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Energy transition and path creation for natural gas in the Brazilian electricity mix

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ABSTRACT

Emerging economies will account for more than 90% of net energy demand growth to 2035. Although there is international consent about the need for reducing green-house gas (GHG) emissions, reduction targets have been left to governments' responsibility. Such opening lead to different energy policies and approaches among countries, specially comparing developing economies to developed ones. Technology development and new reserves found have set natural gas as the lead resource for transitioning energy mixes to lower carbon levels. However, hydropower has been the main source for the Brazilian electricity grid, and increasing dispatch of natural gas in fact increases GHG, which has been the core of current Brazilian energy policies. We estimated future Brazilian market shares of hydro, thermal, wind and nuclear power, through historical data analysis of power dispatch and installed capacity. The findings propose that current Brazilian administration is creating a new technological path, which will lead far from the desired GHG targets. If actual growth rate of thermal power continues, by the year 2022 thermal plants will be major suppliers of the Brazilian electricity grid, leaving hydro with the second largest market share. Furthermore, we propose several approaches for increasing adoption of renewable distributed generation and the development of other market niches for natural gas in Brazil, as alternative paths.

1. Introduction

International consent about reducing greenhouse gas (GHG) emissions has been achieved in the last decades. However, in order not to interfere in each country's sovereignty, reduction targets and approaches were left at national governments' responsibility (IPCC, 1990). Such decision has led to differences in energy policies and reduction achievements among countries (Laird and Stefes, 2009; Lipp, 2007). Moreover, fast developing economies as Brazil, China, India, Russia and South Africa present greater differences in targets and policies comparing to developed countries (IEA, 2013a; Rubio and Folchi, 2012), with much less consideration and effort regarding the reduction of GHG emissions, as it brings short-term economic constraints. Also, several studies on industrialized countries' energy transitions have been accomplished, although such transitions in emerging economies have not been covered with similar effort (Grubler, 2012). Such issue is a worldwide concern, since global energy demand is expected to move towards emerging economies in the next decades, which is expected to account for more than 90% of net energy demand growth until 2035 (IEA, 2013b).

Many societal problems, including environmental issues, result from social dilemmas. Although uniform cooperation would benefit everyone, each individual can benefit from free-riding (Hardin, 1968). Societies have found ways to overcome 'tragedies of the commons', and many studies have presented models and approaches which may mitigate such dilemma efficiently. Coevolutionary games clearly show that coevolution is a promising concept to follow, as it constitutes the most natural upgrade of evolutionary games in the sense that not only strategies evolve in time, but so does the environment, and indeed many other factors that in turn affect back the outcome of the evolution of strategies (Perk and Szolnoki, 2010). For Grund et al. (2013), biological competition is widely believed to result in the evolution of selfish preferences. Assuming conditions promoting non-cooperative behavior, the authors demonstrate that intergenerational migration determines whether evolutionary competition results in a 'homo economicus', showing self-regarding preferences, or a 'homo socialis', having other-regarding preferences. Such approaches demonstrate the need for complementary economic theory

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embracing 'networked minds' (the 'homo socialis') and evolutionarily grounded theory of other-regarding agents, explaining individually different utility functions as well as conditional cooperation.

Regarding empirical data analysis, GHG emissions have currently been measured and compared to the first targets settled in 1990 (benchmark), as proposed by IPCC (Intergovernmental Panel on Climate Change) (IPCC, 1990, 2007, 2013), allowing cross-country comparisons of targets, achievements, and efficiency of policies bred. The results of such analysis shall provide knowledge through experience in order to correct previous projections for future emissions, after initiatives have already been enforced, which will in sequence alter either policies or targets, whatever suits better each country.

The electricity sector demonstrates different GHG emissions share among countries, which is a result of each particular energy mix. It is the major GHG emitter in many countries due to thermal power plants (IEA, 2013a; NREL, 2012). Recent technology development and new reserves found have set natural gas as the lead resource for transitioning electrical energy mixes to lower carbon levels throughout the globe, especially complementing renewables' intermittency (Mohareb and Kennedy, 2014; IEA, 2013b; NREL, 2012). Such assumption is true when we compare a thermal power plant fueled with coal or oil to one burning natural gas, since coal emits twice GHG levels than natural gas. On the other hand, the Brazilian electricity grid has been mainly supplied from hydropower for decades, and it seems that current policies are aiming to increase market share of natural gas, which in fact increases GHG levels of the grid. Installed capacity of different plants in the Brazilian National Integrated System (SIN) is demonstrated in Fig. 1, where the increase of thermal power share is visible in recent years. Despite such scenario, Brazilian per-capita CO_2 emissions is expected to increase by 50% to reach 3 tonnes of CO_2 in 2035, which is still only 70% of the world average (IEA, 2013b).

The discovery of offshore fields (Pre-salt) has set Brazil as one of the world's largest oil and gas reserves (Goldemberg et al., 2014; IEA, 2013b). Hence, increasing dispatches from thermal power plants in Brazil may be seen as technological path dependence stirred by the oil and gas industry, spurred by supply availability. Such tendency fosters technology adoption for these energy sources, directly supported by the government, since Petrobras, the major player in the market, is a company controlled by the State.

