 2, a comprehensive literature review is provided, which presents the current state of the art on renewable electricity development and the role of energy policies in Latin America. Next, I discuss the theoretical framework of the prospects for renewables in Latin America and present the data and methodology for the calculations, alongside the limitations that future feasibility studies should seek to overcome. In chapter 4, the empirical findings and results are displayed, which allows for a comparison of projected growth vs. established goals and between the achieved maximum growth rates vs. growth rates required for targets fulfilment. Chapter 5 provides a discussion on the findings and their broader implications for the prospects of the green transition in Latin America. Finally, in section 6 the conclusions and recommendations extracted from this analysis are presented.

Figure 1. Electricity generation by region (source: BP Statistical Review of World Energy 2020)



2. Literature review

The role of energy transition in climate mitigation scenarios has been extensively discussed in academic literature. Scientists have manifested the need to decarbonize our current energy system to reduce GHG emission and fulfill the Paris Agreement objectives, mainly through the increasing deployment of renewable energy sources. This thesis aims to contribute to this body of literature by providing an evaluation of Latin American countries' performance regarding wind and solar historical development to assess whether this region is on track to meet its renewable targets assumed under the Paris Agreement commitments, since a knowledge gap is identified for this region.

2.1. Feasibility of achieving climate targets

Analyzing the feasibility of achieving climate targets can be approached from different angles. Jewell and Cherp (2019) propose to evaluate three components: the set of actions comprising the envisioned scenarios ("technical" feasibility), the political and socio-economic context (as climate actions are dependent on political and economic costs), and the relevance of actors and their ability to bear these costs. They argue that the required climate actions are constrained by these costs (whether economic or political), and its overcoming relies on stakeholders' capacity to afford their implementation, which they referred to as the "political feasibility" of achieving a climate target. When analyzing historical examples of decarbonization measures, it is evidenced that political feasibility plays a significant role in the adoption of technologies, as countries introduce innovations at different paces. Regions are differentiated as the "core", the "rim", and the "periphery" according to where the technology is diffused (Jewell and Cherp 2019), which is influenced by the capacity that each country holds for this diffusion. Generally, politically stable and wealthy nations can introduce technology innovation first, and the case of energy is not an exception. Cherp *et al.* (forthcoming) show that wind and solar deployment achieved stable growth first in the European Union, followed by OECD countries and large emerging economies, by fitting growth models to historical wind and solar deployment data. However, the growth values they find are still not fast enough as most envisioned 1.5° and 2°C IPCC climate mitigation scenarios require.

Moreover, renewable energy development represents a more complex challenge as their deployment needs to proliferate in areas outside of their original introduction and diffusion (Cherp *et al.* forthcoming). Previous literature also disagrees on whether we are on track to meet our climate targets. For example, in their NetZero 2050 Roadmap of 2021, the IEA affirms that annual additions of wind and solar electricity need to scale up to four times the levels achieved in 2020 in order to stay on the net-zero pathway, which could represent a significant challenge for countries that have reached stagnation levels of renewables deployment. Furthermore, IRENA's 2020 Energy Outlook estimates that we need to raise the share of renewables in electricity generation globally from 26% currently to 57% by 2030 and 86% by 2050 to limit temperature increase to 1.5°C. On the other hand, Grubb *et al.* (2020) assert that "recent trends in the growth in generation from these sources (wind and solar) are well within the range required to achieve key benchmarks for growth to net-zero goals" (3). In light of these disagreements, how can we assess if our actions are on track with the climate targets? Wilson *et al.* (2013) use historical growth of energy technologies to look into future deployment trajectories, which demonstrates that the expansion of low-carbon energy technologies can be estimated through the analysis of historical diffusion, proving this method as a "basis for assessing model-generated future trajectories" (394). Accordingly, Cherp *et al.* (forthcoming) also use historical data to fit growth models to evaluate if wind and solar growth is on track with climate mitigation scenarios. They find that the maximum growth rates achieved in the world are still lower than those required by 1.5°C and 2°C pathways. Moreover, the ability to expand renewable deployment outside of its niche levels is a pivotal point in our decarbonization efforts (Jewell and Cherp 2019).

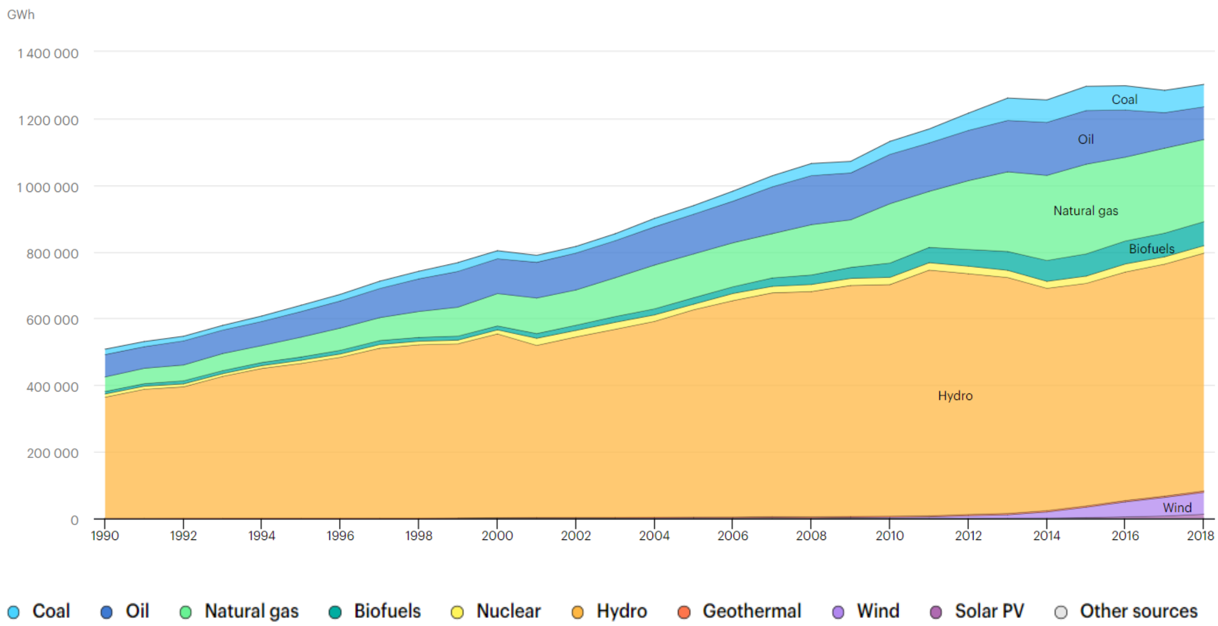
In this sense, IRENA stresses that the feasibility of advancing in the energy transition increases if regions cooperate and act together. Regional targets and collaboration consistent with climate objectives are a vital component of 2050 climate mitigation scenarios (2020). These scenarios require "almost complete decarbonization of the electricity sector by 2050" (68) by increasing the share of renewable technologies and the wider electrification of economic sectors. This transformation is expected to be led by wind and solar power, which would contribute to 35 and 25% of global electricity demand, correspondingly, which entails a massive expansion of both technologies.

But where does Latin America stand in this global pursuit? A revision of the region's current state is provided in the subsections below as background, alongside an overview of the regional targets in place in view of the Paris Agreement objectives.

2.2. Renewables in Latin America

Latin America is the proud possessor of the least carbon-intensive electricity mix in the world (BID 2018), with about 68% of its electricity coming from low-carbon sources in 2018, while the world average is near 36% (IEA 2021). As shown in Figure 2, thermal sources represent only 31% of the LATAM electricity mix, of which natural gas provides the largest part (19%). However, this is mainly due to the significant contribution of hydropower plants, which represented 55% of total electricity generation in 2018 (IEA 2021). Hydroelectric power has played an important role in Latin American economic development throughout history: the exploitation of the vast hydroelectric resources since the late XIX century facilitated the establishment of electricity companies, the expansion of transmission systems and the development of local technical capacity (BID 2018). Between 1970 and 1980, the region reached its most robust growth in hydropower capacity, from 19 to 93 GW, which accounted for 15% of global capacity (BID 2018). However, this dependency on hydraulic resources has made the region vulnerable to climatic variations, such as draughts or El Niño phenomena, potentially jeopardizing supply security in countries that rely heavily on this power source. In addition, the "sustainability" of large-scale hydropower plants is under discussion, since they have significant impacts on ecosystems, biodiversity, and watersheds, besides population displacement of mainly indigenous communities (Ribeiro and Krink 2013).

Figure 2. Electricity generation by source in Latin America (source: IEA 2021)



That being said, the last decade has witnessed the spectacular rise in non-conventional renewable sources, namely wind and solar power, stemming from the need to diversify the energy mix, reduce

CO2 emissions and the dependence on fossil fuels, and utilize the huge potential in the region. According to Carbon Tracker (2021), the technical potential (amount of energy that can be captured using current technologies in suitable locations) for wind and solar in the region is between 100 – 1000 times the total demand (Figure 3). With electricity generation costs from renewables already below those of fossil fuels and still falling, an even more significant expansion of these technologies is expected in the upcoming decades as we move further in their learning curve (Figure 4).

Figure 3. Solar and wind energy potential in function of energy demand (source: Carbon Tracker 2021)

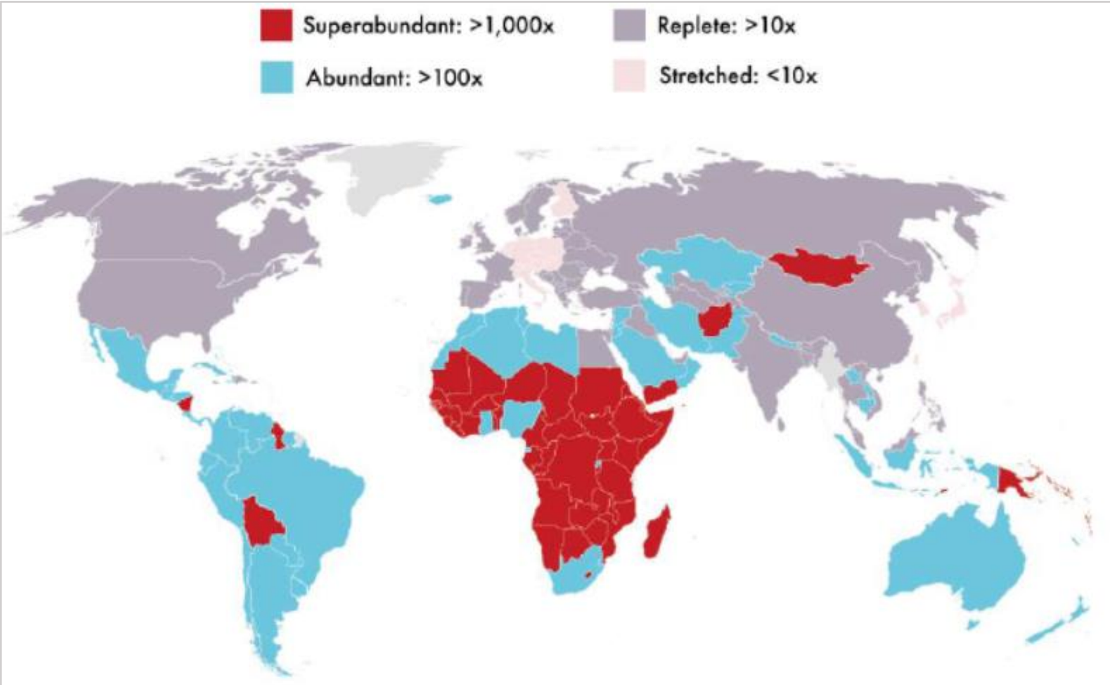
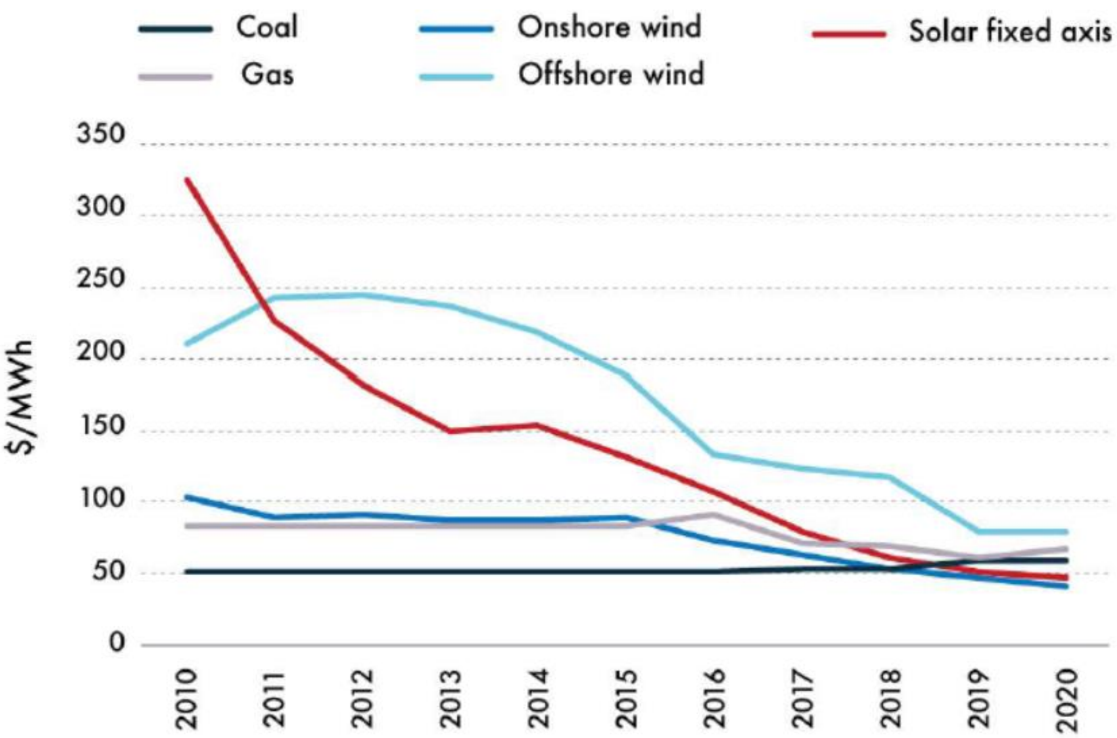


Figure 4. Levelized cost of electricity ($/MWh) (source: Carbon Tracker 2021)



Latin America is a firm contributor to this green revolution: between 2006 and 2015, the non-hydro power installed capacity rose from 10GW to 36GW (IRENA 2016), driven mainly by economic growth, urbanization and the increase in electricity access. In the last five years, the region has seen remarkable growth as well, with Brazil adding 1.76 GW of wind capacity and 3.27 GW of solar in 2020 alone, while Chile reached 2.15 GW of wind capacity and 3.2 GW of solar in 2020, to name a few examples (Atxalandabaso 2021). Uruguay remains the country with the highest share of non-conventional generation in the continent (around 47.6% in 2019), showing the highest growth rate in wind capacity, from 59 MW in 2013 to 1504 MW in 2017, which represents around 30% of their total installed capacity (OLADE 2020). According to Rystad Energy (2021), the region is expected to reach 123 GW of modern renewable capacity by 2025, as seen in Figure 5, with Brazil, Mexico, Chile, Colombia, and Argentina spearheading this growth. DNV GL's energy transition forecast for 2050 (2020) estimates that wind and solar will account for over 60% of global electricity supply, and specifically for Latin America, this will be 35% of total electricity generation coming from wind and 30% from solar PV (Figure 6).

