MODELING ALTERNATIVES SUSTAINABLE-ENERGY-POLICY FOR THE SUPPLY CHAIN OF WIND POWER IN BRAZIL

Thesis presented by Milton M. Herrera for obtaining the degree of:
Doctor in Modelling Public Policy and Management - PhD in Model based Public Planning, Design Policy and Management

Supervised by:
Isaac Dyner Ph.D.
Federico Cosenz Ph.D.

University of Bogotá Jorge Tadeo Lozano
Faculty of Science Natural and Engineering
Università Degli Studi di Palermo
Department of Political Sciences and International Relations
Bogotá D.C., Colombia
2019

For my family which always
has been my inspiration.

For Laura, Carlos, Juliana, Paula and Mauricio,
the future will be writing by their persistent and patience.

CONTENTS

ACKNOWLEDGEMENTS 8

ABSTRACT 9

CHAPTER 1: INTRODUCTION AND MOTIVATION 10

1.1. PROBLEM IDENTIFICATION 12
1.2. OBJECTIVES 14
1.3. RESEARCH APPROACH 14

CHAPTER 2: ASSESSING THE EFFECT OF TRANSMISSION CONSTRAINTS ON WIND POWER EXPANSION IN NORTHEAST BRAZIL 17

2.1. INTRODUCTION 17
2.2. POLICY COORDINATION PROBLEMS IN THE BRAZILIAN ELECTRICITY MARKET 21
2.3. MODEL-BASED APPROACH 25
2.4. SIMULATION RESULTS 32
2.5. CONCLUSION 39

CHAPTER 3: BENEFITS FROM ENERGY POLICY SYNCHRONISATION OF THE NORTH-NORTHEAST INTERCONNECTION OF BRAZIL 40

3.1. INTRODUCTION 40
3.2. THE INSERTION CHALLENGE OF RENEWABLE ENERGY IN BRAZIL 42
3.3. THE METHODOLOGICAL APPROACH 46
3.4. SIMULATION RESULTS: WIND-INDUSTRY POLICY ALTERNATIVES 52
3.5. CONCLUSIONS AND POLICY IMPLICATIONS 58

CHAPTER 4: HOW TO SUPPORT ENERGY POLICY COORDINATION OF WIND POWER SUPPLY CHAIN? COLLABORATIVE GOVERNANCE THROUGH A DPM APPROACH 60

4.1. INTRODUCTION 60
4.2. THEORETICAL BACKGROUND 63
4.3. ENERGY SUPPLY CHAIN MODELLING 70
4.4. SIMULATION RESULTS 76
4.5. DISCUSSION 81
4.6. CONCLUSIONS 84

CHAPTER 5: ALTERNATIVE ENERGY POLICY FOR MITIGATING THE ASYNCHRONY OF THE WIND-POWER INDUSTRY'S SUPPLY CHAIN IN BRAZIL 85

5.1. INTRODUCTION 85
5.2. ASYNCHRONOUS POLICY IN THE WIND-POWER SUPPLY CHAIN INDUSTRY 88
5.3. METHODOLOGY 92
5.4. SIMULATION RESULTS 103
5.5. CONCLUSIONS 109

CONCLUSIONS AND FUTURES PERSPECTIVES 110

CONTRIBUTIONS 112

REFERENCES 114

LIST OF FIGURE

Figure 1. Delayed transmission lines with regard to the contractual delivery date. Source: Own elaboration based on (Operador Nacional Do Sistema Elétrico - ONS, 2017). *19*
Figure 2. Useful reservoir volumes in North of Brazil Source: Own elaboration based on (ONS, 2018). *22*
Figure 3. Dynamics of transmission capacity, installed generation capacity and peak demand of the North and Northeast of Brazil *24*
Figure 4. Dynamic behaviour hypothesis for generation capacity *27*
Figure 5. Inclusion of the effect of transmission congestion on the electricity price *28*
Figure 6. Simulation results for the installed capacity wind and hydropower in the Northeast region of Brazil for the period 2016-2050 *33*
Figure 7. Behaviour of installed capacity of wind generation vs. installed capacity of transmission in the Northeast *34*
Figure 8. Simulation scenarios with unsynchronised and synchronised energy policies *37*
Figure 9. Effects of transmission congestion on the electricity price *38*
Figure 10. Interconnected regions of North and Northeast with constrained transmission. *44*
Figure 11. Dynamics of the interconnection between the two Brazilian regions capacity expansion and grid congestion. *47*
Figure 12. Model structure of the forecasted transmission, supply curves and demand. *48*
Figure 13. Results of behaviour reproduction test for electricity prices. *51*
Figure 14. Business as Usual case. *53*
Figure 15. North's generation capacity expansion (NTCE case). *54*
Figure 16. North's generation capacity expansion and transmission limited (NTCE-TL case). *55*
Figure 17. Northeast's generation capacity expansion (NECE case). *55*
Figure 18. Electricity prices of the North-Northeast interconnection for BaU and NTCE-TL cases. *57*
Figure 19. Electricity prices of the North-Northeast interconnection for NTCE and NECE cases. *58*
Figure 20. A Collaborative Governance approach supported by an Outcome-based Dynamic Performance Management framework (adapted from Bianchi 2016, p. 73). *69*
Figure 21. Stock-and-flow diagram of wind power supply chain in Brazil. *71*
Figure 22. Applying a Collaborative Governance approach supported by an Outcome-based Dynamic Performance Management framework to the wind power supply chain. *74*
Figure 23. An SD-based DPM model showing the effects of auctions policy on the wind power supply chain performance. *76*
Figure 24. Behaviour of end results with uncoordinated policy due to change in the auctions. *78*
Figure 25. Response of strategic resources to the uncoordinated policy in the supply chain. *79*
Figure 26. Behaviour of end results with coordinated policy due to change in the auctions. *80*
Figure 27. Response of strategic resources to the coordinated policy in the supply chain. *81*
Figure 28. Structure of the wind-power supply chain *91*
Figure 29. Dynamic hypotheses for the asynchrony of the wind-power supply chain *96*
Figure 30. Stock-and-flow diagram of wind-power supply chain in Brazil *99*
Figure 31. Validation process, calibration and analysis of the simulation model *103*
Figure 32. Impact of asynchronous energy-policies over the time period 2016-2050 on the wind-power supply chain, with a 5% growth in wind industry electricity generation *104*
Figure 33. Impact of synchronous energy-policies over the time period 2016-2050 on the wind-power supply chain, with a 10% increase in wind industry electricity generation *106*

Figure 34. Effects of maintenance rate on the developing wind power. Scenario_1: current state, and Scenario_2: with a 4% decrease in the maintenance time *108*

LIST OF TABLE

Table 1. Input data in the simulation model to December 2017 *31*
Table 2. Error analysis of the simulation model *32*
Table 3. Proposed policy *35*
Table 4. Error analysis and correlation of the model *51*
Table 5. Error analysis of the simulation model *73*
Table 6. Scenarios for analysing coordination impact of policies on wind power supply chain *76*
Table 7. Error analysis of the simulation model in the validation process *101*
Table 7. Simulation for different delivery times between industry and developers of the Brazilian wind farms vs. coordinating investment policy for transmission capacity *107*

Acknowledgements

I would like to thank the advice of Professor Isaac Dyner, Universidad Jorge Tadeo Lozano – Colombia and Federico Cosenz, University of Palermo – Italy. A special acknowledgement to the Professor Mauricio Uriona of the University of Santa Catarina – Brazil, Javier Orjuela-Castro of the Universidad Distrital Francisco José de Caldas – Colombia, Carmine Bianchi of the University of Palermo – Italy, Hassan Qudrat-Ullah of the York University – Canada, Carlos Franco of the Universidad Nacional de Colombia, Gerard Olivar of the Universidad Nacional de Colombia, Camilo Olaya of the Universidad de los Andes – Colombia and Jorge Andrick Parra of the Universidad Autónoma de Bucaramanga – Colombia for their invaluable recommendations and suggestions.

The author acknowledgement to everybody in CED4 system dynamics group at the University of Palermo in Italy as well as the system dynamics community. Also, I would like to thank the recommendations of referees, which have helped clarify arguments in this research.

Abstract

Renewable energy studies have received high attention in the last few years due the increasing deployment of alternatives such as wind, solar and biomass, as a result of the urgency in reducing fossil fuels consumption. This situation has involved an important challenge for long-term renewables policy and energy system planning. Brazil is the richest country in terms of renewable sources in Latin American. Brazil has energy generation portfolio not much different form the Colombia one, and the understanding of this very important country will contribute to inspire other countries in the region, particularly Colombia. Since 2004 the Brazilian energy policy promotes wind power development aimed at complementing hydropower generation. Despite the energy policies adopted in Brazil, the supply chain of wind power has experienced barriers that include: insufficient transmission lines and the delays in energy projects caused by lack synchronic among the energy policies. Thus, the unsynchronised energy policy has affected the performance of renewable energy supply chain, which has produced an impact on the electricity market. This thesis addresses these issues by evaluating alternative sustainable energy-policy, which must reflect new institutional guidelines to support wind power penetration and their dynamics performance in supply chain.

Keywords: Policy modelling, simulation, wind power, dynamics performance management, supply chain, renewable energy, Brazil

Chapter 1: Introduction and Motivation

Energy use in Brazil has increased rapidly in the last decades because of the rapid industrialization that takes place in that country, including high growth of some energy-intensive industries and increases in residential and commercial energy services (Almeida Prado et al., 2016; Geller et al., 2004; Pao and Fu, 2013). As consequence, Brazil has increased its gross domestic product (GDP) at an average rate of 3.18% yearly (Almeida Prado et al., 2016). Economic planners predict that Brazil could become the world's fifth largest economic in the next few years (Pao and Fu, 2013). Given the economic growth projections of Brazil, it requires more efficient energy policy to support high electricity consumption of industry.

Since the Kyoto Protocol in 1997, the countries have searched alternative technologies that could generate lower environmental impacts. Although Brazil is promoting renewable technologies, especially in the Northeast region, it depends on hydrological regimes as its energy production is based on hydropower. In the last years, climate variability has affected water level of hydropower dams resulting in scarcity of some reservoirs. The effects of climate variability and sedimentation problems with dams have led to decreases in the availability of hydropower and increases in the participation of others renewable technologies (e.g. wind power) in the electricity generation matrix.

Brazil is the richest Latin American country in terms of renewable sources, but its wind regimes and sun radiation availability per Km^2 is not very different from many others in the region. As this country is incorporating vast amounts of renewables into its power matrix, it turns of utmost importance to understand its policy approach and the lessons that may be drawn from its experience.

Since 2002, the Brazilian federal government established the PROINFA program (Incentive Program for Alternative Sources) to develop the wind industry. A globally significant cluster of wind farms have been developed in coastal areas of north-eastern Brazil in response to governments subsidies, high wind conditions, and increasing demand for electricity (Gorayeb et al., 2018). In this sense, the wind industry has progressed significantly over the last decades, complementing the Brazilian energy matrix. However, some barriers related to the conversion cost, locations constraints and complex distribution networks (infrastructure) might affect to the expansion of the wind power industry (Wee et al., 2012).

Energy policy plays a key role on the deployment of electricity infrastructure and secure energy supply (Burke and Stephens, 2018; Lund, 2009). However, the decoupling between design and energy policy implementation can affect the outcomes of the electricity industry. In the case of Brazil, the extensive distance of transmission lines, infrastructure construction time and mainly the imbalance between planning of wind farm and energy grid reduces the connection of wind power into electricity grids. The insufficient of financial resources and delays in transmission infrastructure by cause of unsuitable planning generate an impact on the supply chain performance (Herrera et al., 2018). Thus, the coordination between the renewable's expansion and infrastructure industrial-policies is needed.

Frequently, construction delays are present along the electricity supply chain. Despite that Brazil has successfully implemented energy policies and economic incentives, delays in transmission construction have threatened the growth of the wind industry. This problem is associated with the lack synchronization of energy policy along the supply chain. While the wind industry increases rapidly, the transmission infrastructure growth does it more slowly. This calls for more coordinated planning and policy synchronization (Dyner and Larsen, 2001; Ford, 1999; Morcillo et al., 2017).

When promoting a renewable energy policy, it is important to assess the potential benefit and drawbacks in long-term (Bukarica and Tomsic, 2017; Lund, 2009). One major theoretical issue that have addressed other studies are related with the electricity market and environmental impact (Aquila et al., 2017b; De Jong et al., 2015; González et al., 2017; Silva et al., 2013); however, far little attention has been paid to the performance of renewable energy supply chain (Ahmad et al., 2016; Cucchiella and D'Adamo, 2013).

Under these conditions, it is essential to evaluate energy policy synchronization and its effects on the dynamic performance of wind-power supply chain. Additionally, it is important that policy-makers design a robust sustainable energy-policy framework that considers the dynamic performance of supply chain. *The main thesis contribution is an* *alternative approach to assessing a sustainable energy policy and dynamic performance of wind power supply chain of Brazil for mitigating the asynchrony in the long-term.* It also provides a model-based framework for analyse the performance of government policies and provide guidance at the design stage of policy formulation, supporting in blending collaborative governance and dynamic performance management (DPM).

1.1. Problem Identification

In 2001 Brazil suffered an electricity crisis caused by increasing electricity demand so that federal government declared electricity rationing. After an electrical energy crisis, Brazil adopted the PROINFA program seeking the development of the renewable energy industry (Kissel and Krauter, 2006). As a result of this, wind power has shown significant increases in installed capacity; currently representing 8.8% of all installed capacity. In this sense, the expansion of wind power industry is playing an important role in diversification of electricity matrix and energy growth. Unfortunately, the wind power expansion faces drawbacks related to its integration into electricity grid. Thus, the research addresses some important concerns regarding this issue, including the following:

First, although the wind resource is complementary to hydropower resources, it depends on the presence of sufficient electrical grid capacity (De Jong et al., 2016). The absence of well-defined network expansion plans may be critical to the deployment of both hydro and wind power. Brazil has had tremendous growth in the number of wind projects but increase in transmission-infrastructure has not been at the same pace (Bayer, 2018; Cardoso Júnior et al., 2014; Global Transmission Report, 2016; Miranda et al., 2017). The uncertainty and delays in the transmission auctions has had an adverse impact on the investors, affecting the wind industry growth (Bayer, 2018). Thus, the lack transmission-infrastructure could affect in a near future to the consumer behaviour.

Second, a higher fragmented governance is likely to facilitate the outbreak of "wicked problems" in the decision-making processes of the stakeholders of wind-power supply chain. For instance, in energy policy-making, conflicts of interest among stakeholders may arise generating a lack of strategic coordination and delays between the design and implementation of policies affecting the overall performance of the wind power supply chain (Herrera et al., 2018).

Third, although the North-Northeast region has suitable conditions to produce wind power, in many cases, local conflicts have delayed or even halted its adoption (Brannstrom et al., 2017; Gorayeb et al., 2018; Troost et al., 2015). The changes of land-use provoke by electrical infrastructure have generate several protests of nearby traditional communities, who are largely invisible in the planning and siting processes. For instance, the strong protests by residents in Ceará state have generate that developers undisposed to build new wind farms (Brannstrom et al., 2017). In this particular case, the Brazilian poorest regions have become increasingly vulnerable to a shortage energy in long run.

Fourth, due to climate variability, wind power is intermittent and cannot be easily integrated into the electrical grid (De Jong et al., 2016; Miranda et al., 2017; Ochoa et al., 2013). The solution to integrate the intermittent generation from this power source is likely to involve the synchronisation of energy policy, including the deployment of strategies in the wind industry.

Fifth, the Brazilian energy policy has suffered different reforms, generating several positive and negative impacts on energy market and supply chains (Bayer, 2018; Bradshaw, 2017; Cardoso Júnior et al., 2014; Herrera et al., 2018). At present, the environmental licensing process is the subject of heated public debate, with many uncertainties involved in the planning of future energy generation and transmission projects (Cardoso Júnior et al., 2014).

Sixth, although prior studies have discussed the promoting wind power (Dutra and Szklo, 2008; Herrera et al., 2017a; Menz and Vachon, 2006; Pereira et al., 2012; Silva et al., 2013), wind power integration into grid (De Jong et al., 2016; Miranda et al., 2017), energy policy reforms (Bayer, 2018; Gorayeb et al., 2018; Lund, 2009), and complementarity of renewable sources (De Jong et al., 2013; Lopes and Borges, 2015; Schmidt et al., 2016b; Silva et al., 2016) in Brazil, few studies assess the synchronization between energy policies regarding dynamic of wind-power supply chain performance. In summary, the main problem of this research is stated as follows:

Do the current energy policies induce energy sustainability taking into account the dynamic performance management in wind-power supply chain?

In the other words, *are both the energy policies and dynamic of wind-power supply chain performance synchronized in such ways that contribute to guaranteeing energy supply?*

1.2. Objectives

This research aims at assessing alternative sustainable and synchronised energy-policy taking into account the wind-power supply chain performance in Brazil; and this, based on a structured and formal model approach.

Specific Objectives

- Analyse the wind power expansion in the North and Northeast regions of Brazil to understand impacts of unsynchronised energy policy on electricity market.
- Develop a formal framework to support design of consistent and robust energy policy for the wind-power supply chain, blending collaborative governance and dynamics performance management approach.
- Develop a simulation model that contributes to assesses energy-policy alternatives for mitigating the asynchrony of the wind-power supply chain in Brazil.

The manuscript analyses and discusses these objectives into four chapters: First, the wind power expansion in north-eastern Brazil (Chapter 2) and its interconnection with the North region (Chapter 3) are discussed and analysed to achieve the first objective. These chapters provide valuable insights to synchronising the wind industry policy in Brazil. Second, a novel framework is proposed for enabling collaborative governance through system dynamics modelling for supporting energy policy design (Chapter 4) and so to achieve the second objective. This framework could support the design and assessment of policies by different players, aiming at fostering supply chain resilience. Third, policy alternatives to synchronise wind power industry's supply chain in Brazil (Chapter 5) are evaluated to achieve the third objective. This chapter contributes to improve the operational thinking skills required for designing of the wind power supply chain.

1.3. Research approach

Considering the asynchrony between wind power deployment and electricity grid expansion, this research assessed policy alternatives to synchronise resources allocation. To synchronise resources allocation in supply chain, this manuscript applied a simulation-based approach. The simulation is a methodological approach appropriate, which contributes to computational representation of the decision-making process.

The delays in information feedback with respect to the effect of policy and strategy on supply chain behaviour, are fundamental in the decision-making process (Forrester, 1961; Herrera et al., 2018; Qudrat-Ullah, 2016; Sterman, 2000). System dynamics simulation may provide the required technology support to address the modelling problems of continuous system adjustment for dealing with uncertainty (Dyner, 2000). This approach also has been a model-based policy-design discipline (Wheat, 2010). Thus, the modelling-oriented approach developed here can support managers and policy-makers, incorporating delays and feedback loops in the decision-making process (Morcillo et al., 2017; Oliveira et al., 2016; Rahmandad et al., 2009).

On the one hand, a considerable amount of literature has been published on energy policy in the case of Brazil for wind power expansion (Aquila et al., 2017a; Dantas et al., 2017; Lima et al., 2015; Schmidt et al., 2016a; Silva et al., 2013); however, except few studies has been carried out as a result of the systemic analysis previously conducted. System dynamics has been used extensively to aid in resources planning in the electricity power industry (Ford, 1997). Qudrat-Ullah (2015) identifies major themes addressed in energy modelling: capacity expansion and economy analysis, distribution energy, carbon capture, energy policies and climate action plans. In her review of the system dynamics research, Aslani et al. (2014a) identifies three groups of research approaches: environmental, market and security of energy supply. While, this research identified six combinations using the system dynamics approach and other methods: agent-based modelling (Choong and McKay, 2013), decision tree, quality function deployment (Shin et al., 2013), Monte Carlo simulation (Jeon et al., 2015), fuzzy multi-objective programming (Wu and Xu, 2013) and triple bottom line (Lee et al., 2012).

On the other hand, the complexity, dynamics and interactions deep into a supply chain requires new modelling methods to understand the dynamics of energy policy. System dynamics methodology with the support of dynamics performance management (DPM) proposed by Bianchi (2012a) are used, in this research, how modelling approaches to evaluate and identify the strategy resources, performance drivers and end-results for the wind-power supply chain of Brazil. The latter approach allows to blend collaborative governance to support policy-makers in energy policy design.

Eventually, few studies have been explored the renewable energy expansion, including a supply chain approach using system dynamics-based simulation (Ahmad et al., 2016; Cosenz and Noto, 2016; Saavedra M. et al., 2018). Wee et al. (2012) evaluated the renewable energy sources focusing on the renewables supply chain, the performance and barriers to the renewable energy development. This study concluded that the involvement of governments, researchers and stakeholders in the development of renewable energy is needed. Other studies analysed the risk variables between different actors of supply chain in wind power projects that implicated a public procurement procedure (Prostean et al., 2014). In this context, the policy-makers must recognize the barriers to adoption of renewables and risks involved at the various stages in the wind power projects (Wüstemeyer et al., 2015). Yuan et al. (2014) identify the relevant policies in both upstream and downstream for wind power supply chain and their concerns. However, these studies do not take into account the synchronization between policies and performance of energy supply chain as well as the sustainability of energy supply chain since a dynamic perspective.

The Doctoral thesis is organized as follows: the first chapter presents introduction and motivation of research, the main problem, the research aims and approach. Chapter 2 presents a theoretical dimension of the research through wind power expansion analysis and insufficient of transmission-infrastructure in the North-eastern Brazil. Chapter 3 evaluates policy aimed to capacity expansion of wind generation and transmission capacity for the North-Northeast interconnection. Chapter 4 identifies the performance drivers, strategic resources and end results of the wind power supply chain, using the DPM approach. This chapter proposes a novel framework in management and governance, blending collaborative governance and DPM. Chapter 5 presents the evaluation of alternatives sustainable policy in the dynamic performance of wind-power supply chain management in terms of synchrony. The last chapter concludes with major findings and future works of research.

Chapter 2: Assessing the effect of transmission constraints on wind power expansion in northeast Brazil ♣

Abstract

The rapid growth of the wind industry in Brazil presents new opportunities and challenges for its electricity industry. As new capacity becomes available, more transmission infrastructure is required for security of supply. The Brazilian electricity system has experienced congestion in the northeast region, affecting the coordinated expansion of transmission and new wind power capacity. This paper uses a simulation model for better assessing long-term policy synchrony of the wind industry. The simulation shows that the resulting prices are competitive in the middle to long terms.

Keywords: transmission congestion; simulation; wind power.

2.1. Introduction

Brazil is predominantly hydropower based with a contribution of 61% of the total capacity in place (ANEEL, 2017a). Throughout history, several large hydro-reservoir power plants, such as Itaipu and Tucuruí, have been built seeking security of supply. However, recurrent droughts and sedimentation have significantly reduced electricity generation capacity as volumes of water stored in dams have been reduced over time (Miranda and Mauad, 2014; Von Sperling, 2012). In these conditions, wind power provides an opportunity for complementing the current capacity.

Brazil has experienced significant advances in energy policy (Aquila et al., 2017a; Bradshaw, 2017), which have promoted the expansion of the wind power capacity at a rate of 40% during the period 2012-2017 (ABEEólica, 2018a). This has been achieved

♣ Results of this chapter have been included in: i) a paper published in the *Utilities Policy*, Elsevier, V59, p 9-24. https://doi.org/10.1016/j.jup.2019.05.010, ii) a paper presented at the workshop on "Engineering applications" (WEA) held in Bogotá in 2016.

through an auction-based mechanism that has also increased the number of investors, from 16 to 49 (Bayer, 2018).

In this context, despite considerable progress in wind power farms, Brazilian transmission infrastructure is not supporting the required transactions, principally in the Northeast of Brazil (Da Silva et al., 2016; De Jong et al., 2017; De Melo et al., 2016a; Global Transmission Report, 2016; Hunt. et al., 2018; Miranda et al., 2017; Operador Nacional Do Sistema Elétrico - ONS, 2017). The auctions of transmission lines have been facing delays, compromising wind-power operation and security of supply for the region (Cardoso Júnior et al., 2014; De Jong et al., 2015; Moreira et al., 2015). Over 30% of wind projects with expired implementation deadlines still do not have a grid connection and only 14% from the first eight auction rounds were completed on schedule (Bayer, 2018). Figure 1 presents a diagram of delayed transmission lines (yellow lines), highlighting that the completion deadlines have already expired. To date, Brazil was expecting to have 7,800 km of transmission lines in place but only 2,000 km has been built (ONS, 2018) – representing a delay up to three years. This problem does not only reduce electricity supply capacity and increase electricity prices but also threatens the wind power expansion plan in the mid-term (De Melo et al., 2016a), raising questions on how time-delays in transmission infrastructure may affect the development of the wind power industry in the mid- to long-term.

Figure 1. Delayed transmission lines with regard to the contractual delivery date. Source: Own elaboration based on (Operador Nacional Do Sistema Elétrico - ONS, 2017).

Previous studies have analysed the expansion of wind power sources in Brazil (Brannstrom et al., 2017; Da Silva et al., 2016; Pereira et al., 2012; Silva et al., 2013); other works discuss the effects of environmental and other barriers to wind power penetration (De Jong et al., 2016; E. B. Pereira et al., 2013; Silva et al., 2013). Da Silva et al. (2016) show a strong seasonal correlation between precipitation and offshore winds in the North, Northeast, Southeast, and Southern regions of Brazil which counters the intermittent nature of wind power supply. However, research draws attention to the need for significant increases in long transmission lines to better integrate wind power into the Brazilian electricity system (De Jong et al., 2016; WWF-Brasil – Fundo Mundial para a Natureza, 2015). The existing literature offers valuable insight for the design and formulation of wind power policy in Brazil. Nevertheless, wind power growth is not sufficiently analysed with respect to the transmission congestion in the Brazilian energy system and its implications for electricity prices.

During the last decade, the country's power generation capacity grew at an annual rate of 5%, while transmission capacity increased only by 4% (Global Transmission Report, 2018). In the Northeast, starting from a significant deficit, transmission capacity increased by 11% between 2016 and 2017, which was insufficient to cover the expected transmission capacity increases of 30% that were required for transporting wind-generated electricity (ONS, 2018; Operador Nacional Do Sistema Elétrico - ONS, 2017); this describes an unbalanced growth rate that could extend over the next few years. Furthermore, as the economy is decelerating, though infrastructure will be available, resources may not be needed and the wind industry will suffer (De Jong et al., 2015; Global Transmission Report, 2016).

In this context, energy policy plays a key role in coordinating infrastructure development and the different actors involved. Unsynchronised policy may result in poor resource allocation and failures in the electricity market. This implies the need for a careful planning process that synchronises the stakeholders involved in the energy system.

Given the role of the wind industry for the Brazilian electricity market, this paper examines unsynchronised energy policy in terms of time delays for the construction of transmission lines and auctions for the development of wind power farms. This research is not critical of an auction-based policy, but rather calls for a sustainable and coordinated expansion of the wind industry along all elements of the supply chain.

To better understand the electricity industry dynamics and the corresponding unsynchronised policy of the Northeast region of Brazil, a simulation model was developed. This model provides an interesting context to examine the impacts of uncoordinated contracting policies on electricity prices, followed by the presentation of alternative policy scenarios that have been created to alleviate likely congestion in the system.

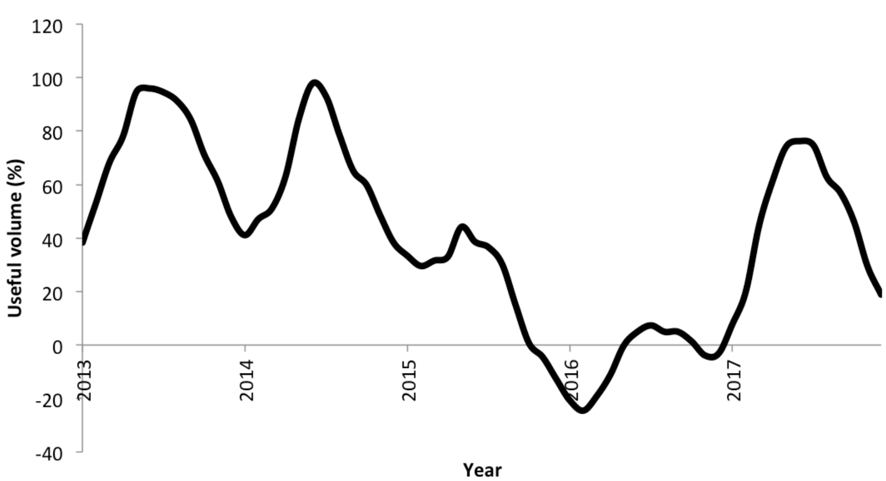
The chapter is organized as follows: Section 2.2 discusses policy coordination problems in the Brazilian electricity market. Section 2.3 describes the modelling approach that was applied as well as the proposed dynamic behaviour hypothesis; this section also assesses and validates the simulation model built for this study. Section 2.4, presents and interprets simulation runs, and analyses policy implications. Finally, the discussion-and-conclusions section provides some significant findings of the research.

2.2. Policy coordination problems in the Brazilian electricity market

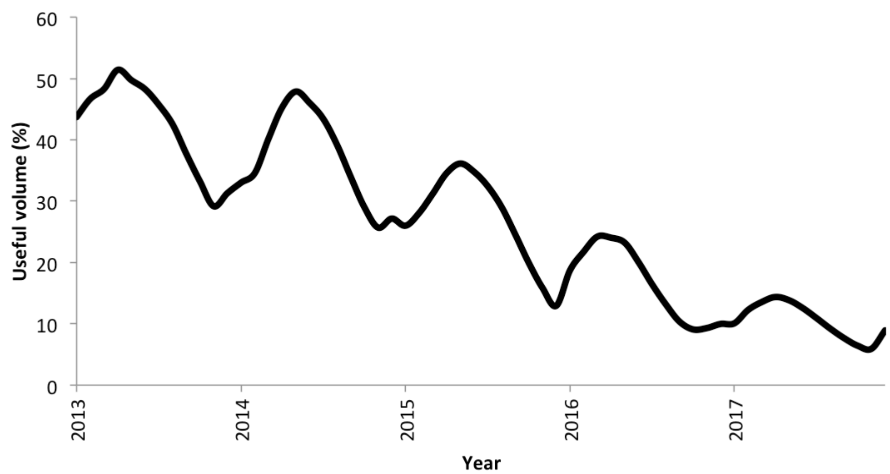
Brazil is rich in natural renewable resources that can be used for electricity generation (Silva et al., 2016). At the end of 2017, the installed capacity of the country was 163.92 GW: 61% from hydropower; 17% from fossil fuels; 7% from wind power, and 15% from other sources (ANEEL, 2017a). This section reviews the main aspects of the Brazilian electricity market, including concerns and opportunities.

2.2.1. Hydropower generation: Current conditions and barriers

The net hydropower additions in 2017 were 3.18 GW, increasing the total hydropower capacity to 100.02 GW (ANEEL, 2017a). Despite significant increases, as mentioned, the useful reserves of hydropower have decreased. De Lucena et al. (2009) evaluate how different rainfall regimes affect flows to hydropower plants and how these have an effect on the security of supply of the energy system; Brazil recently registered some reservoirs at all-time lows. Figure 2 shows significant useful volume reductions in two of the principal dams in the North of Brazil between 2013 and 2017. As a result of prolonged droughts, the Northeast region imported more than 20% of its electricity from the North and Southeast regions (De Jong et al., 2017).



(a) Reservoir of Balbina



(b) Reservoir of Serra da Mesa

Figure 2. Useful reservoir volumes in North of Brazil Source: Own elaboration based on (ONS, 2018).

Although electricity production from hydropower has been of immense importance for the Brazilian economy, it has shown weaknesses related to its lack of reliability and associated with environmental and social impacts, including:

- Reductions in water flows (Andrade et al., 2012);
- Population displacements that delay project completions (Cardenas et al., 2016);
- Outflow temperature changes (Mendes et al., 2017);
- Climatic variations and threats (Von Sperling, 2012); and
- Changes in the natural sedimentation rates (Miranda and Mauad, 2014).

As the electricity industry has been highly dependent on hydropower, Brazil has promoted natural gas-based generation because of its abundant gas reserves (Goldemberg et al., 2014; Vahl and Filho, 2015). However, as Brazil's gas is mostly in deep offshore fields, gas extraction has been lengthy and expensive (Campos et al., 2017; De Melo et al., 2016a). In this regard, Brazil is seeking to further diversify its electricity matrix through renewable resources (e.g. wind power and solar) that are supported by its PROINFA program (Silva et al., 2013).

2.2.2. Deployment of renewable energy in Brazil

In recent years, implemented incentives for alternative electricity sources have favoured increasing installed capacity from renewable resources. The Brazilian power industry uses an auction-based mechanism to promote its expansion that is supported by the Brazilian National Development Bank (BNDES). From 2004 to 2018, wind power showed a significant increase with a current capacity of 13 GW installed at 518 wind power sites within Brazilian territory (ABEEólica, 2018b). The main potential for wind power generation is in the Northeast (75 GW); the lowest is in the North (12.8 GW) and Midwest (3.1 GW). The South (22.8 GW) and Southeast (29.7 GW) have important potential (Da Silva et al., 2016; Juárez et al., 2014; A. O. Pereira et al., 2013) that could reach 500 GW (ABEEólica, 2016).

The rapid expansion of wind power in Brazil was in response responded to an electricity crisis in 2001 caused by the failure of hydropower to meet increasing electricity demand (Brannstrom et al., 2017; Gorayeb et al., 2018). Even though the hydroelectric potential of Northeast Brazil is limited, this region has, until recently, largely relied on large-scale hydropower. However, the region has great wind potential, particularly along its coastline, and the physical location of the Northeast and favourable wind speed conditions have contributed to an increase in the number of wind farms.

Whilst the Northeast region has not only the highest potential but also the best daily solar radiation (5.9 kWh/m^2) in Brazil, little capacity is in place (418 MW) because of the limited transmission capacity and insufficient incentives for its expansion (ANEEL, 2017a; De Faria et al., 2017; De Jong et al., 2015; Silveira et al., 2013).

2.2.3. Transmission system concerns and barriers to wind power

In Northeast Brazil, the delivery of wind power has been affected by grid connection delays (Global Transmission Report, 2016). In some cases, the completion of transmission capacity has been years behind schedule. The suspension of 4,600 MVA of transmission capacity, which should have been in operation by 2015, has affected energy exports from the Northeast region (Operador Nacional Do Sistema Elétrico - ONS, 2017).

In 2017, the National Agency for Electric Energy (ANEEL) allocated eleven transmission concession lots to build 4,919 km of transmission lines (ANEEL, 2017b); however transmission projects again faced delays in environmental licensing. In addition, the higher costs of wind projects due to legislative changes transferred the financial risk of transmission delays to wind project developers (Bayer, 2018). This legislative change provoked increases in the wind auction price of 15% (Bayer et al., 2018).

Figure 3 presents the evolution over time of installed generation capacity, transmission capacity and peak demand in the North and Northeast (N-NE) of Brazil for the period 2008 to 2017. Installed generation capacity increased by 15 GW, while the transmission capacity and demand of the N-NE increased by 10 GW and 6 GW, respectively. This situation generated a shortage of transmission capacity and trapped energy (Operador Nacional Do Sistema Elétrico - ONS, 2017). Between 2008 and 2015, the shortage of transmission capacity nearly reached 7 GW, and was only nearly balanced in 2013. By 2017, trapped energy has reached approximately 9 GW in the Northeast region.

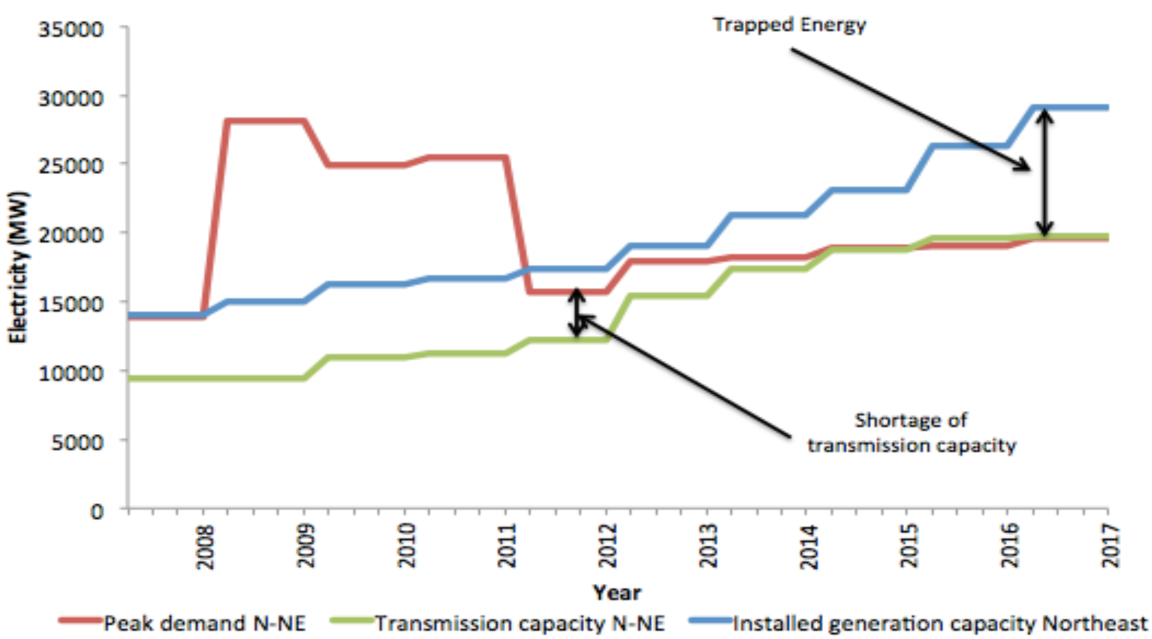


Figure 3. Dynamics of transmission capacity, installed generation capacity and peak demand of the North and Northeast of Brazil

Source: Own elaboration based on (ONS, 2018).