Thus, this paper demonstrates that current Brazilian policies regarding electricity generation and consumption are creating a new technological path, less sustainable, which will lead the administration far from the desired GHG emissions cut as advertised. Furthermore, we present historical data analysis obtained

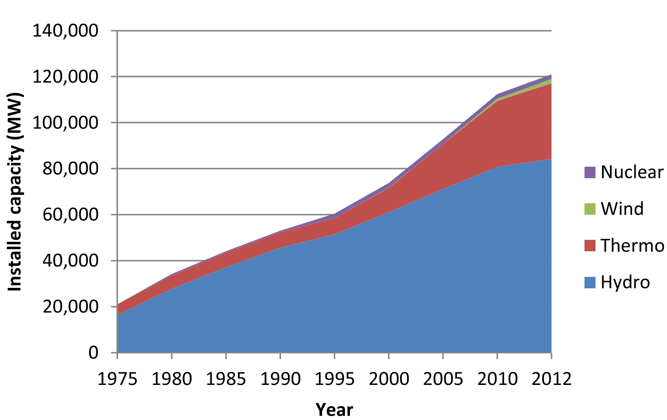

Fig. 1. Brazilian electricity generation installed capacity for different sources (EPE, 2013).

from Brazilian public agencies related to the power sector in order to compare predictions of future GHG emissions, according to the path currently being created, to administration targets. In spite of such future scenarios, we propose alternative policies for developing new paths for electricity generation and the smarter use of natural gas, keeping the Brazilian electricity mix mainly renewable.

Section two presents the methods used in the study. Section three shows the background of technological path dependence and creation, as well as their relation to energy transitions and the development of national energy policies. Section four demonstrates results and discussion of the current Brazilian scenario regarding the electricity mix and possible future energy transitions, comparing the findings to predictions released by Brazilian administration reports. In section five, several approaches considering both supply and demand side management are presented as alternative policies in order to create an alternative new path.

2. Methods

Although some authors argue that energy transition evidence requires the analysis of long-term data for energy consumption (Verbong and Geels, 2007), the pace which it has occurred has varied greatly among countries, decades of difference, specially comparing developed economies to industrialized countries (Rubio and Folchi, 2012; Grubler, 2012; Solomon and Krishna, 2011). It also depends on the technological stage which the country is found, the diffusion rate of adoption and time. Such phenomenon can be understood through the evolution of energy sources market share (Rubio and Folchi, 2012), which demonstrates a country's energy mix in a given time.

Diffusion research does not necessarily have to be conducted after an innovation has diffused in a system. It is possible to investigate the diffusion of an innovation while the diffusion process is still ongoing, and data can be gathered during the diffusion process. This type of research design is similar to field experiments, where data are gathered before and after an intervention (Rogers, 1995), providing a suitable approach to analyze diffusion of new technologies before and after related policies are enforced.

Regression analysis has proven a reliable statistics tool for the investigation of relationships between variables. Regression techniques have long been central to econometrics, and have become useful to policy makers, widely used for prediction and forecasting (Freedman, 2005). Thus, we propose using regression analysis of historical data from several Brazilian institutions, which present reliable information about installed capacity and energy produced over the years, in order to analyze the adoption rate of new technologies for electricity generation and future energy transitions in Brazil. The regressions were taken with different timelines, representing different policy profiles and thus tendencies, in order to compare historical market shares, paths and embedded shifts. In this sense, path dependence of energy sources is compared to diffusion of innovations guided by national policies. Regression analysis is then a quantitative approach in order to evaluate current energy policies and their implications to future scenarios, making viable the prediction of their efficiency regarding GHG emissions targets and the actual paths being built. For such objective, the results were compared to the administration GHG emissions targets.

3. Path dependence and innovation diffusion in the energy industry

Path dependence leads the next generation of technologies towards historically shaped innovations, which is either pushed by research and development advances or by policies molding the characteristics of future technologies, through incentives and regulations. For Pierson (2004), path dependence concerns dynamic processes involving "positive feedback", which may generate multiple outcomes, depending on the particular sequence in which events unfold. According to Laird and Stefes (2009) the positive feedback depends on certain characteristics as institutional structures, political alignments, and other factors which may support political actors once they have started a particular policy path. For instance, the recent increase in new wind capacity in the US is a result from joint public and private actions, as supportive policies and incentives along with decreasing technology costs (NREL, 2012).

The positive feedback implies some initiatives that set the country (or company) on a new path, thus it also implies path creation. Path creation requires active entrepreneurs in order to shape new technological paths, which reflect emerging social practices and technology breakthroughs (Garud and Karnøe, 2001; Schumpeter, 1983). Therefore, path creation also stresses the need for collective actions. Such process includes the destabilization of the existing path, reinforcement of new approaches and active use of social networks to span boundaries and generate momentum (Heiskanen et al., 2011). Diffusion of innovations occur through efficient communication channels, taking some time depending on rate of adoption, and it often requires entrepreneurs performing the role of change agents in order to establish the innovation in markets (Rogers, 1995).

3.1. Energy transition, path dependence and creation of energy supply

Through historical series and data analysis, as regression models, many scholars have identified national level energy transitions, determining stages in which an energy carrier predominates in one time frame, and then gradually recedes with the advance of a new energy source, which eventually replaces the previous one (Lay et al., 2013; Zhang, 2013; Rubio and Folchi, 2012; Verbong and Geels, 2007). The logic of such phenomenon is retrofitting technologies and shifting to energy sources aiming higher quality and efficiency, determined by technical, economic, and social attributes as energy density, emissions, conversion cost and efficiency, financial risk, storage capability, risk to human health, and ease of transport (Vahl et al., 2013b; Rubio and Folchi, 2012).

However, energy transition may also be understood as path creation for new technologies regarding energy generation and use. The turning point, when a previous major energy source declines to another, is the result of a path been bred for many years, and it settles the start of a new path dependence. For instance, the transition from wood to coal marked the end of path dependence on wood burning technologies and the start of new dependence on coal burning technologies. In spite of market sizes for such commodities, creating a new technological path implies creating new markets and new corporations, being as necessary as radical the innovations appear. Thus, in order not to lose market share and profit, corporations based on outdated technology tend to either slow the pace of energy transition (or rate of adoption) or drive it towards adaptive technologies or substitute sources. This argument is based on competitive advantage issues, as shifting a power plant from coal to natural gas is a coherent strategy, however shifting to wind or solar farms concerns building an entirely new plant, probably in another location as well.