Figure 5. Renewables capacity growth outlook (source: Rystad Energy 2021)

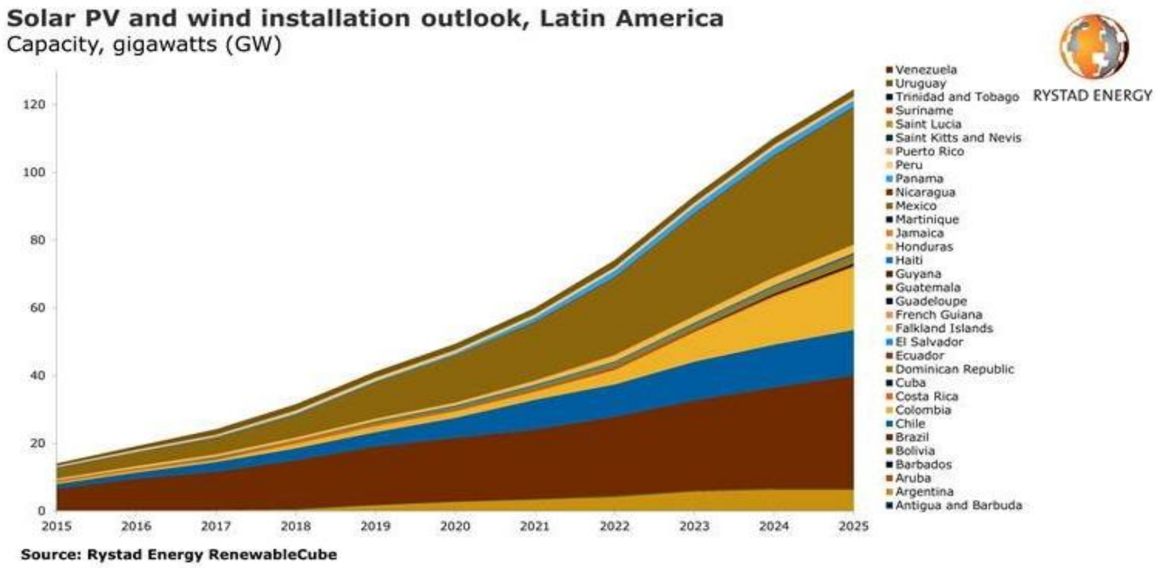
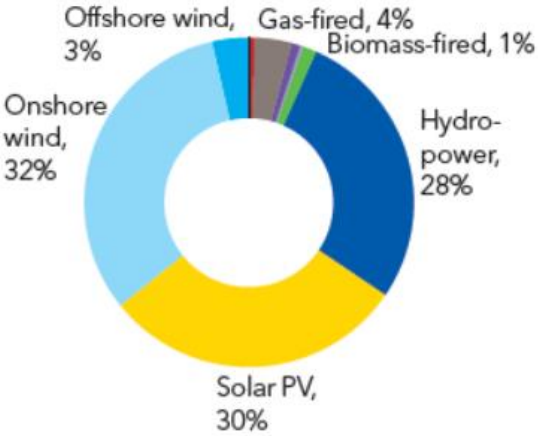


Figure 6. Electricity generation forecast in Latin America 2050 (source: DNV GL 2020)



In this sense, countries have relied on financial, legislative and fiscal mechanisms for the promotion of renewable energy projects, with auctions and biddings as the most popular regulatory instrument (UN ECLAC 2019). As defined by IRENA, energy auctions refer to "competitive bidding procurement processes for electricity from renewable energy or where renewable energy technologies are eligible. The auctioned product can be either capacity (MW) or energy (MWh). Project developers who participate in the auction submit a bid with a price per unit of electricity at which they are able to realize the project" (IRENA 2015, 12). In fact, the Global Wind Energy Council (GWEC) and OLADE found that "80% of the current renewable capacity in Latin

America and the Caribbean has been driven by public tenders and auctions" (2020). With prices dropping to around $20 per MWh in Brazil and Mexico in recent auctions (Table 1), the opportunities for extensive investment in the region are increasingly attractive for local and foreign competitors, as these technologies are economically feasible (in some cases even cheaper) compared to conventional sources (Americas Market Intelligence 2021). This impressive drop in prices has positioned Latin America as one of the most promising regions to reach carbon neutrality in light of the Paris Agreement objectives.

Table 1. Average auction prices, most recent auctions (source: Americas Market Intelligence 2021)

Country	**Solar generation (price per MWh and year of auction)**	**Wind generation (price per MWh and year of auction)**
Peru	$48,10, 2016	$37.70, 2016
Chile	$34.10, 2017	$33.60, 2017
Mexico	$20.00, 2017	$17.70, 2017
Brazil	$20.52, 2019	$24.06, 2019
Argentina	$57.58, 2019	$58.04, 2019
Colombia	$27.00*, 2019	$27.00*, 2019

*auction price was not differentiated between solar and wind

2.3. National renewable electricity targets

Renewable targets framed on national energy policies lie at the heart of the energy transition worldwide, enabling costs reduction and innovation, as regulatory frameworks are expected to be responsible for 60% of all renewable capacity expansion globally in the next five years (IEA 2020b). As recognized by IEA and OLADE in 2020, "the regulatory framework needs to be modernized to leverage the potential of new technologies and innovation" (Birol and Blanco 2020, 2), and with that purpose in mind, countries have set ambitious goals for renewable electricity deployment. In a regional initiative coordinated by OLADE (Latin American Energy Organization), the goal of a minimum 70% share of renewables (including large scale hydro) in electricity consumption by 2030 has been set (Silveira Martins 2020). However, each nation is free to establish its own targets independently.

Table 2. Renewable energy targets in South America (source: Arango-Aramburo et al. 2020)

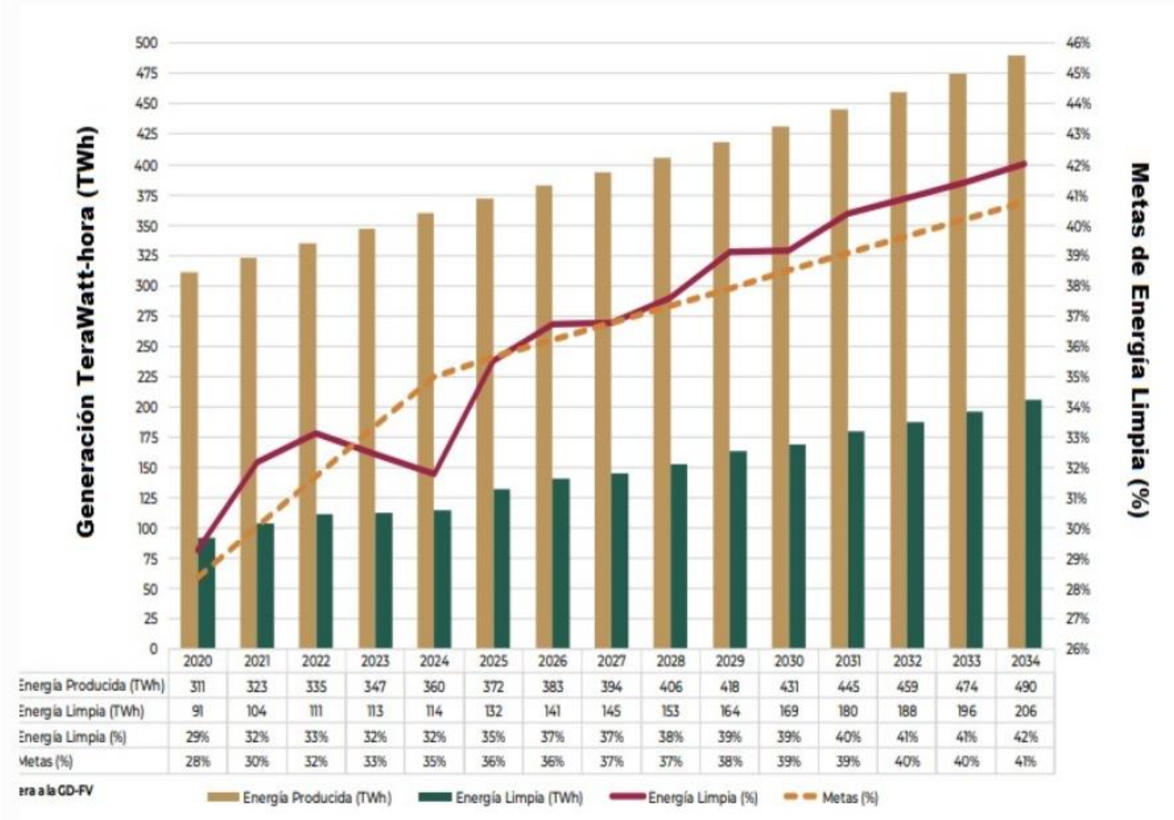
Country	Policies and Targets for Renewables
Argentina	10 000 MW of (potential) renewable energy by 2025. 20% of national electricity consumption by 2025, supported by Law 27191
Bolivia	183 MW of renewable capacity by 2025 Increase of 10% of the renewable energy in the mix in 5 years. 120 MW in geothermal
Brazil	42.5% of the supply of primary energy by 2023. Wind power expanding 20 GW Additional wind capacity of 3.3 GW and 34.5 GW of hydropower capacity by 2030
Chile	20% of the electricity generation from renewable sources by 2025 (not considering hydropower larger than 20 MW) 45% of the new capacity by 2025 At least 60% of the electricity generation from renewable sources by 2035 and 70% by 2050
Colombia	6.5% of electricity by 2020, without big hydropower 15% of the energy park based on non-conventional renewable energy by 2029
Ecuador	4.2 GW in hydropower by 2022 277 MW from sources other than hydropower by 2022
Peru	5% of electricity generation by 2021 (excluding hydropower) Greater than 60% of electricity generation by 2025 (including hydropower)
Uruguay	Policy 2005-2030. Promotion of non-conventional renewable sources

Moreover, 19 of 20 Latin American countries have at least one type of renewable target in place at the national level. It is worth mentioning that these objectives do not always differentiate between hydropower and other non-conventional renewable sources, but they are exclusively focused on promoting wind and solar expansion (Arango-Aramburo *et al.* 2020). Table 2 depicts an overview of national commitments from selected countries amid GHG emissions reduction efforts.

Based on the aforementioned considerations, we can expect most front-runner countries to achieve their renewable targets considering their current performance and envisioned sustainable scenarios. Such is the case of Chile, which in December 2020 reached 21.74% of electricity generation from renewables (wind, solar, biomass, and small-scale hydro), surpassing five years in advance the target of 20% of renewable electricity by 2025 (El Mercurio 2020). Accordingly, the Chilean Association of Renewable Energy (ACERA) estimates that renewable installed capacity will grow at a steady rate of at least 1 GW per year (El Mercurio 2020), which is in line with the long-term national target of generating 70% renewable electricity by 2050. On the other hand, Brazil has put forward very ambitious pledges on its NDCs, committing to "increase the share of renewables (other than hydropower) in the power supply to at least 23% by 2030, by raising the share of wind, biomass and solar" (UN 2015, 3), also supported by its national energy development plan ("Plano Nacional de Energia 2050") released in December 2020, which further expands this commitment to 45% of total energy met by renewable sources. The country seems to be on track to achieve these goals, as wind power reached more than 10% of the electricity installed capacity (17.52 GW) in March 2021 (BNAmericas 2021), as verified by ANEEL (National Electric Energy Agency). In the case of Mexico, renewable prospects are not so promising since the country failed to achieve its 2018's target of 25% participation of clean sources in electricity generation (Forbes Mexico 2021; Expansion MX Magazine 2020). Moreover, forecasts from the National Energy Secretary (SENER) estimate that Mexico will not be able to meet its 2024 target of 35% electricity from clean sources until one year after, as evidenced in Figure 7 (Forbes Mexico 2021). With political measures currently halting renewables development and limiting their production under the government's justification of "protecting the integrity of the electrical grid" (Bloomberg 2021) from the intermittency of non-conventional renewable sources, expectations are not favorable for Mexico's energy transition goals.

Consequently, the feasibility of such electricity targets in the above-stated countries is explored in the following chapters.

Figure 7: Mexico’s electricity generation forecast by SENER (source: Forbes Mexico 2021)



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Energía Producida (TWh)	311	323	335	347	360	372	383	394	406	418	431	445	459	474	490
Energía Limpia (TWh)	91	104	111	113	114	132	141	145	153	164	169	180	188	196	206
Energía Limpia (%)	29%	32%	33%	32%	32%	35%	37%	37%	38%	39%	39%	40%	41%	41%	42%
Metas (%)	28%	30%	32%	33%	35%	36%	36%	37%	37%	38%	39%	39%	40%	40%	41%

3. Theory and Methods

3.1. Evaluating the feasibility of energy transitions

As briefly mentioned in Section 1, assessing the feasibility of renewable energy deployment is not a simple task, as there is not one established methodology to do so. As highlighted by Cherp *et al.* (2018), national energy transitions are a "co-evolution of three types of systems: energy flows and markets, energy technologies and energy-related policies" (187), which requires the input of multiple disciplines. Jewell and Cherp (2019) propose to analyze the feasibility of climate mitigation scenarios to achieve the Paris Agreement commitments by evaluating the actions necessary to achieve climate targets, the economic and political costs of these actions and the capacity of actors involved. Jewell *et al.* (2019) provide evidence for the relevance of such economic and political costs in energy transitions by evaluating the feasibility of coal phase-out pledges. They find that the major drivers for the adoption of the pledges to phase out coal power are the phase-out costs (in regards to employment, national dependency on coal production/share in the electricity mix and stranded assets stemming from young coal plants) and a country's capacity to bear these costs, which not only refers to GDP but also involves political stability and governments' transparency.

Historical data allows us to predict a technology's future behavior in order to assess the feasibility of reaching a certain level of technology deployment or growth rate. For example, Arango-Aramburo *et al.* (2020) compare historical data on the evolution of thermal and hydro electricity generation capacity in South America to argue that the renewable share in these countries has in fact declined in relation to thermal sources over time, which presents a paradox given the region's stated climate commitments. However, this decrease in renewables share could be reversed if we take into account the latest trends in wind and solar massive expansion worldwide that are also transforming Latin America's energy sector.

But how can we assess whether this renewable electricity expansion is on track to meet the climate targets? Although there is not a single answer, Cherp *et al.* (forthcoming) turn to historical data to fit growth models to empirical observations of wind and solar power to calculate maximum achieved growth rates and compare them to the required growth in envisioned 1.5°C and 2°C scenarios globally. The observed growth follows S-shaped curves, in agreement with several other studies (Rogers 1983; Grübler 1997; Rotmans *et al.* 2001; Bento *et al.* 2018; Markard 2018) that show that the diffusion of new technologies follows a period of accelerated growth until reaching the inflection point (where the growth rate is at its maximum, the steepest), and finally decelerating until they reach the saturation point (the asymptote or "ceiling"). For this thesis, I also use the concept of S-shaped growth to assess national targets in selected Latin American countries.

3.2. S-curves of technology diffusion and growth models

As noted by Grübler (1997), "no innovation spreads instantaneously. Instead, a typical S-shaped temporal pattern seems to be the rule" (38). Likewise, Rogers (1983) formalized the diffusion of innovation theory by presuming that "most innovations have an S-shaped rate of adoption" (23). Energy technologies also evolve following this shape. First introduced by Pierre-Francois Verhulst in 1838, the equation for a logistic curve was used to describe the self-limiting growth of a population, characterized by "the basic concept of limiting resources that lies at the basis of any growth process" (Kucharavy and De Guio 2011, 560). S-curves are widely applied in diverse disciplines to analyze historical data in order to unveil trends and project all types of performance: technologies diffusion, population growth, knowledge acquisition, and market penetration analysis, among others.

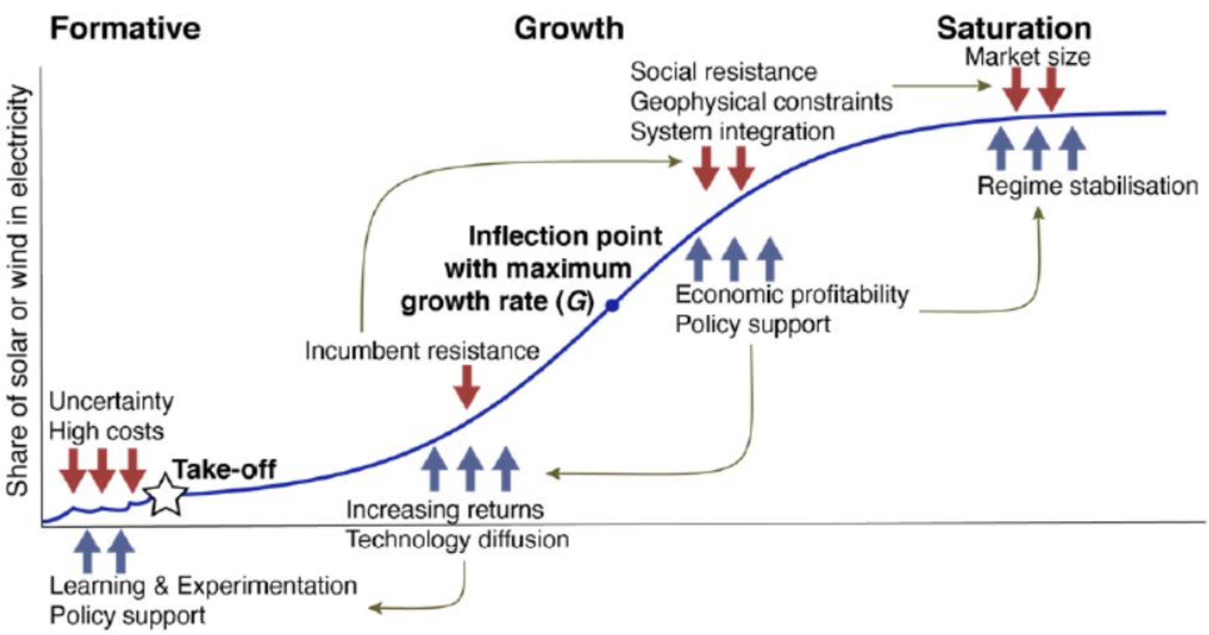
Thus, with respect to wind and solar technologies, we see that three phases comprise their adoption through an S-shaped growth curve:

- *Formative phase:* a period characterized by slow growth and high technical, economic, and political uncertainties and costs, during which "the conditions are created for a new technology to emerge and prepare for large-scale commercialization" (Bento *et al.* 2018, 282). This phase ends when the "take-off" milestone is reached, when "socio-technical regimes formed around new technologies become capable of steady expansion" (Cherp *et al.* forthcoming, 2), and the technology is set to diffuse in new markets.
- *Growth phase:* growth accelerates during this phase, as more comprehensive imitation and adoption in markets allow for costs reduction, technology learning and political support (Grübler *et al.* 1999; Cherp *et al.* forthcoming). This phase culminates when growth reaches its maximum level (the inflection point, the steepest part of the curve) and then slows down.
- *Saturation phase:* eventually, growth no longer increases due to "increasing marginal costs, grid and system integration challenges, geophysical constraints and political and social resistance" (Cherp *et al.* forthcoming, 2), when the market share of this technology saturates.