Electricity consumption in Brazil has increased by around 4% annually in the period of 2005 to 2015 (De Jong et al., 2015; Schmidt et al., 2016a; Zurn et al., 2017); in January 2016, however, electricity demand decreased by 5.9% with respect to the previous year, because of demand drops of 9.3% and 5.4% in the industrial and residential sectors, respectively (Global Transmission Report, 2016). In addition, in the year 2017, surpluses in energy supply caused by high rainfall regimes and a slowdown of the economy prompted the cancellation of wind farm auctions.

While the economy was booming, the wind industry expanded rapidly, propelled by low-cost financial loans and high demand for power (Dantas et al., 2017; De Melo et al., 2016a; Porrua et al., 2010). Currently, Brazil faces a reduction in auctions in the short term, which represents a major challenge for wind industry investments. This will create new asynchronies when the economy recovers again, posing new policy challenges that are the focus of this chapter. The next section proposes a model-based approach to assess these concerns.

2.3. Model-based approach

Various methods can be used for policy assessment in this area. This research adopts the System Dynamics (SD) modelling approach, which has been used successfully for more than 30 years (Aslani et al., 2014b; Cardenas et al., 2016; Ford, 1997; Larsen et al., 2004; Naill and Belanger, 1989; Qudrat-Ullah, 2013; Trappey et al., 2012b; Zuluaga and Dyner, 2007). SD modelling facilitates the assessment of complex problems and systems, including interactive effects, to inform policy analysis and design. The usefulness of simulation models is in identifying dynamic systemic behaviour patterns (Qudrat-Ullah and Seong, 2010). SD is considered an appropriate tool for the evaluation of different scenarios with regard to energy policy (Qudrat-Ullah and Seong, 2010; Romagnoli et al., 2013; Sterman, 2000). SD modelling has been used to assess energy policies for generation capacity expansion internationally (Ahmad et al., 2016) and in Latin America (Arango et al., 2006; Haselip et al., 2005; Larsen et al., 2004; Ochoa and van Ackere, 2014; Ponzo et al., 2011; Zuluaga and Dyner, 2007). Many of these studies consider the effect of incorporating renewables, but little work has been done with respect to integrating generation with transmission along the supply chain.

The model developed here seeks to identify the dynamics related to the asynchrony of the Brazilian electricity market and their effects on electricity prices.

The focus of the model is to assess the synchronisation policy regarding power generation capacity in place and the transmission capacity that will take a few years to build. The intermittency of resources is not considered in this paper because: i) Brazil has a high component of hydroelectricity capacity, ii) rainfall complements wind speed in Brazil (De Jong et al., 2016); iii) reservoir capacity in the county is substantial; iv) reservoirs behave as batteries and dampen wind variation, and; v) the building cycle of transmission infrastructure is annual.

The modelling approach used here proposes a dynamic behaviour hypothesis, builds a simulation model, conducts its validation, and assesses policy through simulation scenarios.

2.3.1. Dynamic behaviour hypothesis

The dynamic behaviour hypothesis is a conceptual structure that represents the systematic involved. It theorizes about structure and relationship as well as the consequential behavioural dynamics that might be involved (Oliva, 2003). Energy markets are characterized by complex relationships among their variables; for instance, electricity prices depend on several factors, including the Levelised Cost of Electricity, resource availability, and peak demand. These factors, in turn, are associated with energy policy. Thus, this paper proposes a dynamic behaviour hypothesis (Figure 4) that first examines the relationships among demand, supply, and electricity price through the feedback structure (Dyner, 2000).

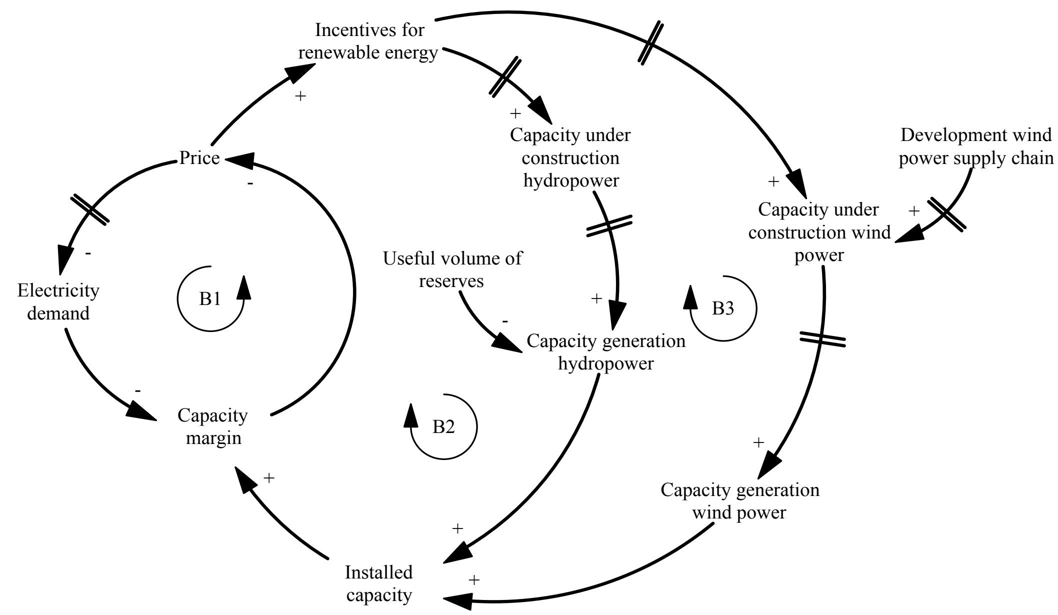


Figure 4. Dynamic behaviour hypothesis for generation capacity

The first balancing loop (B1) shows the dynamics of the capacity margin (also known as the reserve margin), which is calculated as the difference between the installed capacity and the peak demand, divided by peak demand. The capacity margin affects the price of electricity, which in turn reduces electricity demand, closing the balancing loop B1.

The capacity margin also influences the total installed capacity. Increases in electricity prices incentivise investment, leading to the construction of generation capacity, which in the medium term reduces the reserve margin (Dyner, 2000). After some time for construction (time lags are indicated by small parallel lines that cross arrows), increases in total installed capacity are achieved, which in the mid-term influences the capacity margin; creating balancing loops B2 and B3.

Given the dynamic behaviour of electricity markets, it is important to have sufficient transmission capacity in place for the supply of peak demand (Ochoa and van Ackere, 2015). While too much generation capacity results in higher generation cost (Cepeda and Finon, 2013), insufficient transmission capacity induces congestion and higher electricity prices. Figure 5 shows the dynamic behaviour hypothesis that describes the inclusion of the effect of transmission congestion on electricity price.

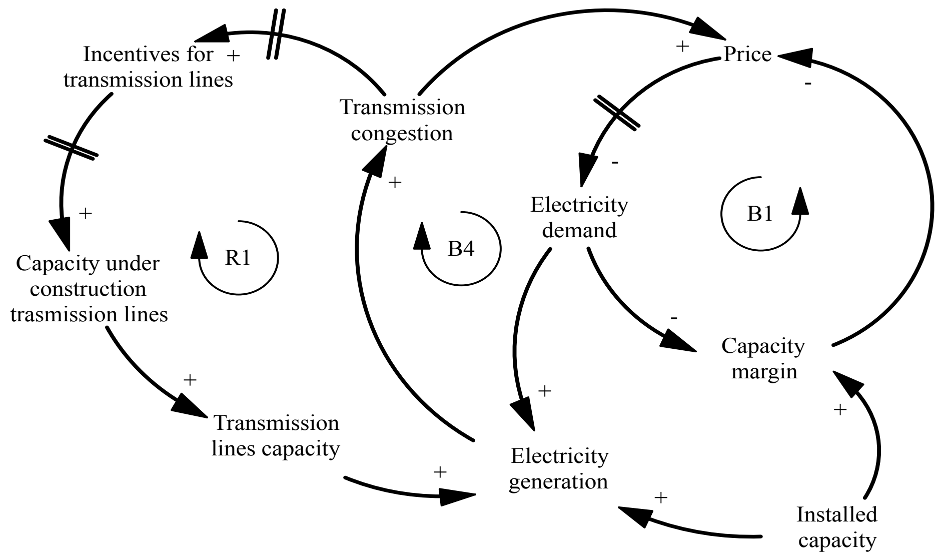


Figure 5. Inclusion of the effect of transmission congestion on the electricity price

The fourth balancing loop (B4) describes the dynamics between electricity generation and transmission congestion as well as their effects on electricity price and demand. As the installed power capacity increases, there is a need for more transmission infrastructure, but investments in transmission capacity have been insufficient and involve lengthy timescales, prompting congestion. Transmission congestion depends on the electricity that must be transmitted (electricity generated) and greatly affects electricity prices. This is a consequence of the lack of transmission infrastructure in terms of reducing power supply (Herrera et al., 2018; Ochoa et al., 2013).

Demand can be served when sufficient generation and transmission capacities are in place. Although onshore and offshore sources of wind power are available alternatives, their eventual dispatch depends on transmission resources. This also raises the issue of congestion, which will in time promote new transmission capacity and close the reinforcing loop R1. This positive feedback structure involves a time lag that offers challenges in terms of coordinating policy.

Summarising, though the policy of capacity auctioning promotes investment along the wind power supply chain industry, it may induce grid congestion because of uncoordinated planning and delays in the construction of transmission lines. These situations generate asynchronies between wind generation expansion and the transmission infrastructure in place, posing challenges that are investigated here with the support of simulation modelling.

2.3.2. Simulation model

The traditional representation of SD uses stock and flow diagrams, which correspond to a set of differential equations that are based on a proposed dynamic behaviour hypothesis. The model built here is based on structures included in earlier works (Cardenas et al., 2016; Franco et al., 2015). The main addition in this work is the supply chain structure of the industry, including the transmission component. This model considers the dynamics of three basic components: (1) generation capacity, (2) transmission capacity, and (3) electricity market.

The structure of the supply chain includes the production capacity of assemblers and manufacturers of wind power technology. The main drivers of the wind-power supply chain are calculated by Equations (1), (2) and (3). The *installed capacity of wind power* (IC_w) has a useful life cycle, which determines *depreciation* (D) and *maintenance* (M). *Factory capacity* (FC) and *developing wind power* (DW), capture length of time for construction and time delays in building the *capacity of the wind industry* (CWI_w), and the *capacity of assemblers* (CA), respectively.

$$IC_w(t) = IC_w(t-dt) + \int_{t=o}^{T} [DW(s) - D(s) + M(s)]ds \quad [GW] \quad (1)$$

$$FC = CWI_w\,(1 - wind\ industry\ delay) \quad [\frac{GW}{year}] \quad (2)$$

$$DW = CA\,(1 - construction\ time) \quad [\frac{GW}{year}] (3)$$

The transmission infrastructure is an essential component of the electricity supply-chain structure. *Developing transmission capacity* (DTC) depends on two main aspects: *economic availability factors* (ef) and *time of construction* (tc). This is determined by delaying the value of the *needed capacity for transmitting electricity* *generation* (Cn), as shown in Equation (4).

$$dtc = [Cn\,(1 - tc)\,] * ef \quad [\frac{GW}{year}] \qquad (4)$$

If wind power capacity increases, transmission lines must be built to be able to deliver the generated electricity. Therefore, time is required to build the transmission lines and towers that are needed as a result of the auctions policy. The *capacity under construction* (CC_T) is added to the *installed capacity of transmission* (IC_T) according to the *time needed to build transmission lines* (tbt), as shown in Equations (5), (6) and (7).

$$CC_T(t) = CC_T(t - dt) + \int_{t=o}^{T} [\,dtc(s) - Tr(s)]ds \;\; [GW] \quad (5)$$

$$IC_T(t) = IC_T(t - dt) + \int_{t=o}^{T} [\,tbt(s) - D(s)]ds \;\; [GW] \quad (6)$$

$$tbt = [CC_T\,(1 - tc)\,] \quad [\frac{GW}{year}] \quad (7)$$

The price of electricity is a crucial factor to be considered for investments among the available generation technologies. Reserve margins determine electricity price, which influences: a) investments in new hydro and wind power capacity, and b) electricity demand (balancing loops B1, B2, and B3). Investment decisions are computed representing a discrete choice model (Castaneda et al., 2017; Herrera et al., 2017c), which is used for determining the *share of investment in hydro and wind power* (Si) as observed in Equation (8). The parameter β is the relative weight assigned to choose the technology i (hydro or wind) considering the cost of electricity production C_i.

$$S_i = \frac{exp^{\,\beta * C_i}}{\sum exp^{\,\beta * C_i}} \qquad (8)$$

The main assumptions and inputs in the model are:

- The simulation model uses databases produced by the Brazilian energy agency (ANEEL), the National Electricity System Operator (ONS) and other sources that publish historical data on the operation of the electrical power system in Brazil and installed capacities, as shown in Table 1.
- To validate the accuracy of the proposed model, the results were compared to actual outputs for the years 2004 to 2017.

- One assumption considered in the model is the average time taken to build 1000 km of transmission lines, which was estimated to be four years, including the environmental feasibility studies and financing approval through BNDES (Bayer, 2018; De Jong et al., 2016; Hunt. et al., 2018).
- The annual loss of the storage volume of reservoirs in Brazil caused by processes of sedimentation has reached 0.5 percentage of its storage volume (Miranda and Mauad, 2014).
- Although the Brazilian interconnected power system is divided into four subsystems (Southeast, South, Northeast, and North), the simulation model assesses the asynchrony of wind power generation and transmission capacity for the Northeast region only.
- The simulation model considers the values of bids in March 2009 for 1.8 GW, and in October 2013 for 2.3 GW, as these represent particularly important wind-power auctions.

Table 1. Input data in the simulation model to December 2017

Variable	Input data	Source
Installed capacity of wind power in the Northeast region	10090 MW	(ONS, 2018)
Initial peak demand	12905 MW	(ONS, 2018)
Electricity price of the Northeast region	422 R$/MWh	(ANEEL, 2018)
Average of wind power auctions	1.8 GW	(ANEEL, 2017)
Time to build wind farms	1.6 years	(Simas and Pacca, 2014)
Implementation period of wind power auctions	3 years	(Bayer, 2018)
Average time to build a hydroelectric facility	6 years	(Qudrat-Ullah and Seong, 2010)

2.3.3. Model validation

The validation process is fundamental for building confidence in model outputs (Barlas, 1996; Sterman, 1984). One of the main objectives of this research is to investigate the model's capability to both reproduce historical data and support policy assessments. This research follows structural and behavioural validation methods (Qudrat-Ullah and Seong, 2010; Sterman, 2000) for the period 1999-2017.

The Theil inequality statistics provide excellent error decomposition to reflect the fraction of the mean squared error (MSE) related with bias (U^m), unequal variance (U^S), and unequal covariance (U^C). The error analysis for the variables representing installed wind power capacity, electricity demand, and transmission capacity is presented in Table 2. The Theil inequality statistics reveal low MSE and low bias, which indicate closeness in the mean of actual and simulated values with similar dominant trends. Thus, the fit between model and history is particularly strong for policy analysis.

Table 2. Error analysis of the simulation model

Variable	MSE (units^2)	U^m	U^S	U^C
Wind power capacity	0.20	0.05	0.22	0.73
Electricity demand	0.23	0.02	0.41	0.57
Transmission capacity	0.9	0.08	0.12	0.8

A dimensional consistency test was also conducted for each mathematical equation (Barlas, 1996). This test determined that the simulation model corresponds dimensionally to the real-world system.

2.3.4. Limitations

The purpose of the model is to evaluate unsynchronised energy policy for the wind power industry in Brazil for the Northeast region. The analysis considers, in particular, how insufficient policy coordination affects a region with favourable conditions for wind power and reduced hydroelectricity capacity. To this end, this paper does not conduct spatial analysis and focuses on the sustainability of the wind industry and its complementarity with hydroelectricity. Though the location of load centres, installed capacity, transmission lines, and demand sites are relevant, these were not considered as the analysis is undertaken at an aggregated level for the purpose of policy assessment. The model also assumes invariable energy losses (De Jong et al., 2017).

2.4. Simulation results

This section first analyses the current electricity market policy in Brazil (Section 2.4.1) and in Section 2.4.2 examines scenarios for alternatives aimed at overcoming unsynchronised policy..

2.4.1. Analysis of uncoordinated policy in the Brazilian electricity market

The proposed model was adjusted to represent the Northeast region of Brazil, which represents 18% of Brazilian territory, with a population of 54 million inhabitants. The region receives only a fraction of the country's total annual national rainfall, with hydroelectricity producing 25% of the Northeast's electricity in 2016, in contrast with wind power production that reaches 30% of the total (De Jong et al., 2017). Figure 6 shows simulations of wind and hydropower for the base case scenario (business as usual, BAU). It is expected that wind power will increase its contribution over the long-term. Hydropower grows more slowly because hydro resources in the Northeast region are already overexploited. Although new hydropower capacity is possible, its development causes significant environmental impacts and takes several years to complete. Simulations are consistent with other projections of wind capacity for the Northeast (Da Silva et al., 2016; De Jong et al., 2016).

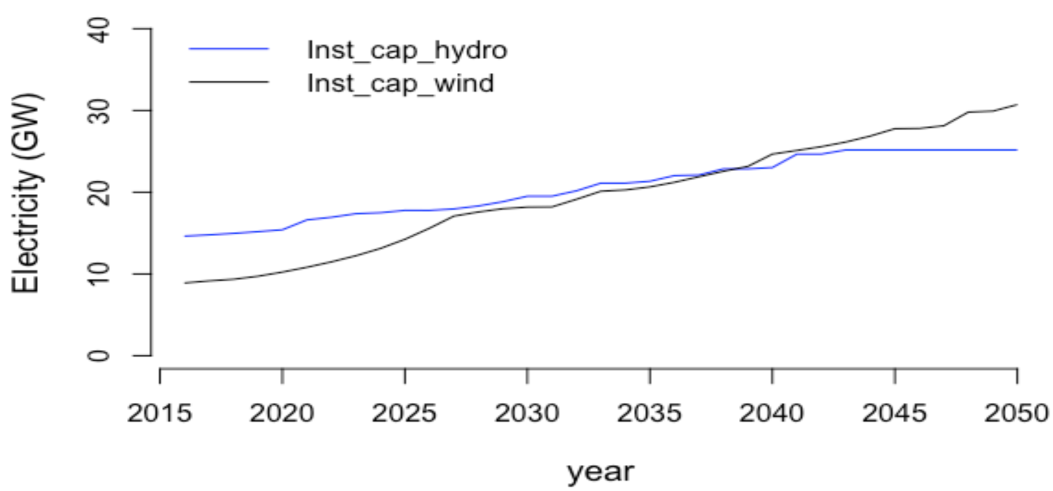


Figure 6. Simulation results for the installed capacity wind and hydropower in the Northeast region of Brazil for the period 2016-2050

Results show moderate and prolonged growth rates for electricity generated from wind and hydro resources, confirming the need for more transmission infrastructure in this region in the middle term. Though potential power generation capacity is abundant, transmission capacity will be inadequate under the current policy in place (BAU scenario), as illustrated in Figure 7. The requirement for transmission connection will be of the order of 24,500 km by 2023 (Da Silva et al., 2016). This highlights problems with electricity dispatch in the near future. Construction delays increase the asynchrony between generation and transmission, with consequences in terms of congestion and "trapped" energy that cannot be dispatched.

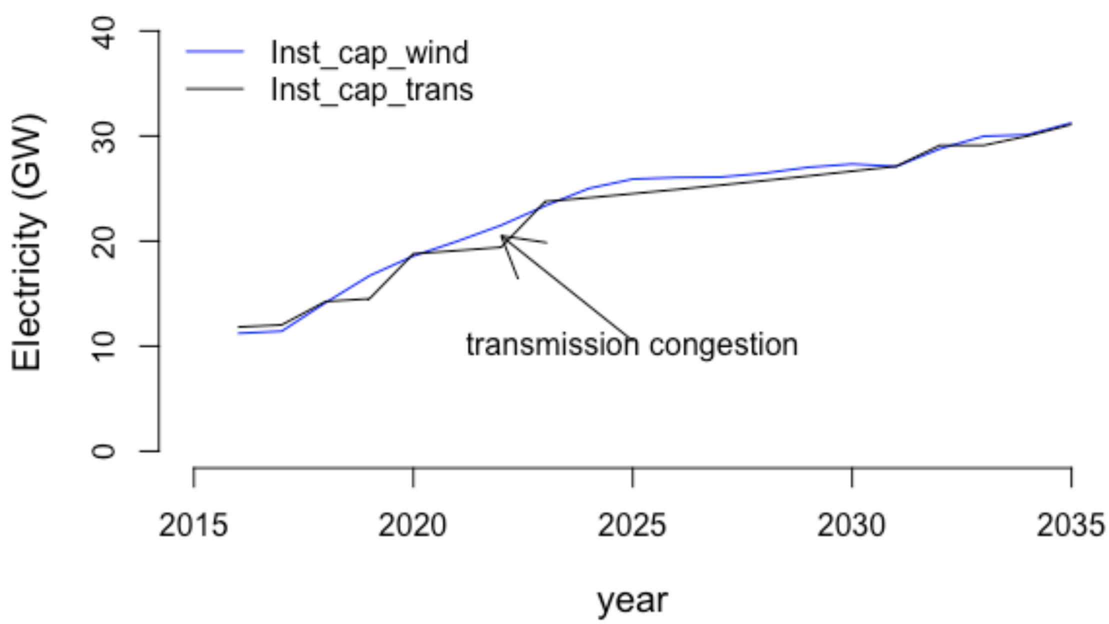


Figure 7. Behaviour of installed capacity of wind generation vs. installed capacity of transmission in the Northeast

If there is not enough transmission capacity in the Northeast, electricity exports to other regions could be negatively affected (De Jong et al., 2017; Miranda et al., 2017). It has been argued an appropriate matching of hydro and solar power, supported by energy policy, could secure electricity supply to the Northeast and provide surpluses to other regions (Aquila et al., 2017a; De Jong et al., 2013; Fichter et al., 2017; Miranda et al., 2017; Silva et al., 2016). However, this scenario has not been studied sufficiently and for that reason, this research examines how coordinated policy might eliminate transmission congestion and reduce electricity prices. The following section considers alternative policy scenarios along these lines.

2.4.2. Alternative policy analysis

This section discusses the impact of two scenarios on the electricity market, produced by unsynchronized and synchronized energy policies regarding the expansion of wind power and transmission capacity. The selected scenarios are based on the analysis of the electricity market (De Jong et al., 2017; Neuhoff and Newberry, 2005; Smith et al., 2005). The simulation scenarios consider combinations of energy policies in terms of wind power auctions and delays in building transmission infrastructure.

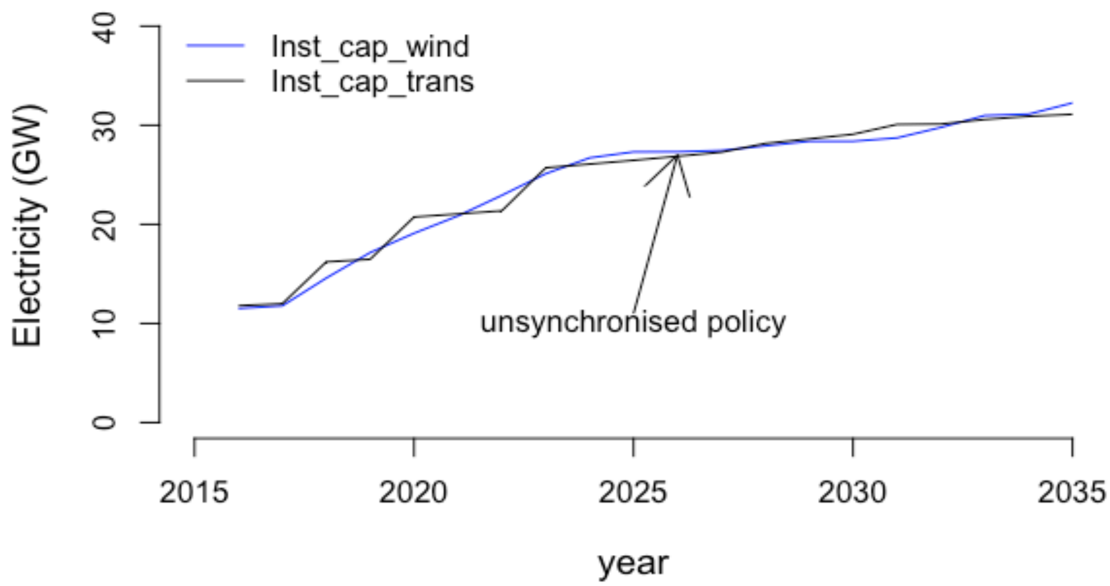
Table 3 establishes those policy instruments that have been proposed for each scenario; these are aimed at addressing the issue of how energy policy would achieve a coordinated expansion of wind power and transmission capacity in the Brazilian electricity market. Scenario 1 is characterised by elevated levels of congestion and assumes delivery time certainty for the construction of transmission lines and demand uncertainty. However, lead time is not deterministic and some uncertainties are involved in delivery time. The second scenario considers uncertainties in both lead time and future demand. To coordinate transmission auctions, the regulator may adopt simple arguments that take into account average annual demand ($\overline{D}$) and lead time (LT). This paper uses these elements to determine the level of new transmission capacity to be auctioned through a function of classical production scheduling.

Table 3. Proposed policy

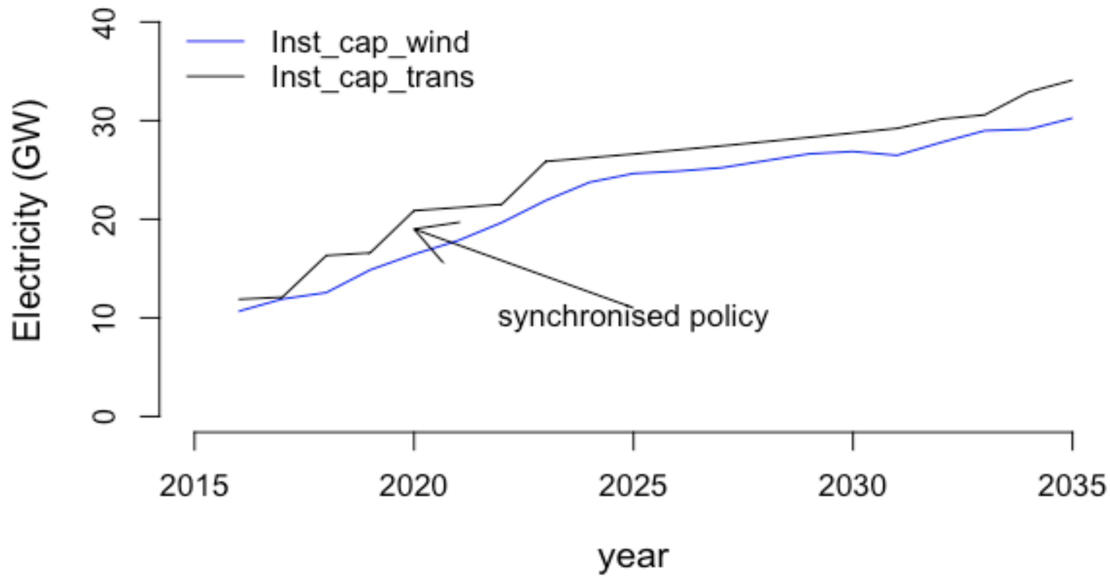
Scenarios	Definition of scenarios	Policy
Scenario 1	Unbalanced and insufficient growth policy	$\overline{D} * LT + Z * S_d * \sqrt{LT}$
Scenario 2	Balanced growth policy	$\overline{D} * LT + Z * \sqrt{LT * {S_d}^2 + \overline{D}^2 * {S_{LT}}^2}$

Z : Number of standard deviations corresponding to the compliance level probability
S_d: Standard deviation of annual demand
S_{LT}: Standard deviation of lead-time

Figure 8 shows the simulation evolutions of wind power capacity and transmission capacity over time, under the different scenarios considered in Table 3. Policies simulated under Scenario 1, corresponding to Figures 8(a), do not achieve a balance between power and transmission expansion, either because they do not account for delays in building infrastructure or because they stressed more importance to either power generation or transmission initiatives. Figure 8(b) shows that policy synchrony is only attained for Scenario 2.



(a) Scenario 1: Unbalanced growth policy



(b) Scenario 2: Balanced growth policy

Figure 8. Simulation scenarios with unsynchronised and synchronised energy policies

In the case of Brazil, the auctions policy has promoted the expansion of wind farms in the Northeast region (Bayer, 2018; Mastropietro et al., 2014; Porrua et al., 2010); however, the transmission infrastructure for connecting demand centres is a constraint. Installed wind power capacity could reach as much as 18 GW by 2020 under a favourable scenario for sustainable and efficient expansion (Scenario 2). In contrast, in the absence of synchronised policies, expansion of wind power could reach no more than 16 GW by 2020, which could affect the energy supply from the Northeast region to other regions in the country (BAU scenario). The expected growth in wind power capacity in the Northeast region seen in Scenario 1 (16 GW) coincides with the results of others (De Jong et al., 2016). However, this scenario suggests potential problems with transmission congestion.

Brazil opted out of the development of wind-farm-systems interconnected to the main national grid for the purpose of complementing hydrology (precipitation) with wind regimes (Bayer et al., 2018). For this reason, distributed generation was not an option. Figure 9 shows the effect of transmission congestion on electricity prices under the three proposed scenarios, including the BAU scenario.

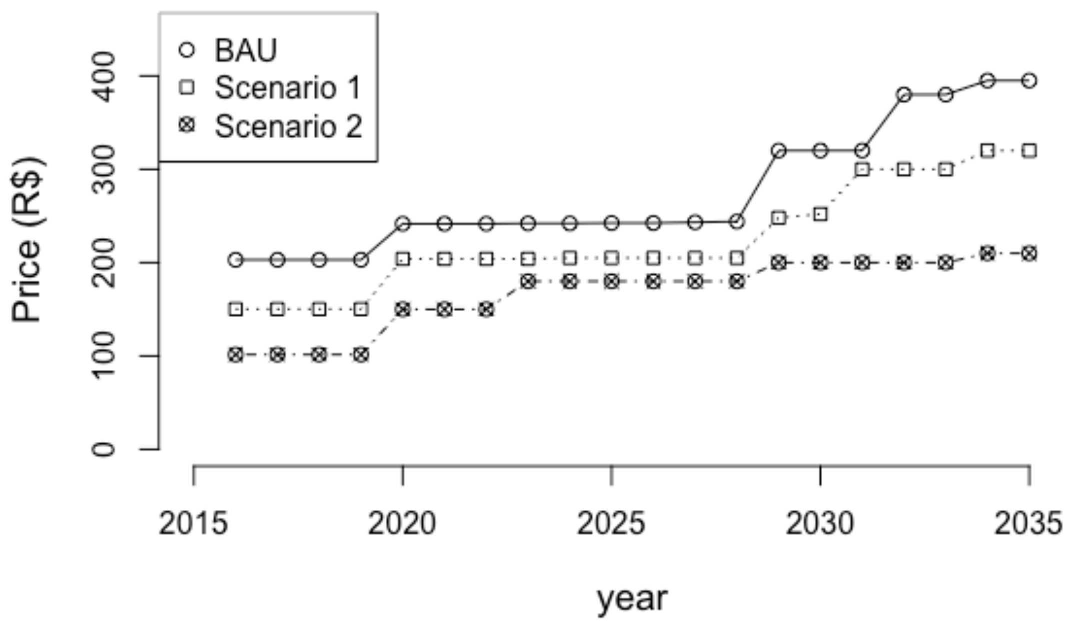


Figure 9. Effects of transmission congestion on the electricity price

Simulation results for the BAU scenario show that under the current wind power conditions, electricity prices increase because transmission lines are insufficient. The problem is exacerbated in 2040, when the prices double. The asynchrony produced by low contracting for the construction of new transmission lines and rapid expansion of the wind industry, principally in the Northeast region, contributes to an elevated level of transmission congestion.

Simulations for Scenario 1 lower the congestion charges at the expense of higher costs associated with idle transmission infrastructure. Simulation results for Scenario 2 (balanced policy) show low prices from 2016 to 2019 and a slightly higher price from 2020 to 2022. In the period 2023 to 2035, the electricity price is much lower in this scenario as a result of the balanced policies for wind power and transmission capacity. Furthermore, this scenario exhibits a relatively lower electricity price due to a decrease in the time to build transmission capacity.

The results presented for the different scenarios provide insights for policy assessment. As may be appreciated, the synchronised policy has the lowest impact on electricity prices and is associated with the lowest cost associated with idle transmission infrastructure.

2.5. Conclusion

The current Brazilian energy policy, which aims at diversifying the country's electricity portfolio, though moving in the right direction, needs careful design to attain sustainable and efficient growth. The delay and cancellation of auctions associated with new wind farm projects and transmission lines could have repercussions for wind industry expansion. The growth of clean technologies calls for synchronization among stakeholders along the supply chain, with planning that integrates the construction of new wind farms with transmission auctions and environmental licensing.

Simulations validate the paper's hypothesis, based on the results of the base case scenario (BAU), that the main obstacles for the future development of wind power are deficiencies of the transmission infrastructure due to the asynchrony of energy policies in Brazil. The elevated level of accumulated congestion (the difference between generation and transmission capacities) in the base case scenario reaches 6 GW between 2024 and 2030, which has a significant impact on electricity prices. We find that the construction of extensive transmission infrastructure for electricity supply is needed to capitalise on renewable resources, in agreement with De Jong et al., (2016), De Melo et al., (2016), Herrera et al., (2017a), and Lima et al., (2015).

Simulation results show that increases in wind power farms must be synchronized with the evolution of the transmission infrastructure in the Brazilian Northeast region. This analysis also finds that, for attaining policy synchrony, planning must consider an adequate system margin that incorporates construction time and delays in environmental licensing to avoid significant congestion and high electricity prices. The analysis suggests that investment incentives should also be applied in a synchronised and sustainable way.

The analysis of the synchrony of the Brazilian electricity market associated with energy exchange among regions may be an opportunity for future research. A similar approach could be used to analyse energy exchanges using the simulation model applied here.

Chapter 3: Benefits from energy policy synchronisation of the North-Northeast interconnection of Brazil ♣

Abstract

The high growth of wind power in Brazil calls for an associated progression of electricity transmission infrastructures. The reported delays in the construction of grid infrastructures affect the effective expansion of renewables in the country. With the purpose of assessing the effects generated by transmission infrastructure delays on the wind power expansion in the North and Northeast regions of Brazil, this research adopts System Dynamics and emerging simulation scenarios exploring alternative wind industry policies for mitigating the uncoupled planning coordination between both power generation and transmission capacities. Simulation results show that policy synchronisation within the wind industry improves the interconnection across the multiple regions of the country. This article concludes that, as for the Brazilian case, energy policy for wind power expansion benefits from coordinated and systemic interventions.

Keywords: wind industry; energy policy; transmission; system dynamics; Brazil.

3.1. Introduction

Wind power resources are growing significantly in Brazil since the early 2000s (Da Silva et al., 2016; De Jong et al., 2017). However, the current transmission grid capacity is insufficient for transporting the electricity generated in the new power sites to the demand centres (De Jong et al., 2016; Miranda et al., 2017; Oliveira et al., 2017). Although the North-Northeast region of Brazil presents favourable conditions for wind power generation (De Jong et al., 2017; Lima et al., 2015; Pereira et al., 2012), the auctioned transmission lines that connect it with the rest of the country are suffering

♣ Results of this chapter have been included in: i) a paper presented at the XIV Latin-American Conference of System Dynamics held in San Paolo (Brazil) in 2016, ii) a paper published in Iberoamerican Journal of Industrial Engineering, V. 9 Nº 18, ISSN 2175-8018, iii) a paper submitted at the journal of Energy Policy.

from significant delays (Bayer, 2018; Global Transmission Report, 2018). This situation has left some wind projects offline, forcing the country to use standby oil, diesel and thermoelectric power generators (Global Transmission Report, 2016).

