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Analyses and perspectives for Brazilian low carbon technological development in the energy sector

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A B S T R A C T

This review paper discusses the perspectives for development of low carbon technologies in the Brazilian energy sector, leading the country to less carbon intensive emission patterns within the next decades. Brazil's current plans for expansion of its electricity matrix and overall energy sector data are briefly presented along with demand growth expectancy to illustrate the challenge faced. Existing literature on development scenarios for the country's energy sector is then analyzed separately, including IPCC's global emission scenarios, International Energy Agency's scenarios for South American industry, specific country focused reports and ongoing governmental plans. Selected low carbon technologies for the energy sector are then individually reviewed, providing an insight into their current stage of development, perspectives and bottlenecks within Brazil, based on a diversity of sources. As a conclusion the authors expose their opinion on what can be expected for the future of Brazil's energy sector, based on the likeliness of deployment of the selected technologies, giving overall recommendations on how to achieve optimistic expectations.

Contents

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1. Introduction

The provision of affordable and environmentally sound energy services is a prerequisite for further social and economic development in the world and especially in economies in transition. This challenge is particularly interesting in Brazil, where the ongoing governmental Growth Acceleration Plan [1] traces a path for an increasingly carbon intensive power matrix, mainly due to the foreseen use of coal and gas fired thermo power and for the iron and steel sectors in the coming decades, deviating from the existing scenario which ranks it as one of the cleanest worldwide. In 2009 renewable energies represented 47.3% of the total energy offer, mainly because of sugar cane products, other biomass energy sources, and the power sector's hydroelectric supply, which accounted for 76.7% of all the electricity generated in 2009 [2].

Industrial development, economic growth and demographic expansion [3],[1] will be responsible for most of the expected increase in electricity demand from 401 TWh/year in 2005 to 933 TWh/year in 2030 [4], so the country is going through a period of transition in which its future energy provision structure and consequent technological pathways are being defined. This review intends to provide an overview of the Brazilian technological perspectives for the energy sector, one that manages to see the wide picture of its possibilities, variables involved, and constraints. Comprehending the significance of the technological variables in defining different possible outcomes of emission patterns, item 2 presents evaluations on sequence of existing studies on perspectives for Brazilian technological development, which include scenarios for future energy demand, supply, and GHG emissions. Separately, item 3 presents further development on a selection of technologies which were considered as being the most significant for the Brazilian case, based on the studies analyzed and authors 'plus specialists' opinions. Individual outlines of their current situation, perspectives, discussions on bottlenecks and recommended pathways for successful deployment into 2030 are presented. As a conclusion, item 4 presents a discussion on general perspectives, as authors expose their opinion on what can be expected for Brazil's future, as well as for the likeliness of deployment of the technologies elected in item 3 into 2030, giving overall recommendations on how to achieve optimistic expectations.

2. Evaluation of existing studies for Brazilian energy sector's technological development

2.1. The Intergovernmental Panel for Climate Change's (IPCC's) Special Report on Emission Scenarios (SRES)

Analyzing the A1 scenario family in the Intergovernmental Panel for Climate Change (IPCC) Special Report on Emission Scenarios [5], it is clear that technological variables are as influential as demographic and economic variables in the sense that different technological paths lead to very distinct future emission patterns. In recognition of the considerable uncertainty in describing future technological trends, the IPCC SRES authors created a scenario approach that varies technology-specific assumptions in the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) runs of the SRES scenarios. Depending on the specific interpretation of the four SRES scenario storylines – A1, A2, B1 and B2 – alternative technologies and alternative ranges of their future characteristics were assumed as model inputs.

The A1 scenarios are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). The emission outcomes of A1FI and A1T end up on 2 extreme ranges by 2100, indicating how different technological choices may lead us to different emission patterns, and probably to distinct climate alterations. In the dynamic technology scenario group A1T, technological change driven by market mechanisms and policies to promote innovation, favors non-fossil technologies and synfuels, especially hydrogen from non-fossil sources [5]. Solar, wind and geothermal energies become available at 12.4 UScent/kWh by 2020 progressing to 6.2 UScent/kWh by 2050 in Asian Pacific Integrated Model (A1T-AIM) through exploitation of learning-curve effects. The A1T results in the Multiregional Approach for Resource and Industry Allocation (MARIA), and also projects declining costs for biofuels, from about US$30 to US$20, after 2020; non-fossil electricity (e.g., photovoltaic) begin massive market penetration at costs of about 1–3 UScent/kWh in MESSAGE, MARIA and AIM, and could continue to improve further (perhaps as low as 0.1 UScent/kWh in MESSAGE) [5] as a result of learning-curve effects. An important difference between the marker scenario A1B and the A1T group is that in A1T additional end-use efficiency improvements are assumed to take place with the diffusion of new end-use devices for decentralized production of electricity (fuel cells, micro turbines) [5]. Adding up assumption differences, results in MESSAGE project global energy output in 2050 for the A1T to be 509.5 EJ, or 15% lower compared to 595.7 EJ projected for the A1C (Coal Intensive) scenario.