Besides the producer side of view, the consumer purchase motivations play important roles in energy transitions, as transformations in energy end-use were fundamental drivers in historical shifts (Grubler, 2012). Although petroleum at first was more expensive to produce than coal, it was much cheaper to transport, either by tanker or pipeline. Furthermore, along with price per calorie unit, petroleum had other technical attributes, such as versatility, weight and volume, which gave it competitive advantage over coal in important sectors, as motorized transport (Solomon and Krishna, 2011). Therefore, it was not scarcity of coal that led to increasing adoption of oil, even more expensive. Instead, these were technology shifts at the level of energy end use (Grubler, 2012). The life cycle of coal was not over though. Instead, there was a new path created for it in power plants generating electricity, which has sustained coal producers until today (Solomon and Krishna, 2011).

Recently, many countries are seeking energy transitions for the electricity sector, shifting from coal and oil-fired plants to natural gas. Although the main advertisement for such transition is reduction of GHG emissions, many improvements in natural gas technologies have enabled its extraction more efficiently and from previously unreachable locations. NREL (2012) points out that in the US the largest near-term effect of natural gas surplus and low prices (lowest in a decade in 2012) has been the rapid displacement of coal-generated electricity by natural gas generation.

Hence, energy transition could be understood as a process of energy modernization (Grubler, 2012). However, the penetration of a product into markets is not simply a consequence of free–market activity, especially dealing with commodities, but rather a consequence of policies and the effectiveness of lobbying strategies developed by the companies that trade these products (Vahl et al., 2013b; Rubio and Folchi, 2012). Thus, the petroleum companies became the first large corporations and the first trust in history (Pratt, 1983), creating a new technological path dependence on petroleum. First oil came to substitute coal, and it made feasible motorized transportations and internal combustion engines. Returns in investments and market growth enabled research and development to reach new markets, empowering the entire value chain of petroleum, gaining market share and added value. Thus, it outgrew to substitute other energy sources, recently with natural gas.

3.2. Path dependence of energy end-use: the case of electric vehicles

From the demand side perspective, technological breakthroughs and institutional reforms in energy end-use are the fundamental drivers of historical energy transitions (Grubler, 2012; Grubler and Cutler, 2008; Garud and Karnøe 2003). For instance, bio-fueled, electric, and hybrid vehicles are promising technologies to be adopted in order to reduce GHG emissions, which have also been restrained by larger corporations, competitors, as well as consumer purchase motivations (Dijk et al., 2013; Egbue and Long, 2012; Ozaki and Sevastyanova, 2011). The first electric vehicles (EV) appeared in the 1880s. Gasoline fueled cars were adopted by the majority of buyers since 1920's (IEA, 2014; AVT, 2014). Given the time circumstances, the petroleum and automobile industries matched even younger technology for electricity generation and distribution, which gave competitive advantage to gasoline when it reached lower cost for the end user, thus developing both the auto and petroleum industry altogether.

Investments in research and development guarantee and accelerate technological path dependence as it aggregates value to products, either reducing costs for the final user or inferring (or offering) a new market necessity, through marketing strategies. For instance. electric vehicles had many advantages over their competitors: they did not have the vibration, smell, and noise of gasoline cars; changing gears on gasoline cars was the most difficult part of driving, while EVs did not require gear changes; steam-powered cars suffered from long start-up times, and they had less range before needing water than an EV on a single charge. Electric cars were popular providing comfort and ease of operation, which were not provided by the gasoline cars of the time, and the short range was not a concern, since the only good roads were in town (IEA, 2014).

However, advances in internal combustion engine technology, especially the electric starter invented in 1912, provided the necessary market characteristics to diffuse oil adoption. Greater range of gasoline cars, quicker refueling times, better roads, growing petroleum infrastructure (thus cheaper gasoline), and mass production of cheaper gasoline vehicles (by companies such as the Ford Motor Company), led to a decline in the use of electric vehicles, been removed from important markets by the 1930s (IEA, 2014). Another similar transition occurred with the introduction of diesel locomotives, which provided greater fuel efficiency, inexpensive maintenance, and capability of mass-production techniques, which enabled its rapid commercialization and adoption over steam locomotives (Solomon and Krishna, 2011).

Recently new policies and regulations, together with stakeholder pressure about sustainability levels, have turned R&D (research and development) efforts towards low emissions vehicles. These embed technological advances in power electronics and resulted in several new models of EVs, hybrids or vehicles using renewable bio-fuels for combustion (Dijk et al., 2013; Ozaki and Sevastyanova, 2011; Diamond, 2009; Sperling and Gordon, 2009; Sandalow, 2009).

3.3. Path creation for the electricity industry: towards low carbon footprint

GHG emissions targets in 1990 (IPCC, 1990) reflected stakeholder pressure of the time. However, setting targets is only part of the problem; achieving them on schedule is the main performance issue. We are facing a turning point of energy sources dependency, but differently than history has shown, not driven exclusively by companies but through stakeholders' pressure, thanks to new information technologies and efficient innovations. The histories of technology, science or human development show that rates of adoption of technologies have not been linear, and that latecomers may transit at faster pace than pioneers (Diamond, 1999; Rogers, 1995). The transition from organic to mineral energy or the shift from coal to oil have ranged from several decades to over a century. However, for Rubio and Folchi (2012), during the past 30 years developing countries have made energy transitions faster and with greater diversity than previously. The authors demonstrate that 'leapfrogging' allowed follower economies to pass from coal to oil domination 30 years in advance of most developed economies.