Power systems require a sustainable balance between supply and demand at all times to guarantee electricity flows through all regions (Cepeda and Finon, 2011; Ford, 1999; Ochoa and van Ackere, 2015). However, as planning and the associated asset construction of electricity systems are inherently characterised by delays (Dyner, 2000; Ford, 1999, 1997; Morcillo et al., 2017), policy coordination is criticality required for securing electricity supply at all times. Despite an extensive strategic planning activity, Brazil faces severe delays in implementing planned energy policies along the supply chain. Currently, the grid connection backlog caused by the complex regulations associated with environmental feasibility studies has significantly limited the wind power expansion (Bayer, 2018). In this context, the deployment of wind power has been delayed by unsynchronised energy policy along the supply chain, i.e. policy outcomes significantly and systematically diverged from the expected system behaviour. This explains why policy targets are not met in the mid-term.

The performance of wind industry supply chain is importantly determined by the synchronisation among the multiple stakeholders intervening throughout the supply chain (Herrera et al., 2019, 2018). In fact, the synchronisation among stakeholders should help to overcome problems associated with the construction delays that occur in the electricity sector. Thus, the main aim of this article is to identify and test policy alternatives that may mitigate the asynchrony along the supply chain of the wind power industry and their effects on the power exchange among regions, namely between the North and Northeast regions of Brazil. Emerging results may be extended and taken into account elsewhere.

Congestions, trapped energy, and high electricity prices increase whenever generation capacity grows and transmission infrastructures are inadequate. Through the use of simulation scenarios, this paper aims to capture the dynamic aspect of electricity exchanges among regions, thus contributing to the existing literature on grid congestion issues.

The chapter is structured as follows: after this introduction, section 3.2 provides an overview of the limited transmission capacity, with emphasis on the interconnection between North and Northeast of Brazil. The methodological framework is described in section 3.3. Section 3.4 depicts simulation results and explores alternative wind industry policies. Eventually, the conclusions and policy implications are reported in section 3.5.

3.2. The insertion challenge of renewable energy in Brazil

The insertion of renewable energy sources (RES) is taking place at a good pace in the developed world (Foley et al., 2015), including Latin America. However, despite this rapid growth of RES, transmission restrictions are often affecting power supply (Cepeda and Finon, 2011; Kunz and Zerrahn, 2015; Ochoa and Gore, 2015; Zakeri et al., 2016).

In general, although the insertion of RES and the issue of interconnection have been extensively considered in European countries, such as Germany (Hoffmann et al., 2013; Kunz and Zerrahn, 2015; Zakeri et al., 2016) and in some Latin American countries (Cardenas et al., 2016; Cepeda and Finon, 2011; Ochoa et al., 2013; Redondo et al., 2018; Zuluaga and Dyner, 2007), the mid- to long-term dynamics of interconnection among Brazilian regions and their policy implications have received little attention in the literature so far.

Brazil has implemented its policy on renewable energies and carbon emissions reduction, which has triggered the wind power industry growth in recent years, principally in northeast Brazil. Over 2 GW of wind power were added in 2017, via 79 new wind farms (ABEEolica, 2017). The total installed capacity of wind power in the Northeast region reached 11,147 MW, while the North had 221 MW (ONS, 2018). Although the installed capacity in Northeast was considerable, its electricity transmission capacity towards the North was limited to only 4,400 MW due to delays in new transmission lines, which were planned four years earlier. In November 2015, one of the largest private players in Brazil's power transmission sector filed for bankruptcy, thus affecting the development of about 6,100 km of the new lines and the operation of 6,800 km of existing transmission projects (Global Transmission Report, 2016). Currently, the main obstacles to network construction are the bureaucracy related to environmental feasibility studies, delayed approval of funds and poor transmission project-management (Bayer, 2018; De Jong et al., 2016).

The bureaucracy to obtain environmental licensing for both wind farm construction and transmission projects is hampering the development of electricity infrastructures in the country. According to the Brazilian Association of Transmission System Operations, this bureaucratic procedure takes 17 months on average to be completed, instead of the planned four months that this should take (Bayer, 2018; Medeiros and Renan, 2016), although the environmental licensing process was updated in 2011. This updating process has still left many issues unresolved (Cardoso Júnior et al., 2014), such as, for instance, the identification of lands susceptible to the environmental and social impact for the construction of both wind generation capacity and transmission lines (Brannstrom et al., 2017; Silva et al., 2013).

Legal disputes regarding land use rights and land prices are delaying upcoming transmission projects (Brannstrom et al., 2017; De Jong et al., 2015). In some cases, this situation made some projects unfeasible and affected the supply from wind farm generation to the demand centres. Although wind farm developers receive government refunds for an unsold generation in case transmission lines are delayed, other costs - such as land lease - must be counted for them (ABEEolica, 2017). Thus, this condition brings problems for both developers and consumers. It is worth underlining that over costs of connecting power projects to the grid could be transferred to Brazilian electricity consumers.

In this context, insufficient transmission capacity has hampered the North-Northeast interconnection, affecting electricity prices in each region. The electricity prices – determined at the intersection between the supply curves and peak demand - are equal to $R 394.82/MW in the Northeast region, and $R477.99 in the North region. In each region, the supply curve increases as more expensive generators are dispatched. The peak demand is 12,905 MW for generators in the Northeast region, while peak demand is 6,784 MW for generators in the North region.

Figure 10 shows the constrained transmission system of the North-Northeast interconnection, based on the classical supply curves scheme (Hunt, 2002; Lesieutre and Eto, 2004). This analysis is fundamental to evaluate the construction of new transmission lines due to those constrains affecting electricity price. The total demand for both regions is 19,653 MW (i.e., 6,748 MW and 12,905 MW respectively). This demand has to be generated in one region or the other, taking into account that the interconnection across regions is limited. Load in the North region must pay $R477.99/MW, rather than $R400/MW ($R394.82/MW+$R5.18/MW) that could be dispatched from the North-eastern region if the constraint is released. In the current situation, the price is even higher as there is transmission capacity for only 4,400 MW, against a reported need for 6,200 MW. Although the least cost solution would be in the intersection of the two supply curves, where the electricity prices to be equal in both regions, there are electricity transmission restrictions.

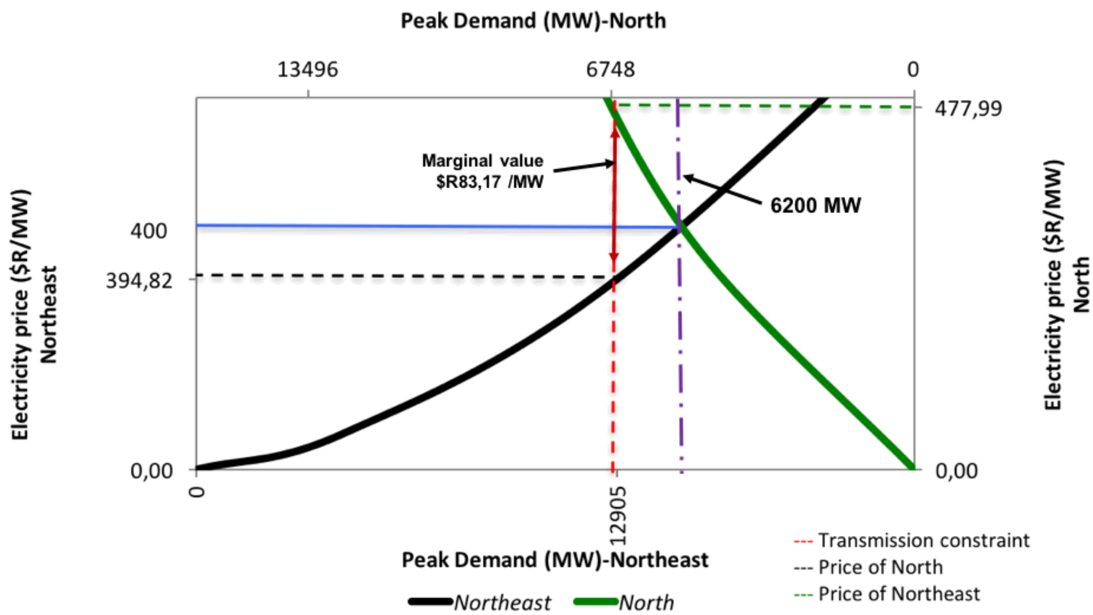


Figure 10. Interconnected regions of North and Northeast with constrained transmission.

According to the supply curve analysis, the North-Northeast interconnection additional transmission capacity would benefit the North region. Capacity expansion is justified when the average marginal value of current transmission is higher than the marginal value after transmission expansion (Hunt, 2002). In this case, the marginal value of transmission before the expansion reaches $R83.17/ MW (i.e. 477.99 – 394.82), which leads to over costs for both regions.

Naturally, the construction of new electricity infrastructures always takes time. The construction of power facilities might take several years until its completion. In this context, the growth of power generation could be constrained by a variety of factors, such as long siting and construction delays, inability to raise needed capital and escalation in production costs (Sterman, 1981). As the insertion of RES requires to synchronise energy generation with the construction of new transmission lines, delays in construction capacity could affect the electricity expansion plan. The insertion of RES is a process that naturally prompts uncertainty and asynchrony in electricity market in the mid-term. In this perspective, the approaches based on scenario simulation can be appropriate to assess and manage this complexity.

Nowadays, electricity expansion policy is complex, not only due to the number of large market and environmental uncertainties involved, but also because of the challenge of coordinating traditional power technologies with the insertion of RES. In the case of Brazil, the dependency of hydroelectricity and the intermittency of renewable resources makes it particularly difficult (De Lucena et al., 2009; de Queiroz et al., 2016). Thus, as for the purpose of supporting planning under high uncertainty, simulation methods have proven to be appropriate (Dyner and Larsen, 2001). In particular, system dynamics (SD) is a modelling approach that, through the use of simulation scenarios, enhances strategic learning processes in complex socio-economic systems (Cosenz and Noto, 2016; Dyner, 2000; Torres et al., 2017). Also, SD is a powerful tool to understand the relationships between organizational structure and behaviour, with a focus on performance metrics, strategic resources and strategy levers (Bianchi, 2012b, 2016; Sterman, 2000). In this case, this methodological approach is used to support the design and implementation of sustainable policies for the wind power industry through an in-depth exploration of scenarios emerging from the simulation of these policies.

In recent years, several research studies have analysed policy making processes for the transition towards renewables (Burke and Stephens, 2018; Castaneda et al., 2017; Jimenez et al., 2016; Musango et al., 2014). Energy policy assessment is important for a better understanding its impact on society. The challenge for policy analysts is to reduce the likelihood of problems during the implementation stages (Wheat, 2010). In this context, with the support of simulation-based modelling , understanding the dynamics of the wind industry supply chain is crucial for assessing synchronised policies (Franco et al., 2015; Gómez et al., 2017; Trappey et al., 2012a).

Several studies have shown that SD simulation modelling is a useful approach for understanding a wide number of issues of the electricity industry (Ahmad et al., 2016; Ford, 1997; Liu and Zeng, 2017; Qudrat-Ullah, 2016; Strachan, 2011). Some analyse the impacts of different trading arrangements and national policies on the interconnected electricity market in different European countries (Ochoa and Gore, 2015), as well as in Latin America (Ochoa et al., 2013), while others evaluated the use of the capacity mechanisms to compensate long-term effects of large-scale wind power development on prices and security of supply (Cepeda and Finon, 2013, 2011). However, only few focus on the gap between interconnection and generation capacity (i.e. unsynchronised energy policy) and its impacts on the Brazilian electricity market (De Jong et al., 2016). Further to this, no SD-based approach has explored the coordination problem of the wind supply chain with a focus on the delays in transmission lines that connect northern in Brazil.

In this context, the renewables insertion challenge of the Brazilian electricity industry comprises a number of critical issues, including: (i) How will the delays in transmission construction impact on the insertion of RES in the mid- to long-term? (ii) How can the synchronisation of energy policies mitigate issues such as congestion, trapped energy, and high electricity prices in interconnected regions? (iii) What is the mid- to long-term effect of insufficient transmission capacity on the RES prices? (iv) What are the advantages of a synchronised energy policy for Brazil's expected electricity demand?

This paper aims at contributing to the understanding of energy policy alternatives for creating an environment that is conducive to weigh congestion issues and its impacts on the wind industry expansion. Thus, to provide possible answers to the above research questions, an in-depth description of the methodological approach used in this paper is described in the following section.

3.3. The methodological approach

The complexity of energy systems involves a large number of variables and many actors that are called to jointly coordinate their operations throughout the supply chain. System constraints and conflicting objectives of these players further complicate decision-making and the long-term assessment of system performance. Therefore, framing, exploring and assessing the contribution of each operation is crucial for policy analysis, decision making and coordination (Ford, 1997; Ochoa and van Ackere, 2015; Qudrat-Ullah, 2016). This section presents the simulation modelling approach, including an excerpt of the dynamic hypothesis, validation and the scenarios considered for simulation analysis.

3.3.1. Dynamic hypothesis

This study considers the convergence of supply-demand structure, involving the transmission capacity component. Figure 11 illustrates the dynamic hypotheses tailored to the Brazilian energy setting. A higher electricity price leads to more incentives for capacity expansion which, in turn, positively influences the generation of installed capacity in the long-term. Then, capacity margin rises up determining a decrease in the electricity price. Such a decrease stimulates the local electricity demand which, on the one side, reduces the local capacity margin and, on the other, fosters the need for increasing transmission as a result of balancing loops B1 and B2. This, alongside the need of transmission in other regions, leads to higher grid congestion that again affects the local price, caused by an insufficient transmission capacity of the system (balancing loop B3).

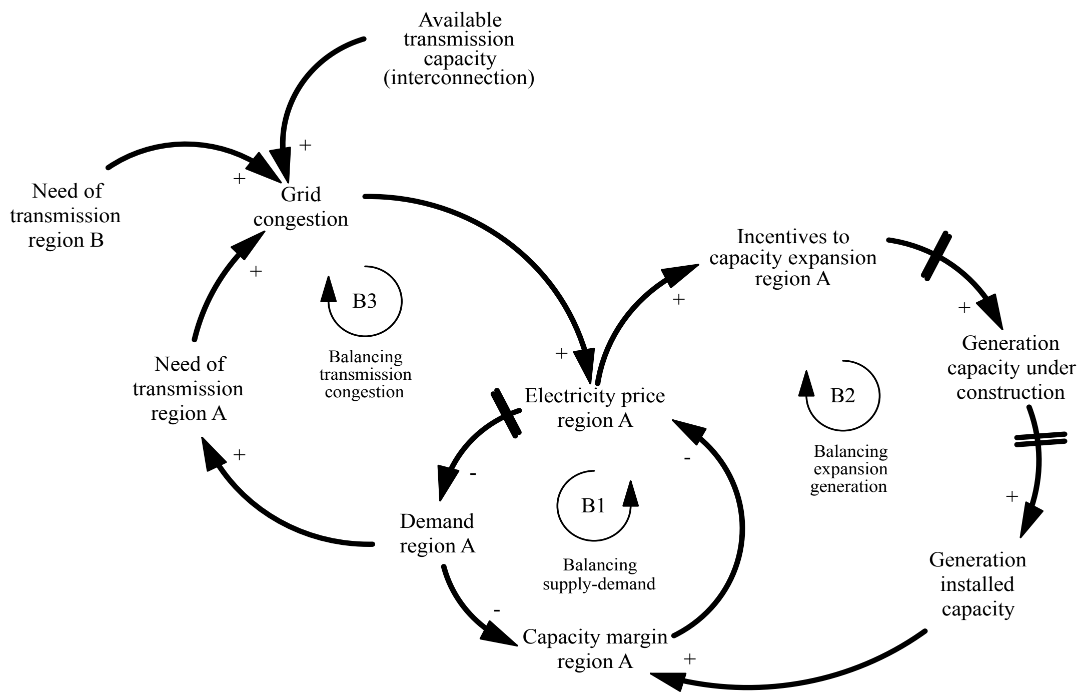


Figure 11. Dynamics of the interconnection between the two Brazilian regions capacity expansion and grid congestion.

3.3.2. Simulation model

SD-based simulation offers the possibility to experiment policy alternatives and strategic decisions, thus facilitating the analysis of the energy system structure. Knowledge about the dynamic behaviour of a complex system through stocks that can be controlled by associated inflows and outflows, plays a key role in policy analysis in the long-term (Qudrat-Ullah, 2016). To evaluate the effect of a given policy on the wind power industry, this research proposes a stock-and-flow diagram, and the corresponding simulation scenario, for understanding the core dynamics of how the energy system evolves over time. Figure 12 displays a model structure that shows the coupling between capacity under construction and installed transmission capacity. Demand, supply curves and interconnector capacity are components of the developed model.

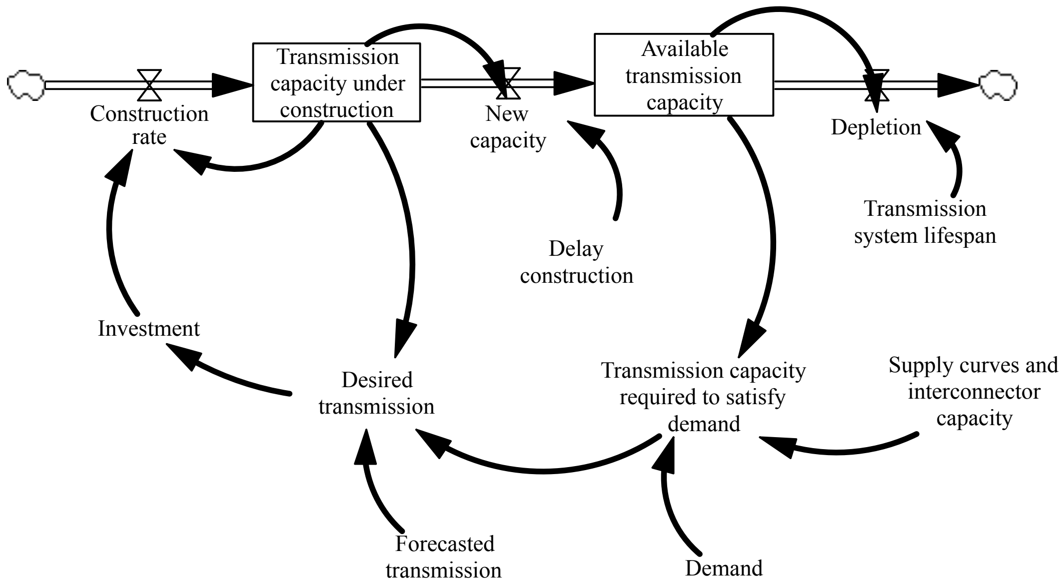


Figure 12. Model structure of the forecasted transmission, supply curves and demand.

This model helps to assess the long-term effect of policy implementation by considering the following factors (i) transmission in place, (ii) demand, and (iii) production capacity. The construction of transmission infrastructures was calculated by taking into account investments in new transmission lines considering the net present values (Ochoa and van Ackere, 2015), and the desired transmission capacity. The desired transmission capacity (DTC) is calculated as a function of capacity under construction (CUC), forecasted transmission (FT) through auctions and deficit of transmission capacity required to satisfy demand (DD), as shown in Equation (9).

$$DTC = FT - CUC + DD \qquad (9)$$

To coordinate forecasted transmission (i.e., auctions), the regulator may adopt simple arguments that take into account the average annual demand ($\overline{D}$) and the lead-time (LT) (Herrera et al., 2019). This research uses these elements to determine the level of new transmission capacity to be auctioned, through a function of classical production scheduling, which represents two situations: unsynchronised expansion policy in Equation 10 and synchronised expansion policy in Equation 11.

$$\bar{D} * LT + Z * S_d * \sqrt{LT} \qquad (10)$$

$$\bar{D} * LT + Z * \sqrt{LT * S_d{}^2 + \bar{D}^2 * S_{LT}{}^2} \qquad (11)$$

where,

Z : Number of standard deviations corresponding to the compliance level probability
S_d: Standard deviation of annual demand
S_{LT}: Standard deviation of lead-time

The regional integration scheme is defined by the reserve margin (MR_i), resulting from the division of wind generation capacity (WGC_i) and the electricity demand (D_i) considering the following conditions based on the integration model by Redondo et al. (2018):

- The reserve margin for the Northeast with surplus ($MRr_i > 1$), while the North has a capacity deficit ($MRr_k < 1$). Also, a lower price in the Northeast and a higher price in the North ($P_i < P_k$). In this case, the sum of the demands of each region is considered ($D_i + D_k$).
- The reserve margin for the Northeast with deficit ($MRr_i < 1$), while the North has a capacity surplus ($MRr_k > 1$). Also, a higher price in the Northeast and a lower price in the North ($P_i > P_k$).
- All other cases, that is, situations in which electricity transfer among regions is not needed.

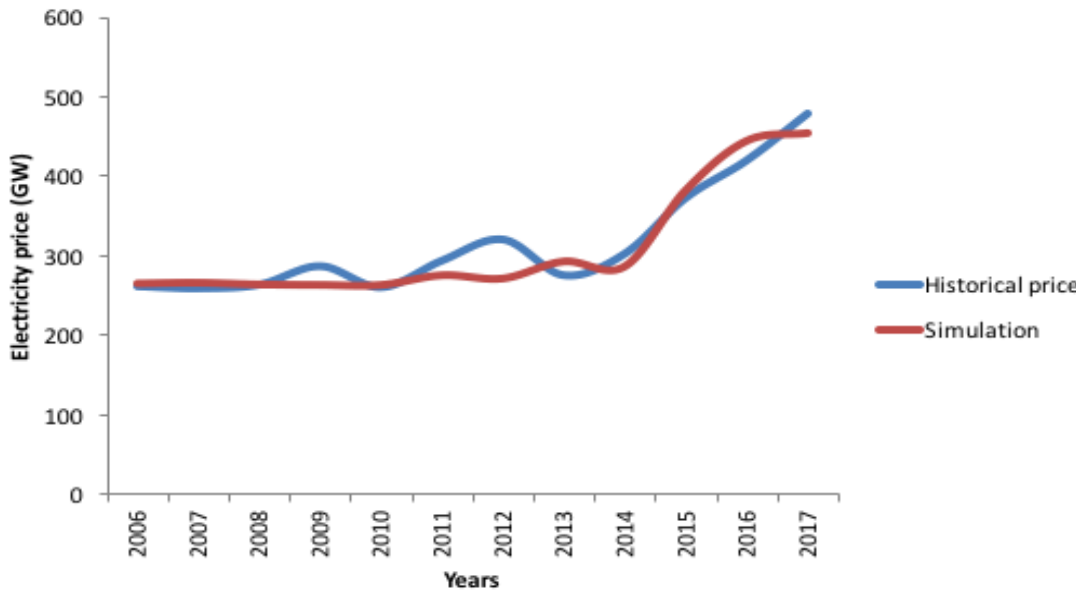
To calculate the dispatch between regions, a transmission capacity constraint to the model proposed by Redondo et al. (2018) is added. This constraint is modelled as a function of the difference between the Northeast's price (P_i) and North's price (P_k), divided by the lowest price among them and multiplied by the electricity demand, as illustrated in Equation (12).

$$MR_i = \begin{cases} \dfrac{WGC_i}{(D_i + D_k) * \left(\dfrac{P_k - P_i}{Min(P_i, P_k)}\right)}, & If\, MRr_i > 1, MRr_k < 1, P_i < P_k \\ \quad \dots \\ \dfrac{WGC_i + Exp_j}{D_i * \left(\dfrac{P_i - P_k}{Min(P_i, P_k)}\right)}, & If\ MRr_i < 1, MRr_j > 1, P_i > P_k \\ \quad \dots \\ \dfrac{WGC_i}{D_i}, & All\ other\ cases \end{cases} \quad (12)$$

3.3.3. Model validation

A structural and behavioural validation procedures was applied to the simulation model, according to tests suggested in the SD literature (Barlas, 1996; Oliva, 2003; Qudrat-Ullah and Seong, 2010). The data used in the validation model to the supply curves and electricity prices were obtained from the Brazilian Agency for Electric Energy (ANEEL, 2017a) and the Brazilian Operator for Electricity System (ONS, 2018). Figure 13 presents results of the validation process for the electricity price for each region. The historical fit of simulation model was evaluated using the Theil inequality statistics and the correlation coefficient, as presented in Table 4. These exhibit a good fit between historical data and obtained data by simulation.

(a) Electricity prices of the North region



(b) Electricity prices of the Northeast region

Figure 13. Results of behaviour reproduction test for electricity prices.

Table 4. Error analysis and correlation of the model

Variable	U^m	U^S	U^C	R^2
Electricity prices of the Northern	0.05	0.009	0.93	0.95
Electricity prices of the Northeast	0.05	0.03	0.90	0.97

3.3.4. Simulation scenarios

The model enables to build four scenarios that incorporate the decision rules previously mentioned, taking into account the generation and transmission expansion in both regions and its effects on the electricity market, namely:

Business as Usual (BaU): this scenario corresponds to the current electricity market situation. The North-Northeast interconnection capacity is limited because of transmission-construction delays. Also, the scenario assumes a capacity expansion in the Northeast region, while the North's generation capacity remains unchanged. In this case, both electricity prices do not converge, namely electricity market would be affected by the insufficient transmission capacity.

North's generation capacity expansion (NTCE): in this scenario, the generation capacity in the North is increased, while the Northeast's generation capacity remains unchanged. The interconnection capacity is expanded through the implementation of a synchronised expansion policy, which considers the lead-time in transmission construction. This could be the case if Brazil adopts a stronger energy policy based on hydroelectricity generation plants (e.g. small hydropower) in this region.

North's generation capacity expansion and transmission limited (NTCE-TL): in this scenario, **al**though the generation capacity in the North is expanded, the transmission capacity is limited between regions. Also, the installed capacity of wind power in the Northeast remains unchanged. As this scenario assumes delivery time certainty for the construction of transmission lines, it might happen that congestion and electricity prices do not converge.

Northeast's generation capacity expansion (NECE): conversely to the NTCE scenario, in the NECE scenario the electricity flows from the low-price region to the high-price region until both regions meet their target needs. This situation occurs only if Brazil implements a synchronised energy policy to expand its transmission grid where low-price electricity is trapped. In this case, the interconnection is expanded based on uncertainties in both lead-time and future demand.

3.4. Simulation results: wind-industry policy alternatives

This section discusses simulation results for each scenario from two perspectives: the expansion of transmission and generation capacities analysed in Section 3.4.1., and the behaviour of electricity price of the North-Northeast interconnection reported in Section 3.4.2.

3.4.1. Interconnection capacity vs. generation capacity expansion

The simulation results for the BaU scenario are shown in Figure 14. The installed capacity of wind power significantly differs from the transmission capacity. Given the limited interconnection capacity caused by delays in grid construction, it will affect the electricity flow from Northeast to other regions (Lopes and Borges, 2015; Miranda et al., 2017; Schmidt et al., 2016a). Thus, in the long term, the Northeast region will have trapped wind energy.

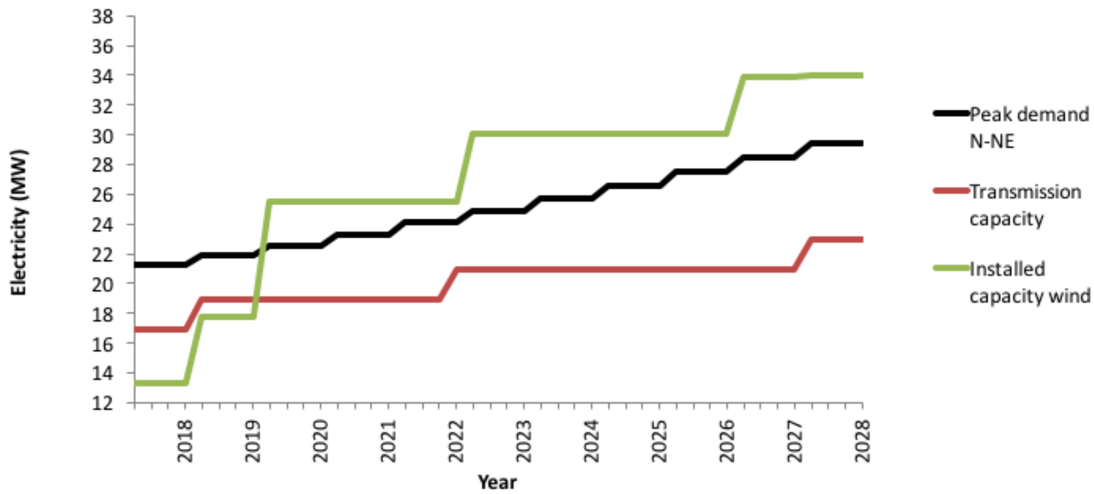


Figure 14. Business as Usual case.

Despite the expansion of wind power in the Northeast region covers the peak demand (see Figure 14), the transmission congestion among regions affects governmental resources. In recent years, the government had to pay around $150 millions to the contracted wind-power companies that completed projects, but had no access to sell the energy (Spatuzza, 2014). Bayer (2018) estimated that, by the end of 2013, over 30% wind projects were not connected because of delays in the grid implementation. In this context, the amount of wind power awaiting connection to the grid could continue to grow, thus affecting the wind power expansion plan in the long term.

The NTCE scenario analyses the deployment of small hydropower plants in the North to evaluate the effect of a synchronised expansion policy for transmission auctions, as presented in Figure 15. This case leads to an increased surplus, inducing the full exploitation of the hydro source in the North region. However, the simulation shows that climate conditions directly affect the hydro generation and, consequently, the electricity production (de Queiroz et al., 2016; Von Sperling, 2012). So, despite the transmission expansion and hydro generation deployment in the North region, the results show that the persistent conditions of insufficient transmission capacity have a significant impact on the peak demand in both North and Northeast regions. As a result, greater transmission capacity would be high costly, more than the cost of hydro generation.

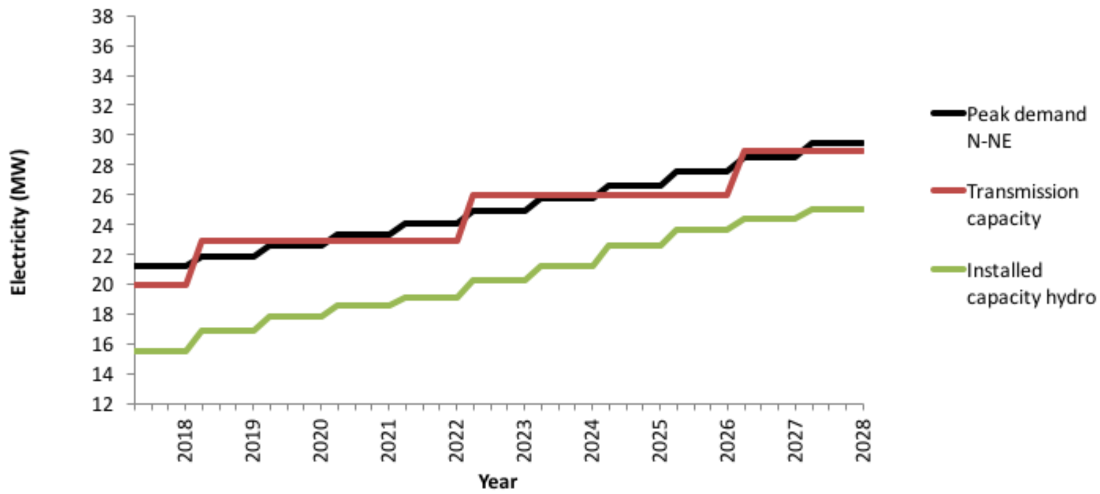


Figure 15. North's generation capacity expansion (NTCE case).

The national interconnection grid allows the operation of the hydro-thermos power system to compensate losses in certain regions, and increase production in others (De Lucena et al., 2009). However, as illustrated in Figure 15, the results show that in some periods (e.g., 2024 to 2026) the insufficient transmission capacity could affect the supply of energy. Similarly, as illustrated in Figure 16, when the transmission capacity is not expanded, but a generation expansion is planned, a trapped energy issue could occur from 2018 to 2021. These results are similar to those obtained by De Jong et al. (2017) and Miranda et al. (2017). This is because the transmission line is congested or expansion is insufficient.

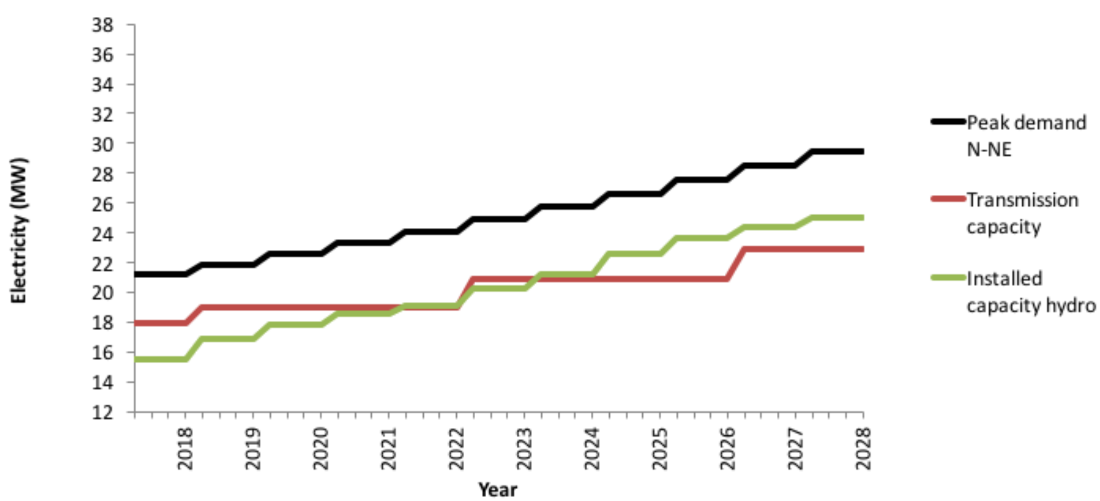


Figure 16. North's generation capacity expansion and transmission limited (NTCE-TL case).

Looking at the results of the NECE scenario in Figure 17, the wind power expansion from Northeast is better synchronised with transmission capacity. This synchronised policy consists in a combined decision to increase both the transmission and wind power capacity over the next 10 years (see, Equation 11 and 12). The combination of a function of classical production scheduling within the simulation model helps to understand the energy policy evolution in the long term. Expanding wind power and transmission through a synchronised energy policy could help to diversify energy supply and stimulate wind industry (Geller et al., 2004; Herrera et al., 2018; Lund, 2009).

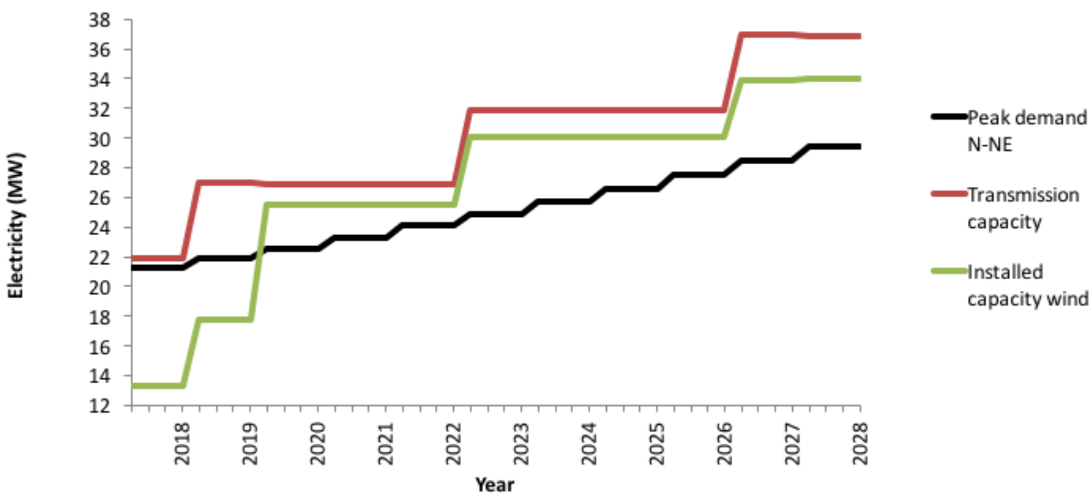


Figure 17. Northeast's generation capacity expansion (NECE case).

Considering the large potential of wind power in the Northeast of Brazil, it is possible that different wind farms within the same region present complementary, thereby mitigating the risk of power shortage (Lopes and Borges, 2015). However, the trapped energy could affect energy supply in other regions. In the NECE scenario, the deployment of transmission capacity synchronised with wind industry allows mitigating trapped energy, as well as transmission congestion issues.

3.4.2. Electricity market scenarios

To assess the impact of capacity expansion on the interconnected electricity market, this research considers two cases: first, insufficient transmission capacity in the BaU and NTCE-TL scenarios and, second, sufficient transmission capacity among interconnected regions in NTCE and NECE scenarios.

Insufficient transmission capacity

When interconnection capacity between the two regions is insufficient, electricity prices increase exponentially at a very high rate. As a consequence, the generation capacity margin will drop generating a high price associated with insufficient transmission capacity between the interconnected regions. Although the higher electricity price is an incentive for the introduction of new lower-cost sources of supply, the transmission should be used to enlarge the sources of supply available to meet the demand for electricity (Lesieutre and Eto, 2004).