2.2. The IEA Technology Transitions for Industry

The International Energy Agency (IEA) has developed a number of scenarios with descriptions of the efforts needed to reduce carbon dioxide emissions into 2050. The baseline scenario foresees emission patterns in the absence of policy change and major supply constraints leading to continuous fossil based pathways and steady increase in GHG emissions until 2050. Other scenarios explore different technological pathways to achieve emission reductions separated into two subgroups, depending on emission reduction objectives: the Accelerated Technology (ACT) scenarios bring back CO_2 emissions to 2005 levels by 2050 through a number of technological developments. The "BLUE" scenarios are more ambitious, bringing emissions to 50% of the 2005 level by 2050, in accordance with the IPCC's recommendations for non-catastrophic human intervention in the climate system.

[1] Demographic expansion is expected to add 23 million people to the Brazilian population from 2010 to 2030, going from present 193 million to 216 million people [3].

The IEAs report Technology Transitions for Industry [6] shows that Latin America's high production growth, especially in cement, iron and steel sub sectors will lead direct energy and process emissions to increase between 95% and 158% compared to 2006 levels, reaching between 0.55 $GtCO_2$/year and 0.73 $GtCO_2$/year in the baseline low and high scenarios by 2050. Strictly in Latin American industrial sector, energy efficiency and fuel switching on supply and demand sides, demand reduction, and CCS added up, are projected to have a potential of reducing between 0.5 $GtCO_2$/year and 0.6 $GtCO_2$/year in the BLUE low and high demand scenarios respectively in 2050. The latter implies much higher investment costs, along with greater demand for technological and policy developments, but political feasibility is not discussed in the report.

Projections are very sensitive to assumptions about technological developments [7]. The IEA assumes in the baseline scenarios that the performance of currently available technologies such as energy efficiency, fuel and feedstock switching, greater levels of recycling, and CO_2 capture and storage improve on various operational criteria. However, assumptions about the pace of technological advance vary depending on the assessment of the potential for efficiency improvements and the stage of technology development and commercialization. Many new technologies which can support these outcomes, such as smelt reduction, new separation membranes, black liquor and biomass gasification and advanced cogeneration, are currently being developed, demonstrated and adopted by industry [7]. Crucially, no new technologies on the demand or supply side, beyond those known about today, are assumed to be deployed before the end of the projection period, since it cannot be known whether or when such breakthroughs might occur and how quickly they may be commercialized.

The need for additional research, development and demonstration (RD&D) is highlighted by the IEA as a way to develop breakthrough process technologies that allow for the CO_2-free production of materials, and to advance understanding of system approaches such as the optimization of life-cycles through recycling and using more efficient materials. However, achieving the level of deployment for mitigation options considered would require substantial investments in new technologies, which brings along the need for clear, long-term policies that put a price on CO_2 emissions, and moreover the need for technology transfer from developed to developing countries, since most of the future growth in industry production will take place in regions outside the OECD. The IEA also warns that for achieving optimistic scenarios, individual governments would need to play a role in mitigating some of the policy and economic risks that, especially in the early stages, industry may be unwilling to take.

2.3. Pathways to a low carbon economy for Brazil

The report by McKinsey & Company determines several abatement options while still considering an increasing fossil participation in the country's energy matrix. Results show that GHG emissions may be reduced from 2.8 $GtCO_2$ equiv. in 2010 to 0.9 $GtCO_2$ equiv. in 2030, from which 72% would come from the forestry sector, basically by reducing deforestation. The power, industrial and transportation sectors account for 18.2% of current Brazilian emissions [8], their emission reduction potentials add up to 199 $MtCO_2$ equiv. in 2030, which would represent 11% of the country's total abatement potential.

According to the report, the power sector is expected to more than double its energy offer in the base case until 2030, raising related emissions from 30 $MtCO_2$ equiv. in 2005 to 90 $MtCO_2$ equiv. in 2030 [4]. The study does not consider efficiency measures in the sector or fuel switching to predict an abatement potential, but rather concentrates on the demand reduction expected from abatement initiatives in other sectors, which impacts the energy sector, lowering its energy offer and emissions. In this scenario, reductions of around 90 TWh/year in demand could be distributed across all power sources, and still fossil sources would raise its participation from 9% in 2005 to 14% in 2030. Abatement potential remains a modest 7 $MtCO_2$ equiv. in 2030, based on the increase of small hydro power plant energy offer suppressing fossil investments.

The transport sector has a potential of reducing its base case emissions by 25% in 2030 or 69 $MtCO_2$ equiv., at an average cost of €12 per tCO_2 equiv., due to technology improvements and end use fuel switch through an increased penetration of biofuels – the study assumes 80% of the automobile fleet to be running on ethanol by 2020, and biodiesel penetration levels at a 5% compulsory concentration in end use diesel. Vehicle technology improvements are not specified, but are said to be related to light vehicles, especially into engine, transmission box, aerodynamics, weight and tires. Hybrid and electric cars have also been considered, but with minor effects considering technological and economic bottlenecks.