Although one may argue that such leapfrogging may also help developing countries regarding the use of greener technologies, there seems to be a reverse path: when developed countries are currently seeking to abandon or diminish fossil fuels for electricity generation, enforcing relatively fast adoption rates for renewable energy generation (Mohareb and Kennedy, 2014; Lipp, 2007; Wüstenhagen and Bilharz, 2006), developing economies are still expanding thermal plants (Goldemberg et al., 2014; Rubio and Folchi, 2012). Nonetheless, even developed countries have struggled reaching greener economies. For instance, despite Germany's success story on renewable adoption, resistance to the promotion of renewable energy through feed-in tariffs did not vanish easily. There has been opposition from political parties, large utilities, and the coal and nuclear lobby groups (Laird and Stefes, 2009).

The limited cost-competitiveness of renewable energy technologies in the near-term also deters greater levels of deployment. NREL (2012) reports that after natural gas wind has been the second-largest contributor of new capacity in the US, with particularly strong growth in the past five years. However, only the most favorable wind sites, along with supportive policies, can compete with natural gas costs. Less favorable wind sites, solar, and other renewable energy technologies remain costlier or less competitive until continued learning curve efficiency gains and cost reductions are made. Path dependence (including trade and technological partnerships), domestic energy endowment (which dictates relative prices) and policy decisions seem to be the variables which have shaped past energy transitions (Rubio and Folchi, 2012), and these are key factors for developing the next generation energy mixes.

4. Results and discussion

4.1. Greenhouse emissions targets and the Brazilian electricity mix

The Brazilian National Policy on Climate Change (PNMC) has targeted GHG emissions reduction between 36.1% and 38.9% until 2020, which was approved in 2009 (law 12.187/2009). Most decrease is expected to come from deforestation reduction. Concerning the energy sector, Fig. 2 demonstrates market shares for the main sources in Brazil, from recent years and the targets for 2020 and 2030 (EPE, 2007a).

Despite EPE (2007a) decreasing market share projections for thermal power plants, we present results from data analysis using figures from the National Systems Operator (ONS), the National Association of Electricity (ANEEL) and the Ministry of Science and Technology (MCTI), which demonstrate the opposite. We argue that the path dependence currently being created in the Brazilian energy mix, more specifically after the year 2006 in the electricity sector, will derive diverging figures from the proposed emissions reduction targets for the next decades, as presented by the administration in 2009.

4.1.1. CO_2 emissions of Brazilian electricity generation

Calculating emissions of CO_2, SOx and NOx, in order to use such emissions as metrics for energy efficiency actions, requires the knowledge of energy grids' power sources. In Brazil, the emissions of CO_2 per electricity consumed has been calculated 125 gCO_2eq/kWh in 2010, accordingly to the combination of each source's share, as presented in Table 1 (Miranda, 2012). Natural gas was already responsible for 22% of emissions from the grid, despite supplying only 5.34% (25,284 GWh) of electricity in 2010. Hydro supplied 89.3% (422,785 GWh) of electricity that year, with emissions share of 61%.

Dispatch orders and the energy mix follow seasonal demand peaks in the Brazilian grid. In order to meet demand during peak

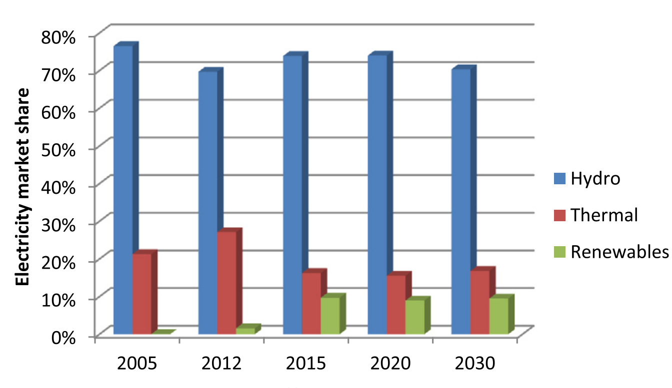

Fig. 2. Projections of the Brazilian electricity market share by source (EPE, 2007a, 2013).

Table 1
CO_2 emissions from the electricity matrix in Brazil (Miranda, 2012).

Technology	Emissions factor (gCO_2eq/kWh)	Electricity generation (GWh/year)	Annual emissions ($tCO_2eq/year$)	Emissions share (%) in 2013
Hydro	86	422,785	36,448,295	61
Wind	16	1445	23,337	0.004
Nuclear	14	14,523	214,650	0.4
Thermo – MC	1144	6124	7,008,061	12
Thermo – NG	518	25,284	13,129,981	22
Thermo – OC	781	2088	1,631,020	3
Thermo – OD	829	1127	934,238	2
Total		473,376	59,341,776	100

seasons, especially in summer (from December through March), the Brazilian operator has hired an increasing amount of energy from thermo power plants, which are currently the primary contingency plan for the maintenance of supply and system reliability. Such strategy increases significantly the amount of GHG emissions (Fig. 3). It is noteworthy that from August 2012 the average monthly factor of CO_2 emissions has increased above average and sustained.