Based on the emerging simulation results, the BaU scenario exhibits a higher price in both regions, that converges by 2021 and 2023. In this case, the interconnection capacity is too small and greatly affects the North region price. While in the NTCE-TL scenario, despite the difference between electricity prices of both regions is less, it only converges by 2020 (see, Figure 18). These results appear logical since the transmission capacity is limited. If there is not enough transmission capacity, the electricity price will rise until new lines become operational. Also, the wind industry could be worse off in the medium-term, since operators will not be able to provide electricity to other regions once transmission capacity is available. This will lead to lower investments in future capacity of wind power in the Northeast, resulting in slightly higher prices for consumers in the long-term, that is more notable in Northeast (BaU and NTCE-TL scenarios).

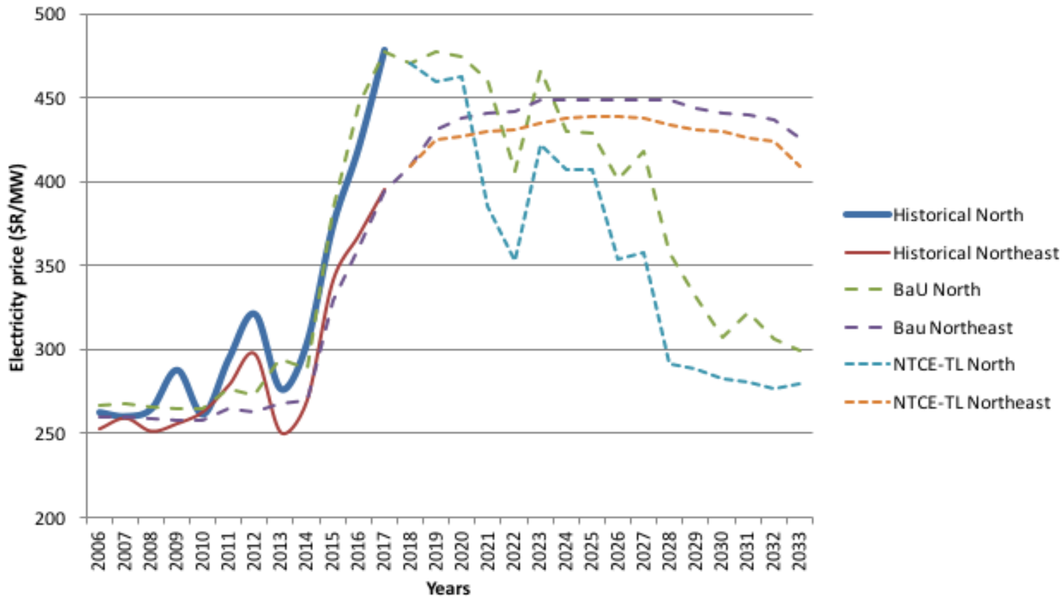


Figure 18. Electricity prices of the North-Northeast interconnection for BaU and NTCE-TL cases.

Sufficient transmission capacity

As shown in Figure 19, for interconnected systems in the NTCE scenario, the hydro expansion in the North region could be more expensive than the wind power expansion in the Northeast. This situation will affect Northeast consumers' behaviour, who will have access to costly electricity from the North. An increase in transmission capacity under asymmetric market design could magnify distortions (Cepeda and Finon, 2011). Conversely, in the NECE scenario customers in the North region have access to competitive offers from producers located in the Northeast region and, consequently, the market price decreases. The reason is that the cost of interconnection capacity is compensated by the wind power complementarities causing a significant price drop compared to the NTCE scenario. In this way, the wind power will help hydro reservoirs in the long run, as their seasonal variability and the impact of droughts diminish (De Jong et al., 2013; Lopes and Borges, 2015; Silva et al., 2016).

An interesting fact in the NTCE scenario is that consumers in both regions gain when the electricity prices converge. In addition, although wind industry's profit decreases as a result of the lower prices, this may not be a concern if one takes into account that their generation investment may still be recovered in comparison with congestion and disconnection costs in long run. If the wind industry pays for the line, the local price will be higher, and this could justify the new investments in generation capacity.

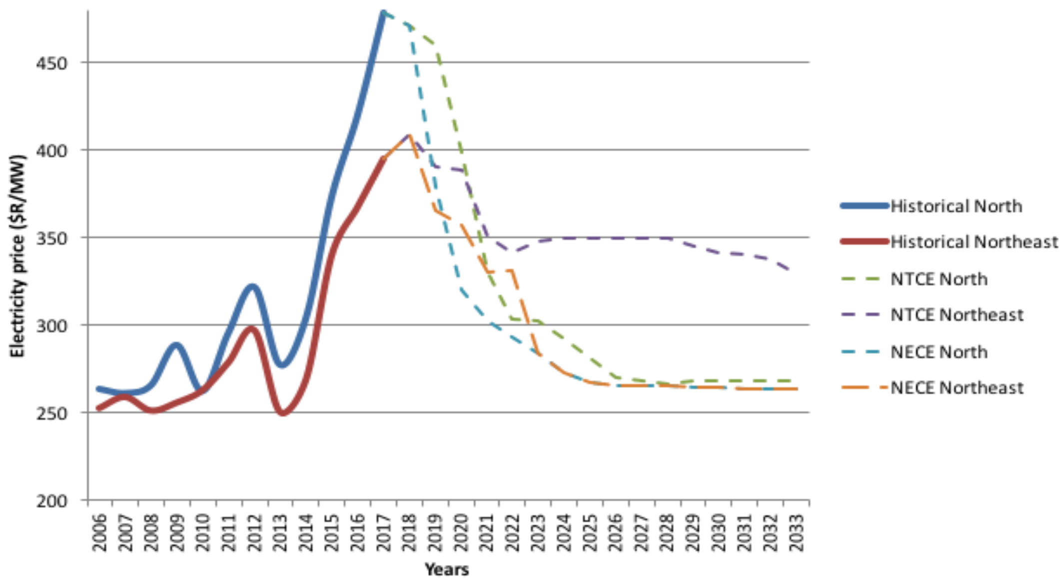


Figure 19. Electricity prices of the North-Northeast interconnection for NTCE and NECE cases.

If transmission capacity is added at infrequent intervals, this could reveal a lack of transmission capacity. Then, the energy policy should be synchronised to regulate the delays in capacity expansion, thus mitigating the difference between prices (i.e., convergence), as illustrated before.

3.5. Conclusions and policy implications

In comparison to other research studies evaluating the large-scale deployment of wind power in Brazil (Aquila et al., 2017a; Brannstrom et al., 2017; Juárez et al., 2014; A. O. Pereira et al., 2013), this paper proposed policy alternatives, including transmission capacity expansion in two interconnected regions, through a simulation model. The results of policy alternatives highlight the importance of understanding the dynamics of interconnection capacity among regions and their effects on the electricity market. Thus, this article offers new insights on the synchronisation of energy policies for the wind industry expansion, with implications to electricity prices and transmission capacity in interconnected regions.

First, although several papers analyse the renewable source deployment and its market coupling (Ochoa and van Ackere, 2015; Redondo et al., 2018), this paper suggests that the synchronisation of energy policies for the wind industry in Brazil contributes to mitigating delays in expansion and enhancing coordination between generation and interconnection capacity, stimulating future investments in wind power. This article emphasises the synchronisation issue through a formal model, which contributes to better understanding causes generating delays in the construction capacity of the energy system.

Second, considering the impacts of insufficient transmission capacity on the wind industry (Miranda et al., 2017), the results from simulations of the Brazil case show that, to coordinate transmission auctions, the federal government should adopt a synchronised policy that takes into account the average annual demand and the lead-time. These simple insights help investors and policy-makers in their decision-making process in long-run.

Although this article explored cases with transmission and generation capacity expansion in interconnected regions, which may lead to different political decisions, the emergent results are a first step towards analysing the interactions between transmission capacity, wind power expansion and synchronised energy policies. Future work could include modelling of the synchronised energy policy that blends other intermittent renewable sources of electricity (e.g. solar, hydro and wind power).

Chapter 4: How to support energy policy coordination of wind power supply chain? Collaborative governance through a DPM approach ♣

Abstract

As the use of renewable energy is growing worldwide, the wind industry is being endorsed as a promising source for clean energy supply. In this context, the strategic management of wind power supply chains is fundamental to pursue a steady expansion of renewable energy. However, the fragmentation between energy policy design and implementation has been considered as a major cause threatening the effectiveness in managing the supply chain. An unsynchronised and uncoordinated decision-making process that involves public and private institutions, affecting the current growth of the wind industry, predominantly causes this problem. This chapter proposes the adoption of a dynamic performance management approach to enhance a collaborative governance perspective aimed at supporting the strategic coordination in designing and implementing wind energy policies in Brazil. Using lessons learned from simulating the supply chain, key performance drivers for mitigating inconsistencies in decision-making processes are identified and discussed.

Keywords: policy coordination; wind power supply chain; collaborative governance; dynamic performance management; Brazil

4.1. Introduction

In the last few years, the prevailing literature on energy management and public governance has increasingly highlighted the importance of supporting energy policy

---

♣ Results of this chapter have been included i) paper of the forthcoming journal: The Electricity Journal, Elsevier, https://doi.org/10.1016/j.tej.2019.106636, ii) a chapter of the forthcoming book "Enabling collaborative governance through systems modelling methods", edited by Bianchi et al. (Springer, 2019), iii) a paper presented in the XV Latin-American Conference of System Dynamics held in Santiago (Chile) in 2017.

design and implementation through a robust strategic coordination among stakeholders (Jimenez et al., 2016; Matos and Silvestre, 2013; Wee et al., 2012; Wüstemeyer et al., 2015). However, similarly to other domains where public and private institutions are called to jointly operate for providing services to communities, the coexistence of multiple stakeholders interacting in a wide governance setting has often increased its complexity and fragmentation, thus leading to poor performance levels (Bouckaert et al., 2010; Bouckaert and Halligan, 2008). A higher complexity and fragmented governance are likely to facilitate the outbreak of "wicked problems" in the decision-making processes of these stakeholders. As argued by Head and Alford (2015), "wicked problems" are meant as public policy and management-related issues hard to define and manage due to the high complexity of the environment which they affect, often leading to counterintuitive implications when actions are taken to resolve them. For instance, in energy policy-making, conflicts of interest among stakeholders may arise generating a lack of strategic coordination and delays between the design and implementation of policies affecting the overall performance of the energy supply chain.

The energy supply chain performance is driven by the actors' operational capacity, which influence the response time of demand changes (Herrera et al., 2018). Although the wind-power industry has recently expanded worldwide, its logistic operations are associated with the delayed implementation of wind farms caused by the lead-times along the supply chain. In this perspective, the concerns related to supply-chain operations generate a negative effect on the security of energy supply, i.e. high freight costs and operational bottlenecks (Nogueira De Oliveira et al., 2016; Prostean et al., 2014).

With the intent to overcome the above shortcomings (i.e., fragmentation in energy policy design and implementation, delays in energy supply operations, poor performances, lack of policy coordination), this chapter aims to explore how to support decision-makers to foster policy coordination in renewable energy supply chains. To this end, this chapter proposes the adoption of a methodological approach based on the combination between "collaborative governance" and "dynamic performance management". On the one side, this methodological choice is oriented to enhance the collaboration among the multiple stakeholders intervening in the decision-making processes throughout the overall renewable energy supply-chain (Ansell and Gash, 2008; Wee et al., 2012). Aiming to reduce policy design fragmentation and coordinate efforts in facing wicked problems, collaborative governance brings public and private stakeholders together in collective forums with public agencies to engage in consensus-oriented decision-making. On the other side, such collaboration may find an additional support by virtue of performance management mechanisms designed through a simulation approach with System Dynamics (SD) methodology (Bianchi, 2016; Bianchi et al., 2017; Cosenz, 2017; Cosenz and Noto, 2016; Torres et al., 2017). Under the sobriquet of Dynamic Performance Management (DPM), this approach uses a systemic perspective to identify key performance drivers fostering energy policy coordination in the wind-power supply chain, as well as simulation-based scenarios supporting strategic learning processes of involved stakeholders.

Such a combined approach has been applied to the Brazilian electricity market which provides a fertile ground for testing its effectiveness due to its great potential in wind power generation. In the last decade, the growth in population and industry has led to an increase in the energy consumption in Latin America. Brazil has become the greater consumer and producer of hydroelectricity with a steady economic growth (Solarin and Ozturk, 2015). However, the production of hydroelectricity greatly depends on climatic conditions, which may impact on the security of energy supply (De Lucena et al., 2009; de Queiroz et al., 2016; Herrera et al., 2017a; Von Sperling, 2012). The generation of wind power can be part of the solution to this problem, since it is a fitting complement for the traditional hydroelectricity generation. Several studies show a strong complementarity between the wind power and hydroelectricity with regard to the Brazilian seasonal regimen (Schmidt et al., 2016a; Silva et al., 2016). Although wind power can contribute in solving the problem of growing power consumption, there exists an insufficient electricity transmission capacity in Brazil. The lack of transmission capacity caused by delays in the transmission lines construction can generate problems of transmission congestion among the regions (Ochoa et al., 2013) and, as such, it has been a concern for wind power expansion, especially in the Northeast region of Brazil (Herrera et al., 2017b). De Jong et al. (2016) have shown the need for constructing new transmission lines depending on the current growth of renewable energy in Brazilian regions, such as North and Northeast. This situation generates an asynchrony effect produced by the uncoordinated energy policies related to electricity generation and transmission that affect the overall energy supply chain. Actually, the Brazilian electricity market has experienced a decoupling of policies for enhancing wind power transmission-infrastructures, especially in isolated regions. The planning process is particularly complex in the energy sector due to a high market uncertainty. In Brazil, the dependency from hydroelectricity and the vulnerability of renewable resources due to climate variations further increase such a complexity affecting the planning process. As a result, Brazilian wind industry has recently been affected by significant political changes (e.g., the cancellations of wind auctions by December 2016 due to tumbling electricity demand in Brazil, principally in the industrial sector). In this context characterized by high uncertainty and complexity, simulation models are particularly valuable rather than optimization models for long-term decision-making (Dyner and Larsen 2001; Dyner 2000; Sterman 2000). Actually, all the above conditions heavily affect the performance of wind power supply chain, making this case study appropriate for our research purposes.

This chapter is organized as follows: section 4.2 discusses the theoretical background in two perspectives: the asynchronous decision-making effect on the performance of the Brazilian wind-power supply chain, and the strategy development process with SD modelling. Section 4.3 explains the emerging simulation model and its connections with DPM approach. The results of uncoordinated and coordinated policies in the supply chain are described and analysed according to simulation scenarios, as exposed in Section 4.4. Section 4.5 highlights the scientific contribution in terms of organizational learning and performance management for wind-power supply chain. In the last section, conclusions and proposals for future research are presented.

4.2. Theoretical background

In this section, two complementary perspectives are discussed. The first perspective describes the need for introducing a collaborative governance setting to face uncoordinated policy design/implementation processes within the wind power supply chain, while the second one discusses the use of a DPM approach to support such a collaborative governance and, thus, policy coordination among the key actors interacting throughout the supply chain.

4.2.1. Challenges of wind power policy coordination: the need for collaborative governance

The stakeholders structure in the wind power supply chain is divided into two parts, upstream and downstream (Yuan et al., 2014). The upstream supply chain comprehends equipment manufacturing and wind farm development. Grid companies and customers compose the downstream supply chain of wind power. The wind-power supply chain can be intended as network of multiple actors with different objectives and complex systemic relations, which is likely to produce conflicts of interest that affect the performance along the supply chain. On this regard, relations among stakeholders have been one of the important themes of analysis in the energy supply chain management literature (de Gooyert et al., 2017; Matos and Silvestre, 2013). In the electricity market system, the interaction among individual decisions is determined by the degree of synchronisation and coordination among policies. Thus, political decisions affecting the wind power supply chain produce performance dynamics that significantly and systematically diverge from expected behaviours.

The lack of synchronisation and coordination among stakeholders is a major challenge and an opportunity for wind power supply chain. A gradual increment in their collaboration allows decision-makers to improve the performance through collaboration-planning tools in the supply chain (Rubiano and Crespo, 2003), while the synchronisation among stakeholders allows them to overcome those problems associated with the delays in the energy supply (Herrera et al., 2018). Wee et al. (2012) propose that the barriers in the supply chain could be overcome if governments, researchers and stakeholders work together to improve the renewable energy development.

In addition, the activities executed throughout the supply chain are determined by decision-making in terms of resource allocation associated with expected results. Decision-making includes the assimilation of policies and, more internally, an analysis focused on the supply chain requirements, such as the identification of required competencies and capabilities at operational level. Given that decision-making considers the resources to be allocated, governments are called to design and implement policies aimed to foster the accumulation and depletion of these resources. A dynamic analysis of energy supply chains may help to better understand the coordination between policy and expected results of electricity market, as well as to manage the system of strategic resources supporting the wind power supply chain (Bianchi 2016; Dyner and Larsen 2001).

Despite a significant increase of wind farms in Brazil, the transmission infrastructure is not sufficiently prepared to support the expansion of wind power. The delays in the delivery of new transmission lines postpone the operation of wind farm generation (Bayer, 2018; De Melo et al., 2016a; Miranda et al., 2017). The value creation along wind-power supply chain presents different levels related to the policy/decision-making of involved stakeholders. For instance, Wüstemeyer et al.

(2015) analysed the added value for the European onshore and offshore wind installations. They found that the more complex logistics and construction processes onshore wind installation has a higher level of added value nearer to the customer. Also, an analysis proposed by Yuan et al. (2014) shows the importance of transmission companies to integrate wind power into the network, which allows added value to the customer along the supply chain.

In Brazil, the time-delays in the construction of electricity networks have been a barrier to the technological expansion for the wind industry that has affected value creation (Bayer, 2018; Hunt. et al., 2018; Matos and Silvestre, 2013). This situation is generated by the asynchronous and uncoordinated implementation of energy policies among the multiple involved actors, thus leading to "wicked problems" in the security of energy supply. Such a dynamic can be described in terms of interaction between a micro level, i.e., business-level learning (e.g., wind farms) and a macro level, i.e., societal learning (e.g., governments and public agencies). In this context, the potential for a "collaborative governance" approach – i.e., the process by which multiple actors, including public and private institutions, come together and evolve, implement, and oversee rules, providing long-term solutions to pervasive challenges – depends on the pace and direction of such learning processes (Purdy, 2012; Zadek, 2006). As argued by Ansell and Gash (2008), collaborative governance has emerged as a consensus-oriented response to the failures of downstream implementation and to the high cost and politicization of regulation. This mode of governance has developed as an alternative paradigm for managing power imbalances among involved actors and strategies that can use to participate more fully in decision-making processes (Purdy, 2012).

The case of Brazil illustrates an early adoption of collaborative governance practices (Laquimia and Eweje, 2014). In the run-up to the 2002 elections, the candidate Luiz Inácio Lula da Silva (Workers Party) proposed the adoption of collaborative governance initiatives aiming to pacify a nervous domestic business community as well as to calm international financial markets (Peña, 2014). After his election, Lula's establishment of a high-level Commission involving many key business and civil society leaders to advise him on economic policy revealed his commitment to an approach that drew business, labour, and civil society into the decision-making process of government. A core part of the approach adopted implied the use of a corporate responsibility discourse to evoke a sense of both the need and the legitimacy of the wider engagement of business in the development of Brazilian society (Zadek, 2008), where in the past the business community had effectively become complicit in supporting the nation's earlier undemocratic experience. As reported by Zadek (2008), in advancing this collaborative vision, Lula made much of engaging with and through Brazil's business networks, such as the example of Institute Ethos emerged as an increasingly important actor in spearheading increasingly the international, corporate responsibility movement. Working with and through such networks, both Lula's successful presidential campaign and, subsequently, his administration has sought to secure political and economic support for his combining of a conservative macro-economic stabilization program (e.g., vis-à-vis monetary and fiscal policy), an aggressive approach to international political economy (e.g., trade negotiations), and a costly social program (e.g., the Zero Hunger program).

Thus, based on these antecedents, the use of collaborative governance in the formulation/implementation of energy policies aims at facilitating both shared understandings and social interactions between policy-making participants around the formal conceptualization of action plans oriented to solve emergent wicked problems. Together with a flexible design perspective, social interaction enables the integration of strategic ideas from multiple actors, such as wind farms, business partners and infrastructure managers, (national, regional) governments, and public agencies. However, the possibility to effectively convey the key actors around this governance setting requires the adoption of performance management frameworks able to systemically address the multiple phases along the supply chain, and associated responsibilities. To this end, the use of DPM may provide a consistent methodological support in engaging and facilitating energy supply chain stakeholders.

4.2.2. A DPM approach to support collaborative governance and policy coordination

Collaborating in governance settings is a complex task due to the potential conflicts in terms of individual vs. collective goals, resource negotiation and allocation, and strategic visions among involved stakeholders. Such, collaborative governance must be supported by a shared methodological approach to manage supply chain performance. In fact, with the intent to promote a shared vision of the overall value creation process, this approach requires to embody not only output measures (i.e., short-term results generated by each involved institution), but also outcome measures (i.e., long-term results generated by the aggregated contribution of involved institutions). In doing so, these performance measures may facilitate governance participants in detecting bottlenecks and weak links along the energy supply chain and, consequently, in fostering a shared understanding of those areas (e.g., institutions) requiring strategic interventions in terms of resource allocation and coordination mechanisms. Such a shared understanding may help in settling conflicts of interest among stakeholders.

Defining a system of outcome and output measures into collaborative governance settings is nowadays a key challenge to take on a broader perspective of public performance management results, as well as to ensure increasing benefits to the territorial area in terms of quality of life and security of energy supply (Brannstrom et al., 2017; Juárez et al., 2014; Pollitt and Bouckaert, 2004). The importance to measure outcomes in the public sector relies on the fact that, unlike the private sector, there is no bottom line against which performance can be measured. In fact, while assessing short-term results of a single institution is generally considered feasible (output), problems show up when to measure the long-term impact produced by the aggregated contribution – in terms of output – of many public/private organizations (e.g., renewable energy supply chain) on the local area in which they operate (outcome). As Bianchi et al. (2017) assert "*the use of a short-term perspective and a sectorial approach in the formulation and implementation of strategies lead to a static view of the system and to a lack of coordination in policy-making between different public agencies, non-profit and private stakeholders. This approach is unlikely to help policy makers to identify sustainable actions, on complex issues which span several jurisdictions, both in terms of level (e.g. national, regional, local) and policy domain (e.g. policing, welfare, education, justice)*". Indeed, the complex interaction between these actors, an idiosyncratic perspective of public performance management, and the lack of a 'robust' coordination, generate critical methodological issues to design and model outcome-based performance measurement systems.

From a collaborative governance perspective, with the intent to overcome the above constraints to outcome measurement design, a synergic coordination between different services and organizations (internal and external coordination) and a methodological approach to performance management are required. A dynamic and outcome-based performance management approach is particularly valuable for this purpose, since time disjunctions between actions and results, and non-linear feedback relationships affecting outcomes, limit decision makers to understand the structure and behaviour of the system in which their polices will be implemented (Bianchi et al., 2017). This approach supports them to manage possible risks related to unintended effects of policies which, although they may look consistent from a static and sectorial perspective, may fail in the long term due to a lack of coordination, or lack of flexibility (Bianchi et al., 2017; Ghaffarzadegan et al., 2011).

This approach is likely to support policy-makers in better coordinating performance measurement reporting and policy design. Such coordination helps policy-makers and public managers to trace both causes and drivers that have led to a given performance level over time. It also contributes in enhancing the diagnosis process to put in place corrective actions and strategies oriented to fill the gap between the actual and the target performance.

Such an approach requires the identification of both end-results (output and outcome) and their respective drivers. To affect such drivers, involved public/private institutions must build up, preserve, and deploy a proper endowment of strategic resources that are linked each other. This also implies that decisions made by different decision-makers upon interdependent strategic resources should be coordinated each other according to a systemic view. Particularly, each strategic resource should provide the basis to sustain and foster others in the same system. The feedback loops underlying the dynamics of the different strategic resources imply that the flows affecting such resources are measured over a time lag (Bianchi, 2016). Thus, understanding how delays influence strategic resources and achieved results becomes a key issue to manage performance in dynamic complex public sectors, and particularly renewable energy supply chain.

Figure 20 illustrates how the end-results provide an endogenous source inside a public organization for the accumulation and depletion processes that affect those strategic resources that cannot be purchased from the market. These are the resources generated by management routines (e.g., image & reputation, organizational climate, employees' burnout), equity and liquidity (Bianchi, 2016). End-results are modelled as in- or out-flows, which over a given time span change the stocks of the corresponding strategic resources, as the result of actions or policies implemented by decision makers.

Performance drivers are associated to critical success factors in the referring public sector. They can be measured in relative terms – as a ratio between the organizational performance perceived by users and a benchmark – or a target value. Such a denominator must be gauged in relation to perceived past performances or users' expectations.

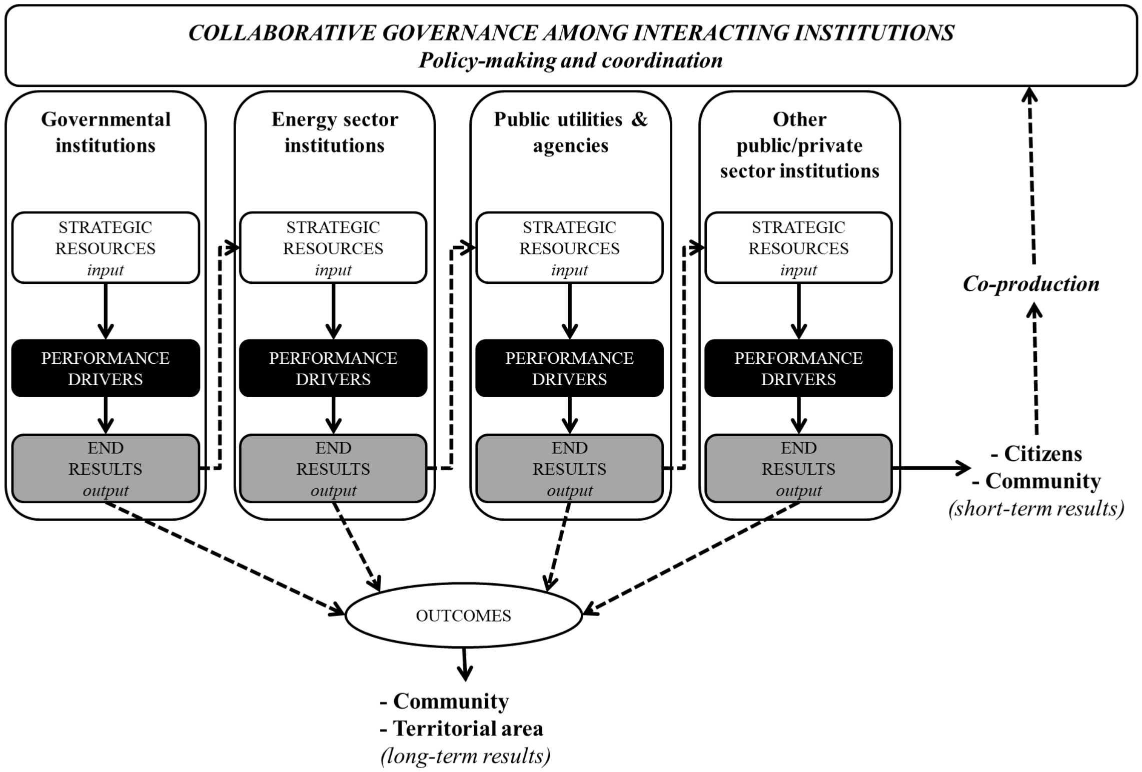


Figure 20. A Collaborative Governance approach supported by an Outcome-based Dynamic Performance Management framework (adapted from Bianchi 2016, p. 73).

Following this approach, it is possible outlining the policy options formulated to affect the strategic resources that will influence performance drivers, and – through them – the end results (i.e., outputs), which in turn will feedback on the strategic resources of the institution located downward the supply chain (i.e., inputs). As such, this performance management perspective does not limit its relevant boundaries to a single institution. Rather, a single player acting on a much wider system aims to design performance measures that can assess the long-term effect and broader impact of implemented policies. A system-wide view of performance eventually requires to be combined with an internal view, by each organization, in order to foster a strategic dialogue and coordination among the key players oriented to improve their aggregated contribution to the overall system.

Eventually, the citizens and communities – who receive the outputs produced by the supply chain actors – may also participate in policy-making processes through *co-*

production actions aimed to improve the offered products/services (Bianchi et al. 2017).

4.3. Energy supply chain modelling

4.3.1. SD modelling for the wind power supply chain

As argued above, overcoming unsynchronised and uncoordinated energy policies requires the adoption of a suitable methodological support to supply chain modelling. Actually, supply chain modelling can provide a deeper analysis of relevant variables within the system, and how they interact (Campuzano, 2011). SD-based simulation provides the possibility to understand the integration of strategic ideas from multiple actors into the model building process (Cosenz and Noto, 2017). It can also be used to experiment alternative policies and decision rules, which enables the analysis by means of performances drivers within the energy supply chain structure.

To analyse decision-making into the wind-power supply chain, this research developed a stock-and-flow diagram, as illustrated in Figure 21. The stock-and-flow diagram aims to replicate the dynamic behaviour of the wind-power supply chain in Brazil. This diagram shows the coupling between suppliers, the wind industry and wind farm developers. It has also related the supply chain with the electricity market dynamics, and installed capacity of transmission. The stock-and-flow diagram may support decision-makers to simulate the behaviour of the wind-power supply chain with the purpose of assessing alternative energy policies in Brazil, particularly regarding coordination among stakeholders under current conditions.

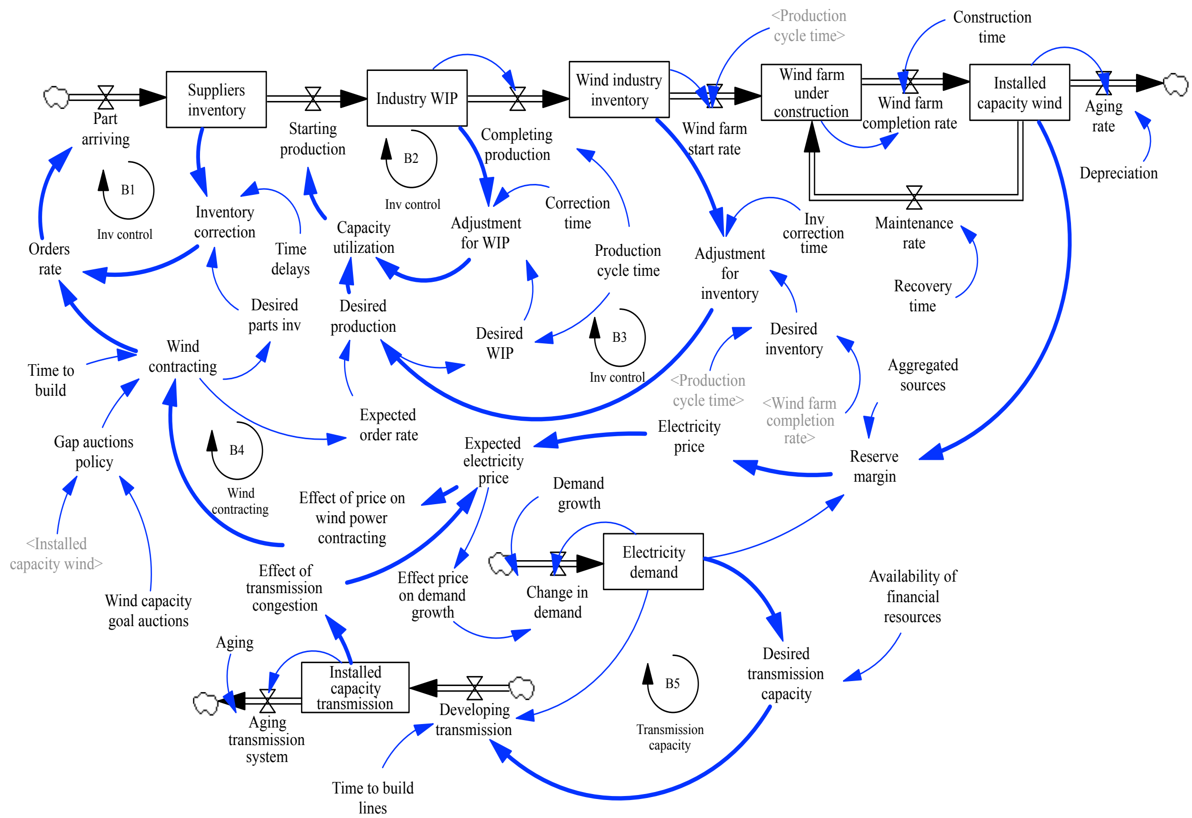


Figure 21. Stock-and-flow diagram of wind power supply chain in Brazil.

The feedback structure shows the decision rules of used inventory by the supply chain to develop installed capacity of wind power. This feedback structure is based on structure diagrams included in earlier works (Dyner 2000; Herrera et al. 2018; Sterman 2000). The main addition in this work is the convergence of supply chain structure with the transmission component. The SD model includes five negative feedbacks (also known as balancing loop). The inventory control loops, B1, B2 and B3, represent the decision structure of inventory management for the supply chain, including work in process (WIP). These loops adjust the production capacity among the *levels of inventory* (LI) of each stakeholder according to their respective *desired levels* (DL) (Sterman, 2000). The *adjustment process for supply line* (APSL) of delayed orders is determined by the driver *adjustment time for inventory* (ATI), as shown in Equation (13).

$$APSL = {}^{(DL - LI)}\!/_{ATI} \qquad (13)$$

The contracting loop (B4) represents the energy policy structure of the wind-power supply chain. This structure depends on both auctions policy and *time to build installed capacity of wind power* (TB).

Given that the auctions-based policy for wind power supply chain is determined by the changes in electricity demand, the electricity price can be affected; therefore, it generates an effect on the installed capacity of wind power (EPWC).

In addition, changes in policies affect the goals of wind power expansion, which causes this discrepancy. In the case of Brazil, the discrepancy is formed by the GAP between the desired capacity of wind power and the current installed capacity. Equation (14) shows the contracting decision rule of wind power.

$$WC = MAX\ (0, EPWC * GAP/TB) \qquad (14)$$

The balancing loop (B5) represents the decision rules that determine the capacity of transmission according to the electricity demand. The building of transmission (BT) was calculated considering the desired transmission capacity (KT), electricity demand (ED) and the time to build lines (TBL), as shown in Equation (15).

$$BT = {}^{(KT - ED)}/_{TBL} \qquad (15)$$

The main assumptions included in the simulation model are the following:

- The simulation time frame is 18 years, from 2017 to 2035.
- Brazilian wind power generation capacity has reached 11.85 GW at the end of 2017 (ANEEL, 2017a).
- The model considers that 31% of currently transmission projects face delays in connection (Bayer, 2018).
- The model takes into account the values of average bids (1.8 GW) on wind power by last ten years (Agencia Nacional de Energía Eléctrica-ANEEL, 2017).

4.3.2. Model validation

The validation process generates confidence to accept or reject the model outcomes (Campuzano, 2011; Oliva, 2003; Qudrat-Ullah and Seong, 2010). Thus, this ensures that the simulation model describes the dynamic behaviour of the system under observation. This section presents the results of the validation process for the Brazilian wind power supply chain. The forecasts used in the validation model of the wind power and electricity demand was based on several sources (ANEEL, 2017a; Ministerio de Minas e Energia, 2007).

The mean squared error (MSE) is a measure of the average squared difference between the estimator and outcomes. An excellent decomposition of MSE is the Theil inequality statistic that provides a measure of the error in the predicted values of simulation through the components of the mean (U^m), variance (U^S), and covariance (U^C). The error decomposition analysis for the variables installed capacity of wind power and electricity demand is presented in Table 5. This error analysis indicates closeness in the mean of actual and simulated values with similar dominant trends. Results show that the error is because of little trend variation, so it is unsystematic. Thus, the fit between the model and historical trend is particularly strong for representing the behaviour of system.

Table 5. Error analysis of the simulation model

Variable	MSE	U^m (%)	U^S (%)	U^C (%)
Installed capacity of wind power	0.004	28	1	71
Electricity demand	0.006	40	12	48

4.3.3. Supporting SD modelling through DPM for the wind supply chain

To understand the performance of wind power supply chain and support collaborative governance in such a context, a DPM framework is adopted. Figure 22 displays the emerging DPM chart focusing on the coordination of policies along the supply chain. The upper section identifies the stakeholders of the wind energy system, as well as the associated policies connected to the common goal of increasing the wind power market share. To identify the end-results of each supply chain stakeholder, a systemic perspective is used. Such a perspective aims at understanding how strategic resources may affect performance drivers and end-results in the supply chain. Particularly, this perspective enables to define a set of measures related to wind power (Cosenz, 2014) in order to evaluate the effects of adopted policies along the supply chain.