The industry sector is expected to increase its emissions from 180 $MtCO_2$ equiv./year in 2005 to 360 $MtCO_2$ equiv./year in 2030 in the base case scenario. Nonetheless it has a wide range of abatement options. In the steel sector, where emissions are expected to rise almost two-fold, abatement may reach up to 50 $MtCO_2$ equiv. avoided, where energy efficiency; fuel switching from coke to reforestation charcoal; the use of new technologies in new mills, and CCS are indicated as the most significant measures in an order of least to most expensive. In the chemical sector, where emissions are expected to raise 2.4 fold by 2030 in the base case scenario, 20% of the abatement potential would come from power generation fuel switching, replacing coal and expanding the use of natural gas and biomass. The use of process energy to generate heat and further reduce fuel use, along with other smaller measures sum up with the above to make the total abatement potential of 33 $MtCO_2$ equiv./year for the chemical sector. From this total, around 9 $MtCO_2$ equiv. avoided emissions could come from CCS, with expected costs at €43 per tCO_2 equiv., and therefore less likely to happen. The analysis of the oil and gas industry does not consider petrochemical emissions, which are accounted for in the chemical sector, nor ground transportation of fuels, accounted for in the transportation sector. Basically considering exploration and refining emissions, the study points to an expected increase of 50% from 2005 reaching 60 $MtCO_2$ equiv. in 2030 in the base case. Opportunities for abatement add up to 20 $MtCO_2$ equiv./year in 2030, from which 40% are in refinery's efficiency in energy use with possible negative costs, and over 50% are based on CCS expectancies with costs over €40 per tCO_2 equiv. The cement industry is pushed by the high demand of a developing country, reaching a three-fold increase in its emissions from 2005 to 2030. Implementing initiatives in this sector could reduce annual emissions by 16 $MtCO_2$ equiv. in 2030, mostly linked to replacing clinker and using alternative fuels such as slag from the steel industry. If slag is coming from blast furnaces using renewable charcoal instead of coke or deforestation charcoal, abating potential is even higher, up to 20 $MtCO_2$ equiv. The use of alternative fuels such as biomass or municipal waste is considered to have a 25% fraction of the total abatement potential in this industry, and CCS could account for 40% of that potential at a €40 per tCO_2e, again less likely to happen. Adding up emission reduction potentials from steel, chemical, oil & gas, and cement industries; 123 $MtCO_2$ equiv./year may be avoided in 2030 [4].

2.4. Study on potential for reduction of CO_2 emissions and a low-carbon scenario for the Brazilian industrial sector

The study performed in the Federal University of Rio de Janeiro [9] shows us that over the past 40 years, the Brazilian industrial sector has passed through clear shifts in main energy sources, due to cost variations and/or increases in supply of certain sources.

Amongst fossil sources, in recent years there has been more intense use of some with higher carbon content, such as coking coal and fuel oil, but this has been offset to some extent by the use of fuels with lower emissions, such as natural gas, along with renewable sources such as sugarcane bagasse, wood, charcoal and black liquor (from pulp and paper mills) [9].

Evaluating the potential for a low carbon industry in Brazil, the study traces a baseline scenario and a low carbon scenario based on the implementation of six main categories of mitigation measures, and their abatement potentials strictly for CO_2 reductions calculated into 2030. The baseline scenario reaches yearly emissions of 291 $MtCO_2$ in 2030, but the set of measures pushes the line down to the low carbon scenario where 167 $MtCO_2$ would be emitted in 2030, which means a reduction of 124 $MtCO_2$ by the year 2030 [9], or 42.6% considering the full scale adoption of the selected measures. This result is slightly overrated if compared to the perspective for the industrial sector shown in Section 2.3, since it is obtained strictly from industrial carbon abatement potentials, not considering other GHG emissions, which should theoretically result in less abatement potential volumes than when all gaseous emission abatements are considered, as in Section 2.3.

The study presents an aggregation of efficiency measures in the industry, as the largest contributor for the emission reduction potential in the 2010–2030 period. Namely, combustion improvement; heat recovery; steam recovery of furnaces and kilns; new processes; and other energy efficiency measures, which add up to a potential emission reduction of over 598 $MtCO_2$ accumulated between 2010 and 2030, reaching over 47 $MtCO_2$/year potential abatement in 2030 [9]. Next in order of accumulated emission potential would come the hypothesis of completely eliminating the use of non-renewable biomass (wood and charcoal from deforestation), reaching over 566 $MtCO_2$ accumulated between 2010 and 2030, reaching alone an abatement potential of over 47 $MtCO_2$/year in 2030. This measure would have a kick start and a sharp growth in its abatement potential beginning around 2017, after the 7 years necessary for harvesting of planted forests. These results indicate it is possible for emissions in 2030 to be only 23% higher than the current 2010 figure (an average yearly increase of 1.04%), even with the industrial sector growing at an annual rate of 3.7% [9].

It is shown that this set of measures would require huge investments, but the majority of them would have significant economic return and negative abatement costs. However, in many cases there would be low economic attractiveness and higher abatement costs, thus requiring more effective incentives. Brazil is already carrying out various actions towards the mitigation measures shown in this study, as discussed throughout the following Section 3, but there are still substantial barriers to realize this potential amidst the different measures and their implications. It is also said that measures such as efficiency improvements, fossil to biomass switch, natural gas use and cogeneration, are most likely to achieve their full potentials, but the extent to which each measure is effectively implemented countrywide is hardly predictable.

2.5. The National Energy Plan for 2030

2.5.1. Overview of scenarios

The National Energy Plan for 2030 (PNE) [10] is the Brazilian government's most recent major effort to monitor in an integrated manner the evolution of the country's overall energy system, taking into account long term policies already defined by the government by the date of the publication. Technological development has been considered as contributing to overcoming challenges towards a secure, efficient, environmentally sound, economically advantageous and publicly beneficial energy system. Evaluating the technological tendencies, and possible outcomes in developments of existing technologies, along with different economical, political and demographic perspectives, this study has focused a set of 4 scenarios into 2030.