Cherp *et al.* (forthcoming) provide a detailed illustration of these phases and the mechanisms affecting them, as shown in Figure 8. At the same time, they propose a classification of countries' wind and solar growth status based on growth parameters extracted from the logistic and Gompertz regressions performed:

- *Accelerating growth* refers to countries that reach their inflection point (t_0) in the future (i.e., that they have not achieved their fastest deployment rate yet) according to both regression models (logistic and Gompertz). Countries classified as accelerating have a maturity level below 50%, and estimations for the value of the maximum growth rate diverge between the two models.
- *Stalling growth:* countries in which the inflection point is located before 2015 and "the most recent empirically measured growth (3 years average) is less than 60% of the estimated G" (value at the inflection point) (Cherp *et al.* forthcoming, 19). These countries have a maturity level above 90% in both regression models.
- *Stable growth:* all the remaining countries that do not present an accelerating nor stalling growth.

Figure 8. Phases of technology adoption (source: Cherp et al. forthcoming)

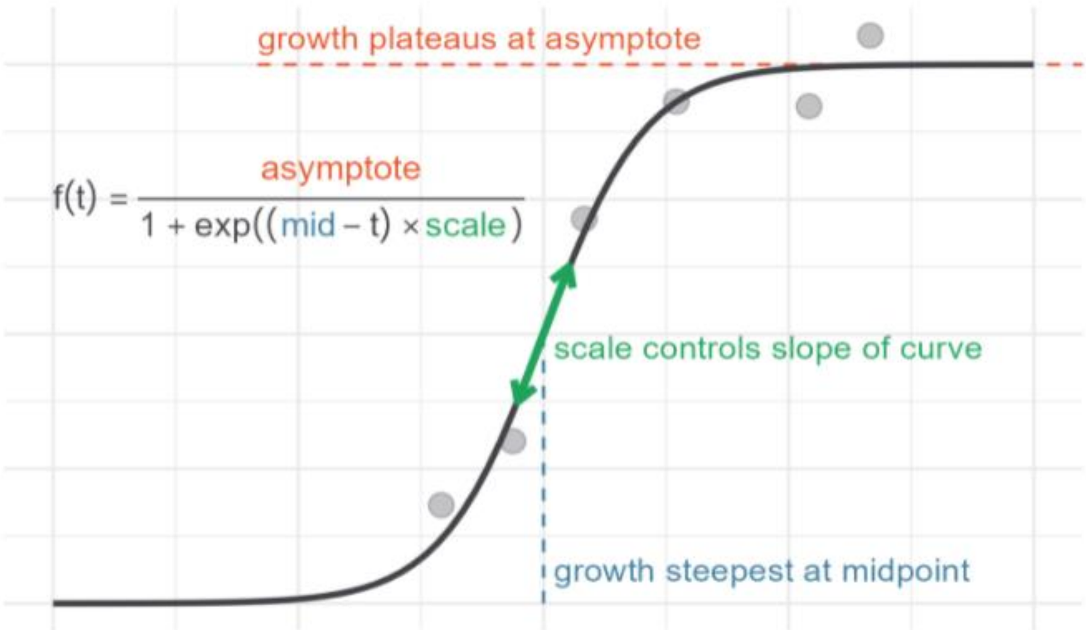


In this context, we define this S-shaped growth curve by a three-parameter function (illustrated in Figure 9):

- An *asymptote* (L) at the ceiling (saturation level, carrying capacity). For most technologies, we expect that their development follows a trajectory towards a ceiling or limit, where they reach a mature level and no longer grow. Referred to also as the "size of change" (Rotmans *et al.* 2001), it is a measure of "the extent of growth" (Wilson *et al.* 2013) that we use to estimate the "ultimate penetration levels" (Cherp *et al.* forthcoming) of wind and solar in a country's electricity mix for Logistic and Gompertz models. In the case of logistic-linear regressions, L represents twice the value where linear growth starts (i.e. linear growth starts at $L/2$)

- t_{max}: Year when the maximum growth rate (inflection point) is achieved, i.e. when the curve is the steepest. For logistic and logistic-linear models, this point is located at 50% of the asymptote, while for the Gompertz model is located at 37% of L.
- A *scale* (k): which sets the slope of the curve and controls how steep the curve is. In the case of logistic, linear and Gompertz models, the steepest point (maximum growth rate, inflection point, G) is located at t_{max}. Cherp *et al.* develop G as a metric for comparison of diffusion of energy technologies, defined as the maximum yearly growth rate of technology adoption on the S-curve "achieved at the inflection point and normalized to electricity supply at this point" (forthcoming, 4), in order to assess the feasibility of renewable electricity deployment in envisioned scenarios.

Figure 9. Components of an S-shape curve



In order to determine accurately this maximum yearly growth rate G and test its "robustness", several mathematical models can be used. This is because prior authors (inter alia Debecker and Modis 1994; Grübler 1997; Comin *et al.* 2008) disagree on which function is more accurate to describe technology diffusion and estimate growth parameters for comparison of energy technologies across different time periods. These parameters define the trajectory of the deployment curve of a technology in a country. Hence, other growth models are considered:

The logistic model is the most straightforward mathematical function that produces an S-curve (Kucharavy and De Guio 2011). It is the most widespread growth model to estimate diffusion of energy technologies (Wilson *et al.* 2013; Bento and Fontes 2015) since it analyses historical records to propose trends and assumes that "the rate of growth is proportional to both the amount of growth already accomplished and the amount of growth remaining to be accomplished" (Kucharavy and De Guio 2011, 560). This means that this curve is symmetrical on both sides of the inflection point G, which allows us to calculate the saturation point or penetration limits of the technology. However, this assumes that growth always follows a symmetrical trajectory, which would not be the case if growth continues after the inflection point (Cherp *et al.* forthcoming). Moreover, it is difficult for this model to realistically estimate the asymptote (ultimate penetration level) of the adoption curve for technologies that are still in early phases of growth. For that reason, several authors (Lekvall and Wahlbin 1973; Dixon 1980; Davies and Diaz-Rainey 2011) are inclined to other saturating growth functions, such as the Gompertz model, which assumes asymmetric growth after the inflection point, "so that the saturation levels are more than twice as high as the penetration at the inflection point and it takes longer time to approach near-saturation level" (Cherp *et al.* forthcoming, 44), which is more precise for policy-driven adoption of technologies, such as the case of wind and solar power. For example, Davies and Diaz-Rainey argue that "a positively skewed curve may be a better representation of the patterns of induced diffusion" (2011, 1230) in the presence of solid policy intervention. Another model to take into consideration is the logistic-linear function. This model assumes logistic growth until the inflection point, where the growth becomes linear at the same maximum annual rate G. This function provides a more "realistic" representation of empirical growth that does not necessarily have its inflection point at half of the saturation level since the maximum linear growth achieved may continue without slowdown. Kramer and Haigh (2009) argue that growth becomes linear after the technology reaches "materiality" (delivering 1% of the total global energy mix in the case of energy technologies), after which it achieves its final market share. This pattern is consistent across energy technologies, which they call "laws of energy deployment".

As mentioned before, the growth models described (logistic, Gompertz, and logistic-linear) are defined by a three-parameter mathematical function:

Logistic model: $f(t) = \frac{L}{1+ e^{-k(t-t_0)}}$

Gompertz model: $f(t) = Le^{-e^{-k(t-t_0)}}$

Logistic-linear model: $f(t) = \frac{L}{1+ e^{-k(t-t_0)}} \quad ; t < t_0$

$kL(t - t_0)/4 \quad ; t \geq t_0$

Where:

$L = asymptote$. This parameter is the saturation point or growth ceiling for logistic and Gompertz models. For the logistic-linear model, the linear growth starts at $L/2$.

$k = growth\ constant$

$t_0 = inflection\ point\ (t_{max})$. It is the maximum growth year for the three models. For the logistic-linear model, it is the point where the linear growth starts. For the logistic and logistic-linear models corresponds to $L/2$. For Gompertz model, it corresponds to $L * 0.368$ (37% of L)

However, the final saturation levels and duration of transition (the time it takes for a technology to be adopted from the designated take-off time until 90% of the penetration level) are still difficult to estimate in growth models of technologies still experiencing accelerating growth. In their recent publication, Cherp *et al.* find that when fitting logistic and Gompertz models to empirical data points of wind and solar deployment, they show agreement on the G metric for countries with maturity levels above 50%. This causes difficulty when using S-curves to predict parameters for emerging technologies, given that "one can identify a more accurate ceiling and steepness with a larger data set" (Kucharavy and De Guio 2011, 561). Maturity refers to the "diagnostic parameter calculated as the level of technology adoption in the last empirically observed year as a percentage of the predicted asymptote" (Cherp *et al.* forthcoming, 13). It is the saturation level achieved by the deployment curve in the last available year in relation to the ultimate penetration level (Cherp *et al.* forthcoming). As mentioned before, this parameter is used by Cherp and his colleagues to classify countries according to their growth stage (accelerating, stable or stalling growth) and to evidence "robustness" of the G metric by showing that G values converge (within 20% accuracy) between the two growth models (logistic and Gompertz) when maturity levels of technology adoption in a country are above 50%.

3.3. Method and data

3.3.1. Growth models

All the historical data for electricity generation for the selected countries: Argentina, Brazil, Chile, Mexico, and Peru was retrieved from the International Energy Agency (IEA) database for the period 1996 – 2019[1].

In order to answer RQ1 of this dissertation, I identified the growth parameters for wind and solar technologies by fitting the historical data of electricity generation from these sources from each selected country (in GWh) into the algorithm developed by Cherp *et al.*[2] in R *studio*. To fit these growth curves, they use the nls function from the R programming environment, which "implements the Gauss-Newton algorithm for least-square fitting of non-linear functions, and $nlsLM$ function from $mimpack.lm$ package, implementing more robust Levenberg-Marquardt algorithm" (Cherp *et al.* forthcoming). The code runs in R *studio*, with the packages *minpack.lm, dplyr, stringr, ggplot2, and patchwork*. This algorithm performs regression analyses for four different growth models: logistic, Gompertz, logistic-linear and exponential. To compare which model is the best fit for the data, the algorithm delivers the parameters described in Table 3:

Table 3. Parameters of growth models

Parameter	**Definition**
Fit	S (logistic); L (linear-logistic); G (Gompertz); E (Exponential)
L	Asymptote

[1] https://www.iea.org/data-and-statistics

[2] https://github.com/poletresearch/RES_article

Parameter	Definition
$L.size$	L as percentage of the system size in t_{max} (or in the last year available if t_{max} is in the future)
t_{max}	Maximum growth year (for all models except E)
k	Growth constant
Δt	Transition time: time to go from 10% to 90% of the asymptote. Calculated only for S and G, as L and E have no growing limits
G	Maximum growth rate, inflection point achieved at t_{max}. Not calculated for E as this model does not have a maximum growth rate
$G.size$	G as percentage of the system size in t_{max} (or in the last year available if t_{max} is in the future)
Maturity	Percentage value of the saturation level achieved by the S-curve by the last available empirical year. Calculated only for S and G, as L and E do not have limits to grow
RSS.Rel	Relative residual sum of squares. This parameter is used to calculate the best fit for each curve (goodness-of-fit) for different models fitting the same dataset. A smaller RSS means a better fit. In this case, the relative residual sum of squares is calculated by dividing the smallest RSS value for each country by the value of the other models.
Good	1 for successful model fitting and 0 if the algorithm was not able to fit the model to the data
Future	1 if t_{max} is in the future and 0 otherwise.

Based on these parameters, I selected the saturating growth model (either Logistic or Gompertz) that fitted best with the empirical data. Using the mathematical equation for each model, I forecasted each country's wind and solar deployment curve until 2050. Once I obtained these curves, I plotted them against the renewable targets stated by each nation for comparison. The results can be found in Section 4.

3.3.2. Identifying national renewable targets

Several sources were reviewed to determine the renewable targets that each country has established. As defined by IRENA, renewable energy targets are "numerical goals established by governments to achieve a specific amount of renewable energy production or consumption. Renewable energy targets can apply to the electricity, heating/cooling or transport sectors, or to the energy sector as a whole, and often include a specific time period or date by which the target is to be reached. They can be stated in capacity (MW) or generation (MWh) terms, or in relative, incremental or absolute terms" (IRENA 2015, 12). Governments have pledged to increase the share of renewable sources in electricity generation as part of their commitments for GHG emissions reduction and, with this purpose in mind, they have enacted national strategies, policies, legislation, and plans. However, these targets are often not disaggregated by technology (they usually include all low-carbon sources without distinction: hydro, wind, solar, biomass, nuclear, and geothermal), except in the case of Brazil, which differentiates targets for wind, solar, and biomass. However, for this dissertation, I have focused on wind and solar objectives for electricity generation (expressed in GWh). In order to come up with a proper breakdown of generation targets by technology, I evaluated: 1) the current electricity mix of each country, in electricity output terms; 2) the installed capacity of renewables by technology; 3) the stated technology national preference for future development, when available (for example solar in the case of Chile, or wind in the case of Peru); and 4) forecasts, reports and roadmaps elaborated from specialized agencies such as the IEA or IRENA, when available. With these considerations, I assigned percentage values to each technology from the total stated target. For example, Chile has promulgated a target of 60% of renewable electricity by 2035, of which 40% could come from non-conventional renewable energy sources (wind, solar, biomass, and small-scale hydro) and the remaining 20% from large-scale hydropower ("Energía 2050", Chile's Energy Policy 2020). I distributed the 40% from NCRE as 35% coming from biomass, 35% from solar, 25% from wind, and 5% from small hydro, reflecting the mix of the current installed capacity and the country preference (in this case, for solar).

A breakdown of these established targets is described in Table 4 for the selected countries, alongside the assigned distribution expressed in GWh and the sources of information. Nevertheless, these targets are provided in percentage values of electricity generation in the future, and for that reason, it is necessary to project total electricity generation in each country. Thus, I used the compound growth equation to forecast total system size until 2050, as shown below:

$$x_n = x_0(k+1)^n$$

Where:

$x_n = electricity\ generation\ in\ year\ n\ (GWh)$

$x_0 = starting\ value\ (GWh)$

$k = growth\ rate$

For the value of k I used the average value of the growth rate in electricity output observed in the last ten years of available data (2008 – 2018) for each country.

Table 4. National targets in case-study countries

Country	**National target**	**Distribution of wind and solar targets**	**Source**
Argentina	Share of renewable sources in electricity consumption: - 8% by 2017 -12% by 2019 -16% by 2021 -18% by 2023 -20% by 2025	Share in total electricity generation: - 8.64% of wind power and 1.5% of solar by 2019 - 11.52% of wind power and 2% of solar by 2021 - 12.96% of wind power and 2.25% of solar by 2023 - 14.4% of wind power and 2.5% of solar by 2025	Law 27191 on Renewable energy
Brazil	- 23% renewables in the power supply by 2030 (not including hydro) - 27% ~ 40% of total electricity for wind power by 2050 - 4% ~ 12% of total electricity for solar power by 2050	Share in total electricity generation: - 16% of wind power and 2% of solar by 2030 - 27% of wind power and 4% of solar by 2050	- Brazil's NDC -National Energy Plan PNE 2050 ("Plano Nacional de Energia PNE 2050")
Chile	Renewable electricity share (including hydro): - 20% by 2025 (only NCRE) - 60% by 2035 (of which 40% can come from NCRE, including small hydro) - 70% by 2050	Share in total electricity generation: - 10% of wind power and 14% of solar by 2035 - 13% of wind power and 16% of solar by 2050	"Energía 2050", Chile's Energy Policy

Country	National target	Distribution of wind and solar targets	Source
Mexico	Minimum participation of clean sources in electricity generation: - 25% until 2018 - 30% until 2021 - 35% until 2024 - 39,9% until 2033 - 50% until 2050 Clean sources include: wind, solar, hydrogen, nuclear power, and efficient CHP power stations with CCS (IRENA 2015)	Share in total electricity generation: - 8.1% of wind power and 4.5% of solar by 2021 - 10.5% of wind power and 7% of solar by 2024 - 12.8% of wind power and 8.8% of solar by 2033 - 17.5% of wind power and 12.5% of solar by 2050	Mexico's Energy Transition Law
Peru	- 5% of electricity generation by 2021 (excluding hydropower) - Greater than 60% of electricity generation by 2025 (including hydropower). - 15% of electricity share from RE by 2030 (solar, wind, biomass and geothermal)	Share in total electricity generation: - 7.5% of wind power and 3.3% of solar by 2030	Decree N°1002 for the promotion of RE for electricity generation

For RQ2 of this dissertation, I selected the countries that have reached a stable or stalling growth phase (maturity levels above 50%) for wind and solar electricity generation on both saturating growth models (logistic and Gompertz). As previously described, the trajectory of growth curves is more accurately estimated for technologies that have achieved a higher saturation level, as emerging deployment does not provide enough data points to forecast the future shape of the curve (i.e., the curve is too young to accurately know where it will go). This is demonstrated by Cherp *et al.* (forthcoming) when testing the robustness of maximum growth rate (G) and Δt across growth models. They find that G converges between the logistic and Gompertz models when maturity levels are above 50%, and for Δt when maturity levels are over 90% (Cherp *et al.* forthcoming). Therefore, I focused on Brazil, Chile, and Mexico for wind production and Brazil and Chile for solar generation. The inclusion of wind power in Mexico in the analysis is the only exception, since it presents a maturity level of 34% for Gompertz model (best fit), but it has a maturity level of 68% in the logistic model.