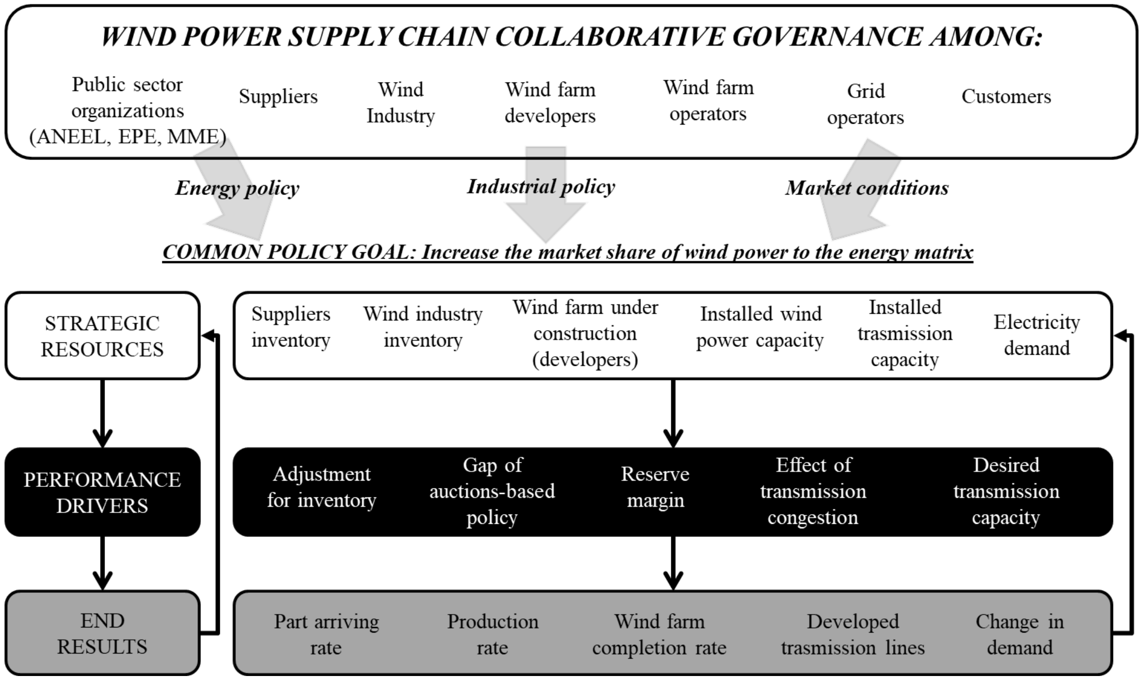


Figure 22. Applying a Collaborative Governance approach supported by an Outcome-based Dynamic Performance Management framework to the wind power supply chain.

This chart identifies the following end-results:

- change in parts and components for the wind industry, variation in production of the wind industry, change in the construction of wind farm and amount of developed transmission lines over time, as results of the energy and industrial policies.
- change in electricity demand growth, as result of the market conditions.

The identification of performance drivers has been based on the significant factors affecting the end-results. In the case of industrial policies, the gap between desired inventory and current inventory influences the change production cycle time for both suppliers and wind industry. Thus, this situation takes time to adjust production capacity that causes delays in the installed wind power capacity. This measure is related to the operational response capacity of the supply chain, which influences the change in production plans.

Regarding the energy policy, the DPM framework recognises two main performance drivers. The first one is related to the energy-policy gap defined as the difference between the desired goal and the current installed capacity of wind power. The second driver is associated with the availability of financial resources for the construction of transmission capacity, which is influenced by the electricity demand. These measures support policy-makers and managers in planning how to allocate the strategic resources.

Similarly, the DPM framework identifies two performance drivers associated with the market conditions, i.e., the reserve margin and the effect of transmission congestion. The first one is calculated as the difference between the installed capacity and the peak demand, divided by peak demand. This driver affects the electricity price, which in turn influences the electricity demand. The second driver is related to the lack of transmission lines (known as transmission congestion), which influences the electricity price. These performance drivers affect the behaviour of auctions market, which influences the wind power expansion in Brazil.

The strategic resources are allocated as a result of decision-making processes, and produce an effect on the associated performance drivers. The analysis of the causal relations between resources and drivers serves as a management information support for improving the coordination of policies and strategic planning. In this case, the strategic resources include the inventories along the supply chain affecting the installed capacity of wind power, as well as its demand within the electricity market.

4.3.4. Simulating the DPM chart through System Dynamics modelling

Applying the above DPM chart forms an effective mean to support policy design, coordination, and implementation. In this case, SD simulation provides an additional methodological support to the DPM framework. This section illustrates the combination of SD model with performance management enabling decision-makers to better identify and understand the changes in energy and industrial policies. Figure 23 shows the emerging model of the wind power supply chain, based on blending the DPM chart and the stock-and-flow diagram. This model namely highlights the relation between performance drivers and end results, contributing to fuel associated strategic resources in the wind power supply chain.

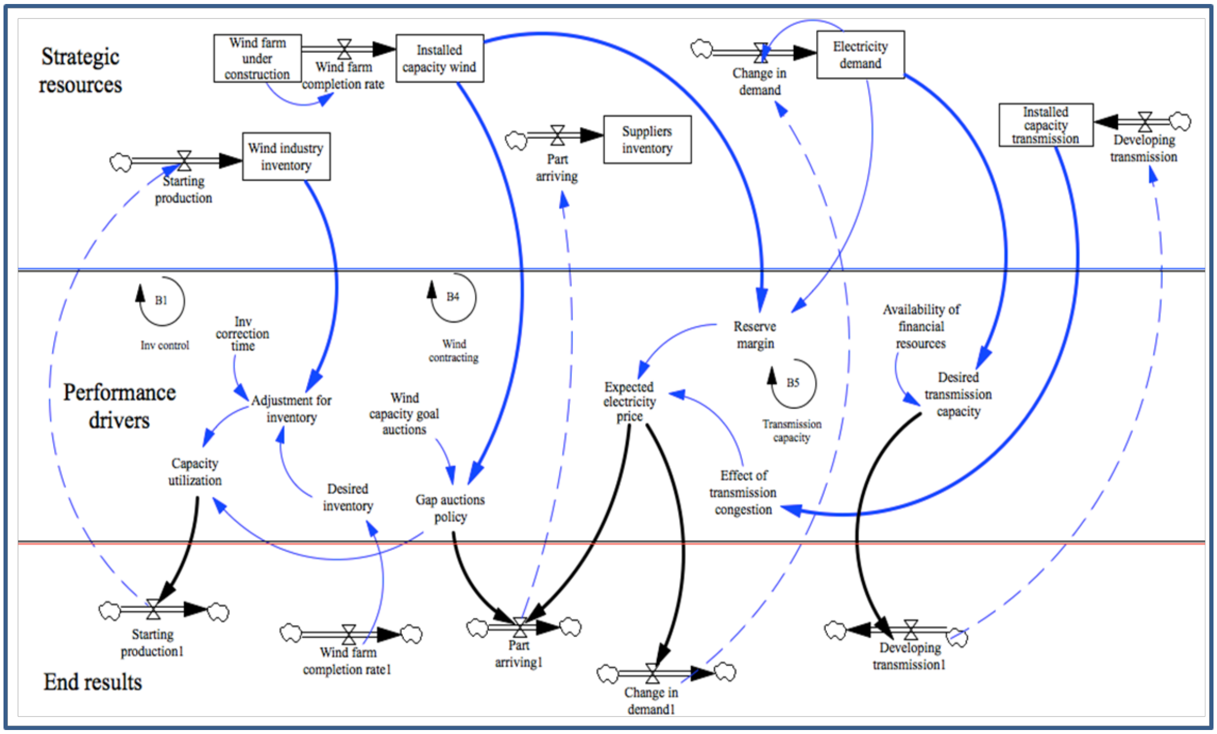


Figure 23. An SD-based DPM model showing the effects of auctions policy on the wind power supply chain performance.

4.4. Simulation results

This section reports the main findings of the case study conducted in Brazil. By analysing two simulation scenarios, the results of the model show the effects that uncoordinated and coordinated policies might produce on the operational capacity of the supply chain. Table 6 describes both scenarios designed to evaluate the auctions policy reform based on model's Equations 14 and 15. With the intent to coordinate transmission auctions and wind generation, the regulator may adopt arguments considering a collaborative governance coefficient and standard deviation of annual demand. These arguments contribute to the evaluation of coordination and synchrony in policy/decision-making.

Table 6. Scenarios for analysing coordination impact of policies on wind power supply chain

Scenarios	Definition of scenarios	Policy

Scenario 1	Uncoordinated policy	$$BT = \frac{(KT - ED)}{TBL}$$ $$WC = MAX\left(0, \frac{EPWC * GAP}{TB}\right)$$
Scenario 2	Coordinated policy	$$BT = \frac{(KT - ED)}{TBL * \delta * S_{ED}}$$ $$WC = MAX\left(0, \frac{EPWC * GAP}{TB * \delta * S_{ED}}\right)$$

δ : Collaborative governance coefficient
S_{ED}: Standard deviation of annual demand

4.4.1. Simulation results without a coordinated policy in the supply chain

To understand the results of this scenario, the energy policy (i.e., bids of the wind power auctions) was modified in the simulation according to the previously mentioned equations. In this scenario, a collaborative governance policy of consensus among actors aimed to build transmission and generation capacity is not considered. The response capacity of the wind industry is determined by the changes both in the production rate of wind industry and the wind farm completion rate. Figure 24 shows the end results related to production rate and wind farm completion rate for the wind industry. Results indicate that the response capacity (corrective action) of wind farm developers to a 1.8 GW increase in the bids of power auctions generates a gap between manufacturing and construction because of delays in the bidding process that could alter the wind power expansion. This can imply a quite serious backlog of orders in the long term. Thus, the adjustment of response capacity to align the supply chain creates a significant amplification.

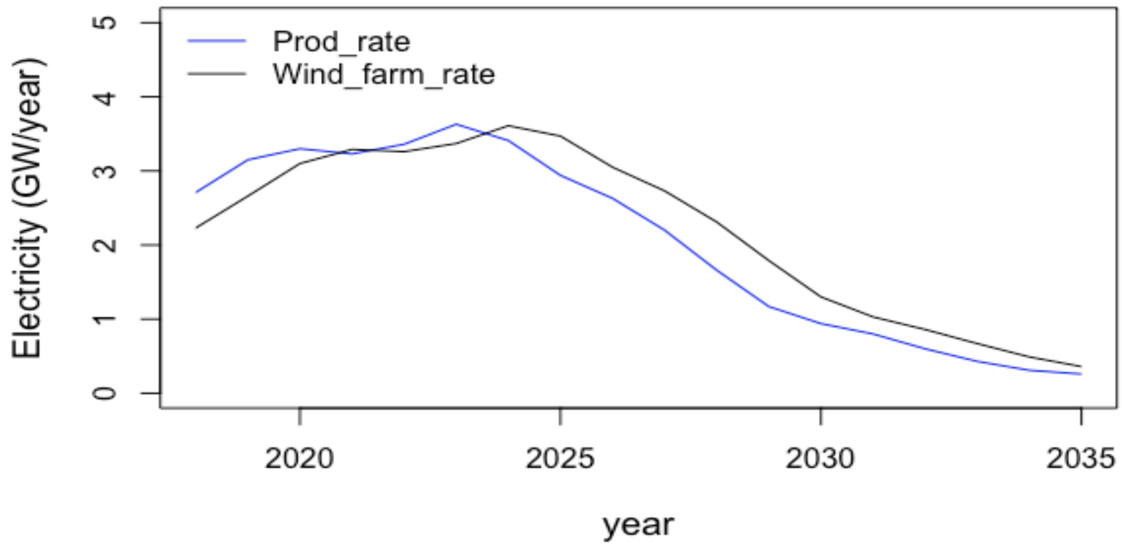


Figure 24. Behaviour of end results with uncoordinated policy due to change in the auctions.

Simulation results of the wind industry show that the wind farm completion rate increased by 62% within the simulated period (calculated as the peak wind farm completion rate divided by the initial value), while the production rate increases by 34%. Thus, the ratio of maximum change in the output and input (known as amplification ratio) for the wind industry is 1.82%. Increasing delays affects the amplification ratio of the wind power supply chain. Delays in the response of the developers of wind farms to changes in the industry might affect the strategic resources. This highlights how an auctions-based policy (performance drivers) affects outcome indicators due to delays that increase the amplification ratio.

The discrepancy between desired and actual inventory can cause drawbacks on actors along the supply chain, such as shortages and surplus. Figure 25 shows the discrepancy of supply chain inventory (strategic resources) with respect to desired inventory. This situation is created by the delays to build wind farms and insufficient bids for wind auctions (i.e., fragmentation in energy policy design and implementation). Results exhibit that the delays between the adjustment time and their effects on inventories generate a surplus in the supplier's inventory, while the developer's inventory presents shortages with respect to the desired inventory. In addition, the firm's suppliers face much larger changes in inventory that the industry. Thus, it is required a greater supply chain capacity in response to changes in the energy policy that fosters the consensus between public and private sector.

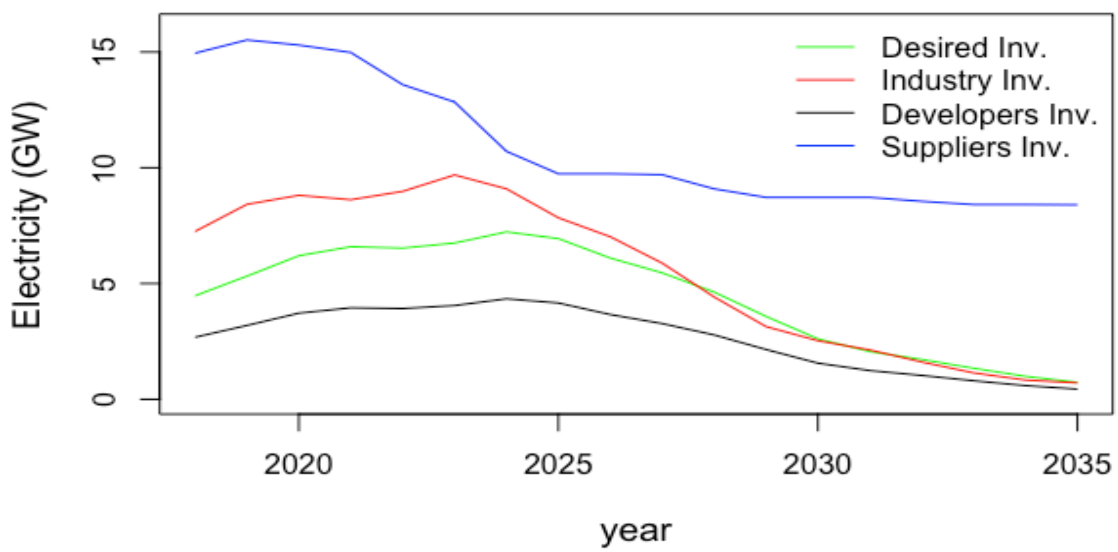


Figure 25. Response of strategic resources to the uncoordinated policy in the supply chain.

The behaviour of the desired inventory is assumed by the changes in wind power auctions, which constitute a dynamic behaviour affecting the decision-making of actors in the supply chain. Given the response of strategic resources to the uncoordinated policy, the amplification ratio of the supply chain for each actor is: 62% to desired inventory, 34% to industry, 62% to developers and 4% to suppliers. This indicates that a lack of coordination among actors exists and, therefore, actions aimed to close the gap to reach the desired inventory are required.

4.4.2. Simulation results with a coordinated policy in the supply chain

To illustrate the coordination in wind energy policy design, the bids of the wind power auctions were adjusted with a 1.8 GW increase each year from 2018 to 2035. Figure 26 shows the simulation of production rate and wind farm completion rate (end results) with delayed bids of wind auctions set to 6 months. In addition, this scenario supposes two coefficients associated to construction time, i.e., collaborative governance and demand uncertainty. Considering the changes in the auctions policy, the simulation results estimate a fast response capacity of the wind farm completion rate to the changes in the production rate of the wind industry. This stimulates a significant increase in the installed capacity of wind power. Results show that the continuous increase of wind auctions and the reduction of the delays in the construction of transmission lines contribute to foster the coordination among actors of the supply chain. In this way, the alignment of actors should be obtained through the synchrony and coordination of energy policies (e.g., time to build and response capacity) through the performance drivers influencing the outcomes of the supply chain.

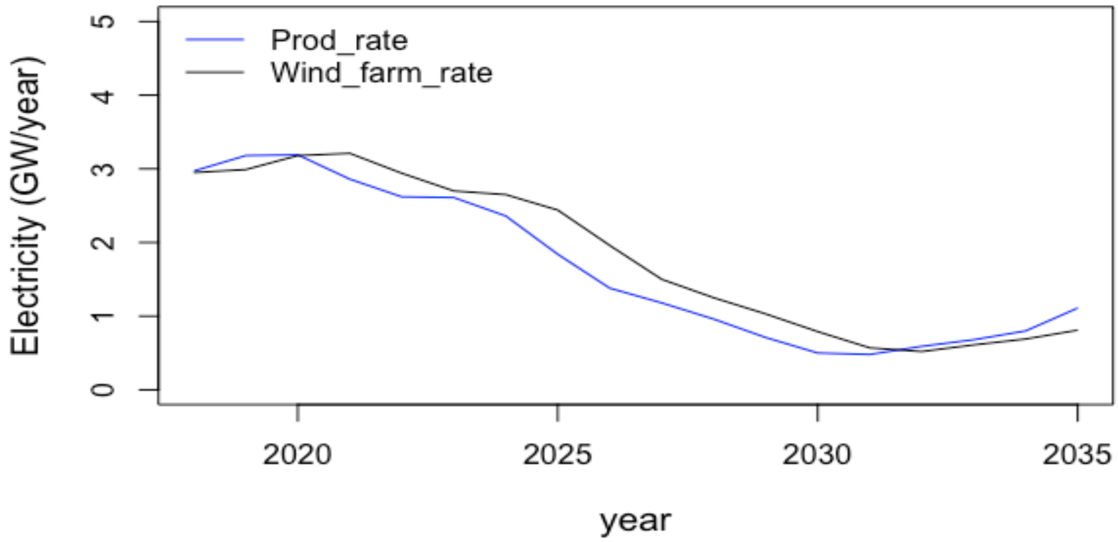


Figure 26. Behaviour of end results with coordinated policy due to change in the auctions.

Regarding the amplification ratio of end results, the model shows that the wind farm completion rate increased by 9% within the simulated period, while the production rate increases by 7%. Thus, the ratio of maximum change in the output and input for the wind industry with coordinated policy is 1.19% (compared to 1.82 without coordinated policy). Noticeable is the difference between the amplification ratio with and without coordinated policy and its related with the response capacity. The response capacity, therefore, exhibits the end results affecting strategic resources along the supply chain.

The simulated supply chain shows the response for each strategic resource according to the changes in the desired inventory, as illustrated in Figure 27. Given that the coordinated policy affects the desired inventory (performance driver), the response capacity of strategic resources better reacts to the discrepancy of the supply chain. The amplification ratio for each actor in the supply chain improves in comparison to the results of uncoordinated policy (9% to desired inventory, 8% to industry, 9% to developers and 0% to suppliers). This condition is produced by a balance between the interest of each actor and the interdependency among them within supply chain (i.e., collaborative governance), which contributes to provide a resilient response to uncertainties or perturbations.

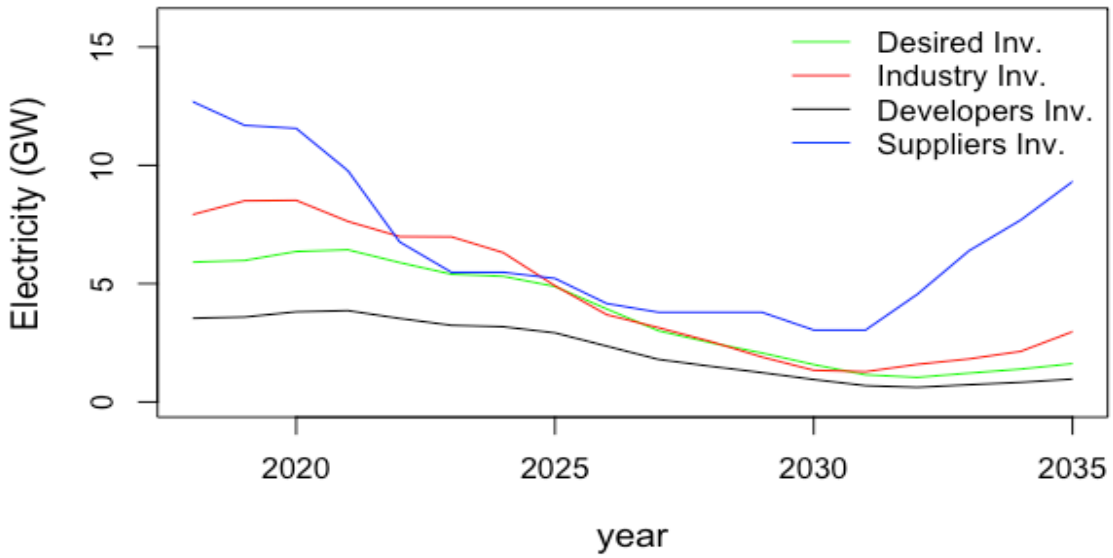


Figure 27. Response of strategic resources to the coordinated policy in the supply chain.

In summary, the performance of wind power supply chain is associated with the capability of the system to deliver electricity as soon as the wind farms are installed. That is, all elements of the wind supply chain are in synchrony and, particularly, there is no time-delay in the construction of transmission lines.

4.5. Discussion

This section reviews the study contributions generated by SD modelling and the DPM approach to collaborative governance. In particular, it discusses the contributions in terms of organizational learning and performance management in the wind-power supply chain.

4.5.1. Contributions to organizational learning

Every organization needs learning like a prerequisite for growth (Bianchi, 2016). Policy modelling helps decision-makers learning about the drawbacks of policy implementation that limit the system's growth (Ghaffarzadegan et al., 2011; Wheat, 2010). Building learning environments for experimentation provides estimates for the adoption of strategies aimed at lowering the concerns associated with the energy policy implementation. This research provides simulation scenarios that contribute to better understand how decision-making and policy implementation affect the structure of the wind power supply chain. The simulation scenarios present an analysis of auctions-based policy related to the intervention of policy-makers and managers within the systemic structure of the supply chain. It is important to note that SD and DPM allow one to identify the main performance drivers in the implementation processes influencing the supply chain structure. In addition, these approaches contribute to foster a governability policy change.

The complex relationships among the actors of the supply chain, as well as the challenges associated with an intermittent generation caused by climate change, involve the use of strategic alternatives to face the uncertainty of this system. Given this rapidly changing environment, the wind industry should adopt strategy analysis, formulation and implementation that include sustainable alternatives in the long term (Herrera et al., 2018). The simulation model offers strategies aimed at lowering the uncertainty associated with the dynamic of electricity market through policy analysis (Aquila et al., 2017b; Dyner, 2000; Ford, 1997). In this perspective, this chapter developed simulation scenarios to foster the coordination of the supply chain by means of the blending collaborative governance and dynamic performance management.

The green economy is a new model of development in contrast to the economic model based on fossil fuel, in which the renewable energy supply chain attracts the attention of both public and private actors (Cucchiella and D'Adamo, 2013). As a result, the promotion of renewable energy is a priority for policy-makers and managers of the supply chain. However, the conflict of interest that may arise in the promotion of renewable energies underlines the need for recognising the trade-offs of specific policies (Bayer, 2018). For instance, the lack of continued and long-term political support is a major limitation for the future of wind power in the case of France and Canada (Feurtey et al., 2016). This situation also occurs in the case of the Brazilian electricity market due to the gap between design and implementation of a policy aimed at supporting the generation and transmission system (González et al., 2017). Thus, our research comprises the evaluation of energy policy implementation and its effects, it modelling the delay that is involved.

Simulation results show why it is important to recognise the time delays produced by the uncoordinated policy and its effects on corrective actions. Understanding these barriers is central to framing and analysing supply chain performance (Rahmandad et al., 2009).

4.5.2. Contributions to performance management

Designing a policy coordination structure for the energy sector is not an easy task (Bale et al., 2015; Wheat, 2010). The gap between design and implementation of policy caused by delays in implementation generates underachievement of the desired target for actors of the supply chain. To foster the coordination in designing energy policy, the simulation scenarios demonstrate that the time to build capacity should consider the demand uncertainty. In addition, the consensus and participation of actors in the bids for wind power contribute to improve the outcomes of the supply chain. This depends on the fact that reducing delays through a collavorative governance approach could increase response capacity of the supply chain.

Although the collaboration in the supply chain could be reached with the cooperation between partners sharing the core information (Prostean et al., 2014), the contribution of this chapter indicates that the policies play an important role to overcome dysfunctions in the coordination among supply chain partners. The DPM-based analysis includes not only the behaviour of inventories in the supply chain, but also how performance drivers associated with the energy policy affect the outcomes. In addition, the chapter emphasises how policy-makers can use the suggested framework to improve policy design through a deeper understanding of the relations between end-results, performance drivers and strategic results.

As a result of combining SD methodology with DPM, the potential undesired effects of energy policies on the wind-power supply chain are identified. A lack of coordination and synchronisation of the investments aimed at supporting the generation and transmission system affects the response capacity along the supply chain. This complexity is associated with the changes in the performance drivers affected by the strategic resource allocation strategies. In this context, the DPM approach can foster performance management, thereby supporting a more effective decision-making within the collaborative governance setting, that implies a number of major challenges for both political and organizational systems (Bianchi, 2016).

Others simulation approaches discuss individual strategies based on the quality of information on which to develop key actors' decisions (Agusdinata et al., 2014). One major implication of using these approaches is related to the focus of supply chain performance management on only particular objectives or single institutions, while the suggested methodological approach enables to explore the trade-offs in terms of performance metrics between suppliers, manufacturing and developers of wind farms, thus supporting an inter-institutional perspective as a key to implement coordination-oriented actions throughout the wind power supply chain.

4.6. Conclusions

There are multiple complex institutional, political and managerial factors that influence energy policy governance, design and implementation (Feurtey et al., 2016). The construction delay in the electricity market caused by the unavailability of resources is one major factor generating concerns for policy-makers. Consequently, the energy policy applied might be inappropriate, further maintaining the gap between design and implementation. To overcome this complexity, the chapter proposed to combine performance management systems with collaborative governance to better understand the outcomes of political decisions on the renewable energy supply chain. Thus, the simulation scenarios analysed the gap between implementation of wind auctions and time to build transmission lines.

Collaborative governance is a response to a failure of traditional mechanisms for allocating resources (Zadek, 2008). In this case, with the intent to foster the wind power supply chain collaborative governance, the simulation scenarios demonstrate that a collaboration coefficient, as well as the time to build capacity should be considered. The dynamic interaction of business strategy and changing political expectations should consider to blending collaborative governance and DPM to develop alternative and more effective policies.

The alignment of supply chain strategies and policies among supply chain actors enables improvements of the response to changes in the electricity demand. On this regard, DPM supporting collaborative governance contributes to align decision-making along the supply chain. This chapter contributes to a model-based strategic framework that incorporates response capacity of the wind power supply chain.

Chapter 5: Alternative energy policy for mitigating the asynchrony of the wind-power industry's supply chain in Brazil ♣

Abstract

High dependency on hydroelectricity has revealed drawbacks in the security of power supplies as a consequence of the climate variability in South America. Under these conditions, Brazil is starting to consider alternative renewable sources for energy production, seeking to avoid periods of scarcity, while also promoting clean technologies in its electricity market. Since 2004, wind power has shown a significant rise in terms of installed capacity in this country. Despite increases in wind power units, Brazil suffers from delays in setting up its transmission infrastructure, which affects the performance of the wind-power supply chain. This chapter presents a simulation model that helps assess the long-term effects of an alternative sustainable energy policy, which may contribute to overcoming the asynchrony between renewables generation policy and the insufficiency of transmission infrastructure. Using lessons learned from simulations, the research concludes that the transmission industry in Brazil requires appropriate investment incentives for just-in-time synchrony with the expansion of the wind industry.

Keywords: simulation; wind power in Brazil; supply chain; asynchronous policy; electricity transmission

5.1. Introduction

One of the main concerns of the Brazilian electricity market is its high dependency on hydroelectricity. The impacts generated by changing climate conditions and the sedimentation of dams have strongly affected hydroelectricity generation, causing a

♣ Results of this chapter has been included in: i) a chapter of the published book "Innovative Solutions for Sustainable Supply Chains", edited by Qudrat-Ullah, H. Springer International Publishing, Cham, pp. 199–221. https://doi.org/10.1007/978-3-319-94322-0_8 , ii) a paper presented in the XVI Latin-American Conference of System Dynamics hold in Puebla (Mexico) in 2018.

reduction of storage levels in dams (De Lucena et al. 2009). In recent decades, Brazil initiated its commitment to wind power in order to meet the challenges of sustainable energy development. Though renewable energy policies are achieving improvements in the power sector, the problem of time delays in the construction of new transmission stations affects the rapid expansion of wind power.

In 2013, Brazil faced problems regarding the lack of sufficient transmission lines, which affected generation by the wind farms. Consequently, the country was forced to use diesel and natural thermoelectric power generation. The cost of generation shot up, and this obliged the system to compensate the wind-power companies that had completed their projects by 2012 but had no means to dispatch their power. Though Brazil possesses an extensive network of long-distance transmission lines, the current capacities of transmission facilities are not sufficient to guarantee energy supply, especially in isolated regions. Therefore, this situation compromises the rapid expansion of wind farms in the northern region of Brazil.

Germany and China are making significant progress in developing their transmission infrastructure, thanks to their favourable legal and regulatory frameworks, which positively promote their wind-power supply chains (Yuan et al. 2014; de Melo et al. 2016). Conversely, Brazil during the last two decades has been facing two critical concerns relating to the transformation of its energy sector: accumulated time-delays in the expansion of transmission lines, and rapid expansion of wind power. This situation has generated an asynchronous growth between the transmission industry and the wind industry that affects the sustainability of the supply chain. The concern is thus the misalignment between the industry policy of wind power development and energy policy for transmission expansion.

The Brazilian power sector is the largest in Latin America, with 158 GW (ANEEL, 2016). While hydropower represents 61% of the total capacity, with 96.8 GW, wind power embodies 6.2% of the total and solar only 0.0145%. However, this profile may change significantly, as the current energy policy considers climate variation issues, including lower flows into hydroelectric reservoirs. Aligned with this, since 2004 Brazil has promoted the development of the wind power industry through its Incentive Programme for Alternative Sources (PROINFA), resulting in increases of wind power participation in the electricity matrix. This initiative, based on the European feed-in policies, principally promotes the diversification of power generation sources and the reduction of greenhouse gas emissions. In this sense, Brazil and South Korea are emerging as producers of wind technology, evidenced by their increased numbers of wind energy manufacturers (Foley et al., 2015).

Supply chain management is an area of growing attention due to its impact on the industry (Georgiadis and Besiou, 2008). The structure of the energy supply chain is characterized by situations of dynamic complexity when information is not available among all the players involved in the different industrial stages. In this context, econometric methods and linear programming are not adequate to deal with the complexity of the relationships between the players involved in the wind-power supply chain (Dyner and Larsen 2001; Kunsch and Friesewinkel 2014; Qudrat-Ullah 2015; Franco et al. 2015). Therefore, system dynamics modelling is a more appropriate approach as it can capture much of the complexity of supply chains.

Numerous studies have examined the various perspectives regarding the expansion of wind power in Brazil (Brannstrom et al., 2017; Juárez et al., 2014; A. O. Pereira et al., 2013; Silva et al., 2013). However, few have analysed the effects of the expansion of renewable energy on the sustainability of the wind-power supply chain. In this sense, Wee et al. (2012) assessed renewable energy growth from the supply chain perspective. This study provides managerial insights into renewable energy use, and makes proposals for overcoming the barriers to its development. Others studies have also identified the relationships and concerns of stakeholders along energy supply chains associated with wind industry growth (Wüstemeyer et al., 2015; Yuan et al., 2014). Despite the fact that some studies show the concerns of stakeholders in the wind-power supply chain, the asynchrony between the transmission capacity and the wind industry has not been taken into account. In particular, the wind-industry growth effects in Brazil have not yet been sufficiently analysed, from an energy supply chain perspective.

Given the complexities of asynchronies, this research uses simulation modelling to gain better understanding of the dynamics of wind-power supply chain performance and its effect on the energy sector. This modelling approach is also helpful for assessing alternative effective energy policy that may mitigate the asynchrony resulting from insufficient transmission infrastructure for the wind-power supply chain. Thus, this approach better gauges the consequences of the energy policies that might affect the performance of the supply chain.

This chapter is divided into five parts. The Introduction is followed by a section that reviews the development of the wind-power supply chain and its asynchrony in Brazil. Section 5.3 describes the model-based methodology used for studying this issue. Section 5.4 discusses simulation results, which explain the asynchrony of the wind-power supply chain and its effects on performance and sustainability. Further, a model-based alternative policy is proposed that shows the synchrony from the supply chain perspective. Finally, the Conclusions section establishes the benefits of coordinated policies on the supply chain performance and identifies future research.

5.2. Asynchronous policy in the wind-power supply chain industry

In many countries, the rapid penetration of renewable energies has been driven by several factors, primarily those related to environmental- and energy-policy. Furthermore, as renewable energies are intermittent, they require important infrastructure and technology support for their synchronization with other supply sources. Despite the several studies aimed at estimating Brazil's renewable energy potential (Geller et al. 2004; Pereira et al. 2012; de Jong et al. 2015; Corrêa Da Silva et al. 2016), the synchronization problems between the Brazilian policies on transmission infrastructure and renewables generation will affect the sustainability and performance of the wind-power supply chain.

The Brazilian energy sector has been highly dependent on hydropower, which has motivated the diversification of its electricity matrix. In response to the dependency on hydropower, Brazil is promoting other renewable energies to hedge hydropower risks through the PROINFA programme (Da Silva et al., 2016).

5.2.1. Development of the wind-power supply chain in Brazil

Hydropower has dominated the Brazilian electricity market for years and this has made the sector vulnerable to droughts, and consequently to high electricity prices. As wind power is getting cheaper, it is becoming an interesting option for complementing hydropower during dry seasons (Brannstrom et al. 2017; de Melo et al. 2016; Juárez et al. 2014; Silva et al. 2016; Aslani et al. 2014). Reports on the Brazilian Northeast are highly optimistic for energy generation because of the periods of high wind potential (Brannstrom et al., 2017). According to ANEEL (2016), total installed wind-power capacity changed between 2005 and 2016, from 0.027 GW to 9.8 GW. The North and Northeast regions have experienced a rapid growth in wind farms (Tiba et al. 2010; de Jong et al. 2015).

In Brazil, industry promotion-policies play an important role in achieving economic viability for wind power projects (Kissel and Krauter, 2006). Indeed, the wind power industry has had an annual growth rate of about 15% since 2010. Brazil started by importing wind turbines, but this has changed rapidly as the policy has been to promote the domestic supply-chain of the wind industry. In this direction, the wind turbine industry is experiencing rapid growth (Simas and Pacca, 2014). Despite the efforts of the Brazilian government, the performance and sustainability of the supply chain has been affected by the lack of synchronization between wind industry expansion and development of the transmission infrastructure.

Brazil faces barriers associated with delays in the delivery of new transmission lines postponing the operation of wind farm generation (de Melo et al. 2016). This situation is the result of a backlog of construction delays in recently-auctioned transmission lines, for connecting wind projects, across the country. Transmission infrastructure has not kept up with the rapid growth in capacity, leaving wind farms with inappropriate infrastructure for power transmission to demand centres in the south and east (Foley et al., 2015). Even though the North and Northeast regions are quite suitable for the generation of wind power, environmental licensing issues have been a matter of concern in the construction of transmission infrastructure. Additionally, land price has been a constraint on the expansion of transmission in these regions. Thus, the great difficulties for transmitting wind power from generation towers in the Brazilian North to demand centres elsewhere involve a lack of synchrony between energy policies and the supply chain development.

5.2.2. Asynchrony between policies and performance of the wind-power supply chain

Development of the wind power industry is driven by the initiative of the Federal Government. In this way, Brazil has demonstrated its ability to adopt and implement energy policies through electricity-sector incentives (Geller et al., 2004). These Brazilian energy policies have a significant impact on both emission reductions and the diffusion of clean technologies. Despite this, the wind-power supply chain performance was strongly out of synchrony with the transmission infrastructure. Thus, the asynchronous implementation of energy policies involves a conflict of interest associated with the targets of each stakeholder in the supply chain and electricity supply. In terms of transmission network investment, the stakeholders have different interests; in other words they will have different investment perspectives and strategies along the wind-power supply chain, including the network expansion (Pudjianto et al., 2016). This motivates studying the asynchrony between energy policies and its effects on the wind-power supply chain in terms of a performance measure and security of energy supply.