Scenario A is associated with a global unity view, in which Brazil is able to contour its main growth obstacles enjoying an extremely favorable external situation. It is characterized by a high GDP average growth rate of 5.1%/year resulting in high infrastructure and education investments. As a whole there is an impulse towards technological advances given the favorable situation for RD&I, and the growing investments in modern machinery. Scenarios B1 and B2 are both associated with a global vision of a world divided into economic blocks, in which there is a favorable external economic and political context, but that does not necessarily sustain domestic growth. The scenarios differ in the way the country's administration is able to overcome obstacles. Scenario B1 is characterized by an internal average GDP growth of 4.1%/year which is larger than the expected average for global economy, as a result of an active policy on dealing with internal problems. Scenario B2 foresees an economy with lower GDP average growth of 3.2%/year, in equivalence with global expected averages due to difficulties in confronting internal structural problems. Scenario C is based on a key assumption that USA's difficulties in balancing its macroeconomic conditions generates further crisis affecting the international growth patterns. It is characterized by a troubled international scenario where capital flows are virtually interrupted and international commerce expands with modest numbers or even retracts, leading to average GDP growth in Brazil of 2.2%/year [10].

2.5.2. Energy efficiency perspectives in the National Energy Plan (PNE)

Projections for energy efficiency in the National Energy Plan have considered two distinct movements; an autonomous progress happening due to 'natural' dynamics of the sectors, such as technology substitution with the end of old equipment's life cycles, or substitution due to market pressures or environmental regulations when motivated by existing programs or conservation actions; and an induced progress, which refers to the implementation of specific actions oriented towards certain sectors by public policies. The projections for energy conservation contained in the PNE have only considered induced progress in relation to electric energy consumption, based on two of the existing governmental plans – Electric Energy Conservation Program (PROCEL) [11] and Brazilian Labeling Program (PBE) – aimed towards energy conservation and efficiency incentives in different sectors. The A scenario results in most energy consumption, and yearly energy tax rates, but it is also the one in which most efficiency measures are projected, given its favorable technological impulse. The following scenarios consider less energy savings per year, ranging from 11% savings in 2030 for the A scenario and 4.5% savings in 2030 for the C scenario.

The model used throughout the PNE assumes that the choices towards one or another technological pathway will depend basically on resource availability, costs of different energy sources, institutional restrictions and technology investment costs; directing perspectives differently within each scenario. Even with favorable economical and political conditions, as projected in scenario A, different technological advances and path choices, may result in different market outcomes. As highlighted by Grubler et al. [12] technological change is one of the least developed parts of existing global change models, and advancing technological knowledge is the most important single factor that contributes to long-term productivity and economic growth. The model outcome of efficiency in the PNE was achieved by considering a set of key technological advances per sector applied in different

Table 1
Most significant technological advances and efficiency measures considered in different sectors.

Sector/segment	Technology advances
Power	- Combined cycle turbines reducing demand for oil & coal derivates; - Leftover biomass use for electricity generation; - Technological learning diminishing costs for wind energy.
Industry	
Iron/steel	- Energy conserved from new equipment; - Gradual non-renewable biomass fuel switch.
Aluminum	- Gradual expansion of plants based on pre-cooked anodes, with increased efficiency in electricity use.
Chemical	- % and speed of natural gas penetration; - Less impacting technologies in soda-chlorine segment.
Cement	- Reduction in kcal/kg clinker fraction.
Paper/cellulose	- Specific consuming of thermal and electric energy for cellulose and paper production.
Residential	- Specific electricity consumption efficiency considering advances in GDP per capita as inducing the purchase of more efficient goods.
Transport	- Penetration of ethanol in fuel demand; - Efficiency gains especially in light vehicles considering increase in per capita income; - Gradual reduction of road transport considering public policies towards train and water cargo transportation.
Bovine agro industry	- More efficient use of diesel and electricity as main power inputs.

Adapted from [10].

scales according to the aforementioned scenario storylines. Table 1 presents the most significant advances considered within different sectors, for all scenarios in different scales.

2.5.3. CO_2 emission perspectives in National Energy Plan

Considering the midterm B1 scenario, the National Energy Plan presents the following graph, Fig. 1, for total emissions exclusively for the Brazilian energy sector projecting a rise to over 970 $MtCO_2$/year in 2030. Other sectors and scenarios are not evaluated regarding emission patterns in the National Energy Plan. According to this storyline, industry and transport sectors are expected to be the greatest contributors for total emissions in 2030, but electricity generation is expected to have the largest growth rates – almost 7% per year on average – increasing its participation from 6% in 2005 to over 10% in 2030 due to the aforementioned power sector expansion plans.

Recent developments regarding power generation have, however, shown that the above emissions estimate can be considered conservative from the initial projection of 2008 to mid 2010. Indeed, as a result of circumstantial reasons (i.e., adverse hydrological conditions), more fossil energy has been used; mainly coal and natural gas fueled power plants. Additionally, some delays in inventory, feasibility studies, and licensing processes restrained the participation of hydro power plants in recent electricity auctions. If this tendency were to continue over a longer term, Brazilian emission estimates would be significantly greater than projected above [13].