In order to identify the growth rates required to achieve the wind and solar targets, I included the value of these targets as data points of electricity generation into the algorithm previously mentioned. I used the resulting parameters in the growth equation corresponding to the best fit (either Logistic, Gompertz or logistic-linear) to forecast how this "ideal" deployment curve would look like compared to the projected one based on historical growth trajectories. However, to obtain the value of these targets in electricity generation terms (GWh), it is also necessary to project the total system size (future electricity generation) using the compound growth equation. For the value of k, I developed three scenarios based on the existing literature and the predictions from national energy plans: an optimistic one that assumes faster economic development and therefore larger electricity expansion, a pessimistic that assumes low electricity expansion and a baseline one based on the average value of the growth rate in the last ten years (same growth constant used in RQ1). Table 5 shows the employed rates.

Table 5. Electricity demand growth rates used for scenario construction

	Growth rates		
	Scenario 1: Pessimistic	**Scenario 2: baseline growth**	**Scenario 3: Optimistic**
Brazil	1%	2.82%	3.50%
Chile	1.80%	2.50%	3.21%
Mexico	0.50%	2.21%	2.50%

In the case of Brazil, the National Energy Plan PNE 2050 released in December 2020 (Ministério de Minas e Energia 2020) considers two scenarios: in the upper limit is the scenario of "Challenge of Expansion" (Desafio de Expansão"), which projects infrastructure expansion and a considerable increase in energy demand, with potential electricity consumption increasing at a 3.5% annual rate between 2015 and 2050; and the "Stagnation" scenario ("Estagnação"), which assumes a relative stagnation in Brazil's per capita energy demand, with electricity potential consumption growing at an annual rate of 1% between 2015 and 2050. The baseline scenario I considered with a yearly growth rate of 2.82% is based on the average electricity generation growth rate of the last ten years.

For Chile, the National Long-term Energy Plan (Ministerio de Energía 2019) proposes three scenarios for electricity consumption growth rates, corresponding to 1.8%, 2.5%, and 3.2%, in relation to the projected energy demand, renewables investment costs and the electrification of services, transport and heating.

Finally, Mexico developed two scenarios for final energy demand in their Energy Transition Strategy: a baseline scenario that represents business-as-usual, which estimates an annual growth rate of 2.5% in electricity demand between 2014 and 2050; and a "Sovereign Energy Transition" that considers policy interventions in energy efficiency to keep a yearly growth rate of 0.5% in electricity demand between 2014 and 2050. The annual growth rate of 2.21% is the average electricity generation growth rate of the last ten years.

4. Results

In order to recalculate the national renewable targets for wind and solar development to the values that would allow comparison across countries and between the historical data and the targets, I used a procedure described in Section 3.3.2, which yields the 'standardized' targets as summarized in Table 6.

Table 6. Electricity generation targets for wind and solar power

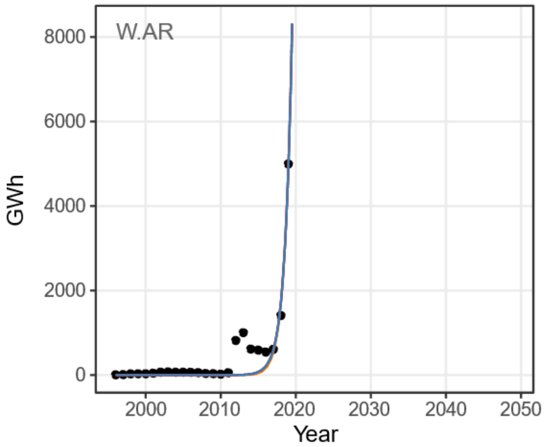
	Renewable targets generation values (GWh)	
	Wind power	**Solar power**
Argentina	12 987 by 2019 18 154 by 2021 21 413 by 2023 24 944 by 2025	2 254 by 2019 3 151 by 2021 3 717 by 2023 4 330 by 2025
Brazil	134 272 by 2030 394 853 by 2050	28 952 by 2030 58 497 by 2050
Chile	14 077 by 2035 29 382 by 2050	19 708 by 2035 36 162 by 2050
Mexico	29 024 by 2021 40 174 by 2024 55 698 by 2030 118 202 by 2050	16 125 by 2021 26 783 by 2024 38 293 by 2030 84 430 by 2050
Peru	8 038 by 2030	3 537 by 2030

4.1. Historical growth parameters of wind and solar power adoption

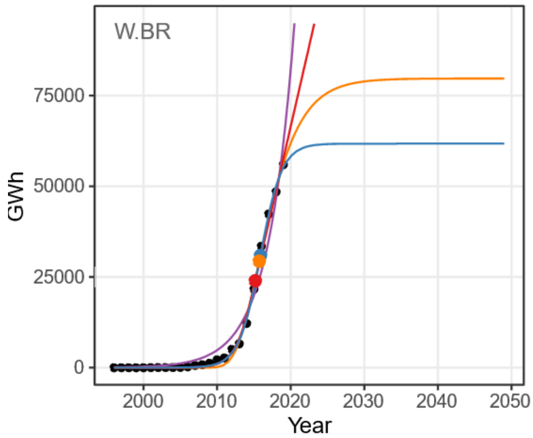
After introducing the historical data of wind and solar generation, the aforementioned algorithm provides the forecasted deployment curves for each country, considering four mathematical growth models: logistic, Gompertz, logistic-linear and exponential.

Figure 10. Use of wind power in the case countries: empirical data and growth models

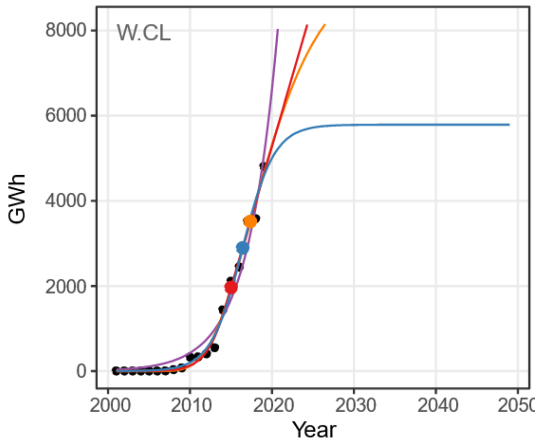
Each panel shows the generation of electricity from wind power in each country. Black dots show historical deployments, color lines show fit growth models (purple – exponential, blue – logistic, orange – Gompertz, and red – logistic-linear). Color circles indicate inflection points (points of maximum growth) for each model.



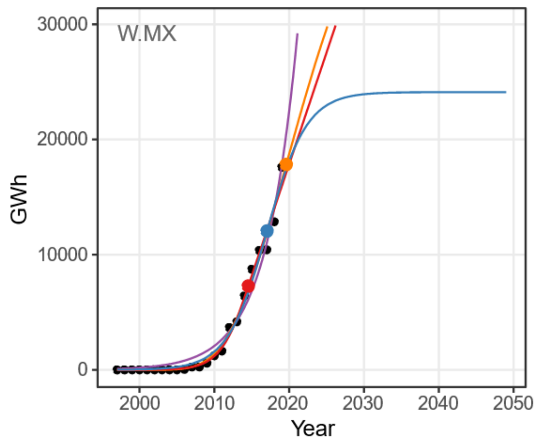
Wind power in Argentina



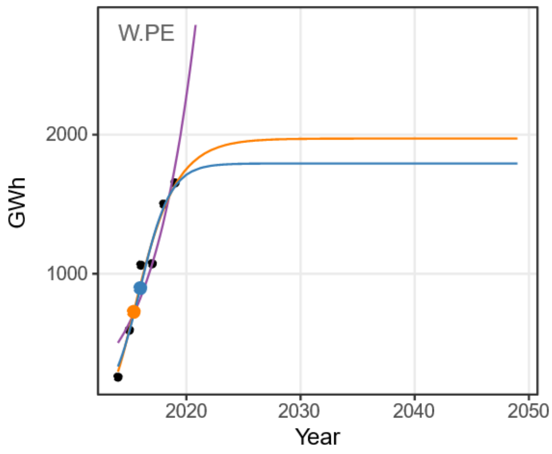
Wind power in Brazil



Wind power in Chile



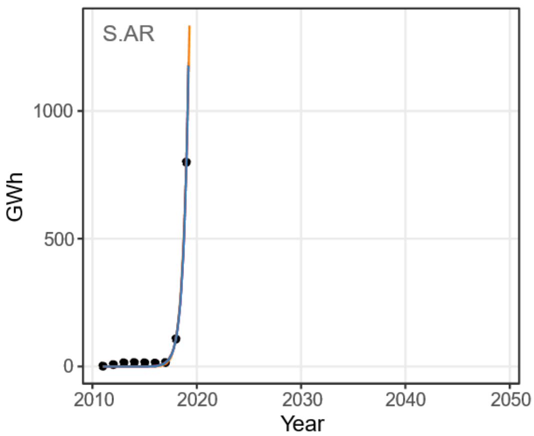
Wind power in Mexico



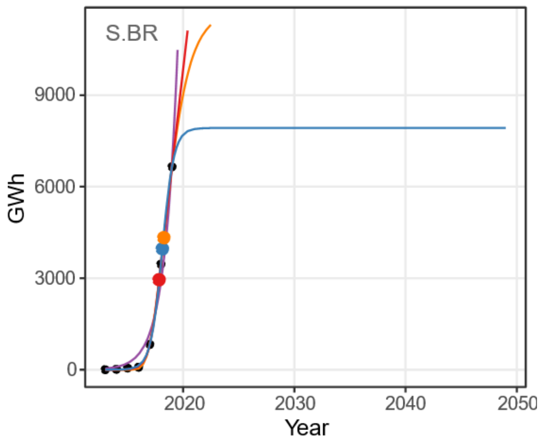
Wind power in Peru

Figure 11. Use of solar power in the case countries: empirical data and growth models

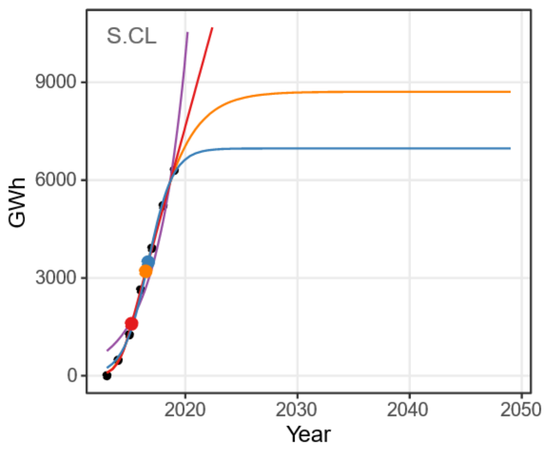
Each panel shows the generation of electricity from solar power in each country. Black dots show historical deployments, color lines show fit growth models (purple – exponential, blue – logistic, orange – Gompertz, and red – logistic-linear). Color circles indicate inflection points (points of maximum growth) for each model.



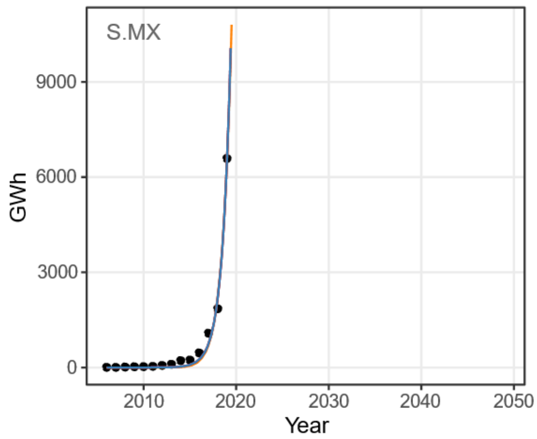
Solar power in Argentina



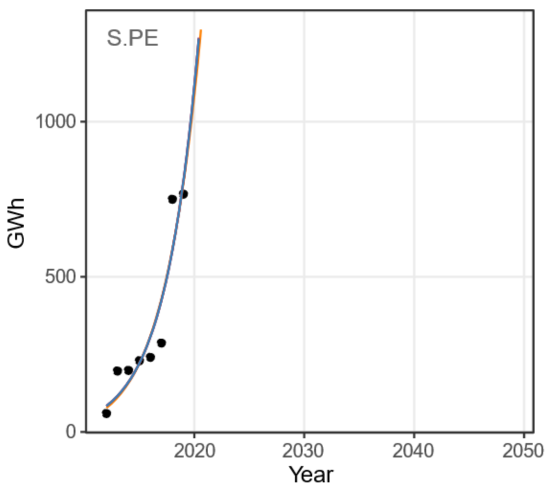
Solar power in Brazil



Solar power in Chile



Solar power in Mexico



Solar power in Peru

The growth parameters resulting from the algorithm for each model are displayed in Table 7 and Table 8. The best fit between Logistic or Gompertz model (according to the residual sums squared value) is highlighted, since I have focused on growth following an S-shaped curve.

Table 7. Growth parameters of wind power growth in the case countries

WIND GENERATION										
Country	***Fit***	***L*** *(GWh/year)*	***L.nrm***	t_{max} *(year)*	***k***	Δt *(years)*	***G*** *(GWh/year)*	***G.nrm***	***Maturity***	***RSS.Rel***
Argentina	S	4 141 557	2 968%	2025	1.05	4.17	1 089 102	780%	0%	1
	G	2.79E+10	2E+07%	2060	0.06	46.5	6.82E+08	5E+05%	0%	1.04
	L	—	—	2025	1.05	—	1 088 808	780%	—	1
	E	—	—	—	1.05	—	—	—	—	1
Brazil	S	61 759	10.67%	2016	0.68	6.42	10 566	1.83%	89%	1
	G	79 730	13.77%	2016	0.32	9.59	9 426	1.63%	71%	2.25
	L	—	—	2015	0.74	—	8 842	1.52%	—	2.20
	E	—	—	—	0.28	—	—	—	—	20.62
Chile	S	5 789	7.30%	2016	0.52	8.48	750	0.95%	79%	1.20
	G	9 554	12.03%	2017	0.20	15.3	707	0.89%	49%	1.12
	L	—	—	2015	0.67	—	664	0.88%	—	1
	E	—	—	—	0.27	—	—	—	—	3.10
Mexico	S	24 113	7.49%	2017	0.37	11.6	2 269	0.70%	68%	1.30
	G	48 458	14.63%	2020	0.13	23.5	2 342	0.71%	34%	1
	L	—	—	2014	0.53	—	1 939	0.62%	—	1.07
	E	—	—	—	0.24	—	—	—	—	2.09
Peru	S	1 793	3.47%	2016	0.76	5.8	339	0.66%	91%	1.23
	G	1 972	4.09%	2015	0.46	6.6	337	0.70%	83%	1
	L	—	—	—	—	—	—	—	—	—
	E	—	—	—	0.25	—	—	—	—	3.21

Table 8. Growth parameters of solar power growth in the case countries

SOLAR GENERATION										
Country	***Fit***	***L*** *(GWh/year)*	***L.nrm***	t_{max} *(year)*	***k***	Δt *(years)*	***G*** *(GWh/year)*	***G.nrm***	***Maturity***	***RSS.Rel***
Argentina	S	25 222	18.07%	2021	2.02	2	12 732	9.12%	3%	1
	G	1 844 995	1 322%	2028	0.23	13	154 985	111%	0%	1.11
	L	—	—	2020	2.02	—	12 731	9.12%	—	1
	E	—	—	—	1.99	—	—	—	—	1
Brazil	S	7 923	1.32%	2018	1.91	2.30	3 783	0.63%	84%	1.42
	G	11 756	1.95%	2018	0.77	4.02	3 315	0.55%	57%	1.98
	L	—	—	2017	2.16	—	3 191	0.53%	—	1
	E	—	—	—	0.87	—	—	—	—	245
Chile	S	6 974	8.79%	2017	0.90	4.87	1 575	1.98%	89%	7.23
	G	8 711	10.98%	2016	0.44	7.01	1 411	1.78%	72%	1
	L	—	—	2015	1.58	—	1 262	1.67%	—	2.08
	E	—	—	—	0.36	—	—	—	—	115
Mexico	S	3 514 545	1061%	2025	0.13	23.48	2 342	0.71%	34%	1
	G	1.21E+10	3E+06%	2056	0.07	43.06	3E+08%	96 847%	0%	1.25
	L	—	—	2024	1.09	—	956 256	288%	—	1
	E	—	—	—	1.09	—	—	—	—	1
Peru	S	138 143	242%	2035	0.32	13.56	11 196	19.59%	1%	1
	G	2.89E+08	5E+05%	2126	0.02	129	2 549 487	4 460%	0%	1.02
	L	—	—	2034	0.32	—	11 093	19.41%	—	1
	E	—	—	—	0.32	—	—	—	—	1

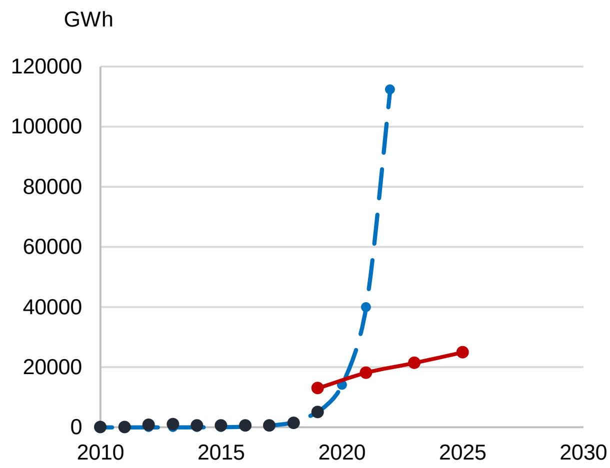
4.2. Do extrapolated trajectories meet the national targets?