4.1.2. The relation of hydro energy stored levels and thermal dispatch

Low hydro-energy stored levels has resulted high levels of thermal power dispatch to the grid, in order to balance supply capacity. Comparing historical data, Fig. 4 illustrates the evolution of CO_2 emissions, hydro-energy stored, electricity from thermal generation and consumption. These were normalized based on the average of 2006:

- CO_2 emissions from electricity generation in Brazil closed 2006 with an average of 0.032 (tCO2/MWh) (MCTI, 2014);
- Hydro energy stored presented an average of 129004.23 GWh/month (ONS, 2014);
- The average monthly thermal electricity generation (coal, oil and natural gas) was 1677.33 GWh/month (ONS, 2014);
- The average consumption of electricity was 19284929.4 GWh/month (ANEEL, 2014).

Dividing the data obtained from ANEEL (2014), ONS (2014) and MCTI (2014), for each month by the average adopted, we created each series. Such approach enables the view of time related behaviors cross-comparing data with different units.

The interval chosen, from 2006, grants better reliability of data and it is very close to the discovery of Pre-salt in 2007. Since the series has been noted, there were two main peaks of emissions in late summer of 2008 (increase of 206% after first oil extraction from

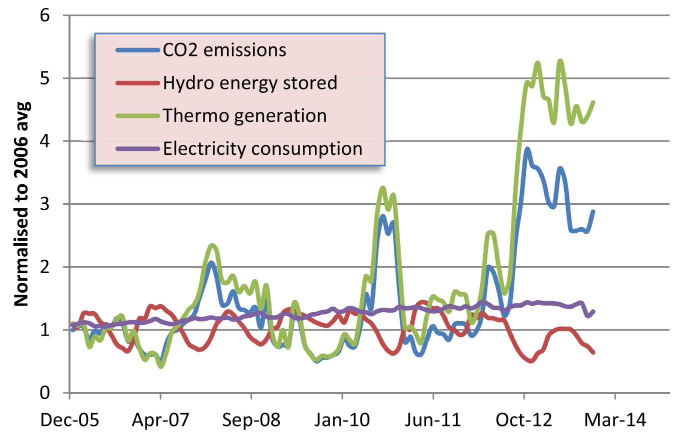

Fig. 4. Normalized series of electricity generation related data.
Sources: ONS (2014); MCTI (2014); ANEEL (2014)

pre-salt) and late spring of 2010 (268%), which were retrieved to regular 2006 average levels. However, there was an increase in February 2012, which reached 385.86% of emissions increase in November the same year, closing 2013 with CO_2 emissions level per kWh 287.7% higher than 2006 average.

Consumption is indeed increasing, though at a much slower pace than thermal generation. In order to balance the utility grid, visually one may identify an inverse relation and synchronism between hydro-energy stored levels and thermal dispatches. Thus, variations on reservoirs levels has accompanied thermal variations closely until two recent situations, first in mid January 2010, when the slope of thermal generation was already higher than usual, and later in October 2012, when thermal dispatch met a new average level, as it seems. The change in policy related to order of dispatch of generators is clearly demonstrated as the evolution of thermal generation reaches 2.35 times higher than on previous occasions with same water scarcity.

CO_2 emissions, as calculated by the administration and published in MCTI (2014), are plotted in Fig. 4 in order to compare its variations to thermal generation. As expected, both curves draw similar shapes, and as figures are normalized values fit for several marks. However, the latest record of thermal dispatch in October 2012 seems to present discrepancy between both figures. Although the shapes prevail, the emissions advertised are much smaller than they should be, since thermal power was much higher.

We have performed a regression analysis on monthly data from ONS (2014) of thermal power produced over the years (starting in 2000), in order to evaluate the tendency of thermal power

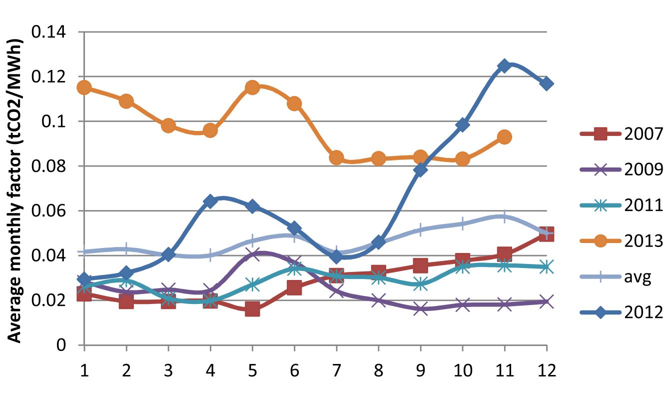

Fig. 3. Average CO_2 emissions factor for recent years (MCTI, 2014).

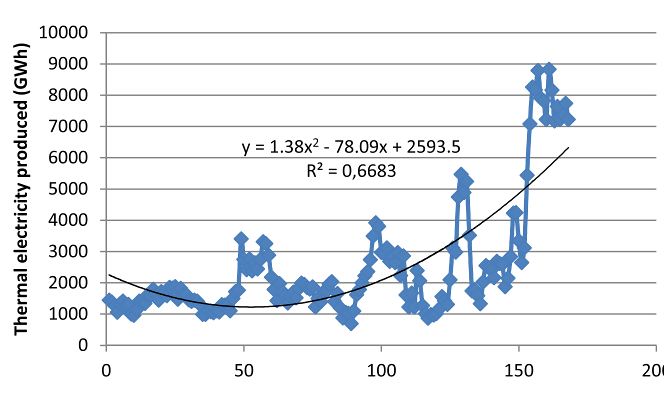

Fig. 5. Thermal power tendency since year 2000 (ONS, 2014).

generation in Brazil (Fig. 5). The plot demonstrates increasing slope tendency and considerable fit, with correlation coefficient $R^2 = 0.6683$ (considering $R^2 = 1$ perfect match), as the tendency line drawn approaches closely to historical figures used. Electricity production from thermal power plants has increased 694% in the Brazilian energy mix from 2005 to 2012, a pace much higher than consumption. Also, the strategy of dispatching energy from thermal power plants only in situations of low hydro energy stored no longer applies for Brazilian scenarios, since the yearly average has also grown regardless of hydro energy stored. Such plants are indeed becoming important suppliers in order to maintain balance between electricity supply and demand.