2.6. World Bank low carbon study for Brazil

The study performed by the World Bank and Brazilian specialists from different sectors [13], used the above midterm scenario of the PNE (average 3.7% annual GDP growth into 2030) as a baseline and created their own mitigation potential curve, tracing a low carbon scenario into 2030. The study evaluates potential abatements for energy, transport, waste, deforestation, livestock and agriculture sectors, evaluating plausible mitigation measures. Industry is not evaluated as a whole individual sector, impeding direct result comparison with Sections 2.3 and 2.4.

The energy sector is evaluated as a whole, and proposed mitigation measures are divided into demand side: energy efficiency, fuel switch to low-carbon content and/or renewable-energy consumption and recycling. And supply side: renewable energy for power generation (wind farm and biomass cogeneration) and optimized refinery schemes and gas-to-liquid (GTL). By implementing all of the mitigation options proposed, the reference scenario of 458 $MtCO_2$ equiv. reached in 2030 (not counting the transport sector), is lowered to 297 $MtCO_2$ equiv. in that year, adding over 1.8 $GtCO_2$ equiv. to accumulated avoided emissions in the 2010–2030 period. The switch to renewable charcoal and energy efficiency are again indicated as the most important measures accounting for 31% and over 28% of accumulated reduction potential respectively.

Transport sector mitigation options include increased ethanol participation, metro, railways for passengers and cargo, demand side management, and bicycle transportation. The reference sce-

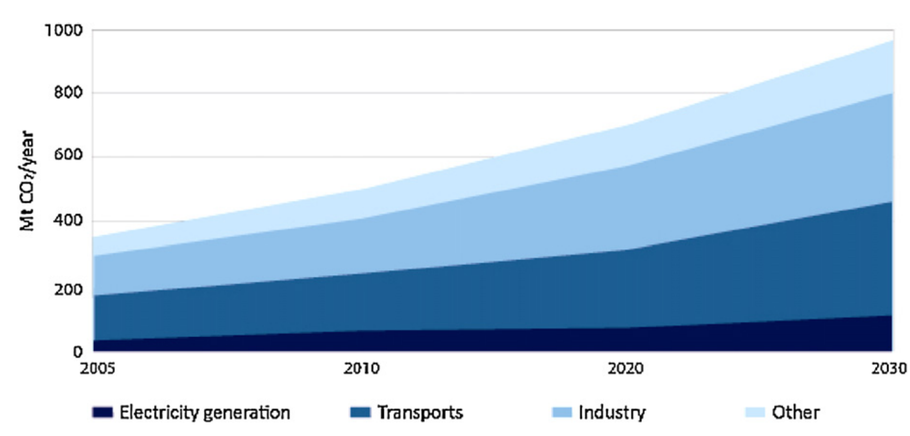

Fig. 1. Evolution of CO_2 emissions in Brazilian energy sector, midterm PNE scenario-$MtCO_2$/year.

nario points to an increase in emissions from 154 $MtCO_2$ equiv./year in 2010 to 247 $MtCO_2$ equiv./year in 2030, and the above measures constitute the potential for a low carbon scenario in which 182 $MtCO_2$ equiv. could be emitted in 2030, thereby avoiding a total of 487 $MtCO_2$ equiv. accumulated in the 20 year period.

The waste sector analysis is based on a reference scenario of emissions increasing from 62 to 99 $MtCO_2$ equiv./year from 2010 to 2030. Emission abatement options include methane recovery and destruction from landfills and from sewage treatment; improvements in landfills; reduction of open air waste deposits; composting; recycling; and incineration with energy recovery. Summing up, the total abatement potential, by the development of these technologies leads to a low carbon scenario in which 18 $MtCO_2$ equiv./year could be emitted in 2030, which means there is a very significant potential reduction of over 81% from the waste sub-sector's emissions.

3. Summarized perspectives for selected low carbon technologies

3.1. Hydropower

Keeping up with the hydropower 'tradition' in Brazil, the Government's Growth Acceleration Plan (PAC, 2007) [2] announces large investments in small and large-scale plants. The National Electric Energy Agency (ANEEL) confirms this perspective, in the databank publicly displayed online [14], which shows that by April 2011 there are 175 installed large scale hydroelectric power plants in Brazil with an associated potency of 77,839 MW of hydropower; another 10 are under construction; and another 17 plants have been primarily approved and are expected to be built in the following years. When all 202 plants are running together, their associated potency will add up to over 100,859 MW of installed hydropower [14]. Publicized governmental plans indicate that there will be an addition of 35 MW from hydropower plants by 2019 [15], indicating that many other large scale hydro power plants sites will be auctioned for entrepreneurs in this decade, still subject to licenses. Small hydroelectric plants are a growing energy source, with advantages of cost competitiveness and generally less environmental impacts due to smaller scale of flooded areas. By now there are 397 operating small hydroelectric power plants in Brazil with an associated potency of 3584 MW installed hydropower; another 53 are under construction; and another 150 plants have been primarily approved and are expected to be built in the following years. When all 600 plants are running together, their associated potency will add up to over 6357 MW of installed hydropower from small plants [14].