Considering the best-fit model and its parameters to build the wind and solar growth curves, I plotted the renewable targets from the projected total electricity generation for each country for comparison, depicted in the figures below, by country and technology:

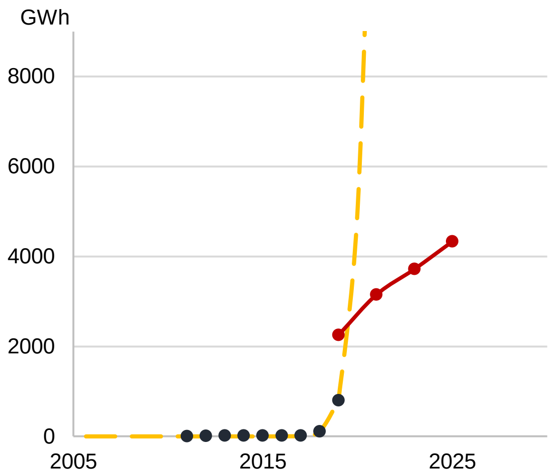
4.2.1 Argentina

Figure 12. Historical data, growth model and the national targets for wind and solar power in Argentina

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – wind power, and yellow – solar power). Red dots show the national renewable targets, in accordance with Table 7 for wind power and Table 8 for solar power, and the red lines show the deployment curve of these targets.



Wind power (maturity level: 0%)



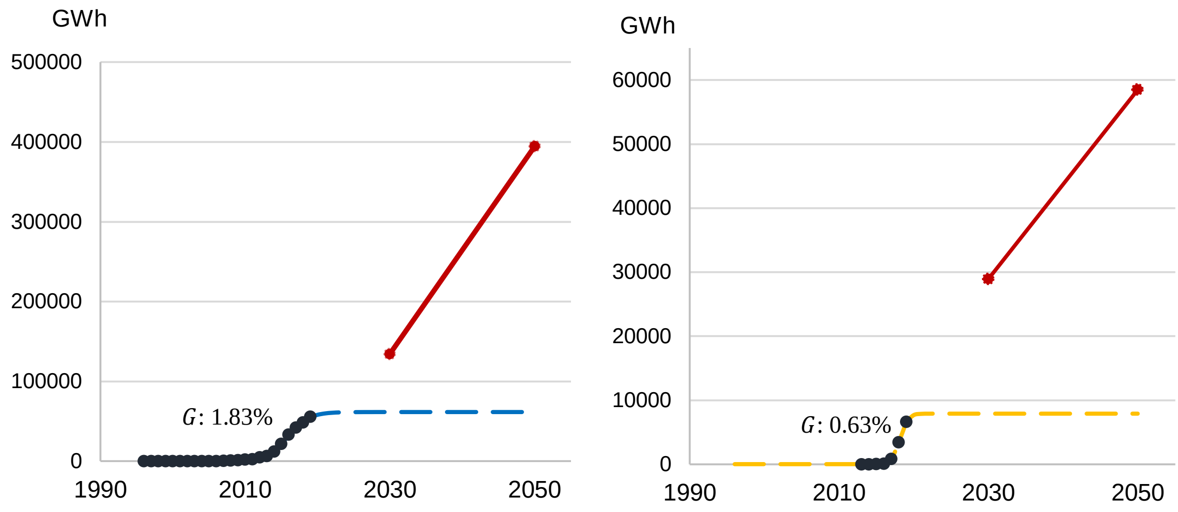
Solar power (maturity level 3%)

We can evidence from the case of Argentina that when maturity levels are so low (0% for wind and 3% for solar) is impossible to accurately predict the growth trajectory of these technologies, as the best fit model projects an spectacular growth that would surpass every target and is not realistic. This is because renewable development is so recent that the model does not know what will be the destination of the curve.

4.2.2 Brazil

Figure 13. Historical data, growth model and the national targets for wind and solar power in Brazil

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – wind power, and yellow – solar power). Red dots show the national renewable targets, in accordance with Table 7 for wind power and Table 8 for solar power, and the red lines show the deployment curve of these targets.



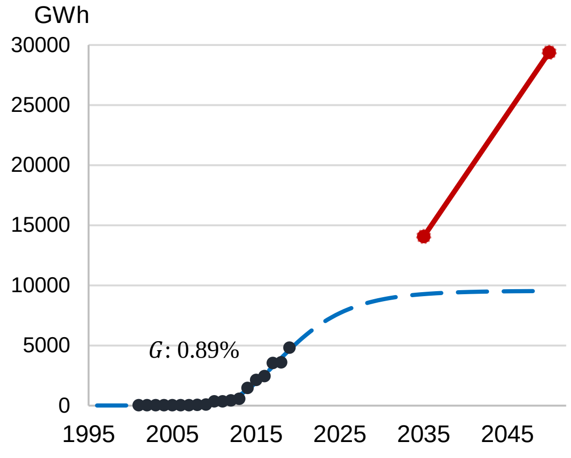
Wind power (maturity level 89%) Solar power (maturity level 84%)

In the case of Brazil, we see that the model estimates a maximum growth rate of 1.83% annually for wind power, but the curve reaches stagnation at around 62 000 GWh in 2022, meaning that it would not achieve its targets. However, if we assume a linear growth after the inflection point, keeping that same annual growth rate, it is possible for the country to meet its targets. In the case of solar power, the targets represent a more significant challenge, even if they keep the maximum growth rates achieved.

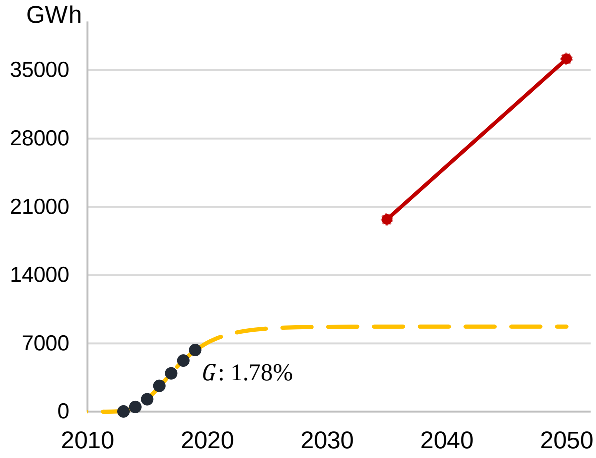
4.2.3 Chile

Figure 14. Historical data, growth model and the national targets for wind and solar power in Chile

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – wind power, and yellow – solar power). Red dots show the national renewable targets, in accordance with Table 7 for wind power and Table 8 for solar power, and the red lines show the deployment curve of these targets.



Wind power (maturity level 49%)



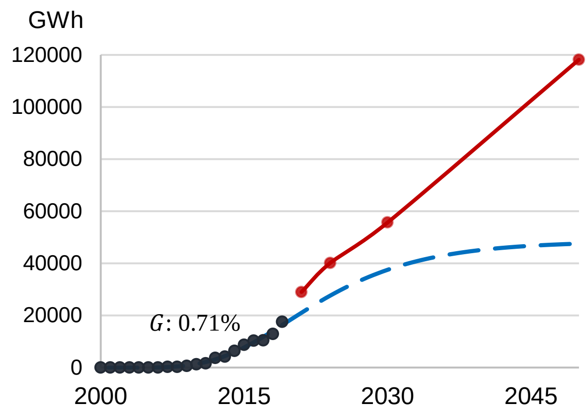
Solar power (maturity level 72%)

The graphs evidence that Chile is much closer to attaining its wind power goals, with the curve only stagnating around 2032. However, we must consider that the maturity level of deployment is only 49%, which indicates that is difficult for the model to accurately predict the curve's trajectory. In the case of solar power, we see that the targets would not be achieved if the deployment indeed follows an S-curve. Nevertheless, if we assume a constant (linear) growth after the inflection point (at the same G rate), the targets could be reached.

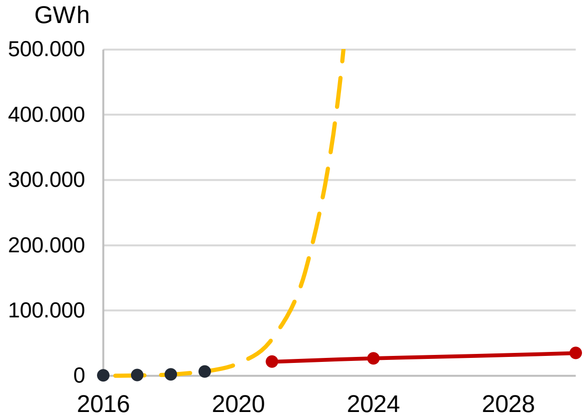
4.2.4 Mexico

Figure 15. Historical data, growth model and the national targets for wind and solar power in Mexico

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – wind power, and yellow – solar power). Red dots show the national renewable targets, in accordance with Table 7 for wind power and Table 8 for solar power, and the red lines show the deployment curve of these targets.



Wind power (maturity level: 34%)



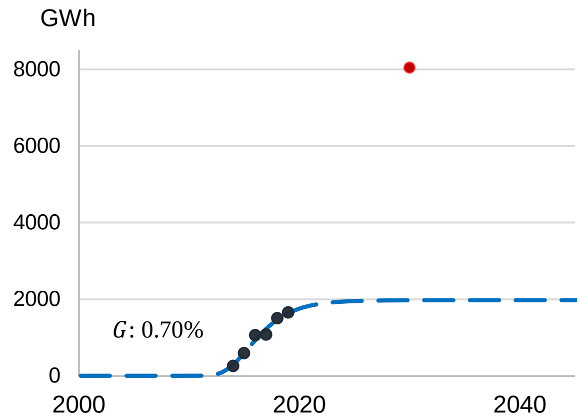
Solar power (maturity level: 34%)

Although the Gompertz curve is the best fit in the regression analysis for wind development in Mexico according to the algorithm calculations, it shows a maturity level of 34%, while for the logistic regression the maturity level is higher, with 68%. However, the country seems to be within reach to meeting its targets, especially in the closest years. Nevertheless, for the furthest targets (such as 2050), it would need to keep constant the maximum growth rate and follow a linear growth after the inflection point. In the case of solar power, we see another example of the inability of the model to predict the curves when maturity levels are below 50%, as it projects an outstanding electricity deployment, which is not realistic.

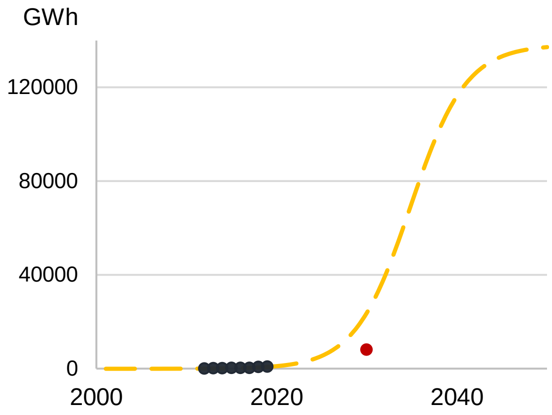
4.2.5 Peru

Figure 16. Historical data, growth model and the national targets for wind and solar power in Peru

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – wind power, and yellow – solar power). Red dots show the national renewable targets, in accordance with Table 7 for wind power and Table 8 for solar power, and the red lines show the deployment curve of these targets.



Wind power (maturity level 83%)



Solar power (maturity level 0%)

In the case of Peru for wind power, we see that targets are far away to be met if the country keeps its current deployment rates. This technology would need to experience an exponential growth in order to achieve the goal of 8 000 GWh of electricity generation by 2030. For solar technology, the model predicts an impressive growth that super-exceeds the established target, but this is due to the low maturity level (0%) and the uncertainty in the trajectory of the curve.

These results show that the established targets are not achieved by any of the studied countries neither in wind nor solar development if they keep their current deployment rates, considering that technologies expand following an S-shaped trajectory.

Therefore, we can proceed to answer RQ2: what are the growth rates required to achieve these targets? How should the deployment curves look like?

4.3. What growth rates are needed to achieve national targets?

For this question, I focused only on the countries that reached a stable or stalling growth level, because, as previously demonstrated, the projections are not realistic for maturity levels below 50%. The countries analyzed are Brazil, Chile, and Mexico for wind power, and Brazil and Chile for solar power. In addition, I present the results for three scenarios that consider different rates for total electricity generation, depending on the development perspectives that countries have considered in their long-term Energy Strategies. I considered ideal S-curves from either Logistic or Gompertz functions, according to the model that best fits the data from residual sums of squares values. However, in some scenarios it is not possible to fit a saturating model for this growth, and in those cases I adopted a logistic-linear curve.

A summary of the renewable targets for wind and solar technologies for each country is displayed in Table 9 and Table 10, which shows the electricity generation (GWh) values that need to be achieved in each proposed scenario.

Table 9. Renewable targets generation values for wind power

		Renewable targets generation values wind power (GWh)		
		Scenario 1: Pessimistic	**Scenario 2: baseline growth**	**Scenario 3: Optimistic**
Brazil	by 2030	108 422	134 272	145 394
	by 2050	223 249	394 853	488 199
Chile	by 2035	11 147	12 525	14 077
	by 2050	18 938	23 582	29 382
Mexico	by 2021	27 592	29 024	29 272
	by 2024	36 306	40 174	40 863
	by 2030	45 490	55 698	57 625
	by 2050	68 889	118 202	129 420

Table 10. Renewable targets generation values for solar power

		Renewable targets generation values solar power (GWh)		
		Scenario 1: Pessimistic	**Scenario 2: baseline growth**	**Scenario 3: Optimistic**
Brazil	by 2030	23 378	28 952	31 350
	by 2050	33 074	58 497	72 326
Chile	by 2035	15 606	17 535	19 708
	by 2050	23 309	29 024	36 162

Including the aforementioned target values as data points in the growth models produces the parameters required to achieve the renewable targets. A breakdown by country and technology is presented in the following subsections.