Regarding development of the wind-power supply chain in Brazil, de Melo et al. (2016) mention that the critical issues are: the legal and regulatory framework, the institutions created to support the energy system and long-term energy planning. Because of high electricity-market uncertainty and rapid change in the wind industry, the energy planning process enables a better understanding of the supply chain. This implies the need for synchronisation of the planning process among the energy system stakeholders. In this sense, there are several model-based planning methodologies that are useful for approaching this issue (Dyner and Larsen, 2001).

Study of the wind-power supply chain involves understanding the execution of a sequential chain of operations and flows, as shown in Figure 28. This mean that the dynamic behaviour of the supply chain is associated with the complex relationships among the raw material suppliers, components, wind turbine manufacturers, wind farm developers, grid operators and service suppliers (Prostean et al., 2014; Yuan et al., 2014). The wind-power supply chain can be divided into two parts, upstream and downstream (Yuan et al., 2014). The first part involves suppliers, industry and developers. The second part is related to the wind power generation, electricity grid and consumption. Some authors have studied the performance of the wind-power supply chain and its implications but little attention has been paid to the energy policy implications (Wee et al., 2012; Wüstemeyer et al., 2015), which is the concern of this chapter.

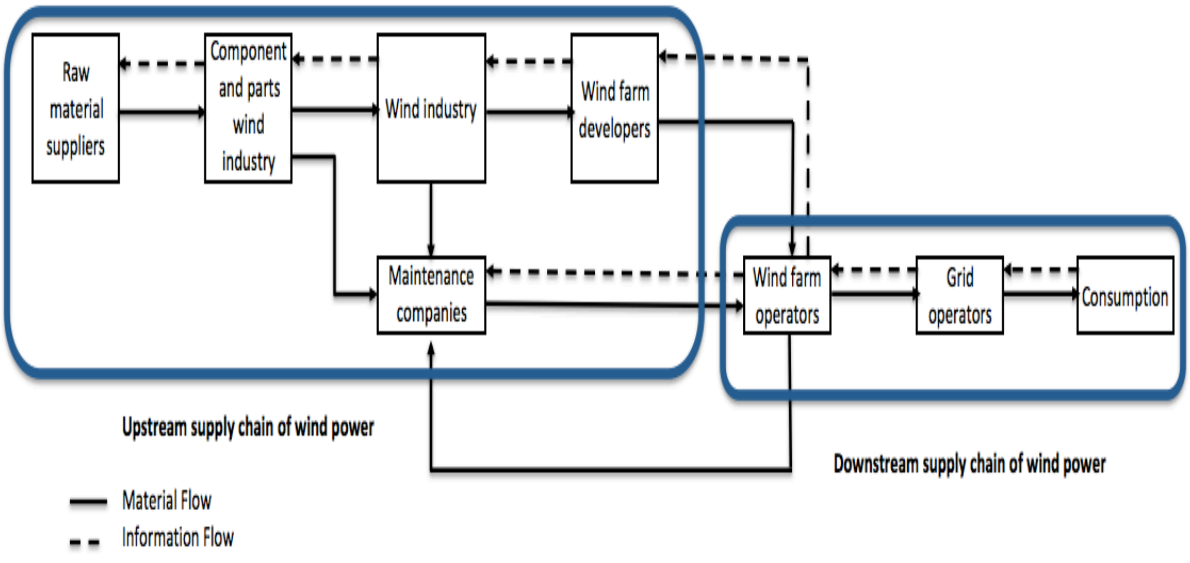


Figure 28. Structure of the wind-power supply chain

5.2.3. Asynchrony and its implications for the sustainability of the wind-power supply chain

Sustainable supply-chain management theory highlights the complex issue associated with stakeholders' relations and energy policy implications (Linton et al., 2007; Wüstemeyer et al., 2015). The interaction between the stakeholders and policies can occur either synchronously or asynchronously (Sahay et al., 2014). While synchrony in the supply chain is achieved by appropriate information exchange resulting from coordination between policy and planning, asynchrony occurs when coordination is not in place. In this context, clean energy policy may lead to poor power industry outcomes (Lund, 2009) without careful planning of the entire supply chain.

In the case of Brazil, policy has led to a rapid expansion of the Brazilian wind power industry, but the development of transmission infrastructure has not kept pace. In this context, Brazil faces delays in the delivery of new transmission lines that generate increased grid congestion (de Melo et al. 2016). To minimize the transmission problem, the government has limited auctioning wind power projects and, consequently, has slowed the rate of increase of wind generation. This situation limits the performance of wind industry operations due to the reduction of financial resources used, which affects the finances of the wind-power supply chain.

Expansion of the wind generation industry involves varied interests that are not aligned with transmission development, producing an asynchrony in the wind-power supply chain. The consequence is that the asynchrony generated by different investment decisions of the various stakeholders might affect the electricity price to customers and compromise security of supply. Therefore, the continuing expansion of the wind-power supply chain is affected.

5.3. Methodology

This chapter addresses the problem of insufficient electricity transmission-infrastructure resulting from the rapid expansion of wind power that affects the North and Northeast of Brazil. This section proposes a model-based approach for assessing alternative sustainable policy that deals with asynchrony in the development of the wind-power supply chain.

5.3.1. The system dynamics approach

A considerable amount of literature has supported renewable energy policy based on general equilibrium modelling and agent-based simulation (Ioakimidis et al. 2012; Bale et al. 2015; Cabalu et al. 2015; Troost et al. 2015; Abrell and Rausch 2016; Karplus et al. 2016). Abundant literature also reports renewable-energy policy assessment based on system dynamics (Dyner and Larsen, 2001; Ford, 1999, 1997; Ochoa et al., 2013; Qudrat-Ullah, 2014; Zuluaga and Dyner, 2007). The research reported here found no system dynamics literature that supports renewable policy from a supply chain perspective, the purpose of this chapter.

Broadly speaking, the system dynamics approach has been used to help understand supply chain behaviour for over 40 years (Asif et al., 2012; Orjuela-Castro et al., 2017; Rendon-Sagardi et al., 2014; Sterman, 2000; Tian et al., 2014). The system dynamics modelling approach facilitates the analysis of problems with complex causality and time delays. More recently, system dynamics modelling of the supply chain has been used to assess transport policies and capacity planning (Orjuela et al., 2015; Vlachos et al., 2007). Though many researchers have addressed the expansion of renewables and the challenges involved in the sustainability of energy systems (Castaneda et al., 2017; Franco et al., 2015; Jimenez et al., 2016; Qudrat-Ullah, 2016, 2013), these researchers have not, however, addressed asynchrony problems from the wind-power supply chain perspective.

The wind-power supply chain consists of many stakeholders with different roles and targets (Wee et al., 2012). System dynamics modelling is useful for simulating and understanding the integration in energy supply chains of distinct roles and targets, in emerging markets (Rendon-Sagardi et al., 2014). The first published system dynamics work related to supply chain management established a link between the downstream flow of material and upstream flow of information (Forrester, 1961; Sterman, 2000). In the wind-power supply chain, downstream and upstream flows are key factors for improving the supply chain performance. These flows are the main concern of both the supply chain's dynamics and the supply chain's stakeholders.

The system dynamics approach, as incorporated here, establishes first a dynamic hypothesis of the system that involves the problem situation. This is followed by the simulation model structure, which combines the main relationships in a stock-and-flow diagram through a set of differential equations. Finally, the simulation model is validated to ensure that it behaves as expected and its behaviour coincides with the dynamic hypothesis.

5.3.2. Dynamic hypothesis

This section presents a general framework that depicts the asynchrony of the wind-power supply chain, which supports the dynamic hypothesis. The main aspects defining the dynamics within the system under study are described next:

- *Promotion and development of the Brazilian wind-power supply chain:* since 2002, the Incentive Programme for Alternative Sources of Energy – PROINFA aimed to increase the electric energy produced from renewable energy, which includes wind projects. Consequently, the Brazilian government has been making efforts for promoting scientific and technological development by investing in research (Juárez et al., 2014). From 2002 to 2016, the wind industry has been reporting rapid growth all along the supply chain. In this sense, the new wind equipment suppliers have experienced significant growth through the financial incentives for the development of a national wind industry supported by the Brazilian government.

- *The impact of inadequate development on the transmission lines and towers:* despite the best wind conditions being found in the Northeast region, Brazil suffers an electricity supply problem due to the lack of transmission infrastructure serving the North and Northeast. According to de Jong et al. (2016) the problem transmission-lines will need to be expanded and upgraded to accommodate the expected increase in wind power penetration in the Northeast region. Otherwise, the currently inadequate transmission infrastructure in the Northeast region can lead to significant increases in electricity prices.
- *Asynchrony between energy policies and supply chain performance:* despite the increase in renewable energy in Brazil, the lack of political support for facing Brazil's current economic crisis is one point that can prevent the development of the wind-power supply chain (Silva et al., 2013). Although a set of policies was adopted to expand the share of renewable energy, the projects for transmission line construction have been delayed in the north of Brazil. The transmission construction delays have a significant impact on the wind-power supply chain development, which involves the synchrony problem. This problem directly affects the performance of the wind-power supply chain as well as the Brazilian electricity market. Government and researchers have not properly addressed this asynchrony. Therefore, this study presents results on the effects of asynchrony on the supply chain performance.

A dynamic hypothesis is a theory of structure and relationship policies (i.e. decision-making) that affect the observed behaviour (Oliva, 2003). To assess the asynchrony of the wind-power supply chain, this study uses a dynamic hypothesis. The causal loop diagram represents the dynamic hypothesis that describes the asynchrony between the growth of the wind industry and the lack of transmission capacity, as shown in Figure 29. The balancing loop (B1) shows the capacity margin, which depends on the difference between electricity demand and installed capacity. Therefore, the capacity margin affects electricity price, and this influences electricity demand, creating the balancing loop B1. The interaction of these variables represents the functioning of the electricity market as well as the relationships between supply capacity and demand. Therefore, the capacity margin depends on the total installed capacity and electricity demand. A large capacity margin induces lower electricity prices; however, higher prices incentivises the wind industry. The response of price to investment incentives involves long delays that affect development of the wind industry. Therefore, this will lead to an increase in the total installed capacity. In this way, the balancing loop B2 describes electricity price effects on investment incentives for the wind industry, which in the medium-term influences the capacity margin. Likewise, this loop shows the supply-chain development effect promoted by Brazilian government policy. In this case, the creation of additional wind power capacity affects the total installed capacity, which determines the offer curve for electricity demand. This feedback structure represents the penetration of wind power as a consequence of the energy policies adopted by Brazil.

The third balancing loop (B3) describes the dynamics between electricity generation and transmission congestion as well as their effects on electricity price and demand. The transmission congestion depends on the electricity generation. Therefore, the lack of transmission infrastructure causes a decrease in the electricity supply, which could result in high electricity price. Because of this, the electricity price will be affected by the inadequate expansion of transmission capacity as well as by development of the wind industry. Feedback loop R1 encourages wind industry expansion, which affect transmission capacity.

Because of the increase in total installed capacity, electricity generation will have an effect on the transmission congestion. Consequently, this is promoting the incentives for transmission lines, which affect its capacity under construction, creating the reinforcing loop R2. This feedback structure is the result of a time delay that occurs between the investment decision and the needed transmission line capacity. Therefore, the loop (R2) limits the effectiveness of wind-power supply-chain adoption due to the high cost of electricity transmission.

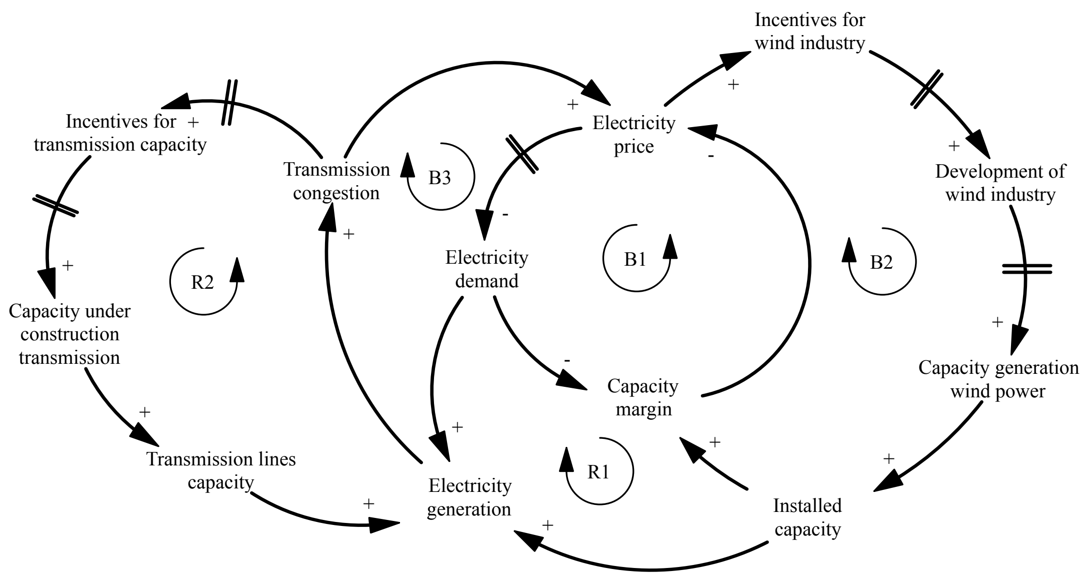


Figure 29. Dynamic hypotheses for the asynchrony of the wind-power supply chain

As the result of huge increases in energy demand, Brazil is projecting important economic growth as well as low-cost energy generation. However, the lack of financial resources and construction delays for transmission infrastructure will act as barriers to reaching this objective. In this sense, the lack of transmission infrastructure may be critical to Brazilian energy sustainability. This problem may cause a delay to widespread use of renewable energy sources and affect the performance of the wind-power supply chain. Consequently, conversion to wind power may become expensive due to the shortage of financial resources for the transmission system.

5.3.3. Simulation model

The simulation approach used here allows evaluation of the dynamic characteristics of a regional energy-industry system. The simulation model was built using detailed descriptions of the players in the wind-power supply chain, such as: suppliers, the wind industry itself and assemblers of wind towers. Likewise, the electricity demand, installed capacity for the wind power as well as transmission lines were also taken into account. In addition to this, other Brazilian energy sources, such as: fossil fuels, nuclear, importation of power and solar photovoltaic are considered. Therefore, the stock-and-flow diagram represents the Brazilian energy-system structure, as shown in Figure 30.

The model design was based on structures proposed by Cardenas et al. (2016), Franco et al. (2015) and Sterman (2000). However, an extension of this model includes a structure for the wind-power supply chain that allows analysis of the asynchrony of Brazilian energy policy. The model structure considers three basic subsystems, as follows: (1) the wind-power supply chain, (2) the electricity market and (3) the dynamics of transmission capacity.

Wind-power supply chain: The structure of the supply chain includes the capacities of suppliers, the wind industry (manufacturers), assemblers and installed capacity of wind power. Other system-related factors identified in the wind-power supply chain are as follows: procurement of raw materials, delivery delay of supply, capacity factory rate, and maintenance and disposal rates.

The wind-power supply chain in Brazil is characterized by significant uncertainties associated with logistics, environmental permits and time lost during infrastructure construction. These uncertainties affect the development of total installed capacity and wind-industry capacity. In this sense, the delay function is used to capture the delayed availability of capacities in the supply chain for the simulation model. For instance, the *capacity factory rate* (CF) and *developing wind power* (DWP) capture this delay time and are determined by delaying the values of the *capacity of wind industry* (CWI_w) and *capacity of assemblers* (CA), respectively. In addition to this, the *installed capacity of wind power* (IC_w) has a useful life cycle, which regulates the depreciation and maintenance rates. Therefore, a closed-loop supply chain modelling for the maintenance service of wind power towers was included. The mathematical equations relating to the main drivers of the wind-power supply chain are the following:

$$IC_w(t) = IC_w(t - dt) + \int_{t=o}^{T}[DWP(s) - Depreciation\ rate(s) + Maintenance\ rate(s)]ds \quad [GW] \quad (16)$$

$$CF = CWI_w\,(1 - fwcdt) \quad [\frac{GW}{year}] \qquad (17)$$

$$DWP = CA\,(1 - wfcdt) \quad [\frac{GW}{year}] \qquad (18)$$

where:

$fwcdt$: Factory wind-power construction delay-time
$wfcdt$: Wind farm construction and implementation delay-time.

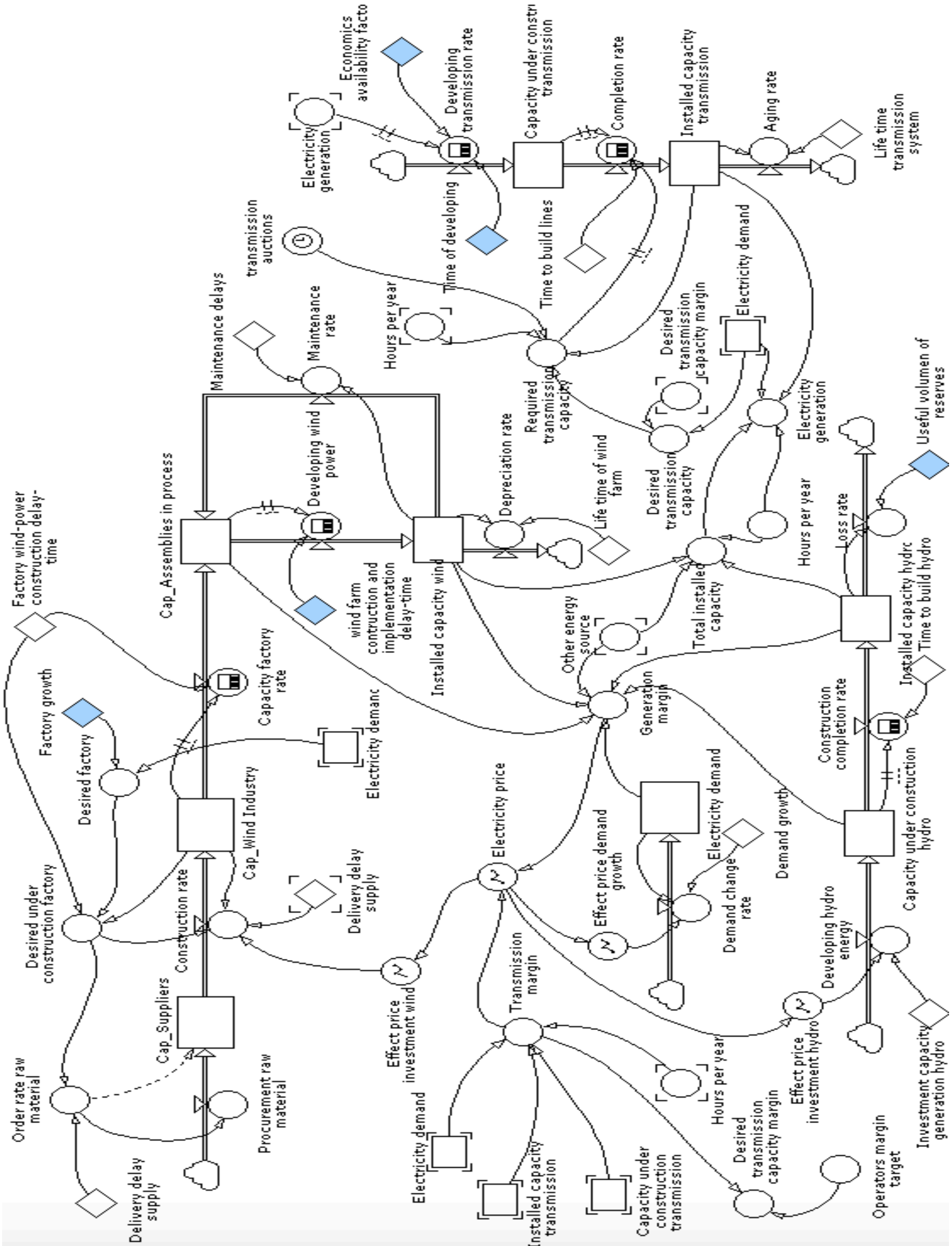


Figure 30. Stock-and-flow diagram of wind-power supply chain in Brazil

Electricity market: The price of electricity is the crucial factor to be considered for investment decisions regarding the different generation technologies. In this sense, reserve margins determine the electricity price, which has an effect on investment in new wind-power capacity and electricity demand (balancing loops B1, B2 and B3). The transmission congestion and generation margin are taken into account while computing the electricity price.

Dynamics of transmission capacity: Considering that transmission lines are essential components of energy supply-chain structure; decision mechanisms must be designed so that they promote adequate expansion of renewable energy. The transmission lines' capacity under construction depends of two main aspects: *economics availability factors* (eaf) and *time of developing* (tdt). These variables affect the 'flow' of developing transmission capacity. The *developing transmission rate* (dtr) captures the delay time involved. This is determined by delaying the value of the needed capacity for transmitting *electricity generation* $(CTEG_T)$, as shown in Equation (20). Given that wind power has had an increase, transmission lines must be built to carry the resulting electricity. Therefore, time is required to build the transmission lines and towers that are needed as a result of the auctions delaying wind power projects in Brazil. The amount of *installed capacity of transmission lines* (IC_T) is calculated as shown in Equation (21).

$$CUC_T(t) = CUC_T(t - dt) + \int_{t=o}^{T} [dtr(s) - tlc(s)]ds \ [GW] \qquad (19)$$

$$dtr = [(CTEG)\ (1 - tdt)\ ] * eaf \quad [\frac{GW}{year}] \qquad (20)$$

$$IC_T(t) = tsc(t - dt) + \int_{t=o}^{T} [tlc(s) - ar(s)]ds \ [GW] \qquad (21)$$

where:

tlc: Transmission lines completion rate

ar: Aging rate

tsc: Installed capacity of transmission

In each period, the transmission system establishes whether the desired capacity is triggered (Equation 22). This is based on the difference between expected transmission margin (projected demand vs. expected capacity) and the transmission operator's margin target. The required transmission capacity (RTC) is calculated as indicated by Equation 23.

$$DTC(t) = epd * (1 + dtcm) \ [GWh] \qquad (22)$$

where:

DTC: Desired transmission capacity

epd: Electricity peak demand

$dtcm$: Desired transmission capacity margin

$$RTC(t) = DTC - IC_T \quad [GWh] \qquad (23)$$

The modelling assumptions and parameter values for the simulation model are as follows:

- Time horizon of the simulation model ranged between 2016 and 2050, to capture the time-delay in transmission construction and the effects of the asynchrony of the wind-power supply chain.
- Initial data on the installed capacity of each technology corresponds to the year 2016, according to ANEEL (2016). In 2016, the installed system capacity in Brazil was 157.86 GW, which was supplied by hydroelectric plants (61%), wind power (6%), fossil fuels (18%), nuclear (1%), importation of power (5%) and biomass (9%) (ANEEL, 2016). In this sense, other generation technologies are considered within the model.
- From 2001 to 2016, Brazil experienced an average 3% per annum increase in electricity demand (ANEEL, 2016; Pereira et al., 2011). However, between 2005 and 2014 the annual growth averaged 4.1% (De Jong et al., 2016).
- Transmission system average life is 20 years (Pudjianto et al., 2016).
- The structure of the wind-power supply chain as represented in the model is supported by previous studies (ABDI, 2014; Varella, 2013).
- Forecasting of the wind power and electricity demand used in the validation model was based on Fiestas and GWEC (2011), ANEEL (2016), Ministério de Minas e Energia (2007) and WWF-Brasil (2015).
- The simulation model evaluated the asynchrony of the wind-power supply chain in Northeast region. In this region of Brazil, the total installed capacity of wind power could reach 16.40 GW by 2020 (De Jong et al., 2016).

5.3.4. Model validation

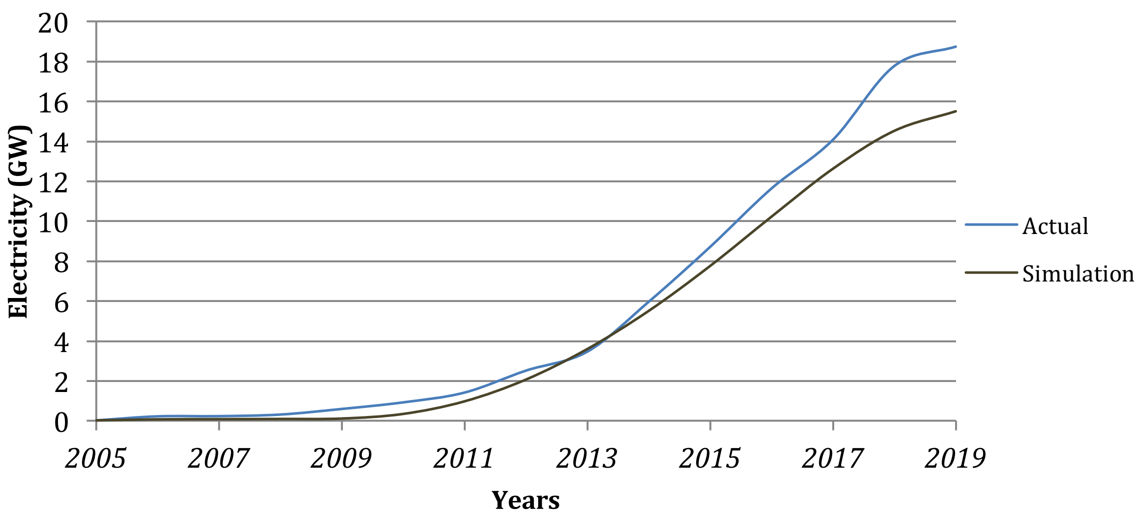
Validation is a continuous process of testing, building confidence in the model (Ahmad et al., 2016; Sterman, 2000). This section conducts several model validation tests, including dimensional consistency and behaviour reproduction tests (Luna-Reyes and Andersen, 2003; Qudrat-Ullah and Seong, 2010; Sterman, 2000). According to Oliva (2003), statistically-based approaches have been used to make the parameter estimation process more rigorous. In order to evaluate the historical fit of the simulation model, the mean-absolute-percentage-error statistic (MAPE) was used, as shown in Table 7.

Table 7. Error analysis of the simulation model in the validation process

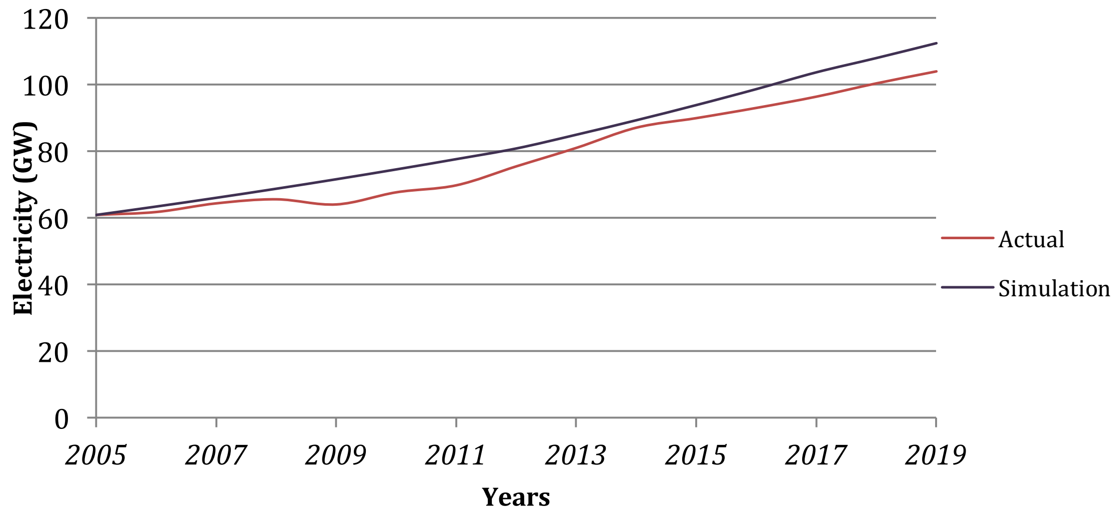
Variable	MAPE	R^2	Standard deviation (Simulation)	Standard deviation (Actual)

Installed capacity of wind power	0.031	0.99	5.75	6.73
Electricity demand	0.061	0.98	83.62	78.73
Total installed capacity	0.037	0.98	123.29	124.99

To validate the accuracy of the proposed model, the results were compared to real outputs and forecasts for the years 2005 to 2019, in terms of the installed capacity of wind power and Brazilian electricity demand. Reviewing the variables with MAPE the error rate is below 6%, R^2 equals 0.97, which presented a small bias, and the residuals do not show a significant trend. The results obtained from the validation analysis are shown in Figure 31. Thus, the simulation has the ability to capture trends and replicate historical data, as shown in the results. In the model calibration process, the results examined differences between simulated output and historical data. Then, we adjusted the model parameters to correct the discrepancy and simulated again.



(a) Installed capacity of wind power



(b) Electricity demand

Figure 31. Validation process, calibration and analysis of the simulation model

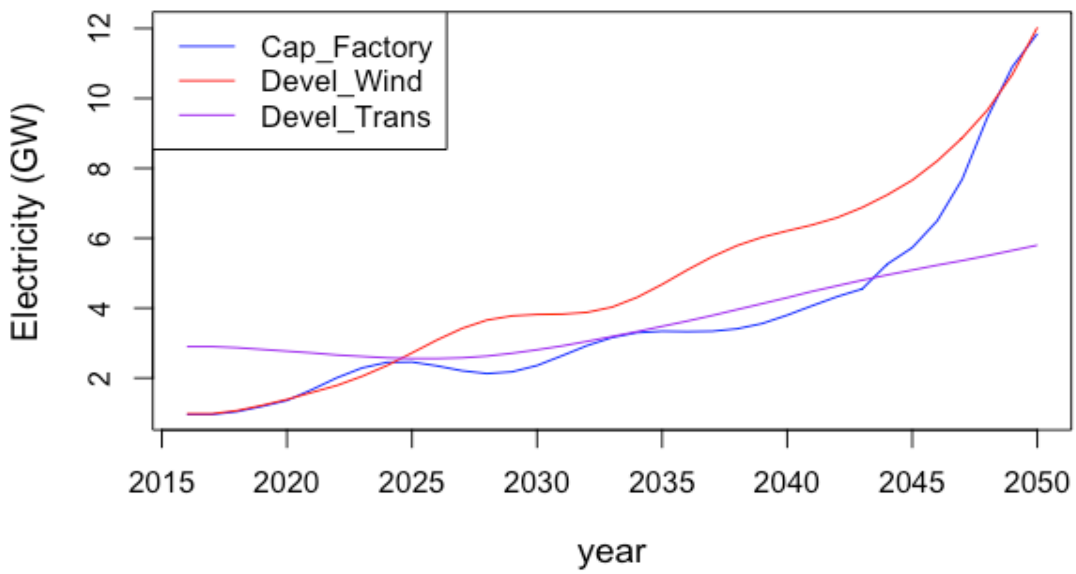
The purpose of the behaviour validation process is to compare how the model reproduces the Brazilian experience of the real system, with regard to electricity supply and demand, in the wind-power supply chain. Thus, these findings suggest that the model does a good job of tracking the observed data.

5.4. Simulation results

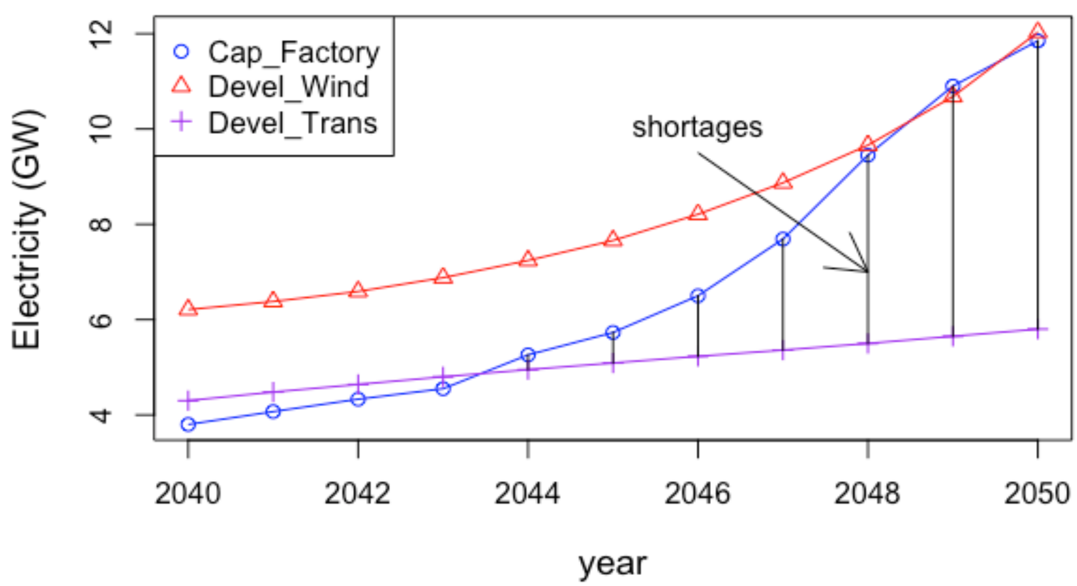
This section includes simulation results that show the asynchrony between the development of wind power farms and transmission facilities. Subsequently, alternative energy-policies for mitigating the asynchrony and improving the performance of the wind-power supply chain are assessed.

5.4.1. Synchrony in the wind-power supply chain and its implications for the industry performance

The simulation model assesses the performance of the wind-power supply chain of Brazil as affected by the asynchrony of energy policies, as shown in Figure 32 (a). The capacity development of transmission facilities and wind farms was assessed by conducting two simulation tests. Simulations test the hypothesis that if no synchronisation is in place, investments in transmission capacity may prove to be inadequate in the face of rapid growth of wind farms, because of the time lags inherent in building the required infrastructure. Figure 32 (b) shows shortages that may occur in transmission lines as the result of a 5% increase for the wind industry power electricity generation over the time period 2040-2050. This shortage may be the result of both long construction-time delays for new transmission lines as well as the inadequacy of investment incentives associated with delays in auctions. Additionally, the delivery times for parts and components for wind farm construction produce an asynchrony in the operations running along the supply chain. Therefore, even though there is an initial steady growth in the wind industry, the developing transmission lines do not keep pace with its growth, consequently affecting the activity of wind farms.



(a) Dynamics of the development of transmission infrastructure (Devel_Trans) and wind power rate (Devel_Wind) with a 5% increase in investment for the wind industry and 2.5% for transmission line development



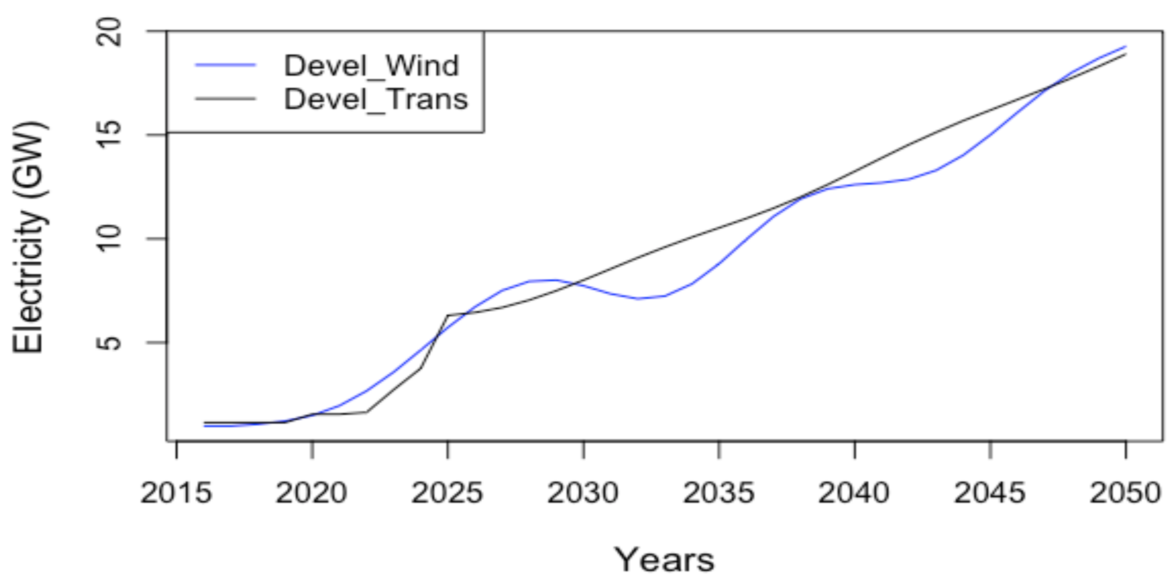
(b) Asynchrony between the capacity development of transmission infrastructure and wind power associated with the growth in the wind industry over the time period 2040-2050 as from a blow-up of figure 5(a)

Figure 32. Impact of asynchronous energy-policies over the time period 2016-2050 on the wind-power supply chain, with a 5% growth in wind industry electricity generation

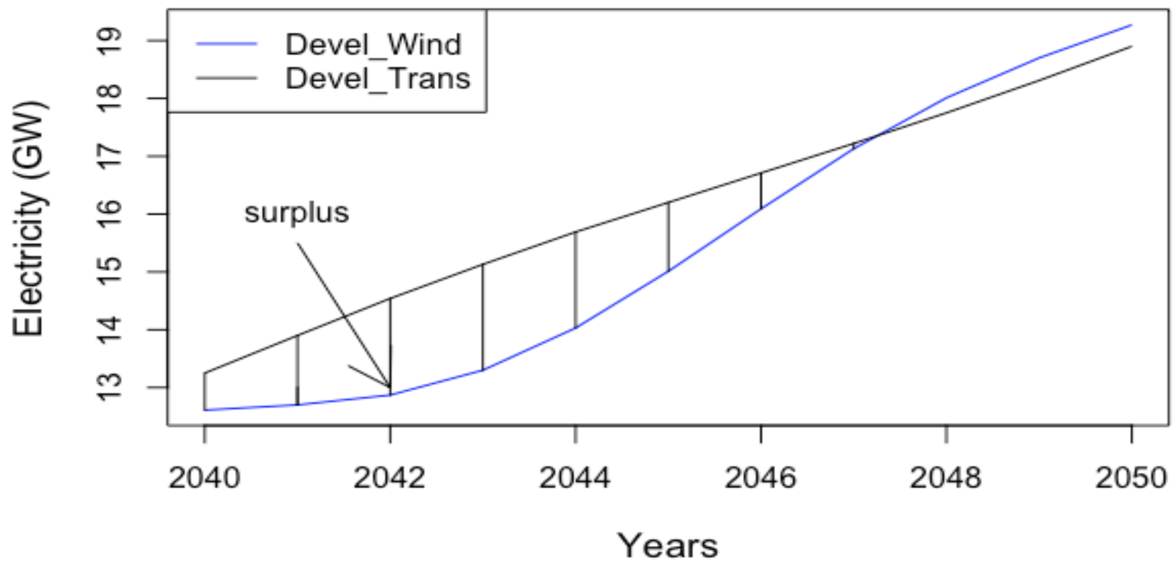
Thus, the wind-power supply chain in Brazil needs to address the issue of coordinating energy policy along the supply chain, including the appropriate incentives for transmission infrastructure (considering the unavoidable delays). A synchronised energy policy might be attained with the help of better coordination and conjoint planning among suppliers, industry and the transmission operator in terms of investment, delivery times and the scheduling of times for wind farm maintenance. The way in which this might be achieved is discussed next.