Hydroelectric power stations however, are not as clean an energy source as is generally thought. Life Cycle Analyses of this energy source indicate that there might be significant amounts of CH_4 and CO_2 being emitted by the organic materials submerged/degraded by the water [16]. Analyses show that the intensity of emissions varies along time, with temperature, wind regime, sun intensity, and physiochemical parameters of atmosphere and water – strongly influenced by organic matter density, decomposition rate and time – acting as the main determinants for emission levels. As an example, the Tucuruí hydroelectric power plant in northern Brazil, which occupies 2850 km^2 of flooded area with an average depth of 78 m, had average emissions calculated to be over 8475 kg/km^2 CO_2/day, and 109 kg/km^2 CH_4/day in 2004 [17]. It is important to note that social conflicts involving hydroelectric plants are also at their highest point in Brazil, and are possible obstacles for hydro technology, as clearly illustrated by the example of the Belo Monte Hydro plant, staging conflicts since the 1980s and not yet built.

In such context, other river energy harnessing technologies, such as run-of-the-river plants have been discussed as possible alternatives to allow for hydropower usage with fewer impacts. Also known as free flow or stream turbines, these could be used as distributed systems installed over a large river basin area, causing less environmental adversities. Their underwater installation, away from public places would cause no noise disturbance and have low visual impact, added to low impacts on river navigation or recreation. Criticisms have however risen as such systems begin to be used in the country, mainly related to their higher energy costs when compared to reservoirs, and low capacity to produce energy or to maintain downstream river flows during dry seasons. Environmentalist pressures to avoid licensing of large dams are then faced with the social advantages brought by dams. Khan et al. [18] presents an overview of the technology from a system engineering perspective, along with discussion on its prospects and pertinent challenges.

3.2. Biomass

In a long-term perspective, biomass is one of the highest potential renewable sources for energy supply, characterized mainly by its diversity of possibilities in terms of origin and conversion technologies into energetic products. The term biomass comprehends vegetable matter generated by photosynthesis and all its sub products such as forests, cultivated crops, agro waste, animal droppings and organic matter even if contained in industrial or urban waste. Biomass contains chemical energy accumulated through the transformation of solar energy, and may be directly liberated through combustion or converted through different processes in energetic products with distinct natures, such as charcoal, ethanol, combustible and syngases, combustible vegetable oils and others. Conversion technologies will range from simple combustion to physiochemical and biochemical processes that result in liquid and gaseous products.

3.2.1. Solid biomass

Sources indicate that water and nutrient supplies are the main abiotic factors affecting plantation forest growth in the tropics [19,20]. Results from empirical experiments in Brazil indicate that high productivity eucalyptus stands could produce wood in a 6-year rotation on half the land area required for commonly used low productivity stands, using only half as much water [21]. Light resources are also pointed as a limiting factor for eucalyptus growth, justifying the inference that Brazil's natural conditions of high rainfall and high solar incidence in eastern and southeastern regions greatly favor the use of such biomass as a resource. Planted forests receive much criticism regarding land degradation and land use competition, both of which should be less of an issue in Brazil than in most developed countries, considering the availability of extensive degraded pastureland, which can be recovered into more profitable agro/energy forests. Regarding the sustainability of the concept, there is need for quality maintenance of soil, water cycles and biodiversity as crucial factors for the maintenance of energy accumulation forests with low externalities in the long-term. In that sense, the feasibility and advantages of growing best adapted eucalyptus trees amongst other native species have been demonstrated in literature [22] and in practice. Götsch's experience in the development of agroforestry systems have reconfirmed the critical importance of understanding and duplicating the model of natural succession in the design of long term sustainable agricultural systems as well as in recovering degraded lands. Consequences include attraction of zoo diversity which avoids the development of plagues such as ants; favoring of soil quality with increased leaf fall; avoidance of excessive runoff; and ground water quality maintenance.

The energetic usage of planted forests through charcoal results in far less net carbon emissions than using mineral coal, since close to all associated CO_2 emissions are seasonally removed from the atmosphere during trees 'growth cycle'. This justifies the large emission abatement potentials attributed to the industrial fuel switch from 'non-renewable' deforestation biomass to reforestation biomass, shown in the above analyzed studies. The wide scale deployment of energy forests providing biomass in a sustainable regime can be pushed through the creation of supply push incentives, such as the financing of projects that comply with a set of environmental standards. Moreover, demand pull can actions can focus on restricting usage of deforestation charcoal in key subsectors and also by providing attractive conditions for the acquisition of biomass processing equipment (e.g., boilers and furnaces). Policies of such nature would require trustable certification methods for renewable energy forests, assuring compliance with pertinent environmental standards; and, evidently, on policing the actual implementation of regulations. Brazil has known problems on the latter, towards which there are a series of methods for ensuring compliance, such as selecting inspected firms by chance.