4.1.3. Brazilian path towards the new electricity mix

The Brazilian power grid carbon footprint is already related to thermal generation. Furthermore, the evolution of thermal energy used for electricity generation, especially from gas, demonstrates biased policies, which seek increasing adoption of thermal power plants, with special interest on natural gas from Pre-salt and also counting on imports increase from Bolivia (EPE, 2007a). Although expected market values and reservoir quantities of Pre-salt lack reliability (Goldemberg et al., 2014), natural gas is indeed seen as major safeguard for the actual development plan of the Brazilian electricity grid. Such path leaves solar photovoltaic generation out of scope until 2030 in the Brazilian market; wind and biomass are also at a slower pace of development (Fig. 6).

In order to evaluate probable scenarios and current path dependence of the Brazilian electricity mix, we have performed several regression analysis using historical data from ONS (2014) and EPE (2013), which were compared to targets proposed in EPE (2007a), summarized in Table 2. Regression equations were obtained considering yearly installed capacity in GW since 1975, using *x* for year. Aiming to increase correlation of series, wind series was taken from 2006 and nuclear from 1985, since they did not appear in the energy mix before then. Thermal power capacity has grown rapidly in the past few years, so we have applied two different regressions: *thermo a*, stands for the regression from 1975 to 2013; *thermo b* from 2000 to 2013.

Historical series demonstrate linear growth of hydropower installed capacity, similarly to wind and nuclear recently. The model utilized for hydropower predicts a difference of −15.67% considering the target of 116 GW in 2020 and -25.94% in 2030. Nonetheless, Brazilian hydro potential is estimated in 261.4 GW (EPE, 2007), of which 32% is considered less reliable estimation and 43% corresponds to the North region of Brazil, the Amazon, far from main industrialized areas and consumer centers. Besides involving several sustainability issues, the increase of hydropower in Brazil relies on other barriers as transmission

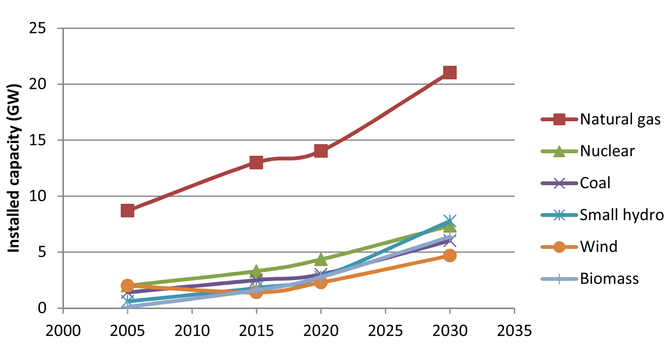

Fig. 6. Projection of installed capacity of current minor electricity sources in Brazil (EPE, 2007a).

Table 2
Regression results, prediction and targets (EPE, 2007a) of installed capacity considering different scenarios in Brazil.

Source	Regression analysis		Targets (GW)		Prediction (GW)		
		R^2	2020	2030	2020	2030	2050
Hydro	$1.7854x - 3508.6$	0.9945	116	156	97.90	115.76	151.47
Thermal a	$e^{0.048x}(10^{-41})$	0.9494	24.37	37.37	35.30	57.34	151.26
Thermal b	$3(10^{-71})e^{0.0917x}$	0.6683			83.79	209.63	1312.10
Wind	$0.3038x - 609.48$	0.936	2.28	4.68	4.18	7.22	13.30
Nuclear	$0.0665x - 131.7$	0.8566	4.34	7.34	2.63	3.29	4.62

expansion, time elapsed in order to acquire all paperwork and impact studies.

The targets for thermal power installed capacity as presented by the government shows increase of 264% from 2005 to 2030, developing thermal capacity from 14.2 GW to 37.7 GW, considering coal, oil, natural gas and nuclear altogether. Although such increase will be mainly due to natural gas, which will reach 21.035 GW (growth of 241.78%), coal-fueled power plants are also expected to grow from 1.4 GW to 6.015 GW, meaning an increase of 429.6% in installed capacity for this source.

If actual growth rate of thermal dispatch occurs to installed capacity (Fig. 7), represented in *thermo b* (with accuracy of tendency line fit or $R^2 = 0.6683$), by the year 2022 the Brazilian electricity mix will be majorly supplied from thermal plants, with installed capacity above 100 GW, leaving hydropower with the second largest market share. Applying scenario *thermo a*, the crossover of the electricity mix will happen in 2050, when installed capacity of thermal power reaches around 150 GW. Thus, thermal targets may present standard deviations between 44.86% and 460.95% in 2020 and 2030, considering historical growth rates.

Moreover, if electricity production and market shares follow the same projections of installed capacity, and consumption maintains its growth rate, emissions will reach between 127.58 MtCO2/year, in *thermo a* scenario, and 168.12 $MtCO_2$/year (*thermo b*) in 2020, which represents 215% and 283% of emissions increase compared to 2010, as calculated by Miranda (2012). In 2030, emissions from the electricity generation share shall reach from 222.07 $MtCO_2$/year (*thermo a*) to 361.41 $MtCO_2$/year (*thermo b*), showing probable increase between 374% and 609% comparing to 2010 values. Furthermore, as electricity consumption shall reach 706,600 GWh in 2020, the ratio of emissions per energy shall reach between 180.56 gCO2eq/kWh and 237.92 gCO2eq/kWh. Considering electricity consumption of 1,030,000 GWh, such ratio may achieve from 215.6 to 350.88 gCO2eq/kWh in 2030.