Three coordination policies are examined: a) promotion of coordinated investment policies for the transmission and manufacturing sectors; b) promotion of reductions in delivery time for developing wind farms, construction of windmills (wind power manufacturing) and the manufacture of windmill components; and c) reduction of time taken for wind farm maintenance.

Coordinating investment policy: Figure 33 (a) shows surpluses in transmission lines as investment increases at a rate of 6% per annum and as the manufacturing input into the wind industry increases its throughput at a rate of 10% per annum. Naturally, when increasing investments in transmissions at higher rates, synchronous coordination might be attained. In this exercise, it was accomplished by increasing the transmission incentives by 40% of the original value (2.5%). Interestingly, a significant increase in the developing transmission lines results in synchrony along the entire supply chain (up to electricity delivery), as illustrated in Figure 33 (b). During the period 2020 to 2050, the developing transmission lines exhibit a pronounced rise attributable to investment incentives for the construction of transmission capacity that guarantees the security of energy supply as well as the synchrony between the transmission and wind power development.



(a) Dynamics of the development of transmission infrastructure (Devel_Trans) and wind power rate (Devel_Wind) with a 10% increase in the investment of wind industry and 6% for the developing transmission lines



(b) Synchrony between the capacity development of transmission infrastructure and wind power associated with the growth in wind industry over the time period 2040-2050 as from a blow-up of figure 6 (a)

Figure 33. Impact of synchronous energy-policies over the time period 2016-2050 on the wind-power supply chain, with a 10% increase in wind industry electricity generation

Although the wind-industry grows in this scenario, assembly of wind farms fell behind as the result of delivery delays from suppliers of parts for towers, which delayed the supply chain downstream. The effects of reductions in delivery time associated with industry capacity are evaluated next.

Promoting reductions in delivery time: To attain the appropriate wind power capacity, it is necessary to consider the delivery delay between industry developers and building wind farms. Delivery time is the main driver for the expansion of installed capacity in the supply chain, which causes the operational resources of both the industry and developers to increase or decrease. Equation (24) calculates the *accumulated capacity average* (ACA) used for the industry and developers of the wind-power supply chain, during the simulation periods.

$$ACA = \frac{\frac{I_0 + I_T}{2} + \sum_{t=0}^{T} I_t}{n} \qquad [GW] \qquad (24)$$

where:

I_0: Initial installed capacity

I_T: Final installed capacity for the period T

I_t: Installed capacity for each period t
n: Number of periods of simulation

The total generation capacity in place, for each year, is established according to Equation (25) and depends on: the wind industry, installed capacity of wind farms, the capacity production of developers and delivery time.

$$GCPR = \frac{\frac{ACA_{IND} + ACA_{WP}}{2} + [ACA_{IND} + ACA_D + ACA_{WP}]}{Dt} \quad [GW] \qquad (25)$$

where:
ACA_{IND}: Average capacity of wind industry
ACA_{WP}: Average installed capacity of wind farms
ACA_D: Average capacity of developers
Dt: Delivery time
$GCPR$: Total generation capacity in place, for each year.

The results of the installation rate in the wind-power supply chain, according to the delivery delays between industry and developers, are shown in Table 7. Results show increases in generation capacity in place as deliveries present reduction in time, supporting the expansion of the transmission system. Thus, the reduction of delivery time will help to coordinate investment policies in transmission and in developing wind farms. In this sense, the simulations suggest that it should be possible to attain policy synchronization.

Table 8. Simulation for different delivery times between industry and developers of the Brazilian wind farms vs. coordinating investment policy for transmission capacity

Delivery time	2 years	3 years	5 years
Generation capacity in place (GW)	4.85	2.39	1.20
	Uncoordinated investment policy		Coordinated investment policy
Transmission capacity in place (GW)	3.78		5.53

Promoting reductions in maintenance time: The same type of closed-loop stock and flow structure used for the wind-power supply chain model is also used for representing the supply chain for the maintenance of wind turbines and towers. In this structure, the maintenance time plays an important role regarding the performance of wind farm developers as well as the on-going development of wind farms. Also, the maintenance rate means the product of the number and power rating of wind turbines that are maintained in a year. Two scenarios have been analysed with the objective of assessing the impact of a reduction in maintenance time along the supply chain. The first scenario showed the maintenance time of the current state of wind turbines and towers. The second scenario exhibits the effect of a 4% reduction in maintenance time observable when simulating the synchrony of an investment policy that's coordinated with reductions in delays of maintenance of wind farms. As shown in Figure 34, the effect of reducing maintenance time has a significant impact on the developing wind power infrastructure. In the other words, the developing wind power is subject to a decrease or increase in the maintenance times for the wind turbines. Results indicate that a maintenance strategy associated with energy policies will have a significant impact on the development of wind farms.

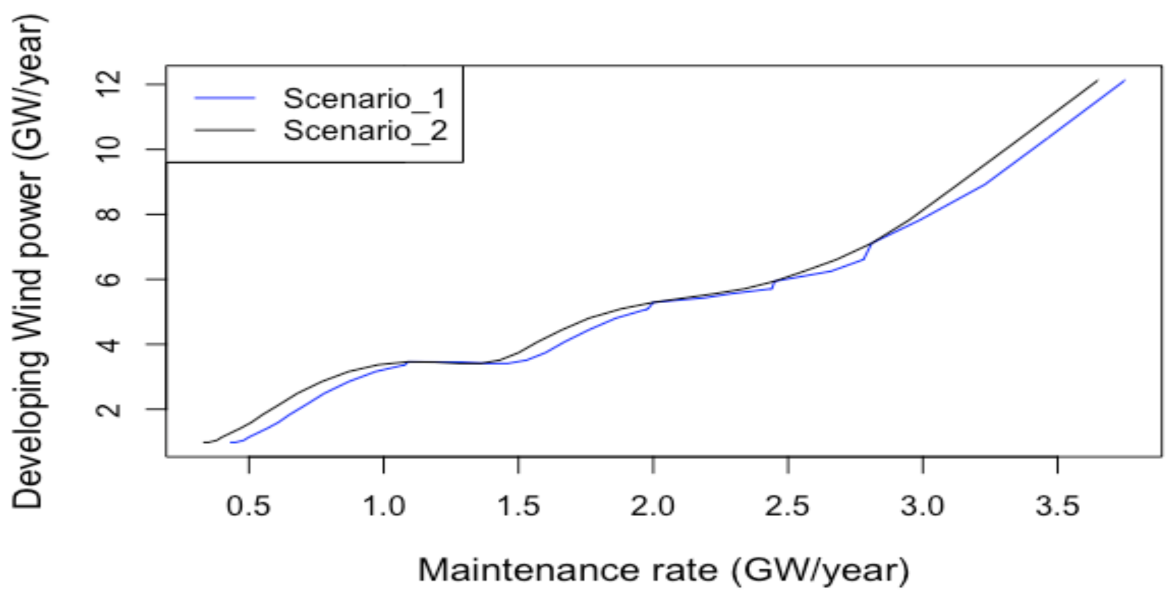


Figure 34. Effects of maintenance rate on the developing wind power. Scenario_1: current state, and Scenario_2: with a 4% decrease in the maintenance time

Simulation results show the need for policy that synchronizes the development of wind capacity and the transmission facilities. Even under a scenario with significant increases of wind power in Brazil, synchronization of the wind-power supply chain is achieved by: investment policy coordination, promotion of reductions in delivery times and reductions in the maintenance time of wind farms. Indeed, synchrony in the wind-power supply chain appears to be achievable with a 6% increase in the investment for developing transmission lines and a steady improvement in the construction times for the wind farms. Simulations of synchronized policy provide significant insights for both sustainable supply-chain management and for energy policies, in the context of strategic planning of resources.

5.5. Conclusions

This study uses system dynamics modelling for understanding how to synchronize wind power expansion and the corresponding transmission facilities to guarantee power supply. The chapter proposes a synchronized alternative policy for mitigating the asynchrony between wind power expansions when there is insufficient transmission infrastructure. The modelling results indicate that despite current wind industry growth in Brazil, the Northeast and North regions will be facing a strong reduction in the energy supply as the result of time delays in the construction of transmission lines. As the best wind conditions can be found in the Brazilian Northeast, and as the transmission infrastructure is not well developed (Kissel and Krauter, 2006), Brazil will benefit from the design of appropriate energy policies and must consider both the expansion of wind power generation and transmission-capacity development. In this sense, the investment costs in wind power should decrease with expansion of transmission systems, making wind power more attractive for other regions in the near future. This chapter shows that synchrony in the supply chain may be achieved with coordinated investment policy together with reductions in delivery times and the maintenance time of wind farms.

Despite Brazil having a major potential for low-cost energy production, a lack of transmission lines should be a concern for the sustainable development of the wind industry. In this sense, the research considers that the investment incentives must be applied throughout the wind-power supply chain, using integrated and coordinated policies. However, the required conditions for this to happen are not yet well established. When both industrial growth policies and energy incentive policies are applied simultaneously, they can have a great impact on both industrial growth and the diffusion of renewables. Then, this situation of synchronous policies guarantees sustainability among stakeholders in the supply chain.

Brazil will benefit from coordinated investment policies in the wind-power supply chain as well as from good management of the supply of components and of wind-farm maintenance. These are important elements for meeting targets in terms of energy security (Da Silva et al., 2016). A similar approach can be used to study the effects of asynchronous policies associated with the electricity price. Therefore, an analysis of the asynchrony of the electricity market, in terms of the impacts on prices, should be an issue for future research.

Conclusions and futures perspectives

The aim of this research has been to contribute on the asynchrony issue related with energy policy for the wind-power supply chain in Brazil. To that end, a model-based approach to synchronise wind industry policy has been outlined and the mathematical functions have been described, along with its contribution to performance and policy management literature. Also, the research allows to highlight the contribution of blending collaborative governance and DPM approach to foster policy coordination within wind power supply chain. The novel framework proposes, in this manuscript contributes to better understand the effects of energy policy on supply chain in long run. This research framework can summarise as following:

First, to identify and evaluate energy policy, this research developed a simulation model for the Northeaster Brazil, which comprised a behaviour analysis of installed capacity both transmission and wind generation (see, Chapter 2). This analysis then discussed the implications of asynchrony on electricity market of Brazil. The main contribution in this part is related with a propose to determine the level of new transmission capacity to be auctioned, through a function of classical production scheduling, which permits to mitigate effects of unsynchronised policy.

Second, the North-Northeast interconnection of Brazil was evaluated through simulation scenarios both transmission and wind generation to better understand the effects of unsynchronised policy (see, Chapter 3). This part thus reveals new insights based on synchronised decision rules (policies) in interconnected regions, which included transmission capacity. In this part, a novel mathematical function is added to improve the capacity of system energy incorporating transmission constraints in interconnected regions.

Third, simulation in this thesis mainly used as a tool for testing policies. However, from a management perspective, the research proposes a theoretical framework based on blending DPM approach and collaborative governance to foster policy coordination for wind power supply chain (see, Chapter 4). This theoretical framework shown how a collaborative governance may fail because of lack of stakeholders' skills such as continuous improvement and management, which can be compensated by the combination of collaborative governance perspective and a dynamic performance management approach. This part also suggests capability building fostering multi-institutional collaboration and learning to overcome energy policy challenges, which is evaluates through a collaborative governance coefficient within simulation model.

Fourth, an integral simulation-model in the last part is formulated, assessing the dynamic performance of wind-power supply chain through policy alternatives (see, Chapter 5). From a supply chain perspective, three coordination policies were examined in this part: a) promotion of coordinated investment policies for the transmission and manufacturing sectors; b) promotion of reductions in delivery time for developing wind farms, construction of windmills and the manufacture of windmill components; and c) reduction of time taken for wind farm maintenance. In this case, a mathematical formulation is proposed to calculate the accumulated capacity average for the wind power industry and developers, including delivery time of transmission lines construction. As result of reduction of delivery time, the coordination in transmission and in developing wind farms could improve.

Simulation results show that the main obstacles for the development of wind power would remain the deficiencies of the transmission infrastructure (see, Chapter 2 and 3), which has a significant impact on electricity prices, conclusion that extend the results of others studies (Bayer, 2018; Cardoso Júnior et al., 2014; De Jong et al., 2016; Miranda et al., 2017). In this case, with the intent to foster the wind power supply chain collaborative governance for mitigating the asynchrony and its impact on electricity market, the simulation scenarios demonstrate that a collaboration coefficient, as well as the time to build capacity should be considered (see, Chapter 4). Thus, wind-power industry strategy should consider to blending collaborative governance and DPM to develop alternative and more effective policies. When both industrial growth policies and energy incentive policies are applied simultaneously, they can have a great impact on both industrial growth and the wind-power supply chain deployment (see, Chapter 5).

This Doctoral thesis declares an interest in understanding how heterogeneity in energy policy decisions influences on energy supply chains, in contrast with others studios that only have studied the performance of the energy supply chains (Ahmad et al., 2016; Saavedra M. et al., 2018; Wee et al., 2012; Wüstemeyer et al., 2015). This research creates a great opportunity to contribute in the energy policy, management and modelling fields by developing explanations of performance differences among public and private sector, including a supply chain perspective. The results of research are a first step towards analysing the interactions between transmission capacity, wind power expansion and synchronised energy policy. Future work could include modelling of the synchronised energy policy that blend others intermittent renewable sources of electricity (e.g. solar, hydro and wind power). Also, other extension of this research could incorporate an analysis of technology innovation system on the wind-power supply chain of Brazil.

Contributions

The contributions of this thesis to the academy community are following:

Conferences

(1) Herrera M. M., Cosenz F., Dyner I., 2016, "Using simulation to analyse wind power penetration: the case of north and northeast Brazil", paper presented at the XIV Latin-American Conference of System Dynamics, San Paolo (Brazil), 19-21 Oct.;
(2) Herrera M. M., Dyner I., Cosenz F., 2016, "Effects of the penetration of wind power in the Brazilian electricity market", paper presented at the workshop on "Engineering applications" (WEA), Bogotá (Colombia), 21-23 Sept.;
(3) Herrera M. M., Cosenz F., Dyner I., 2016, "Using simulation to analyse renewables penetration in Brazil", paper presented at the XIV Colombian Conference of System Dynamics, Medellin (Colombia), 7-9 Sept.
(4) Herrera M. M., Cosenz F., Dyner I., 2016, Modelling boundaries of wind industry of Brazil: causes, consequences and challenges of research. Paper presented at the I Nacional Conference of Production Engineering, Bogotá (Colombia), 23 y 24 Nov.
(5) Herrera M. M., Cosenz F., Dyner I., 2017, Simulating North-Northeast interconnection: a wind power supply chain perspective, paper presented at the XV Colombian Conference of System Dynamics, Cartagena (Colombia), 30-31 Agosto y 1 Sept.
(6) Herrera M. M., Uriona M., Dyner I., 2017, Simulating auctions policy of the wind power supply chain of Brazil, paper presented in the XV Latin-American Conference of System Dynamics, Santiago (Chile), 18-20 Oct.
(7) Herrera M.M. Cosenz, Dyner I. 2018, Alternatives policy for the wind power supply chain in the North and Northeast region, paper presented in the XVI Latin-American Conference of System Dynamics, Puebla (Mexico), 17-19 Oct.

Papers

(8) Herrera M. M., Dyner I., Cosenz F., 2019, "Assessing the effect of transmission constraints on wind power expansion in northeast Brazil", paper published in journal: Utilities Policy, Elsevier, V59, p 9-24. https://doi.org/10.1016/j.jup.2019.05.010.
(9) Herrera M. M., Cosenz F., Dyner I., 2019, "How to support energy policy coordination of wind power supply chain? Collaborative governance through a dynamic performance management approach", paper published in journal: The Electricity Journal, Elsevier, https://doi.org/10.1016/j.tej.2019.106636.
(10) Herrera M. M., Dyner I., Cosenz F., 2019, "Benefits from energy policy synchronisation of the North-Northeast interconnection of Brazil", paper submitted to Energy Journal, Elsevier.

(11) Herrera M. M., Dyner I., Cosenz F., 2016, "Effects of the penetration of wind power in the Brazilian electricity market", paper published in Revista de Ingeniería Bio-Bio, V. 15 Nº 3, p. 309-319. ISSN 0718-8307. Chile.

(12) Herrera M. M., Cosenz F., Dyner I., 2017, "Using simulation to analyse wind power penetration: the case of north and northeast Brazil", paper published in Iberoamerican Journal of Industrial Engineering, V. 9 Nº 18, ISSN 2175-8018. Brazil.

Chapters book

(13) Herrera, M.M., Dyner, I., Cosenz, F., 2018. Alternative Energy Policy for Mitigating the Asynchrony of the Wind-Power Industry's Supply Chain in Brazil, in: Qudrat-Ullah, H. (Ed.), Innovative Solutions for Sustainable Supply Chains. Springer International Publishing, Cham, pp. 199–221. https://doi.org/10.1007/978-3-319-94322-0_8

(14) Herrera M. M., Cosenz F., Dyner I., 2019, "Blending collaborative governance and dynamic performance management to foster policy coordination in renewable energy supply chains", chapter submitted in book: "Enabling collaborative governance through systems modelling methods". Springer.

Utilities Policy 59(2019) 100924

Contents lists available at Science Direct

Utilities Policy

journal home page: www. elsevier.com/locate/j up

Assessing the eff ect of transmission constraints on wind power expansion in northeast Brazil

Milton M. Herrera [a,b], Isaac Dyner [b,*], Federico Cosenz [c]

[a] Universidad Militar Nueva, Granada, Colombia
[b] Universidad Jorge Tadeo, Lozano, Colombia
[c] Università Degli Studi di, Palermo, Colombia

ARTICLE INFO

Keywords:
Transmission congestion
Simulation
Wind power

ABSTRACT

The rapid growth of the wind industry in Brazil presents new opportunities and challenges for its electricity industry. As new capacity becomes available, more transmission infrastructure is required for security of supply. The Brazilian electricity system has experienced congestion in the northeast region, aff ecting the coordinated expansion of transmission and new wind power capacity. This paper uses a simulation model for better assessing long-term policy synchrony of the wind industry. The simulation shows that the resulting prices are competitive in the middle to long terms.

1. Introduction

Brazil is predominantly hydropower based with a contribution of 61% of the total capacity in place (ANEEL, 2017a). Throughout history, several large hydro-reservoir power plants, such as Itaipu and Tucuruí, have been built seeking security of supply. However, recurrent droughts and sedimentation have significantly reduced electricity generation capacity as volumes of water stored in dams have been reduced over time (Miranda and Mauad, 2014; Von Sperling, 2012). In these conditions, wind power provides an opportunity for complementing the current capacity.

Brazil has experienced significant advances in energy policy (Aquila et al., 2017; Bradshaw, 2017), which have promoted the expansion of the wind power capacity at a rate of 40% during the period 2012–2017 (ABEEólica, 2018a). This has been achieved through an auction-based mechanism that has also increased the number of investors, from 16 to 49 (Bayer, 2018).

In this context, despite considerable progress in wind power farms, Brazilian transmission infrastructure is not supporting the required transactions, principally in the Northeast region of Brazil (Da Silva et al., 2016; De Jong et al., 2017; De Melo et al., 2016; Global Transmission Report, 2016; Hunt et al., 2018; Miranda et al., 2017; Operador Nacional Do Sistema Elétrico - ONS, 2017). The auctions of transmission lines have been facing delays, compromising wind-power operation and security of supply for the region (Cardoso Júnior et al., 2014; De Jong et al., 2015; Moreira et al., 2015). More than 30% of wind projects with expired implementation deadlines still do not have a grid connection and only 14% from the first eight auction rounds were completed on schedule (Bayer, 2018). Fig. 1 presents a diagram of delayed transmission lines (yellow lines), highlighting that the completion deadlines have already expired. To date, Brazil was expecting to have 7800 km of transmission lines in place but only 2000 km have been built (ONS, 2018), reflecting a delay of as much as three years. This problem does not only reduce electricity supply capacity and in-crease electricity prices but also threatens the wind power expansion plan (De Melo et al., 2016), raising questions about how time delays in transmission infrastructure might aff ect the development of the wind power industry in the middle and long terms.

Previous studies have analysed the expansion of wind power sources in Brazil (Brannstrom et al., 2017; Da Silva et al., 2016; Pereira et al., 2012; Silva et al., 2013); other works discuss the eff ects of environ-mental and other barriers to wind power penetration (De Jong et al., 2016; E. B. Pereira et al., 2013b; Silva et al., 2013). Da Silva et al. (2016) show a strong seasonal correlation between precipitation and off shore winds in the North, Northeast, Southeast, and Southern regions of Brazil which counters the intermittent nature of wind power supply. However, research draws attention to the need for significant increases in long transmission lines to better integrate wind power into the Brazilian electricity system (De Jong et al., 2016; WWF-Brasil – Fundo Mundial para a Natureza, 2015). The existing literature off ers valuable insight for the design and formulation of wind power policy in Brazil. Nevertheless, wind power growth is not sufficiently analysed with

* Corresponding author. Carrera 4 # 22-61, Universidad Jorge Tadeo, Lozano, Colombia.
E-mail addresses: milton.herrera@unimilitar.edu.co (M.M. Herrera), isaac.dynerr@utadeo.edu.co (I. Dyner), federico.cosenz@unipa.it (F. Cosenz).

https://doi.org/10.1016/j.jup.2019.05.010
Received 12 August 2018; Received in revised form 14 May 2019; Accepted 14 May 2019

The Electricity Journal 32 (2019) xxx-xxx

Contents lists available at ScienceDirect

The Electricity Journal

journal homepage: www.elsevier.com

ELSEVIER

How to support energy policy coordination? Findings from the Brazilian wind industry

Milton M. Herrera [a, b*], Federico Cosenz [b], Isaac Dyner [c]

[a] Centre Research in Economic Sciences, Universidad Militar Nueva Granada, Bogotá, Colombia
[b] Department of Political Sciences and International Relations, University of Palermo, Palermo, Italy
[c] Faculty of Natural Sciences and Engineering, Universidad Jorge Tadeo Lozano, Bogotá, Colombia

ARTICLEINFO

Keywords:
Renewable energy
Policy coordination
Simulation
Collaborative governance
Dynamic performance management

ABSTRACT

Despite a growing sense of urgency, the deployment of clean technologies has been affected by fragmentation of energy policy design and implementation. In some case, wicked policy issues around renewable energy infrastructure have delayed or even halted the uptake of renewables. To find possible answer to consistent policy design that involves public/private institutions of the electricity sector, the authors propose the adoption of a dynamic performance management approach to support the energy policy coordination.

1. Introduction

In the last few years, the prevailing literature on energy management and public governance has increasingly highlighted the importance of supporting energy policy design and implementation through a robust strategic coordination among stakeholders (Jimenez et al., 2016; Matos and Silvestre, 2013; Wee et al., 2012; Wüstemeyer et al., 2015). However, similarly to other domains where public and private institutions are called to jointly operate for providing services to communities, the coexistence of multiple stakeholders interacting in a wide governance setting has often increased its complexity and fragmentation, thus leading to poor performance levels (Bouckaert et al., 2010; Bouckaert and Halligan, 2008). A higher complexity and fragmented governance are likely to facilitate the outbreak of wicked problems in the decision-making processes of these stakeholders. As argued by Head and Alford (2015), wicked problems are meant as public policy andmanagement-related issues hard to define and manage due to the high complexity of the environment which they affect, often leading to counter- intuitive implications when actions are taken to resolve them. For in- stance, in energy policy-making, conflicts of interest among stakeholders may arise generating a lack of strategic coordination and delays be- tween the design and implementation of policies affecting the overall performance of the wind power industry.

The performance of wind industry is driven by the actors operational capacity, which influence the response time of demand changes (Herrera et al., 2018). Although the wind industry has recently expanded worldwide, its logistic operations are associated with the delayed implementation of wind farms caused by the lead-times along the supply chain. In this perspective, the concerns related to supply-chain operations generate a negative effect on the security of energy supply,
i.e. high freight costs and operational bottlenecks (Nogueira De Oliveira et al., 2016; Prostean et al., 2014).

With the intent to overcome the above shortcomings (i.e., frag- mentation in energy policy design and implementation, delays in energy supply operations, poor performances, lack of policy coordination), this article aims to explore how to support decision-makers to foster policy coordination in wind power industry. To this end, this article proposes the adoption of a methodological approach based on the combination between collaborative governance and dynamic performance management. On the one side, this methodological choice is oriented to enhance the collaboration among the multiple stake- holders intervening in the decision-making processes throughout the overall renewable energy supply-chain (Ansell and Gash, 2008; Wee et al., 2012). Aiming to reduce policy design fragmentation and co-
ordinate efforts in facing wicked problems, collaborative governance brings public and private stakeholders together in collective forums with public agencies to engage in consensus-oriented decision-making. On the other side, such collaboration may find an additional support by virtue of performance management mechanisms designed through a simulation approach with System Dynamics (SD) methodology (Bianchi, 2016; Bianchi et al., 2017; Cosenz, 2017; Cosenz and Noto, 2016; Torres et al., 2017). Under the sobriquet of

* Corresponding author at: Centre Research in Economic Sciences, Universidad Militar Nueva Granada, Bogotá, Colombia.
Email addresses: milton.herrera@unimilitar.edu.co (M.M. Herrera); federico.cosenz@unipa.it (F. Cosenz); isaac.dynerr@utadeo.edu.co (I. Dyner)
https://doi.org/10.1016/j.tej.2019.106636
Received 14 February 2019; Accepted 12 July 2019 Available online xxx
1040-6190/ © 2019.

Chapter 8
Alternative Energy Policy for Mitigating the Asynchrony of the Wind-Power Industry's Supply Chain in Brazil

Milton M. Herrera, Isaac Dyner, and Federico Cosenz

8.1 Introduction

One of the main concerns of the Brazilian electricity market is its high dependency on hydroelectricity. The impacts generated by changing climate conditions and the sedimentation of dams have strongly affected hydroelectricity generation, causing a reduction of storage levels in dams (De Lucena et al. 2009). In recent decades, Brazil initiated its commitment to wind power in order to meet the challenges of sustainable energy development. Though renewable energy policies are achieving improvements in the power sector, the problem of time delays in the construction of new transmission stations affects the rapid expansion of wind power.

In 2013, Brazil faced problems regarding the lack of sufficient transmission lines, which affected generation by the wind farms. Consequently, the country was forced to use diesel and natural thermoelectric power generation. The cost of generation shot up, and this obliged the system to compensate the wind-power companies that had completed their projects by 2012 but had no means to dispatch their

M. M. Herrera (✉)
Universidad Jorge Tadeo Lozano, Bogotá, Colombia

Department of European Studies and International Integration (DEMS), Università Degli Studi di Palermo, Palermo, Italy
e-mail: miltonm.herrerar@utadeo.edu.co

I. Dyner
Faculty of Natural Science and Engineering, Universidad Jorge Tadeo Lozano, Bogotá, Colombia
e-mail: isaac.dynerr@utadeo.edu.co

F. Cosenz
Department of European Studies and International Integration (DEMS), Università Degli Studi di Palermo, Palermo, Italy
e-mail: federico.cosenz@unipa.it

H. Qudrat-Ullah (ed.), *Innovative Solutions for Sustainable Supply Chains*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-319-94322-0_8

References

ABDI, 2014. Mapeamento da cadeia produtiva da indústria eólica no Brasil. Agência Bras. Desenvolv. Ind. 1–177.

ABEEolica, 2017. Annual wind energy report. Brazil.

ABEEólica, 2018a. Annual wind energy report 2017 [WWW Document]. URL http://abeeolica.org.br/wp-content/uploads/2018/05/Boletim.pdf (accessed 6.28.18).

ABEEólica, 2018b. Dados ABEEólica [WWW Document]. URL http://www.abeeolica.org.br (accessed 3.29.18).

ABEEólica, 2016. Potencial eólico do Brasil é de 500GW [WWW Document]. URL http://www.abeeolica.org.br/noticias/potencial-eolico-do-brasil-e-de-500gw/ (accessed 3.29.18).

Abrell, B.J., Rausch, S., 2016. Cross-Country Electricity Trade , Renewable Energy and European Transmission Infrastructure Policy. J. Environ. Econ. Manage. https://doi.org/10.1016/j.jeem.2016.04.001

Agencia Nacional de Energía Eléctrica-ANEEL, 2017. Leiloes de Geraçao [WWW Document]. URL http://www.aneel.gov.br/geracao4 (accessed 10.12.17).

Agusdinata, D.B., Lee, S., Zhao, F., Thissen, W., 2014. Simulation modeling framework for uncovering system behaviors in the biofuels supply chain network. Simulation 90, 1103–1116. https://doi.org/10.1177/0037549714544081

Ahmad, S., Mat Tahar, R., Muhammad-Sukki, F., Munir, A.B., Abdul Rahim, R., 2016. Application of system dynamics approach in electricity sector modelling: A review. Renew. Sustain. Energy Rev. 56, 29–37. https://doi.org/10.1016/j.rser.2015.11.034

Almeida Prado, F., Athayde, S., Mossa, J., Bohlman, S., Leite, F., Oliver-Smith, A., 2016. How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. Renew. Sustain. Energy Rev. 53, 1132–1136. https://doi.org/10.1016/j.rser.2015.09.050

Andrade, E.M., Paulo Cosenza, J., Pinguelli Rosa, L., Lacerda, G., 2012. The vulnerability of hydroelectric generation in the Northeast of Brazil: The environmental and business risks for CHESF. Renew. Sustain. Energy Rev. 16, 5760–5769. https://doi.org/10.1016/j.rser.2012.06.028

ANEEL, 2018. Informações Técnicas [WWW Document]. URL http://relatorios.aneel.gov.br/_layouts/xlviewer.aspx?id=/RelatoriosSAS/RelSampRegCC.xlsx&Source=http://relatorios.aneel.gov.br/RelatoriosSAS/Forms/AllItems.aspx&DefaultItemOpen=1

ANEEL, 2017a. Matriz de Energía Eléctrica [WWW Document]. Capacid. Operación. URL http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm (accessed 11.28.17).

ANEEL, 2017b. Leilões de Transmissão [WWW Document]. http://www.aneel.gov.br/transmissao4.

ANEEL, 2016. Matriz de Energia Eléctrica [WWW Document]. Capacid. Operación. URL www2.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm

Ansell, C., Gash, A., 2008. Collaborative Governance in Theory and Practice. J. Public Adm. Res. Theory 18, 543–571. https://doi.org/10.1093/jopart/mum032

Aquila, G., Pamplona, E. de O., Queiroz, A.R. de, Rotela Junior, P., Fonseca, M.N., 2017a. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. Renew. Sustain. Energy Rev. 70, 1090–1098. https://doi.org/10.1016/j.rser.2016.12.013

Aquila, G., Rotela Junior, P., de Oliveira Pamplona, E., de Queiroz, A.R., 2017b. Wind power feasibility analysis under uncertainty in the Brazilian electricity market. Energy Econ. 65, 127–136. https://doi.org/10.1016/j.eneco.2017.04.027

Arango, S., Dyner, I., Larsen, E.R., 2006. Lessons from deregulation: Understanding electricity markets in South America. Util. Policy 14, 196–207. https://doi.org/10.1016/j.jup.2006.02.001

Asif, F.M., Bianchi, C., Rashid, A., Nicolescu, C.M., 2012. Performance analysis of the closed loop supply chain. J. Remanufacturing 2, 4. https://doi.org/10.1186/2210-4690-2-4

Aslani, A., Helo, P., Naaranoja, M., 2014a. Role of renewable energy policies in energy dependency in Finland: System dynamics approach. Appl. Energy 113, 758–765. https://doi.org/10.1016/j.apenergy.2013.08.015

Aslani, A., Helo, P., Naaranoja, M., 2014b. Role of renewable energy policies in energy dependency in Finland: System dynamics approach. Appl. Energy 113, 758–765. https://doi.org/10.1016/j.apenergy.2013.08.015

Bale, C.S.E., Varga, L., Foxon, T.J., 2015. Energy and complexity: New ways forward. Appl. Energy 138, 150–159. https://doi.org/10.1016/j.apenergy.2014.10.057

Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. Syst. Dyn. Rev. 12, 183–210. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Bayer, B., 2018. Experience with auctions for wind power in Brazil. Renew. Sustain. Energy Rev. 81, 2644–2658. https://doi.org/10.1016/j.rser.2017.06.070

Bayer, B., Berthold, L., Moreno Rodrigo de Freitas, B., 2018. The Brazilian experience with auctions for wind power: An assessment of project delays and potential mitigation measures. Energy Policy 122, 97–117. https://doi.org/10.1016/j.enpol.2018.07.004

Bianchi, C., 2016. System Dynamics for Performance Management, First. ed. Springer Switzerland.

Bianchi, C., 2012a. Enhancing performance management and sustainable organizational growth through system dynamics modeling., in: Systemic Management for Intelligent Organizations: Concepts, Models-Based Approaches and Applications. pp. 1–273. https://doi.org/10.1007/978-3-642-29244-6

Bianchi, C., 2012b. Enhancing Performance Management and Sustainable Organizational Growth Through System-Dynamics Modelling, in: Systemic Management for Intelligent Organizations: Concepts, Models-Based Approaches and Applications. Springer-Verlag Berlin Heidelberg, pp. 143–161. https://doi.org/10.1007/978-3-642-29244-6

Bianchi, C., Bovaird, T., Loeffler, E., 2017. Applying a Dynamic Performance Management Framework to Wicked Issues: How Coproduction Helps to Transform Young People's Services in Surrey County Council, UK. Int. J. Public Adm. 40, 833–846. https://doi.org/10.1080/01900692.2017.1280822

Bouckaert, G., Halligan, J., 2008. Managing performance: International comparisons. Routledge, London.

Bouckaert, G., Peters, B.G., Verhoest, K., 2010. Coordination of public sector organizations: Shifting patterns of public management. Palgrave Macmillan, Basingstoke, UK.