The offer of biomass from the sugar–ethanol sector is already a major input for Brazilian total energy matrix, but is beneath its potential in supplying the electricity matrix. Today, cogeneration from biomass totals 8 GW, of which 6.3 GW are based on sugarcane bagasse [14]. Sector's leftovers – bagasse and straw – are used as energy inputs for the sugar–ethanol processes through incineration in generally inefficient thermal units (boilers), but much is still leftover after the sector's energy needs are supplied. These are typically seen as a problem for ethanol producers, since stored bagasse represents a risk of sudden combustion if laid in the sun, and molding if stored indoors. Many of the existing boilers are approaching the end of their life cycle, being working since the 1970s with now obsolete technology at pressures around 21 bar, which means they burn large quantities of bagasse to generate the demanded amount of vapor. Boilers are, therefore, seen as a way of getting rid of bagasse, since the more they burn, the more they avoid the need for storage, or expensive destination, of whatever is still leftover. The substitution of boilers by new efficient ones, operating between 65 and 120 bar, would significantly reduce the amount of bagasse needed to generate the same amount of vapor, which means more bagasse would be left over after all the vapor needs are supplied. Modernization of boilers has thus been a challenge, while ethanol producers have been switching old boilers for other still inefficient ones available in the market for attractive prices and still eliminating most of the leftovers, leaving few remains for possible public electricity generation. Considering the insertion of three main technology configurations: (i) modernization of existing plants, including installation of an extractor-condensing turbine, producing steam at 90 bars and 520 °C, operating year-round and using up to 50% of available straw; (ii) new plants using mainly extractor-condensing turbines, back-pressure steam turbines for the few new plants using additional hydrolysis processes (also 90 bar, 520 °C) and (iii) Biomass Integrated Gasifier to Gas Turbines (BIG-CC systems) for a limited number of new plants [13]. Installed capacity in sugarcane sector could generate excess 39.5 GW compared to 6.8 GW in the reference scenario from the PNE. This would correspond to 200 TWh/year, compared to 44.1 TWh/year available to export into the electricity grid by 2030 [13]. As a result, avoided GHG emissions would amount to 158 $MtCO_2$ over the 2010–30 period (7.5 $MtCO_2$ per year on average).

For the country as a whole, bagasse derived electricity would be an important input into the public grid with economic and environmental benefits. The adoption and deployment of such a measure would require initial investments, but would give ethanol producers an opportunity to transform leftovers into income, selling electricity into the grid. Main barriers for this cogeneration involve the cost of interconnection with the sometimes distant or insufficient transmission grid, and the fact that mill owners, who are the potential investors in such technology have other investing priorities and opportunities, and are not always familiar with the electricity sector [13]. Overcoming of such barriers could come from financial support for usage of best available technologies in the sector, along with a governmental aim for minimal yearly installation based on an evaluation of the benefits provided and the feasibility with interconnection to the grid. Such a strategy should naturally lead to increased efforts in sugar-cane residues recovery from fields to the mills. Table 2 presents the National Energy Plan's estimated potential for electricity generation in sugar cane processing plants based on leftover volumes after the sector's vapor needs are supplied.

Table 2
Potential for electricity generation in sugar cane processing plants. Existing and new perspective installations (MW).

Type of installation	Existing potential	Perspective potential		
	2006	2010	2020	2030
Low efficiency cycles	260	140	90	30
Counter pressure turbine cycles	90	1790	2820	4170
Condensation and extraction cycles	10	240	980	1750
Combined cycle	0	0	220	880
Total	360	2170	4110	6830

Adapted from [10].

3.2.2. *Liquid biofuels*

In 2008 there were 325 plants in operation in Brazil crushing 425 million tons of sugarcane per year, approximately one-half being used for sugar and the other half for ethanol production. Liquid biofuels are already a major contributor to lowering Brazilian net emission scenario, in which the governmental ethanol program (PROALCOOL), established during the military dictatorship in 1975 as an energy security measure; and the National Biodiesel Production and Use Program deserve special attention.

Recent data indicate that the PROALCOOL has up to 2008 avoided emissions of 800 $MtCO_2$ from the transportation sector, or around 30% of vehicle annual emissions [23]. The fuel has a growing demand pushed by the growing popularity and supply of flex fuel cars, leading to lowered emissions of carbon monoxide (CO); carbon dioxide (CO_2); hydrocarbons and sulfur emissions significantly. Exhaust emissions associated with ethanol are also less toxic than those associated to gasoline, and have lower atmospheric reactivity [24]. The positive energy balance associated with pure sugarcane-based ethanol motors is reflected by a considerable reduction (91%) in greenhouse gas emissions if compared to resulting emissions from pure gasoline motors [25].

Presently the production of ethanol in Brazil relies almost exclusively on first-generation technologies that are based on the utilization of the sucrose content of sugarcane, but as discussed above, sucrose represents only one-third of the energy content of sugarcane. The efficiency of sugarcane-to-ethanol production can be further increased through improvements in the agricultural and industrial phases of the production process. For example, in the agricultural phase, a good sugar cane yield and a high index of TRS (total recoverable sugar) are the main drivers for high yield of ethanol per unit of planted area. The increase of TRS from sugarcane has been significant: 1.5% per year in the period 1977–2004, resulting in an increase from 95 to 140 kg/ha [25]. Nonetheless, Brazilian ethanol is a target for major criticisms that question the sustainability of its large-scale production due to low energy recovery on investment. Assessing the quality of agro-fuels as primary

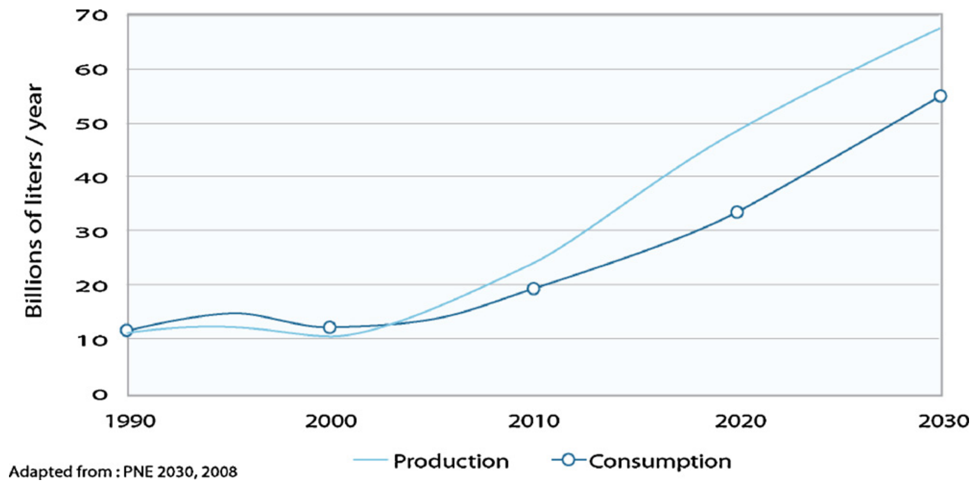

Fig. 2. Ethanol projected consumption and production in B1 (midterm growth) scenario.