Thus, if the same policies are sustained, keeping actual growth and development of thermal power plants installed capacity, CO_2 emissions rate of electricity may increase between 44.4% and 90.3% in 2020, and 72% to 180.7% in 2030, even if we consider all plants with same emission levels as natural gas. If the market does not follow the proposed installed capacity share growth, there will be spare capacity of new thermal plants, which will increase utility costs anyway.

5. Conclusions

As demonstrated, Brazil is indeed creating a new technological path for the energy sector, however a less sustainable one longing the dependency on oil and creating one on natural gas. In order to settle a path embedding greener technologies, many countries have promoted policies efficiently increasing renewable market share and the adoption of substitute sustainable solutions. Moreover, we argue that in order to achieve considerable GHG emissions reduction in Brazil, renewable and distributed generation technologies

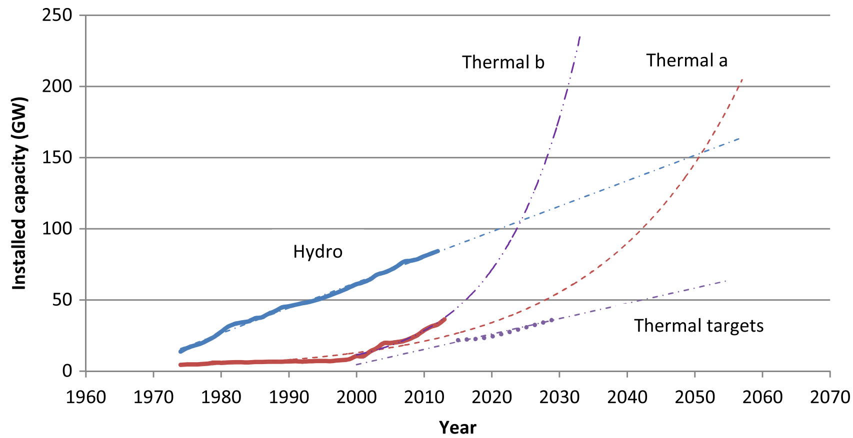

Fig. 7. Evolution of hydro and thermal power installed capacity in the Brazilian electricity mix.

along with the smart use of natural gas are complementary solutions. Brazil has the means for creating a path in such way, since wind potential in Brazil is estimated at 143.5 GW of power capacity and 272.2 TWh/year (Amarante et al., 2001), and one may produce 108 GWp (183 TWh/year) with a solar photovoltaic plant of 1350 km^2, similar size to Itaipu's lake, which produces 80 to 90 TWh/year (14 GW).

5.1. Power supply side

The means to achieve this reduction from supplier side could follow a number of different approaches: coupling renewable electricity development with energy storage options, as electric vehicles, pumped-storage hydroelectricity; greater adoption of biomass and photovoltaic electricity generation; integrated development of wind and natural gas sites; increasing adoption of solar rooftops and micro PV systems. However, such approaches face several issues which must be properly addressed in order to make the transition feasible, and also require building smart grids and the improvement of distributed generation, and Brazil is in its early stages of life cycle for these technologies and policies.

5.1.1. Developing distributed generation and smart-grid infrastructure

ANEEL (2012) resolution allows every Brazilian power end-user to trade energy with the grid, after proper installation of smart-meter, grid-tie inverter and generator. Such regulation came to establish access conditions and reward schemes for micro (<100 kW) and mini (100 kW < P < 1 MW) distributed generation in Brazil. The resolution allows utility companies to reward the micro-producer for energy traded limited to its own consumption. If a micro-generator dispatches more energy to the grid in a month than its consumption, as measured by the smart meter, the consumer won't have any extra revenue; instead he will have the current month's utility bill covered and an extra credit for future energy bills, which expires in thirty-six months. Thus, if the consumer also keeps producing energy surplus, this credit will be continuously lost as months go by.

Despite many issues which occur with the increase of renewable penetration levels (Vahl et al., 2013), the resolution does not focus on technical issues or demand side needs, as it allows producers to inject energy to the grid at free will, with no restrictions or suggestions related to variables as time of day, season of the year, bus voltages, frequency, and capacity levels. The only technical approach of this resolution is to limit the producer's capacity to the same power of its average (declared) load, obeying line capacity constraints. There are no incentives in trading a regular meter to a smart one, or becoming a distributed electricity supplier. Thus, policies supporting the development of distributed generation must be revised in order to accelerate the diffusion of greener technologies in the country, along with proper public advertisement concerning its benefits for society.

Concerning smart grids, utility companies are already investing in technologies for integrating their systems. However, the main aspect focused is reduction of power loss due to informal consumers. There is also a challenge to choose which technology to follow, since there is no national one developed yet and there are many international patterns conducted by brands. Even though, smart grid infrastructure needs to be developed firsthand in order to lower renewables costs and avoid technology retrofits earlier than necessary due to parameter shifts.

5.1.2. Financial support for creating renewables market share

Another issue for adopting small scale distributed generation technologies in Brazil is financing. Most equipment is imported, thus not being eligible for many public loans. Financing is indeed the main struggle for the development of technologies as solar PV panels, small wind turbines and inherent equipment (NREL, 2012), either for the final customer or for the start-ups to establish (Heiskanen et al., 2011). Therefore, funding programs, which focus on supporting greener technological innovations, must be carried in order to create a new path regarding electricity generation and use. Furthermore, institutions must provide funding in order to support start-ups settling in the new energy market, and it has to be linked to entrepreneurial programs.