4.3.1. Brazil

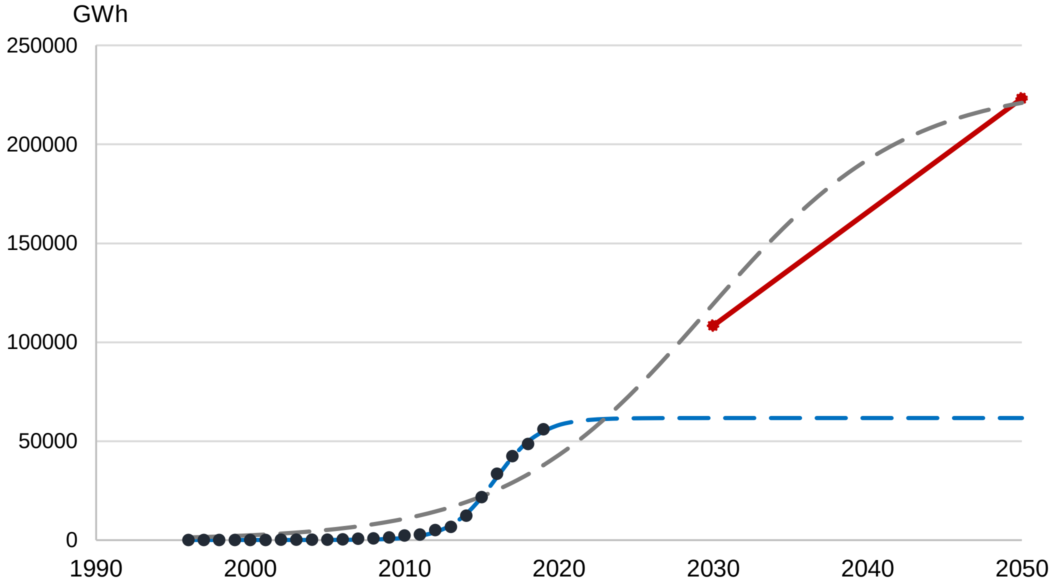
Table 11. Growth parameters in Brazil for the three scenarios of achieving wind targets

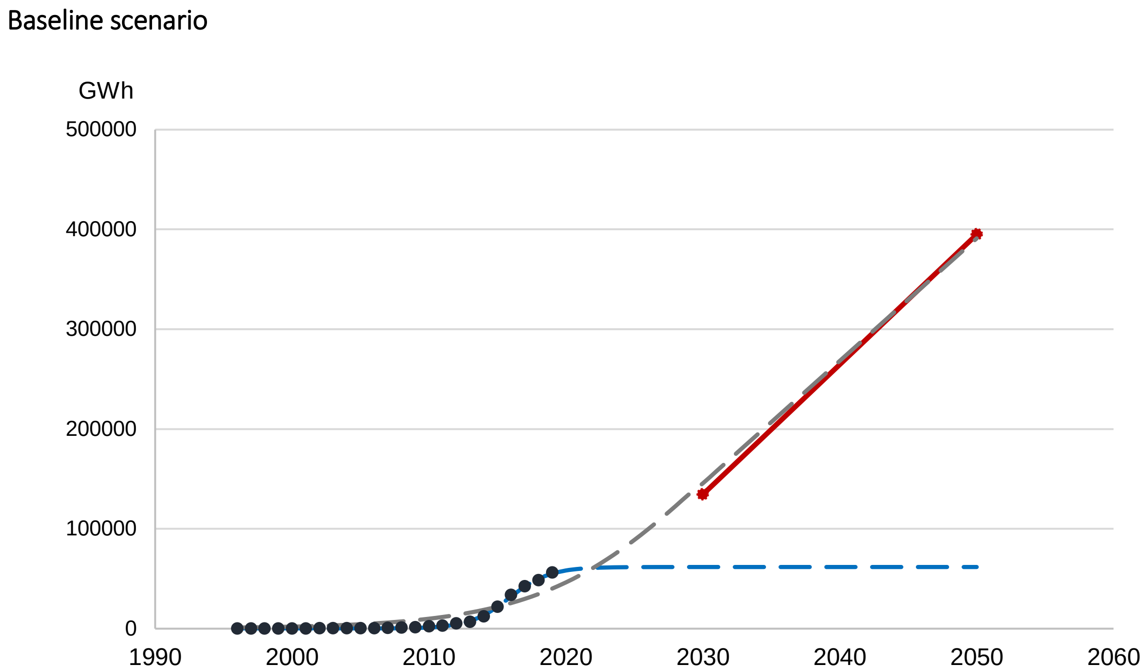
WIND GENERATION											
Sc.	***Fit***	***L*** *(GWh)*	$\boldsymbol{L.nrm}$	$\boldsymbol{t_{max}}$ *(year)*	$\boldsymbol{k}$	$\boldsymbol{\Delta t}$ *(years)*	***G*** *(GWh/year)*	$\boldsymbol{G.nrm}$	***Maturity***	$\boldsymbol{RSS.Rel}$
1 (1%)	L	—	—	2012	1.08	—	5 719	1.03%	—	1.00
	E	—	—	—	0.07	—	—	—	—	21.92
	S	230 387	34%	2030	0.15	28.47	8 891	1.31%	96%	5.79
2 (2.82%)	L	—	—	2030	0.17	—	12 275	1.46%	—	1.00
	E	—	—	—	0.08	—	—	—	—	4.40
3 (3.50%)	L	—	—	0	0.00	—	0.00	0%	—	0.00
	E	—	—	—	0.08	—	—	—	—	4.27

Figure 17. Historical data, best-fit growth model, ideal deployment, and national targets for three scenarios of electricity generation for wind power in Brazil

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – projected wind deployment by the best-fit growth model, and grey – "ideal" deployment required to achieve wind targets). Red dots show the national renewable targets, in accordance with Table 9 for each scenario, and the red lines show the deployment curve of these targets.

Pessimistic scenario





In the case of Brazil for wind power, I only plotted Scenarios 1 and 2, since for Scenario 3 the only good fit is the exponential function. We can see for Scenario 1 that the model projects a slower but much more sustained logistic growth (G in this scenario is lower than the G in the first logistic projection) in order to achieve the target, as t_{max} is only reached in 2030, which allows growth for a longer time. For scenario 2, the best fit is a logistic-linear curve, which estimates a logistic growth until 2030 (t_{max}), from which the deployment becomes linear (i.e., the curve grows constantly at the rate G).

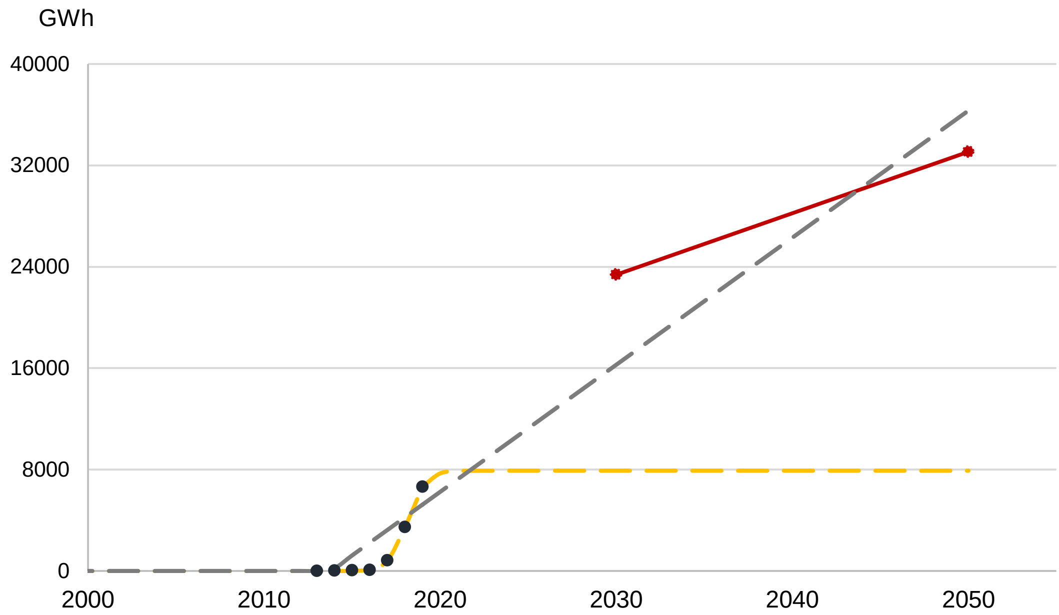
Table 12. Growth parameters in Brazil for the three scenarios of achieving solar targets

SOLAR GENERATION										
$Sc.$	Fit	L (GWh)	$L.nrm$	t_{max} (year)	k	Δt (years)	G (GWh/year)	$G.nrm$	$Maturity$	$RSS.Rel$
1 (1%)	L	—	—	2014	8.98	—	1 003	0%	—	4.37
	E	—	—	—	0.06	—	—	—	—	14.90
2 (2.82%)	L	—	—	2016	4.57	—	1 745	0%	—	1.15
	E	—	—	—	0.07	—	—	—	—	18.28
	S	58 881	7%	2030	0.25	18	3 645	0%	99%	1.00
3 (3.50%)	L	—	—	2017	5.07	—	2 156	0%	—	1.00
	E	—	—	—	0.08	—	—	—	—	87.87

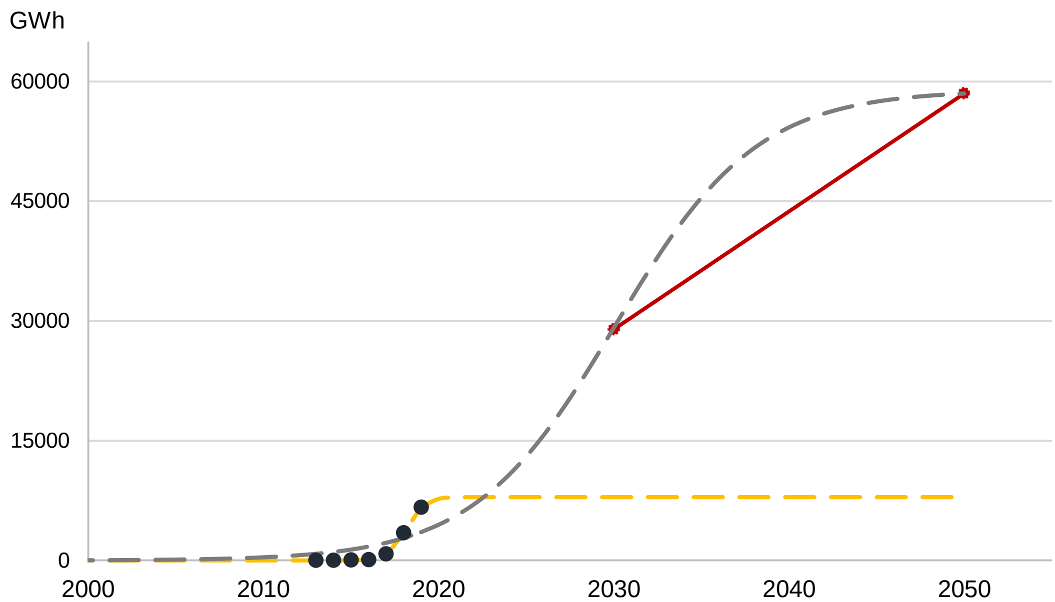
Figure 18. Historical data, best-fit growth model, ideal deployment, and national targets for three scenarios of electricity generation for solar power in Brazil

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (yellow – projected solar deployment by the best-fit growth model, and grey – "ideal" deployment required to achieve wind targets). Red dots show the national renewable targets, in accordance with Table 10 for each scenario, and the red lines show the deployment curve of these targets.

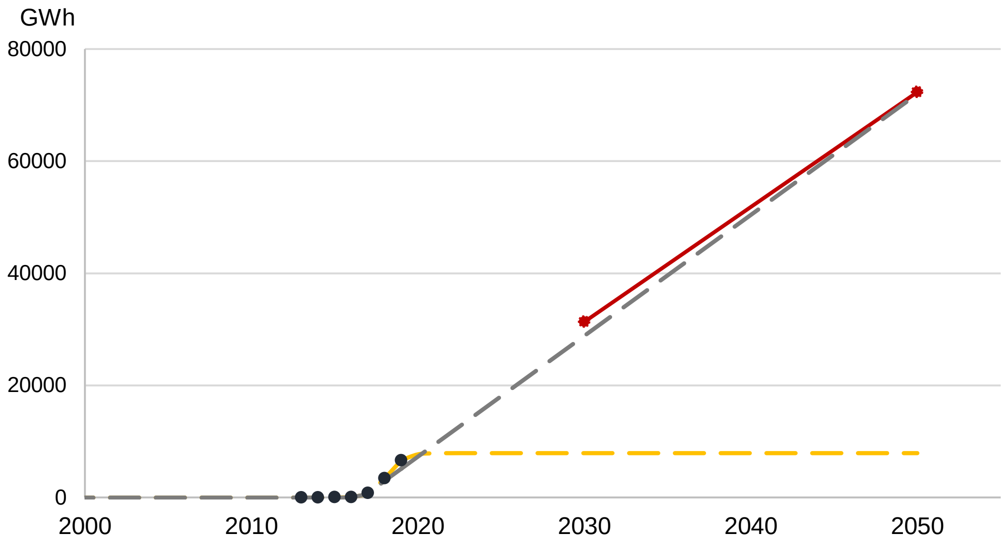
Pessimistic scenario



Baseline scenario



Optimistic scenario



From the three scenarios of Brazil's solar deployment, we can see that for Scenarios 1 and 3 (the growth rates proposed in their National Energy Plan), the algorithm fits logistic-linear curves as the best model. This means that once the country has reached its maximum growth rate, it must keep growing constantly at that rate in order to attain its targets, i.e. 1 002 GWh/year for the pessimistic scenario and 2 156 GWh/year in the case of a larger expansion in the national electricity system. Scenario 2 (baseline) proposes a longer growth that follows an S-shaped curve, with the duration of transition (the time it takes to expand from 10% to 90% of total penetration levels) of 18 years, and reaching the inflection point only in 2030.

4.3.2. Chile

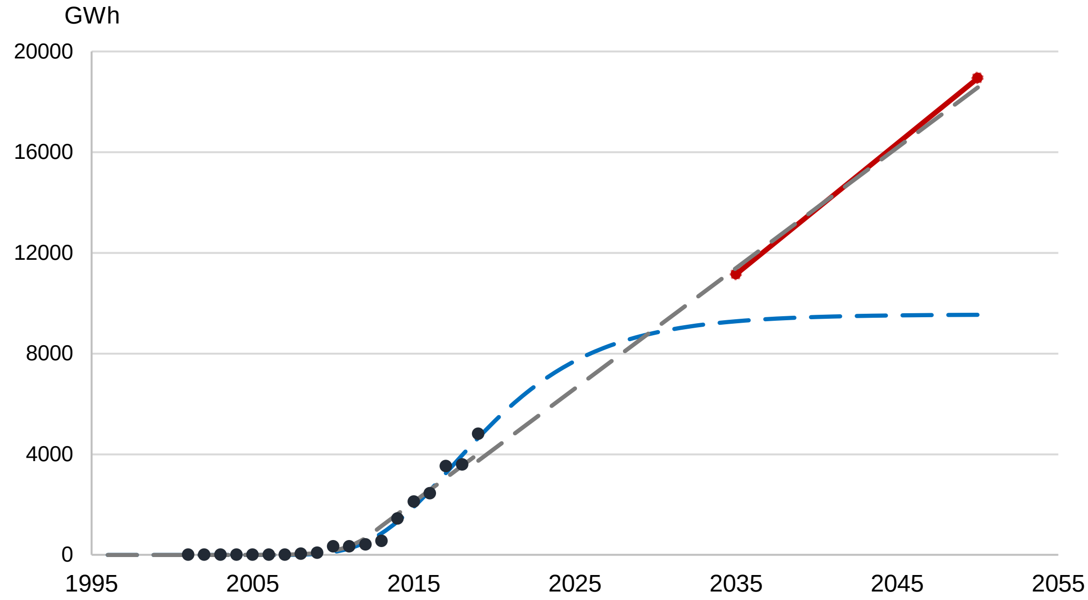
Table 13. Growth parameters in Chile for the three scenarios of achieving wind targets

WIND GENERATION										
Sc.	Fit	L *(GWh)*	$L.nrm$	t_{max} *(year)*	k	Δt *(years)*	G *(GWh/year)*	$G.nrm$	$Maturity$	$RSS.Rel$
1 (1.8%)	L	—	—	2013	0.83	—	478	0.65%	—	1.00
	E	—	—	—	0.07	—	—	—	—	23.47
2 (2.5%)	L	—	—	2015	0.72	—	597	0.79%	—	1.00
	E	—	—	—	0.07	—	—	—	—	13.25
	S	27 007	22%	2035	0.13	34	867	0.69%	87%	4.07
3 (3.21%)	L	—	—	2018	0.38	—	762	1%	—	1.00
	E	—	—	—	0.07	—	—	—	—	4.43

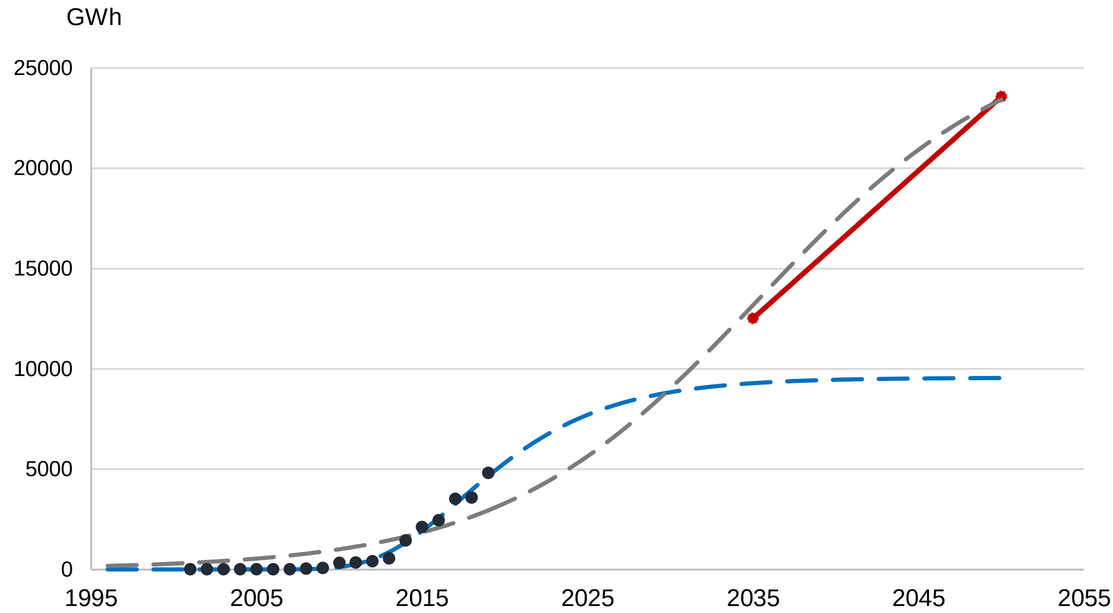
Figure 19. Historical data, best-fit growth model, ideal deployment, and national targets for three scenarios of electricity generation for wind power in Chile

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – projected wind deployment by the best-fit growth model, and grey – "ideal" deployment required to achieve wind targets). Red dots show the national renewable targets, in accordance with Table 9 for each scenario, and the red lines show the deployment curve of these targets.