Bradshaw, A., 2017. Regulatory change and innovation in Latin America: The case of renewable energy in Brazil. Util. Policy 49, 156–164. https://doi.org/10.1016/j.jup.2017.01.006

Brannstrom, C., Gorayeb, A., de Sousa Mendes, J., Loureiro, C., Meireles, A.J. de A., Silva, E.V. da, Freitas, A.L.R. de, Oliveira, R.F. de, 2017. Is Brazilian wind power development sustainable? Insights from a review of conflicts in Ceará state. Renew. Sustain. Energy Rev. 67, 62–71. https://doi.org/10.1016/j.rser.2016.08.047

Bukarica, V., Tomsic, Z., 2017. Design and Evaluation of Policy Instruments for Energy Efficiency Market. IEEE Trans. Sustain. Energy 8, 354–362. https://doi.org/10.1109/TSTE.2016.2599584

Burke, M.J., Stephens, J.C., 2018. Political Power and Renewable Energy Futures: A Critical Review. Energy Res. Soc. Sci. 35, 0–1. https://doi.org/10.1016/j.erss.2017.10.018

Cabalu, H., Koshy, P., Corong, E., Rodriguez, U.-P.E., Endriga, B.A., 2015. Modelling the impact of energy policies on the Philippine economy: Carbon tax, energy efficiency, and changes in the energy mix. Econ. Anal. Policy 48, 222–237. https://doi.org/10.1016/j.eap.2015.11.014

Campos, A.F., da Silva, N.F., Pereira, M.G., Vasconcelos Freitas, M.A., 2017. A review of Brazilian natural gas industry: Challenges and strategies. Renew. Sustain. Energy Rev. 75, 1207–1216. https://doi.org/10.1016/j.rser.2016.11.104

Campuzano, F., 2011. Supply Chain simulation: a systems dynamics approach for improving performance, First. ed. Springer London. https://doi.org/10.1007/978-0-85729-719-8

Cardenas, L.M., Franco, C.J., Dyner, I., 2016. Assessing emissions-mitigation energy policy under integrated supply and demand analysis: The Colombian case. J. Clean. Prod. 112, 3759–3773. https://doi.org/10.1016/j.jclepro.2015.08.089

Cardoso Júnior, R.A.F., Magrini, A., da Hora, A.F., 2014. Environmental licensing process of power transmission in Brazil update analysis: Case study of the Madeira transmission system. Energy Policy 67, 281–289. https://doi.org/10.1016/j.enpol.2013.12.040

Castaneda, M., Franco, C.J., Dyner, I., 2017. Evaluating the effect of technology transformation on the electricity utility industry. Renew. Sustain. Energy Rev. 80, 341–351. https://doi.org/10.1016/j.rser.2017.05.179

Cepeda, M., Finon, D., 2013. How to correct for long-term externalities of large-scale wind power development by a capacity mechanism? Energy Policy 61, 671–685. https://doi.org/10.1016/j.enpol.2013.06.046

Cepeda, M., Finon, D., 2011. Generation capacity adequacy in interdependent electricity markets. Energy Policy 39, 3128–3143. https://doi.org/10.1016/j.enpol.2011.02.063

Choong, C.G., McKay, A., 2013. Sustainability in the Malaysian palm oil industry. J. Clean. Prod. 85, 258–264. https://doi.org/10.1016/j.jclepro.2013.12.009

Cosenz, F., 2017. Supporting start-up business model design through system dynamics modelling. Manag. Decis. 55, 57–80.

Cosenz, F., 2014. A dynamic viewpoint to design performance management systems in academic institutions: Theory and practice. Int. J. Public Adm. 37, 955–969. https://doi.org/10.1080/01900692.2014.952824

Cosenz, F., Noto, G., 2017. A dynamic business modelling approach to design and experiment new business venture strategies. Long Range Plann. 1–14. https://doi.org/10.1016/j.lrp.2017.07.001

Cosenz, F., Noto, G., 2016. Applying System Dynamics Modelling to Strategic Management: A Literature Review. Syst. Res. Behav. Sci. 33, 703–741. https://doi.org/10.1002/sres.2386

Cucchiella, F., D'Adamo, I., 2013. Issue on supply chain of renewable energy. Energy Convers. Manag. 76, 774–780. https://doi.org/10.1016/j.enconman.2013.07.081

Da Silva, R.C., De Marchi Neto, I., Silva Seifert, S., 2016. Electricity supply security and the future role of renewable energy sources in Brazil. Renew. Sustain. Energy Rev. 59, 328–341. https://doi.org/10.1016/j.rser.2016.01.001

Dantas, G. de A., de Castro, N.J., Brandão, R., Rosental, R., Lafranque, A., 2017. Prospects for the Brazilian electricity sector in the 2030s: Scenarios and guidelines for its transformation. Renew. Sustain. Energy Rev. 68, 997–1007. https://doi.org/10.1016/j.rser.2016.08.003

De Faria, H., Trigoso, F.B.M., Cavalcanti, J.A.M., 2017. Review of distributed generation with photovoltaic grid connected systems in Brazil: Challenges and prospects. Renew. Sustain. Energy Rev. 75, 469–475. https://doi.org/10.1016/j.rser.2016.10.076

de Gooyert, V., Rouwette, E., van Kranenburg, H., Freeman, E., 2017. Reviewing the role of stakeholders in Operational Research: A stakeholder theory perspective.

Eur. J. Oper. Res. 262, 402–410. https://doi.org/10.1016/j.ejor.2017.03.079

De Jong, P., Dargaville, R., Silver, J., Utembe, S., Kiperstok, A., Torres, E.A., 2017. Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid. Appl. Energy 195, 538–555. https://doi.org/10.1016/j.apenergy.2017.03.058

De Jong, P., Kiperstok, A., Sánchez, A.S., Dargaville, R., Torres, E.A., 2016. Integrating large scale wind power into the electricity grid in the Northeast of Brazil. Energy 100, 401–415. https://doi.org/10.1016/j.energy.2015.12.026

De Jong, P., Kiperstok, A., Torres, E.A., 2015. Economic and environmental analysis of electricity generation technologies in Brazil. Renew. Sustain. Energy Rev. 52, 725–739. https://doi.org/10.1016/j.rser.2015.06.064

De Jong, P., Sánchez, A.S., Esquerre, K., Kalid, R.A., Torres, E.A., 2013. Solar and wind energy production in relation to the electricity load curve and hydroelectricity in the northeast region of Brazil. Renew. Sustain. Energy Rev. 23, 526–535. https://doi.org/10.1016/j.rser.2013.01.050

De Lucena, A.F.P., Szklo, A.S., Schaeffer, R., de Souza, R.R., Borba, B.S.M.C., da Costa, I.V.L., Júnior, A.O.P., da Cunha, S.H.F., 2009. The vulnerability of renewable energy to climate change in Brazil. Energy Policy 37, 879–889. https://doi.org/10.1016/j.enpol.2008.10.029

De Melo, C.A., Jannuzzi, G.D.M., Bajay, S.V., 2016a. Nonconventional renewable energy governance in Brazil: Lessons to learn from the German experience. Renew. Sustain. Energy Rev. 61, 222–234. https://doi.org/10.1016/j.rser.2016.03.054

De Melo, C.A., Jannuzzi, G.D.M., Bajay, S.V., 2016b. Nonconventional renewable energy governance in Brazil: Lessons to learn from the German experience. Renew. Sustain. Energy Rev. 61, 222–234. https://doi.org/10.1016/j.rser.2016.03.054

de Queiroz, A.R., Marangon Lima, L.M., Marangon Lima, J.W., da Silva, B.C., Scianni, L.A., 2016. Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. Renew. Energy 99, 379–389. https://doi.org/10.1016/j.renene.2016.07.022

Dutra, R.M., Szklo, A.S., 2008. Incentive policies for promoting wind power production in Brazil : Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation. Renew. Energy 33, 65–76. https://doi.org/10.1016/j.renene.2007.01.013

Dyner, I., 2000. Energy modelling platforms for policy and strategy support. J. Oper. Res. Soc. 51, 136–144.

Dyner, I., Larsen, E.R., 2001. From planning to strategy in the electricity industry. Energy Policy 29, 1145–1154. https://doi.org/10.1016/S0301-4215(01)00040-4

Feurtey, É., Ilinca, A., Sakout, A., Saucier, C., 2016. Institutional factors influencing strategic decision-making in energy policy; A case study of wind energy in France and Quebec (Canada). Renew. Sustain. Energy Rev. 59, 1455–1470. https://doi.org/10.1016/j.rser.2016.01.082

Fichter, T., Soria, R., Szklo, A., Schaeffer, R., Lucena, A.F.P., 2017. Assessing the potential role of concentrated solar power (CSP) for the northeast power system of Brazil using a detailed power system model. Energy 121, 695–715. https://doi.org/10.1016/j.energy.2017.01.012

Fiestas, R., GWEC, 2011. Analysis of the regulatory framework for wind power generation in Brazil 1–46.

Foley, T., Thornton, K., Hinrichs-rahlwes, R., Sawyer, S., Sander, M., Taylor, R., Teske, S., Lehmann, H., Alers, M., Hales, D., 2015. Renewables 2015 global status report. https://doi.org/10.1596/978-1-4648-0677-3_ch1

Ford, A., 1999. Cycles in competitive electricity markets: A simulation study of the western United States. Energy Policy 27, 637–658. https://doi.org/10.1016/S0301-4215(99)00050-6

Ford, A., 1997. System Dynamics and the Electric Power Industry. Syst. Dyn. Rev. 13, 57–85. https://doi.org/10.1002/(SICI)1099-1727(199721)13:1<57::AID-SDR117>3.0.CO;2-B

Forrester, J.W., 1961. Industrial dynamics.

Franco, C.J., Castaneda, M., Dyner, I., 2015. Simulating the new British Electricity-Market Reform. Eur. J. Oper. Res. 245, 273–285. https://doi.org/10.1016/j.ejor.2015.02.040

Geller, H., Schaeffer, R., Szklo, A., Tolmasquim, M., 2004. Policies for advancing energy efficiency and renewable energy use in Brazil. Energy Policy 32, 1437–1450. https://doi.org/10.1016/S0301-4215(03)00122-8

Georgiadis, P., Besiou, M., 2008. Sustainability in electrical and electronic equipment closed-loop supply chains: A System Dynamics approach. J. Clean. Prod. 16, 1665–1678. https://doi.org/10.1016/j.jclepro.2008.04.019

Ghaffarzadegan, N., Lyneis, J., Richardson, G.P., 2011. How small system dynamics models can help the public policy process. Syst. Dyn. Rev. 27, 22–44. https://doi.org/10.1002/sdr

Global Transmission Report, 2018. Update on Brazilian power sector: Key highlights of 2017 [WWW Document]. https://www.globaltransmission.info/archive.php?id=32000.

Global Transmission Report, 2016. Brazil’s Economic Downturn: Recession and lack of funds affect grid development [WWW Document]. https://www.globaltransmission.info/archive.php?id=26657.

Goldemberg, J., Schaeffer, R., Szklo, A., Lucchesi, R., 2014. Oil and natural gas prospects in South America: Can the petroleum industry pave the way for renewables in Brazil? Energy Policy 64, 58–70. https://doi.org/10.1016/j.enpol.2013.05.064

Gómez, C.R., Arango-Aramburo, S., Larsen, E.R., 2017. Construction of a Chilean energy matrix portraying energy source substitution: A system dynamics approach. J. Clean. Prod. 162, 903–913. https://doi.org/10.1016/j.jclepro.2017.06.111

González, M.O.A., Gonçalves, J.S., Vasconcelos, R.M., 2017. Sustainable development: Case study in the implementation of renewable energy in Brazil. J. Clean. Prod. 142, 461–475. https://doi.org/10.1016/j.jclepro.2016.10.052

Gorayeb, A., Brannstrom, C., de Andrade Meireles, A.J., de Sousa Mendes, J., 2018. Wind power gone bad: Critiquing wind power planning processes in northeastern Brazil. Energy Res. Soc. Sci. 40, 82–88. https://doi.org/10.1016/j.erss.2017.11.027

Haselip, J., Dyner, I., Cherni, J., 2005. Electricity market reform in Argentina: Assessing the impact for the poor in Buenos Aires. Util. Policy 13, 1–14. https://doi.org/10.1016/j.jup.2004.03.001

Head, B.W., Alford, J., 2015. Wicked Problems: Implications for Public Policy and Management. Adm. Soc. 47, 711–739. https://doi.org/10.1177/0095399713481601

Herrera, M.M., Dyner, I., Cosenz, F., 2019. Assessing the effect of transmission constraints on wind power expansion in northeast Brazil. Util. Policy 59, 100924. https://doi.org/10.1016/j.jup.2019.05.010

Herrera, M.M., Dyner, I., Cosenz, F., 2018. Alternative Energy Policy for Mitigating the Asynchrony of the Wind-Power Industry's Supply Chain in Brazil, in: Qudrat-Ullah, H. (Ed.), Innovative Solutions for Sustainable Supply Chains. Springer International Publishing, Cham, pp. 199–221. https://doi.org/10.1007/978-3-319-94322-0_8

Herrera, M.M., Dyner, I., Cosenz, F., 2017a. Effects of the penetration of wind power in the Brazilian electricity market. Rev. Ing. Ind. 15, 309–319.

Herrera, M.M., Dyner, I., Cosenz, F., 2017b. Using simulation to Analyze wind power penetration : The case of North and Northeast. Iberoam. J. Ind. Eng. 9, 71–83.

Herrera, M.M., Rosero, J., Casas, O., 2017c. Systemic Analysis of the Adoption of Electric Vehicle Technologies in Colombia. Int. Rev. Mech. Eng. 11, 256–269.

Hoffmann, B., Häfele, S., Karl, U., 2013. Analysis of performance losses of thermal power plants in Germany - A System Dynamics model approach using data from regional climate modelling. Energy 49, 193–203. https://doi.org/10.1016/j.energy.2012.10.034

Hunt., J.D., Stilpen, D., de Freitas, M.A.V., 2018. A review of the causes, impacts and solutions for electricity supply crises in Brazil. Renew. Sustain. Energy Rev. 88, 208–222. https://doi.org/10.1016/j.rser.2018.02.030

Hunt, S., 2002. Making competition work in electricity, Wiley Finance. https://doi.org/10.1007/s00347-007-1607-9

Ioakimidis, C., Koukouzas, N., Chatzimichali, A., Casimiro, S., Macarulla, A., 2012. Energy policy scenarios of CCS implementation in the Greek electricity sector. Energy Procedia 23, 354–359. https://doi.org/10.1016/j.egypro.2012.06.025

Jeon, C., Lee, J., Shin, J., 2015. Optimal subsidy estimation method using system dynamics and the real option model: Photovoltaic technology case. Appl. Energy 142, 33–43. https://doi.org/10.1016/j.apenergy.2014.12.067

Jimenez, M., Franco, C.J., Dyner, I., 2016. Diffusion of renewable energy technologies: The need for policy in Colombia. Energy 111, 818–829.

https://doi.org/10.1016/j.energy.2016.06.051
Juárez, A.A., Araújo, A.M., Rohatgi, J.S., De Oliveira Filho, O.D.Q., 2014. Development of the wind power in Brazil: Political, social and technical issues. Renew. Sustain. Energy Rev. 39, 828–834. https://doi.org/10.1016/j.rser.2014.07.086
Kissel, J.M., Krauter, S.C.W., 2006. Adaptations of renewable energy policies to unstable macroeconomic situations-Case study: Wind power in Brazil. Energy Policy 34, 3591–3598. https://doi.org/10.1016/j.enpol.2005.07.013
Kunsch, P.L., Friesewinkel, J., 2014. Nuclear energy policy in Belgium after Fukushima. Energy Policy 66, 462–474. https://doi.org/10.1016/j.enpol.2013.11.035
Kunz, F., Zerrahn, A., 2015. Benefits of coordinating congestion management in electricity transmission networks: Theory and application to Germany. Util. Policy 37, 34–45. https://doi.org/10.1016/j.jup.2015.09.009
Laquimia, M.B., Eweje, G., 2014. Collaborative Governance toward Sustainability: A Global Challenge on Brazil Perspective, in: Corporate Social Responsibility and Sustainability: Emerging Trends in Developing Economies. pp. 371–413. https://doi.org/10.1108/S2043-905920140000008018
Larsen, E.R., Dyner, I., Bedoya, L., Franco, C.J., 2004. Lessons from deregulation in Colombia: Successes, failures and the way ahead. Energy Policy 32, 1767–1780. https://doi.org/10.1016/S0301-4215(03)00167-8
Lee, S., Geum, Y., Lee, H., Park, Y., 2012. Dynamic and multidimensional measurement of product-service system (PSS) sustainability: A triple bottom line (TBL)-based system dynamics approach. J. Clean. Prod. 32, 173–182. https://doi.org/10.1016/j.jclepro.2012.03.032
Lesieutre, B.C., Eto, J.H., 2004. Electricity Transmission Congestion Costs: A review of recent reports, University of Califormia Berkeley. Berkeley, California.
Lima, D.K.S., Leão, R.P.S., dos Santos, A.C.S., de Melo, F.D.C., Couto, V.M., de Noronha, A.W.T., Oliveira, D.S., 2015. Estimating the offshore wind resources of the State of Ceará in Brazil. Renew. Energy 83, 203–221. https://doi.org/10.1016/j.renene.2015.04.025
Linton, J.D., Klassen, R., Jayaraman, V., 2007. Sustainable supply chains: An introduction. J. Oper. Manag. 25, 1075–1082. https://doi.org/10.1016/j.jom.2007.01.012
Liu, X., Zeng, M., 2017. Renewable energy investment risk evaluation model based on system dynamics. Renew. Sustain. Energy Rev. 73, 782–788. https://doi.org/10.1016/j.rser.2017.02.019
Lopes, V.S., Borges, C.L.T., 2015. Impact of the Combined Integration of Wind Generation and Small Hydropower Plants on the System Reliability. IEEE Trans. Sustain. Energy 6, 1169–1177. https://doi.org/10.1109/TSTE.2014.2335895
Luna-Reyes, L.F., Andersen, D.L., 2003. Collecting and analyzing qualitative data for system dynamics: Methods and models. Syst. Dyn. Rev. 19, 271–296. https://doi.org/10.1002/sdr.280

Lund, P.D., 2009. Effects of energy policies on industry expansion in renewable energy. Renew. Energy 34, 53–64. https://doi.org/10.1016/j.renene.2008.03.018

Mastropietro, P., Batlle, C., Barroso, L.A., Rodilla, P., 2014. Electricity auctions in South America: Towards convergence of system adequacy and RES-E support. Renew. Sustain. Energy Rev. 40, 375–385. https://doi.org/10.1016/j.rser.2014.07.074

Matos, S., Silvestre, B.S., 2013. Managing stakeholder relations when developing sustainable business models: The case of the Brazilian energy sector. J. Clean. Prod. 45, 61–73. https://doi.org/10.1016/j.jclepro.2012.04.023

Medeiros, M., Renan, S., 2016. Entrevista com Mario Dias Miranda, presidente da Abrate [WWW Document]. SindiEnergía. URL http://www.sindienergia.org.br/noticia.asp?cod_not=3114 (accessed 1.3.19).

Mendes, C.A.B., Beluco, A., Canales, F.A., 2017. Some important uncertainties related to climate change in projections for the Brazilian hydropower expansion in the Amazon. Energy 141, 123–138. https://doi.org/10.1016/j.energy.2017.09.071

Menz, F.C., Vachon, S., 2006. The effectiveness of different policy regimes for promoting wind power: Experiences from the states. Energy Policy 34, 1786–1796. https://doi.org/10.1016/j.enpol.2004.12.018

Ministerio de Minas e Energia, E., 2007. Plano Nacional de Energia 2030, Ministerio de Minas e Energia. https://doi.org/10.1017/CBO9781107415324.004

Miranda, R.B. De, Mauad, F.F., 2014. Influence of Sedimentation on Hydroelectric Power Generation : Case Study of a Brazilian Reservoir. J. Energy Eng. 04014016, 1–7. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000183.

Miranda, R., Soria, R., Schaeffer, R., Szklo, A., Saporta, L., 2017. Contributions to the analysis of “Integrating large scale wind power into the electricity grid in the Northeast of Brazil” [Energy 100 (2016) 401–415]. Energy 118, 1198–1209. https://doi.org/10.1016/j.energy.2016.10.138

Morcillo, J.D., Franco, C.J., Angulo, F., 2017. Delays in electricity market models. Energy Strateg. Rev. 16, 24–32. https://doi.org/10.1016/j.esr.2017.02.004

Moreira, J.M.L., Cesaretti, M.A., Carajilescov, P., Maiorino, J.R., 2015. Sustainability deterioration of electricity generation in Brazil. Energy Policy 87, 334–346. https://doi.org/10.1016/j.enpol.2015.09.021

Musango, J.K., Brent, A.C., Bassi, A.M., 2014. Modelling the transition towards a green economy in South Africa. Technol. Forecast. Soc. Change 87, 257–273. https://doi.org/10.1016/j.techfore.2013.12.022

Naill, R.F., Belanger, S.D., 1989. A System Dynamics Model For National Energy Policy Planning. Comput. Manag. Complex Syst. 8, 423–433.

Neuhoff, K., Newberry, D., 2005. Evolution of electricity markets: Does sequencing matter? Util. Policy 13, 163–173. https://doi.org/10.1016/j.jup.2004.12.008

Nogueira De Oliveira, L.P., Rodriguez Rochedo, P.R., Portugal-Pereira, J., Hoffmann, B.S., Aragão, R., Milani, R., De Lucena, A.F.P., Szklo, A., Schaeffer, R., 2016. Critical technologies for sustainable energy development in Brazil: Technological foresight based on scenario modelling. J. Clean. Prod. 130, 12–24.

https://doi.org/10.1016/j.jclepro.2016.03.010
Ochoa, C., Dyner, I., Franco, C.J., 2013. Simulating power integration in Latin America to assess challenges, opportunities, and threats. Energy Policy 61, 267–273. https://doi.org/10.1016/j.enpol.2013.07.029
Ochoa, C., Gore, O., 2015. The Finnish power market: Are imports from Russia low-cost? Energy Policy 80, 122–132. https://doi.org/10.1016/j.enpol.2015.01.031
Ochoa, C., van Ackere, A., 2015. Winners and losers of market coupling. Energy 80, 522–534. https://doi.org/10.1016/j.energy.2014.11.088
Ochoa, C., van Ackere, A., 2014. Does size matter? Simulating electricity market coupling between Colombia and Ecuador. Renew. Sustain. Energy Rev. 50, 1108–1124. https://doi.org/10.1016/j.rser.2015.05.054
Oliva, R., 2003. Model calibration as a testing strategy for system dynamics models. Eur. J. Oper. Res. 151, 552–568. https://doi.org/10.1016/S0377-2217(02)00622-7
Oliveira, I.A. de, Schaeffer, R., Szklo, A., 2017. The impact of energy storage in power systems: The case of Brazil's Northeastern grid. Energy 122, 50–61. https://doi.org/10.1016/j.energy.2017.01.064
Oliveira, J.B., Lima, R.S., Montevechi, J.A.B., 2016. Perspectives and relationships in Supply Chain Simulation: A systematic literature review. Simul. Model. Pract. Theory 62, 166–191. https://doi.org/10.1016/j.simpat.2016.02.001
ONS, 2018. Hitórico da Operaçao [WWW Document]. URL http://ons.org.br/pt/paginas/resultados-da-operacao/historico-da-operacao (accessed 1.2.19).
Operador Nacional Do Sistema Elétrico - ONS, 2017. Plano de Ampliações e Reforços nas Instalações de Transmissão do SIN.
Orjuela-Castro, J., Herrera-Ramirez, M., Adarme-Jaimes, W., 2017. Warehousing and transportation logistics of mango in Colombia : A system dynamics model. Rev. Fac. Ing. 26, 71–85. https://doi.org/http://dx.doi.org/10.19053/01211129
Orjuela, J., Herrera, M.M., Casilimas, W., 2015. Impact analysis of transport capacity and food safety in Bogota, in: Workshop Engineering Application. pp. 7–13. https://doi.org/10.1109/WEA.2015.7370138
Pao, H.T., Fu, H.C., 2013. Renewable energy, non-renewable energy and economic growth in Brazil. Renew. Sustain. Energy Rev. 25, 381–392. https://doi.org/10.1016/j.rser.2013.05.004
Peña, A.M., 2014. The political trajectory of the Brazilian CSR movement. Crit. Perspect. Int. Bus. 10, 310–328. https://doi.org/10.1108/cpoib-03-2014-0016
Pereira, A.O., Cunha Da Costa, R., Costa, C.D.V., Marreco, J.D.M., La Rovere, E.L., 2013. Perspectives for the expansion of new renewable energy sources in Brazil. Renew. Sustain. Energy Rev. 23, 49–59. https://doi.org/10.1016/j.rser.2013.02.020
Pereira, A.O., Pereira, A.S., La Rovere, E.L., Barata, M.M.D.L., Villar, S.D.C., Pires, S.H., 2011. Strategies to promote renewable energy in Brazil. Renew. Sustain. Energy Rev. 15, 681–688. https://doi.org/10.1016/j.rser.2010.09.027

Pereira, E.B., Martins, F.R., Pes, M.P., da Cruz Segundo, E.I., Lyra, A. de A., 2013. The impacts of global climate changes on the wind power density in Brazil. Renew. Energy 49, 107–110. https://doi.org/10.1016/j.renene.2012.01.053

Pereira, M.G., Camacho, C.F., Freitas, M.A.V., Silva, N.F. Da, 2012. The renewable energy market in Brazil: Current status and potential. Renew. Sustain. Energy Rev. 16, 3786–3802. https://doi.org/10.1016/j.rser.2012.03.024

Pollitt, C., Bouckaert, G., 2004. Public management reform: A comparative analysis, Second Edi. ed. Oxford University Press, USA.

Ponzo, R., Dyner, I., Arango, S., Larsen, E.R., 2011. Regulation and development of the Argentinean gas market. Energy Policy 39, 1070–1079. https://doi.org/10.1016/j.enpol.2010.11.009

Porrua, F., Bezerra, B., Barroso, L.A., Lino, P., Ralston, F., Pereira, M., 2010. Wind Power Insertion Through Energy Auction in Brazil, in: Power and Energy Society General Meeting. IEEE, pp. 1–8. https://doi.org/10.1109/PES.2010.5589751

Prostean, G., Badea, A., Vasar, C., Octavian, P., 2014. Risk Variables in Wind Power Supply Chain. Procedia - Soc. Behav. Sci. 124, 124–132. https://doi.org/10.1016/j.sbspro.2014.02.468

Pudjianto, D., Castro, M., Strbac, G., Liu, Z., van der Sluis, L., Papaefthymiou, G., 2016. Asymmetric impacts of European transmission network development towards 2050: Stakeholder assessment based on IRENE-40 scenarios. Energy Econ. 53, 261–269. https://doi.org/10.1016/j.eneco.2014.05.003

Purdy, J.M., 2012. A Framework for Assessing Power in Collaborative Governance Processes. Public Adm. Rev. 72, 409–417. https://doi.org/10.1111/j.1540-6210.2011.02525.x

Qudrat-Ullah, H., 2016. The Physics of Stocks and Flows of Energy Systems Applications in Energy Policy. Springer London.

Qudrat-Ullah, H., 2015. Modelling and Simulation in Service of Energy Policy. Energy Procedia 75, 2819–2825. https://doi.org/10.1016/j.egypro.2015.07.558

Qudrat-Ullah, H., 2014. Green power in Ontario: A dynamic model-based analysis. Energy 77, 859–870. https://doi.org/10.1016/j.energy.2014.09.072

Qudrat-Ullah, H., 2013. Understanding the dynamics of electricity generation capacity in Canada: A system dynamics approach. Energy 59, 285–294. https://doi.org/10.1016/j.energy.2013.07.029

Qudrat-Ullah, H., Seong, B.S., 2010. How to do structural validity of a system dynamics type simulation model: The case of an energy policy model. Energy Policy 38, 2216–2224. https://doi.org/10.1016/j.enpol.2009.12.009

Rahmandad, H., Repenning, N., Sterman, J., 2009. Effects of feedback delays on learning. Syst. Dyn. Rev. 25, 309–338. https://doi.org/10.1002/sdr.427

Redondo, J.M., Olivar, G., Ibarra-Vega, D., Dyner, I., 2018. Modeling for the regional integration of electricity markets. Energy Sustain. Dev. 43, 100–113. https://doi.org/10.1016/j.esd.2017.12.003

Rendon-Sagardi, M. a., Sanchez-Ramirez, C., Cortes-Robles, G., Alor-Hernandez, G., Cedillo-Campos, M.G., 2014. Dynamic analysis of feasibility in ethanol supply

chain for biofuel production in Mexico. Appl. Energy 123, 358–367. https://doi.org/10.1016/j.apenergy.2014.01.023
Romagnoli, F., Barisa, A., Dzene, I., Blumberga, A., Blumberga, D., 2013. Implementation of different policy strategies promoting the use of wood fuel in the Latvian district heating system: Impact evaluation through a system dynamic model. Energy 76, 210–222. https://doi.org/10.1016/j.energy.2014.06.046
Rubiano, O., Crespo, A., 2003. The effectiveness of using e-collaboration tools in the supply chain : an assessment study with system dynamics. J. Purch. Supply Manag. 9, 151–163. https://doi.org/10.1016/S1478-4092(03)00005-0
Saavedra M., M.R., de O. Fontes, C.H., M. Freires, F.G., 2018. Sustainable and renewable energy supply chain: A system dynamics overview. Renew. Sustain. Energy Rev. 82, 247–259. https://doi.org/10.1016/j.rser.2017.09.033
Sahay, N., Ierapetritou, M., Wassick, J., 2014. Synchronous and asynchronous decision making strategies in supply chains. Comput. Chem. Eng. 71, 116–129. https://doi.org/10.1016/j.compchemeng.2014.07.005
Santos, G.F., Haddad, E.A., Hewings, G.J.D., 2013. Energy policy and regional inequalities in the Brazilian economy. Energy Econ. 36, 241–255. https://doi.org/10.1016/j.eneco.2012.08.009
Schmidt, J., Cancella, R., Junior, A.O.P., 2016a. The effect of windpower on long-term variability of combined hydro-wind resources: The case of Brazil. Renew. Sustain. Energy Rev. 55, 131–141. https://doi.org/10.1016/j.rser.2015.10.159
Schmidt, J., Cancella, R., Pereira, A.O., 2016b. An optimal mix of solar PV, wind and hydro power for a low-carbon electricity supply in Brazil. Renew. Energy 85, 137–147. https://doi.org/10.1016/j.renene.2015.06.010
Shin, J., Shin, W.-S., Lee, C., 2013. An energy security management model using quality function deployment and system dynamics. Energy Policy 54, 72–86. https://doi.org/10.1016/j.enpol.2012.10.074
Silva, A.R., Pimenta, F.M., Assireu, A.T., Spyrides, M.H.C., 2016. Complementarity of Brazils hydro and offshore wind power. Renew. Sustain. Energy Rev. 56, 413–427. https://doi.org/10.1016/j.rser.2015.11.045
Silva, N.F. Da, Rosa, L.P., Freitas, M.A.V., Pereira, M.G., 2013. Wind energy in Brazil: From the power sector's expansion crisis model to the favorable environment. Renew. Sustain. Energy Rev. 22, 686–697. https://doi.org/10.1016/j.rser.2012.12.054
Silveira, J.L., Tuna, C.E., Lamas, W.D.Q., 2013. The need of subsidy for the implementation of photovoltaic solar energy as supporting of decentralized electrical power generation in Brazil. Renew. Sustain. Energy Rev. 20, 133–141. https://doi.org/10.1016/j.rser.2012.11.054
Simas, M., Pacca, S., 2014. Assessing employment in renewable energy technologies: A case study for wind power in Brazil. Renew. Sustain. Energy Rev. 31, 83–90. https://doi.org/10.1016/j.rser.2013.11.046
Smith, R. a., Vesga, D.R. a, Cadena, A.I., Boman, U., Larsen, E., Dyner, I., 2005. Energy scenarios for Colombia: Process and content. Futures 37, 1–17.

https://doi.org/10.1016/j.futures.2004.03.015
Solarin, S.A., Ozturk, I., 2015. On the causal dynamics between hydroelectricity consumption and economic growth in Latin America countries. Renew. Sustain. Energy Rev. 52, 1857–1868. https://doi.org/10.1016/j.rser.2015.08.003
Spatuzza, A., 2014. Connection problems start to limit growth [WWW Document]. Wind. Mon.
Sterman, J., 1981. The energy transition and the economy: A system dynamics approach. Massachusetts Institute of Technology.
Sterman, J.D., 2000. Business dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill.
Sterman, J.D., 1984. Appropriate summary statistics for evaluating the historical fit of system dynamics models. Dynamica.
Strachan, N., 2011. Business-as-Unusual: Existing policies in energy model baselines. Energy Econ. 33, 153–160. https://doi.org/10.1016/j.eneco.2010.10.009
Tian, Y., Govindan, K., Zhu, Q., 2014. A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. J. Clean. Prod. 80, 96–105. https://doi.org/10.1016/j.jclepro.2014.05.076
Tiba, C., Candeias, A.L.B., Fraidenraich, N., Barbosa, E.M. de S., de Carvalho Neto, P.B., de Melo Filho, J.B., 2010. A GIS-based decision support tool for renewable energy management and planning in semi-arid rural environments of northeast of Brazil. Renew. Energy 35, 2921–2932. https://doi.org/10.1016/j.renene.2010.05.009
Torres, J.P., Kunc, M., O'Brien, F., 2017. Supporting strategy using system dynamics. Eur. J. Oper. Res. 260, 1081–1094. https://doi.org/10.1016/j.ejor.2017.01.018
Trappey, A.J.C., Trappey, C., Hsiao, C.T., Ou, J.J.R., Li, S.J., Chen, K.W.P., 2012a. An evaluation model for low carbon island policy: The case of Taiwan's green transportation policy. Energy Policy 45, 510–515. https://doi.org/10.1016/j.enpol.2012.02.063
Trappey, A.J.C., Trappey, C. V., Lin, G.Y.P., Chang, Y.S., 2012b. The analysis of renewable energy policies for the Taiwan Penghu island administrative region. Renew. Sustain. Energy Rev. 16, 958–965. https://doi.org/10.1016/j.rser.2011.09.016
Troost, C., Walter, T., Berger, T., 2015. Climate, energy and environmental policies in agriculture: Simulating likely farmer responses in Southwest Germany. Land use policy 46, 50–64. https://doi.org/10.1016/j.landusepol.2015.01.028
Vahl, F.P., Filho, N.C., 2015. Energy transition and path creation for natural gas in the Brazilian electricity mix. J. Clean. Prod. 86, 221–229. https://doi.org/10.1016/j.jclepro.2014.08.033
Valerie Karplus, Sebastian Rausch, Da Zhang, 2016. Energy Caps: Alternative Climate Policy Instruments for China? Energy Econ. In press, 422–431. https://doi.org/10.1016/j.eneco.2016.03.019
Varella, H., 2013. Mediçao de desemprenho na cadeia de energia eólica: proposta de

um conjunto de indicadores de desempenho. Univ. Fed. Do Rio Gd. Do Norte. https://doi.org/10.1017/CBO9781107415324.004
Vlachos, D., Georgiadis, P., Iakovou, E., 2007. A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. Comput. Oper. Res. 34, 367–394. https://doi.org/10.1016/j.cor.2005.03.005
Von Sperling, E., 2012. Hydropower in Brazil: Overview of positive and negative environmental aspects. Energy Procedia 18, 110–118. https://doi.org/10.1016/j.egypro.2012.05.023
Wee, H.-M., Yang, W.-H., Chou, C.-W., Padilan, M. V., 2012. Renewable energy supply chains, performance, application barriers, and strategies for further development. Renew. Sustain. Energy Rev. 16, 5451–5465. https://doi.org/10.1016/j.rser.2012.06.006
Wheat, D., 2010. What Can System Dynamics Learn From the Public Policy Implementation Literature? Syst. Res. Behav. Sci. 27, 425–442. https://doi.org/10.1002/sres.1039
Wu, Z., Xu, J., 2013. Predicting and optimization of energy consumption using system dynamics-fuzzy multiple objective programming in world heritage areas. Energy 49, 19–31. https://doi.org/10.1016/j.energy.2012.10.030
Wüstemeyer, C., Madlener, R., Bunn, D.W., 2015. A stakeholder analysis of divergent supply-chain trends for the European onshore and offshore wind installations. Energy Policy 80, 36–44. https://doi.org/10.1016/j.enpol.2015.01.017
WWF-Brasil – Fundo Mundial para a Natureza, 2015. Desafios e oportunidades para a energia solar fotovoltaica no Brasil : recomendações para políticas públicas. 44.
Yuan, J., Sun, S., Shen, J., Xu, Y., Zhao, C., 2014. Wind power supply chain in China. Renew. Sustain. Energy Rev. 39, 356–369. https://doi.org/10.1016/j.rser.2014.07.014
Zadek, S., 2008. Global collaborative governance: there is no alternative. Corp. Gov. Int. J. Bus. Soc. 8, 374–388. https://doi.org/10.1108/14720700810899121
Zadek, S., 2006. The Logic of Collaborative Governance (No. 17), Public Policy.
Zakeri, B., Virasjoki, V., Syri, S., Connolly, D., Mathiesen, B. V, Welsch, M., 2016. Impact of Germany ' s energy transition on the Nordic power market e A market-based multi-region energy system model. Energy. https://doi.org/10.1016/j.energy.2016.07.083
Zuluaga, M.M., Dyner, I., 2007. Incentives for renewable energy in reformed Latin-American electricity markets: the Colombian case. J. Clean. Prod. 15, 153–162. https://doi.org/10.1016/j.jclepro.2005.12.014
Zurn, H.H., Tenfen, D., Rolim, J.G., Richter, A., Hauer, I., 2017. Electrical energy demand efficiency efforts in Brazil, past, lessons learned, present and future: A critical review. Renew. Sustain. Energy Rev. 67, 1081–1086. https://doi.org/10.1016/j.rser.2016.09.037