Goldemberg et al. (2014) proposes that the income generated from the exploration of Pre-salt in Brazil may support renewable sources. Another mechanism for financing renewable generation adoption is the feed-in tariff, which concerns guaranteeing a fixed price based on the learning curve associated with a particular technology, thus supporting various technologies at varying stages of development (Lipp, 2007; Wüstenhagen and Bilharz, 2006). The long-term price guarantee provides market stability and security for investors (Sawin, 2004). Market demand for renewables is then ensured by obligating electricity utilities and grid operators to purchase it. However, according to Lipp (2007), feed-in-tariff may be seen as an expensive way to support renewable energy development, since guaranteed prices may not encourage competition, and renewable power would not be generated at the lowest possible cost.

5.1.3. Renewable variability and natural gas

Although renewable generation, such as wind and solar without energy storage, does not present fuel supply risks, as conventional power plants do, many technologies do experience dynamic resource variability. In this sense, wind and solar energy only provide low capacity value to the utility, regarding reliability of energy systems, which decreases with increasing penetration level. Wind and solar energy, without storage, can only be dispatched within the limits of resource availability (NREL, 2012).

Natural gas can be dispatched flexibly, which offers more capacity for system reliability. The quick ramping ability of natural gas generators makes them ideal for complementing renewable generation. This flexibility also adds additional value as new ancillary service, designed to accommodate increasing levels of intermittent sources on the grid. A balanced electricity mix of both natural gas and renewable energy can adjust generation shares based on continuous optimization of resource availability, fuel costs, and emission requirements.

In Brazil, natural gas distribution pipelines from Pre-salt are still under deployment. Wind farms are also still far away from national wind potential, which is mainly off-shore and on the coast. Therefore, the development of both, coastal and offshore wind sites and natural gas power plants linked to Pre-salt distribution present promising conditions. The same approach could supply the Northeast of Brazil from solar PV systems, tied to natural gas complemented grids. However, if a technological path is not developed under such way, later transition costs will be a barrier for wind and solar PV adoption in Brazil.

5.2. Demand side energy management

Demand side response is much faster than increasing generation. In 2001, Brazil succeeded to reduce load to desired levels with intensive public advertising. Demand response can take several forms, including (IEA, 2013a,b): changing supplier in response to price and product offerings, creating strong incentives and disciplines for efficient retail pricing and innovative product offerings; shifting demand from one time period to another, with the potential to help smooth the profile of consumption, reducing pressure on prices and system resources during peak periods; and reducing demand through more efficient end-use, which can reduce demand-related pressure on power system capacity. These responses can improve system flexibility and resilience, reduce operating costs and create strong incentives for further investments.

Demand response tends to be either price-based or incentive-based. Price-based demand responses concerns the elaboration of pricing arrangements between the utility and consumers. Incentive-based demand response provides an agreed fixed rate payment for switching off during peak price events, and customer participation is rewarded according to the savings associated (NREL, 2012). These additional incentives reflect the additional value of certain types of flexibility, as very short-term response.

5.3. Deployment of natural gas niches

Besides electricity generation, natural gas has many applications as energy source, in niches which are indeed in need of retrofitting. Since natural gas has been scarce and poorly distributed in Brazil, most supply was driven to the industry sector. It is also geographically monopolized to the South and Southeastern. Lately the need in the electricity sector and the discoveries of Pre-salt have brought new investments for its drilling and distribution, which allows the use of natural gas in other Brazilian markets.

Since natural gas emits less GHG than gasoline, oil or coal, substituting such sources is indeed a more sustainable solution. The industry sector has high priority of gas supply in governmental programs, so this sector may achieve considerable decrease in emissions soon. Natural gas hybrid cars, similarly to what has happened to those fueled by sugar cane alcohol, need sturdy support for increasing adoption. As previously presented, some market impressions are difficult to switch. However, the shift from electric vehicles to internal combustion took about 30 years to happen and it was driven by innovation. Actual microprocessor and power electronics technologies evolve at a much higher pace, which may help the adoption of greener vehicles if properly managed. Green innovations and entrepreneurship support, along with stakeholder management are then key factors in Brazil to create a new path for spreading greener vehicles, for natural gas and biofuels.

35% of residential electricity consumption is from electric showers in Brazil (ANEEL, 2014). Many households may be provided of natural gas for heating water. There is also increasing concern about heating spaces, since 2013 presented the coldest year ever measured in the South of Brazil: it snowed in more than 100 cities simultaneously, which had never happened before. Therefore, changes in climate will urge more energy for heating as well, which may be supplied by natural gas more efficiently than using electricity. Furthermore, combined heat and power (CHP) plants may urge as necessary suppliers in the next decades in the South of Brazil, where it will also find use for natural gas in co-combustion with coal.

5.4. Concluding remarks

Current Brazilian energy policies, electricity and natural gas production are biased to path dependence of technologies and the discoveries of new oil and gas fields of Pre-salt. Thermal power plants are losing markets in developed countries but have found their way into developing ones. Financial services are also available for them, and since these are knowledge intensive fields, knowledge transfer to developing countries shall help longing the dependence on the oil and gas industry. Such path dependence will drive the Brazilian energy transition away from desired GHG reduction targets and stakeholders' needs. Alternative greener technological paths may be created, through incentives for renewable and distributed generation adoption and smarter use of natural gas, although these must match large industries' interests.

Concerning the energy sector in Brazil, start-ups must compete with the government itself, thus shifting paths in such market implies political issues as well. If current energy policies are sustained, the deployment of renewable generation will struggle to reach economically sustainable market shares in the next decades, which will indeed increase GHG emissions of the electricity mix.

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