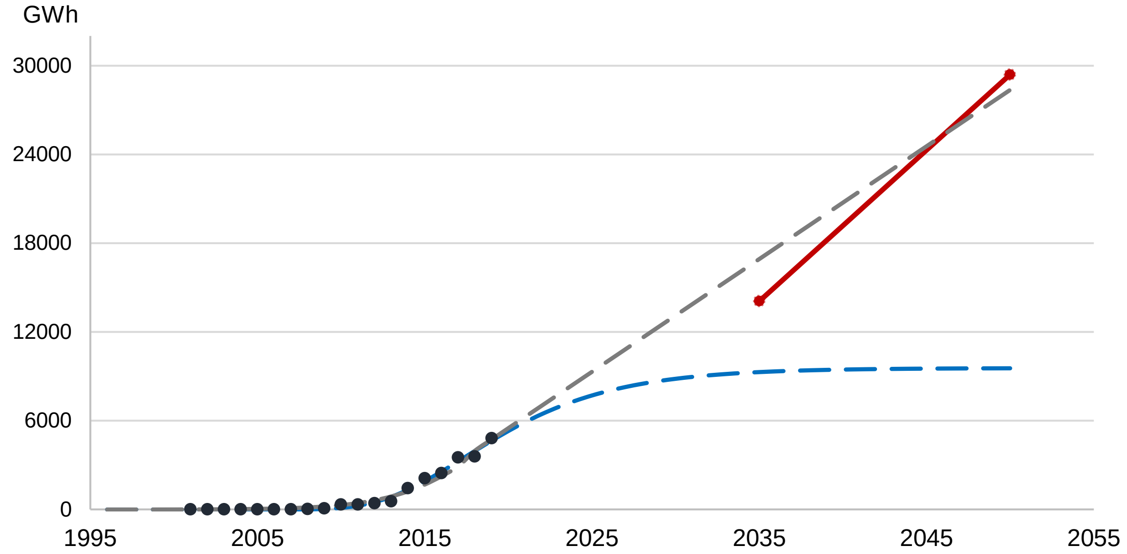
Pessimistic scenario



Baseline scenario



Optimistic scenario



In the example of Chile for wind power, we see that in the pessimistic and optimistic scenarios, deployment should follow a linear curve that ensures targets will be met, contrary to the first projection that suggested growth would follow a Gompertz curve. This means that electricity generated from wind sources should grow at a steady pace of 478 GWh/year or 760 GWh/year depending on the scenario, which is feasible for Chile, since they have achieved similar growth rates in the past (for example, the growth rate of 707 GWh/year achieved in 2017, as per model calculations). We see that the baseline scenario proposes a more prolonged growth and a higher G, reached only 2035 and with a value of 866 GWh/year.

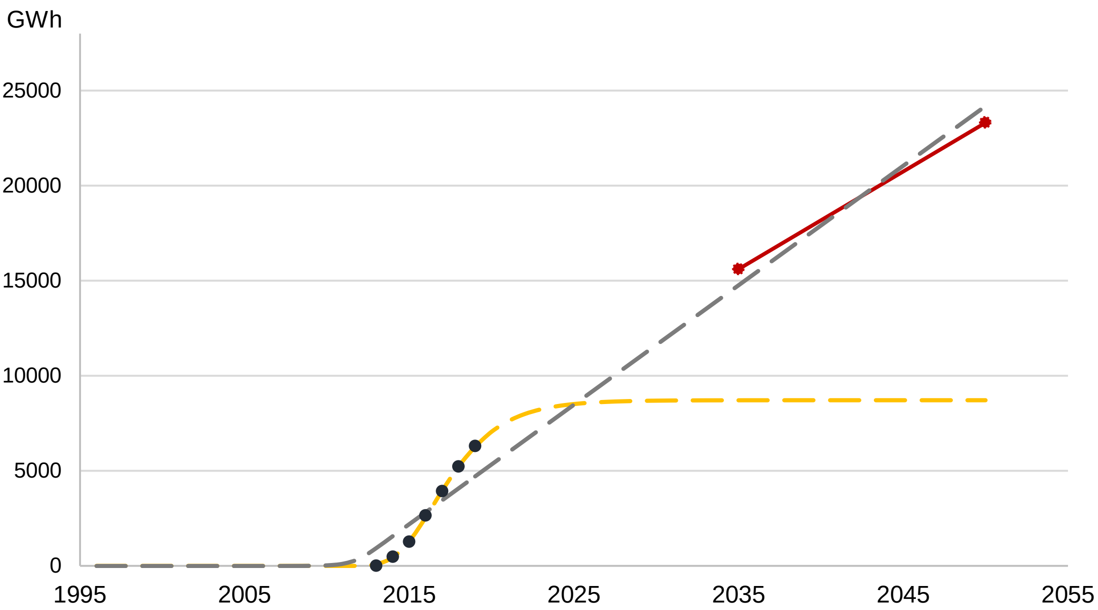
Table 14. Growth parameters in Chile for the three scenarios of achieving solar targets

SOLAR GENERATION										
Sc.	***Fit***	L *(GWh)*	$L.nrm$	t_{max} *(year)*	k	Δt *(years)*	G *(GWh/year)*	$G.nrm$	$Maturity$	$RSS.Rel$
1 (1.8%)	L	—	—	2013	1.33	—	628	1%	—	1.00
	E	—	—	—	0.06	—	—	—	—	6.46
2 (2.5%)	L	—	—	2013	3.40	—	779	1%	—	1.00
	E	—	—	—	0.06	—	—	—	—	16.20
3 (3.21%)	L	—	—	2014	5.29	—	966	1%	—	1.00
	E	—	—	—	0.06	—	—	—	—	19.08
	S	41 279	29%	2035	0.13	33	1 370	1%	87%	4.75

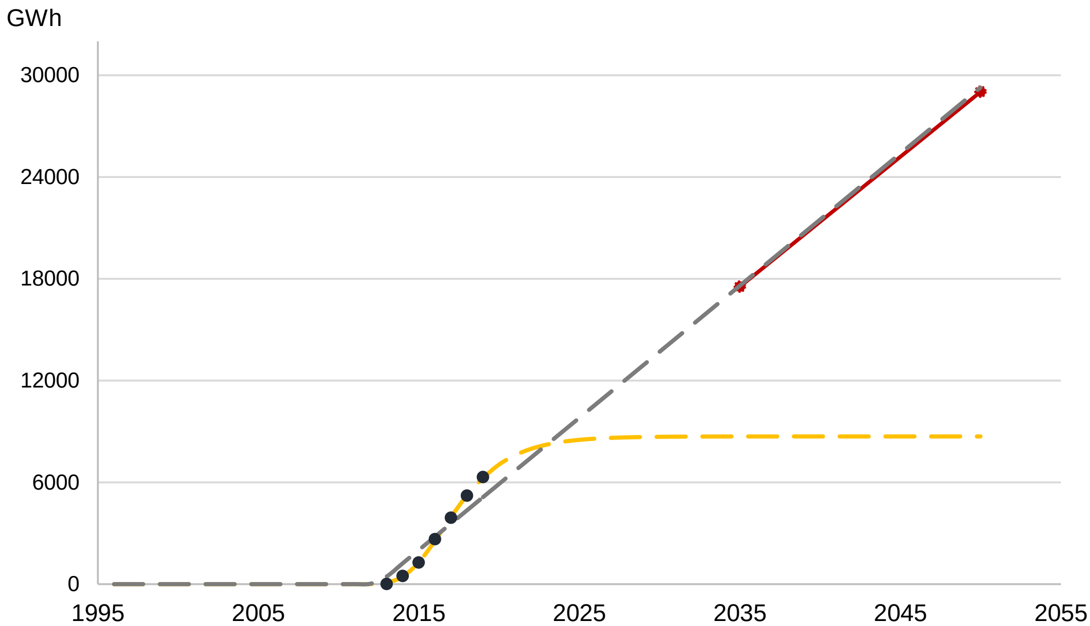
Figure 20. Historical data, best-fit growth model, ideal deployment, and national targets for three scenarios of electricity generation for solar power in Chile

Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (yellow – projected solar deployment by the best-fit growth model, and grey – "ideal" deployment required to achieve wind targets). Red dots show the national renewable targets, in accordance with Table 10 for each scenario, and the red lines show the deployment curve of these targets.

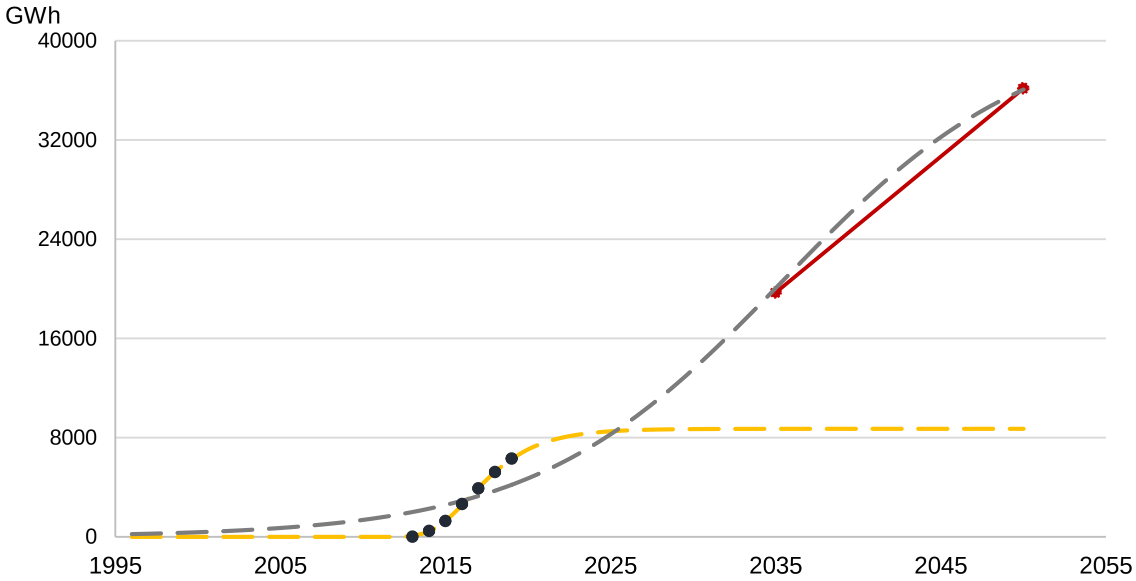
Pessimistic scenario



Baseline scenario



Optimistic scenario



The algorithm fits logistic-linear curves for the first two scenarios of Chile's solar generation, again considering a constant growth rate that the country has demonstrated to achieve previously, since the model suggests to keep a deployment rate of 628 and 779 GWh/year correspondingly, while Chile has achieved maximum rates of 1 410 GWh/year in 2016. In the case of an optimistic scenario, the model projects logistic deployment that would need to complete a higher maximum growth rate until 2035.

4.3.3. Mexico

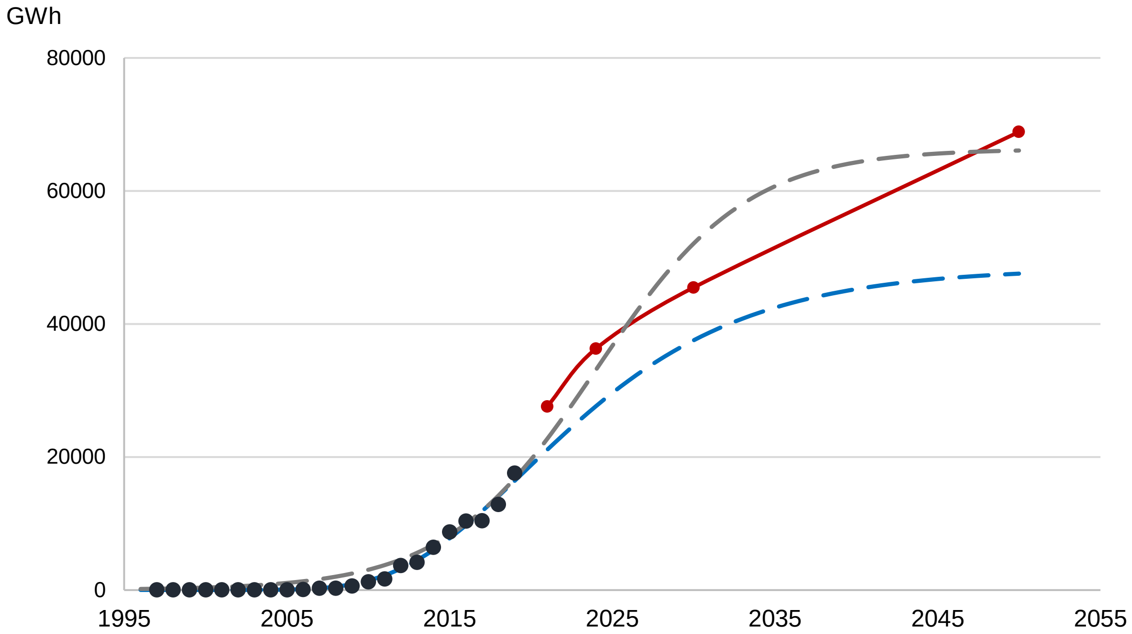
Table 15. Growth parameters in Mexico for the three scenarios of achieving wind targets

WIND GENERATION										
Sc.	***Fit***	***L*** *(GWh)*	$\boldsymbol{L.nrm}$	$\boldsymbol{t_{max}}$ *(year)*	$\boldsymbol{k}$	$\boldsymbol{\Delta t}$ *(years)*	$\boldsymbol{G}$ *(GWh/year)*	$\boldsymbol{G.nrm}$	$\boldsymbol{Maturity}$	$\boldsymbol{RSS.Rel}$
1 (0.5%)	L	—	—	2011	1.09	—	1 860	0.61%	—	2.27
	E	—	—	—	0.06	—	—	—	—	13.82
	S	66 320	19%	2024	0.22	20	3 592	1.04%	100%	1.00
2 (2.21%)	L	—	—	2018	0.37	—	3 226	0.96%	—	1.00
	E	—	—	—	0.07	—	—	—	—	29.11
	S	120 744	28%	2030	0.17	25	5 201	1.19%	97%	3.55
3 (2.50%)	L	—	—	2019	0.35	—	3 566	1%	—	1.00
	E	—	—	—	0.07	—	—	—	—	38.61

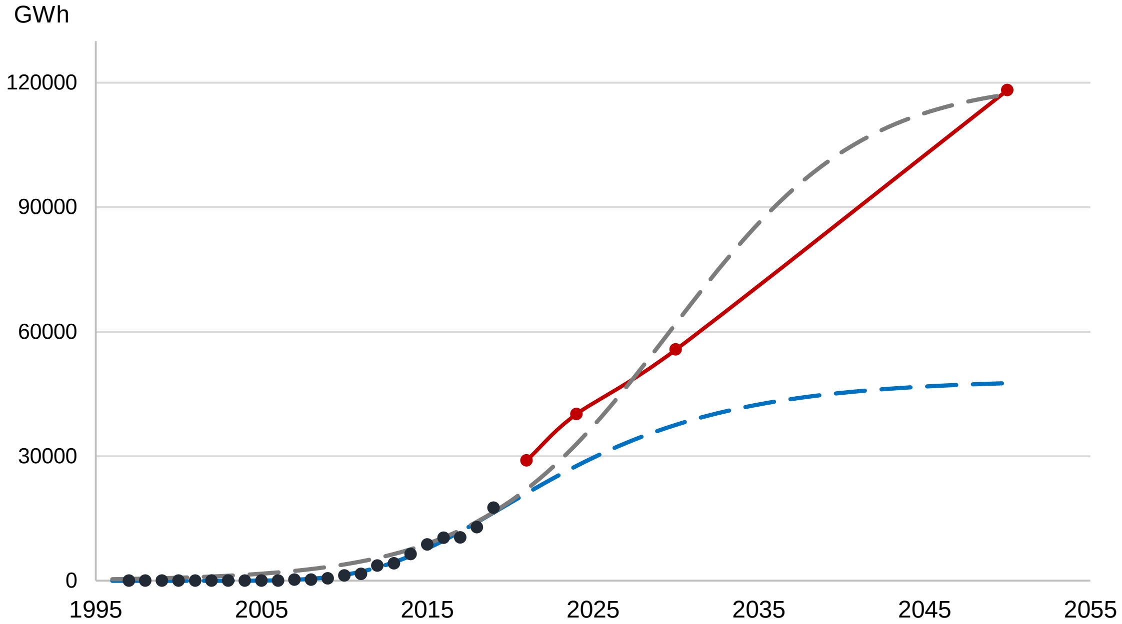
Figure 21. Historical data, best-fit growth model, ideal deployment, and national targets for three scenarios of electricity generation for wind power in Mexico

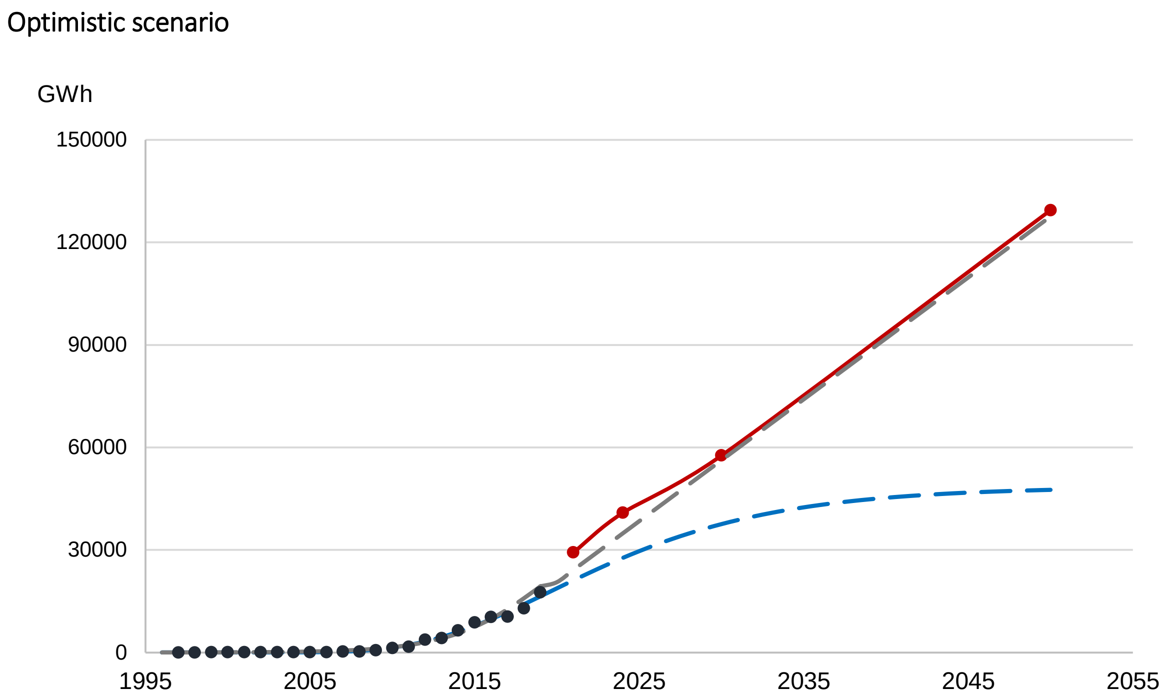
Black dots show historical deployments. Dashed lines show the growth projection based on the best-fit model (blue – projected wind deployment by the best-fit growth model, and grey – "ideal" deployment required to achieve wind targets). Red dots show the national renewable targets, in accordance with Table 9 for each scenario, and the red lines show the deployment curve of these targets.

Pessimistic scenario



Baseline scenario





In the first and second scenario of Mexico's wind electricity deployment, the algorithm finds that wind growth follows a logistic curve to achieve the targets, but the inflection point is reached further in the future and with a higher value, which implies that growth is still accelerating, as evidenced by the maturity levels of the curve. In the case of the optimistic energy expansion, the model finds that electricity generation would need to follow annually the same growth rate it achieved in 2019, based on a logistic-linear curve.

5. Discussion

One key aspect that emerges from the previous chapters and the empirical findings is that Latin American countries have enormous solar and wind power potentials capable of powering their growing economies without GHG emissions. The growth of these technologies is likely to be accelerated by their falling costs and increasing 'know-how'. The favorable conditions (expected growth in energy demand, high electricity prices, dependence on hydropower, and large resources potential, among others) provide an optimal ground for an extensive deployment of wind and solar power, which has also attracted large international investment. Across the literature review, I identified that 19 out of 20 countries in the region have established national renewable electricity targets, which signals the sparking interest in renewables promotion (IRENA 2015). All five countries that are the focus of this thesis have established renewable electricity targets, which are quite ambitious in some cases.

Brazil is the country with the most ambitious target, aiming to have 85% of renewable share in its electricity mix by 2050, of which 27% ~ 40% would come from wind power and 4% ~ 12% from solar; followed by Chile, that aspires to have 70% of its electricity generation coming from renewable sources by 2050, of which ca. 40-45% will come from wind and solar power, and reach carbon-neutrality in that year. Mexico comes next with a target of 50% of electricity generated from clean sources by 2050, and Argentina set a target of 20% of renewable sources share in electricity consumption by 2025. Peru has expressed its willingness to have a share of 15% of electricity from renewables by 2030, but still has not enacted this goal in legislation.

With these considerations, I turned to historical data to analyze if the upcoming renewable electricity targets established by national governments are feasible to attain. However, wind and solar deployment in some countries has been so recent that forecasting the future trajectory of the curve becomes difficult, as the growth models can not accurately predict the parameters of this curve. Such is the case of Argentina and Peru, which have just started expanding their wind and solar share in electricity generation.

To measure the historical growth of wind and solar power, I use the maximum annual growth rate that a technology achieves at the inflection point of the S-curve ("G"), normalized to total electricity generation at this point, as proposed by Cherp *et al.* (forthcoming). I find that the annual rates for wind power growth were 0.7-1.8% and for solar were 0.6-1.8%, as shown in Table 16. These values resemble Cherp *et al.*'s results, who find that worldwide wind power has achieved maximum annual growth rates of 0.8% (IQR 0.6-1.1%), while solar power has reached 0.6% (IQR 0.4-0.9%) (Forthcoming).

Table 16. Maximum achieved annual growth rates and the year when it was achieved

	Wind		Solar	
	G (%, year)	t_{max}	G (%, year)	t_{max}
Argentina	Accelerating (1.32%)*		Accelerating (1.30%)*	
Brazil	1.83%	2016	0.63%	2018
Chile	0.89%	2017	1.78%	2016
Mexico	0.71%	2020	Accelerating (1.53%)*	
Peru	0.70%	2015	Accelerating (0.60%)*	

* indicates the average annual growth over the three most recent observations.

Modelling the recent growth of wind and solar power suggests that the analyzed countries will experience serious challenges in reaching their wind and solar targets, assuming that technology deployment follows an S-shaped curve. As previously mentioned, Table 16 shows the maximum achieved annual rates of the studied Latin American countries for wind and solar technologies based on historical growth, alongside the year when these values are reached (i.e., the inflection point). From these results we can derive two key implications. First, countries that have not yet reached their maximum growth rate (the inflection point is located in the future) and have a low maturity level (<50%) exhibit unrealistic results (such is the case of Argentina that has a forecasted wind power annual growth rate of 780% of their total electricity generation, or Mexico, which shows penetration levels of 1060% of total electricity generation from solar technology), since growth in these countries is still at an accelerating phase and the model cannot predict the future trajectory of the S-curve accurately. Therefore, these results should be discarded. Instead, I calculated the most recent 3-year average growth rates for these countries, which also fall mainly within these ranges (1.32% for Argentina for wind power, and 1.30%, 1.53%, and 0.60% for Argentina, Mexico, and Peru for solar power). Second, the countries where accurate estimations can be performed show maximum annual growth rates still below those required by climate mitigation scenarios. The only exception for wind power is the case of Brazil, which achieved a growth rate of 1.83% in 2016, and it would need to keep this growth rate constant in order to meet its renewable targets, meaning that deployment should follow linear growth. We have the same situation for Chile in solar power, which accomplished a maximum yearly growth rate of 1.78% in 2016, but it would need to continue this deployment rate into the future to reach its targets. This result is corroborated by Merino *et al.* (2019), who, based on their wind and solar data evaluation for Chile, find that "deployment may not be fast enough to reach the 2050 target" (5). These findings suggest that policy-makers expect renewables deployment to follow linear growth when establishing targets. In light of the forecasted increase in energy demand in the region, authors suggest that policy-makers should focus on "maintaining a minimum, if not increased, share of renewables in the electricity sector" (Arango-Aramburo *et al.* 2020, 6) and "more aggressive policies to fulfill the potential of renewable resources for electricity generation" (Arango and Larsen 2010, 2962).

Nevertheless, recent developments in front-runner countries like Chile or Brazil show that governments are committed to fulfilling their national sustainability targets. For example, wind power in Brazil reached more than 10% of the total installed capacity in March 2021 (BNAmericas 2021), and Chile achieved its 2025 goal of 20% of electricity generation from non-conventional renewable sources five years in advance (El Mercurio 2020). On the contrary, countries like Mexico or Argentina have failed to achieve their previous renewable goals. In its Energy Transition Law, Mexico established a target of 25% of electricity generated from clean sources by 2018, which has not been fulfilled yet (Expansion Mexico Magazine 2020). Moreover, analysts consider that Mexico is off track to meet its 2021 and 2024 targets (Bloomberg 2020; Wood Mackenzie 2020), partially due to legal and regulatory changes from the Lopez-Obrador administration that prioritize the purchase of electricity generated by state-run facilities that use fossil fuels over wind or solar production (Forbes 2021), following claims of "grid reliability concerns" resulting in a halt of wind and solar interconnection tests and the reduction in their expansion (Wood Mackenzie 2020).

In light of these findings, I have also estimated how the "ideal" growth curves should look like in countries that have reached a stable or stalling maturity in order to meet their renewable targets. Table 17 displays maximum growth rates for wind and solar technologies in the sample countries, comparing the values obtained by the algorithm based on historical rates with the growth rates required to meet renewable targets in each proposed scenario.

Table 17. Historical and forecasted maximum annual growth rates

Wind power

	Historical maximum annual growth rate	Forecasted required maximum annual growth rates		
		Scenario 1: Pessimistic	Scenario 2: Baseline growth	Scenario 3: Optimistic
Brazil	1.83%	1.31%	1.46%	—*
Chile	0.89%	0.65%	0.69%	0.93%
Mexico	0.71%	1.04%	1.19%	1.04%

*none of the growth model except exponential resolves;

Solar power

	Historical maximum annual growth rate	Forecasted maximum annual growth rates		
		Scenario 1: Pessimistic	Scenario 2: Baseline growth	Scenario 3: Optimistic
Brazil	0.63%	0.17%	0.43%	0.37%
Chile	1.78%	0.86%	1.07%	0.97%

Based on these results, we can establish that the required maximum growth rates to meet wind and solar targets do not represent an overwhelming challenge to these countries, as historically they have achieved even higher growth rates (with the exception of Mexico). The real challenge lies on their ability to sustain this pace of growth for longer time, to ensure that deployment does not stagnate at low penetration levels and achieves the envisioned electricity production values. The exception to this case is Mexico in wind power, which would need to boost their annual growth rate up to 1% yearly, even under a pessimistic scenario, in order to stay on track for their goals. As previously shown, most of the forecasted ideal curves follow a logistic-linear growth model, which means that once the maximum growth rate has been achieved, countries need to keep this rate steady to reach their targets. In the cases where the model predicts a logistic or Gompertz growth curve, the inflection point is located further in the future, which allows extending the "duration of transition" (the time it takes for a technology to grow from take-off until 90% of the penetration level). In both cases, Latin American countries need to keep renewable technologies developing to avoid a deceleration that would hinder them from achieving their targets.

If we look at some of the "energy-champions" countries' maximum growth rates, we see that countries like Denmark or Spain have reached G values of 1% and 1.7% respectively in wind power, as calculated by Cherp *et al.* in their recent publication. In the case of Denmark, even though the maximum growth rate achieved is not substantially high, the country has sustained this growth in wind power for a longer time (the estimated duration of transition is 35 years), which allows it to attain notably high penetration levels, reaching saturation at 32% of the total electricity generation. For Spain, the duration of transition is much shorter (12 years), but the maximum growth rate achieved is considerably high (1.7%/year), which also enables the country to have significant penetration levels (18%). This means that Latin American countries need to ignite their deployment rate and ensure that this rate stays stable to meet their targets, as historically they have not achieved such fast growth rates. Nonetheless, Chile remains an example in solar deployment, as it has attained the highest maximum annual growth rate in the world, with a G value of 1.8% yearly (Cherp *et al.* forthcoming).

<u>Limitations</u>

As stated previously, one of the main limitations in this dissertation was the difficulty to estimate parameters in countries that are still at an accelerating phase, given their low maturity levels (i.e. how recent the deployment of wind and solar power is), since the model is not able to accurately estimate the trajectory that the growth curve will follow in the future. This forced me to exclude some countries from the analysis of ideal deployment curves (Argentina and Peru for wind power, and Argentina, Mexico, and Peru for solar power) because the results were neither realistic nor reliable. Another considerable limitation was the complexity in quantifying the national established renewable targets, since countries express their goals in diverse manners, such as percentage points of total power generation, net production targets, total installed capacity or total renewable supply that includes hydro (large and small-scale) or biomass. Therefore I normalized the targets to the same scale (wind and solar net production in GWh) for comparison across the region, as per the procedure described in Section 3.3.2. However, even though I used several parameters to perform a proper disaggregation and distribution of the targets to the best of my expertise, these are still only estimations. Moreover, it is worth mentioning that forecasts are unable to consider external shocks, such as major technology breakthroughs or fluctuations in fossil fuel prices that could impact renewables deployment, and therefore can only project the future assuming certain underlying parameters as stable. Finally, though this thesis detected considerable differences across countries in the maximum growth rates of renewables that they have achieved, due to time and space limitations I was not able to systematically analyze the causes of these differences.

6. Conclusions and recommendations

Countries have committed to the reduction of GHG emissions following the Paris Agreement, with the purpose of addressing global concerns about climate change. The broader adoption of renewable sources in the electricity mix is often perceived as the first step in achieving these goals. With this purpose in mind, national governments have developed long-term strategies for energy transition. These strategies include targets for the deployment of wind and solar technologies for electricity generation. In this thesis, I evaluated whether Latin American countries are on track to meet their targets based on their historical growth patterns and rates.

There is rich literature analyzing the feasibility of energy transitions in climate mitigation scenarios. This relates to the patterns and rates of new technology diffusion, as this expansion follows an S-shaped curve. It first experiences a period of accelerated growth until achieving the inflection point (where the growth rate is the steepest) and decelerates till reaching stagnation. As expressed by Jewell and Cherp (2019), "the adoption of energy technologies has been uneven between countries and regions" (3), which can hinder the global expansion of wind and solar power technologies necessary for climate mitigation goals. In this sense, Latin American countries have established renewable targets for electricity generation aiming to advance in their energy transition.

Based on the insights from literature, I designed a method for estimating the maximum historically achieved growth rate in a particular country and comparing it to the country's targets. The method involves fitting growth models to historical trajectories of wind and solar power deployment on each country, considering that several models are used for robustness, based on the algorithm developed by Cherp *et al.* (forthcoming). The growth models used include logistic, Gompertz and logistic-linear regressions. These regressions yield growth parameters that allowed me to evaluate whether countries are on track to meet their targets.

I found that the growth models accurately describe the observed trajectories of wind and solar power deployment in the sample countries, which are Argentina, Brazil, Chile, Mexico, and Peru. Two countries, Argentina and Peru, are still at an accelerating phase for wind and solar power deployment, while Mexico is at an accelerating phase only in solar development. The rest of the sample countries have achieved a stalling or stable growth phase. However, an accurate forecasting of future energy deployment is difficult to be performed in countries with accelerating growth, as development is too recent to predict the future trajectory of the curve.

I showed that the three countries suitable for analysis (Brazil, Chile, and Mexico) have by large achieved or even exceeded the growth rates that would be needed to reach their renewable targets. The exception is wind power in Mexico, where the growth would need to be accelerated almost twice to meet the target. Thus, the challenge is not to achieve even higher rates, but rather to sustain the already achieved rates over sufficiently long time periods so that the targets can be met.

Therefore, the main policy recommendation stemming from my thesis is that countries must not allow growth to slow down. Fulfilling their established wind and solar targets is possible with the growth rates they have historically already achieved, but they must ensure that growth remains constant alongside this timeframe. Otherwise, as shown in the model estimations, renewables deployment would stagnate at low penetration levels of their electricity mix. For this reason, policies should be targeted to promote the wider adoption of wind and solar power technologies and guarantee well-grounded legal, economic and political conditions to further enhance renewables development.

The related research recommendation is to investigate worldwide experience on the barriers that slow down the growth and successful strategies to overcome these barriers, taking examples from energy front-runners. For instance, Denmark has sustained growth in wind power deployment for about 30 years, achieving one of the highest maximum growth rates in the world, thanks to the focus of government policies to build on this technology since the 1970s (Napp *et al.* 2017). Another promising direction of research is to understand why growth rates are different across countries. This would be important not only for Latin America but also for the world, as some Latin American countries are global champions in renewables, and their lessons can be learned by other countries, such as the example of Chile's solar power deployment. Chile has achieved one of the highest maximum growth rates worldwide for solar power (1.8%/year) due to the regulatory incentives introduced by the government to boost the development of this technology, which has made the country one of the most attractive locations in the world for investment in renewables (Silva and Nasirov 2017).

Nonetheless, the data from this research is tentative because energy development is changing rapidly. It would be important to continuously update the data, especially for the countries that are at an accelerating phase, since more data points can help to estimate a better projection of the future. In addition, some countries are just starting to take-off in their renewables deployment (such as Colombia), and updates on data can provide a better understanding of the direction they are heading to.

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