energy sources, Giampietro et al. [26] indicate a systematic lack of feasibility of large-scale generation of agro-biofuels to power the metabolic pattern of a modern post-industrial society. The assessment shows that output/input of energy carriers in average Brazilian sugar cane is acceptable, being (7/1), but specifically for the Brazilian case there are extremely low power levels, calculated by the consumption of energy carriers within that sector divided by the specific labor hours dedicated to that sector. Such numbers lead to the inevitable comprehension that biofuels are not as high quality primary energy sources as fossil fuels, therefore requiring much input either of energy carriers, in the form of machineries or human labor to obtain a net energy extraction. Brazilian ethanol and biodiesel development programs must therefore assess for inevitable internal (capital/labor) and external biophysical constraints. Currently, the National Energy Plan [10] projects an increase in internal ethanol consumption in Brazil from around 20 billion l in 2010 to around 55 billion l in 2030, as shown in Fig. 2.

The National Biodiesel Production and Use Program – established by the law 11.097 in 2005 – has steadily increased a compulsory mix of biodiesel into the fossil diesel commercialized for end users in Brazil, going from 2% in 2005 to 5% in 2010, with an expected increase of up to 12% in 2030. As shown in Table 3, the midterm B1 scenario of the National Energy Plan leads to an almost fourfold increase of biodiesel production in Brazil between 2010 and 2030.

As biodiesel displaces fossil diesel in the market there is a decrease in net CO_2 emissions, considering the growing of different plant species subsequently absorbs most of its associated emissions, mainly mammon, soy and palm oil (*dendê*) in Brazil. Other important consequences for the expected increased compulsory mix of vegetable oil, involve mainly social issues. On one side the biodiesel program has shown interesting results in directing energy company's investments, such as Petrobras, towards family agriculture in Brazilian rural areas. Studies indicate that for each 1% of biodiesel increased in the fuel mix, there is a potential for 45 thousand new jobs in rural areas with an average annual income of around[2] US$2,649.00 per job, which is generally very positive considering Brazilian rural standards. One another side, critics highlight the dispute for cropland, indirect land use change, and consequent increase in food prices. Regarding this discussion it is important to highlight again that a large fraction of Brazilian land use is taken by pasturelands – 81.6% of land allocated to agriculture is used for pastureland in Brazil [27] – offering jobs for few, exerting pressures for deforestation in all Brazilian biomes – 32% of the deforested area in the Amazon between 2006 and 2008 was cleared for pastureland [27] – and in which degradation sites are a common view. Associating the growing of oily plant species to the rehabilitation of pastureland within sustainable agroforestry regimes can be amongst the best propositions for family agriculture based supply of biofuel feedstock. The idea is supported by economic advantages of crops over pastureland, but profits would be diffuse amongst families and not concentrated on few landowners. Bottlenecks are vast, and include: Lack of clear land titles; need for land reforms; lack of resources to enforce legislation; informal and illegal market for timber as an unfair competition to sustainable models; and lack of environmental education, making the forest a cash-crop for local communities. Such issues touch deeply into political and economic conflicts attached to such propositions, and will not be further discussed.

Table 3
National fossil diesel and biodiesel production in B1 scenario (billions of l/year).

	2010	2020	2030
Projected fossil diesel consumption	51.2	69.1	97.9
% of Biodiesel added	6%	7%	12%
Biodiesel production	3.1	4.8	11.7

Adapted from [10].

3.2.2.1. Microalgae biofuel. Microalgae reproduce using photosynthesis to convert sun energy into chemical energy, completing an entire growth cycle every few days [28]. Moreover they can grow almost anywhere, requiring sunlight and some simple nutrients, although the growth rates can be accelerated by the addition of specific nutrients and sufficient aeration. Different microalgae species can be adapted to live in a variety of environmental conditions. They have much higher growth rates and productivity when compared to conventional forestry, agricultural crops, and other aquatic plants, requiring much less land area than other biodiesel feedstocks of agricultural origin, up to 49 or 132 times less when compared to rapeseed or soybean crops [29]. Therefore, the competition for arable soil with other crops, in particular for human consumption, is greatly reduced. Microalgae oil represents one of the best options in the energetic availability per hectare – 202 million kcal/ha – compared to 50.5 million kcal/ha for palm oil and 3.4 million kcal/ha for soya oil [28], providing feedstock for several different types of renewable fuels such as biodiesel, methane,

[2] Based on R$ × US$ levels on 21st May 2010.

hydrogen and ethanol. Algae biodiesel contains no sulfur and performs as well as petroleum diesel, while reducing emissions of particulate matter, CO, hydrocarbons, and SO_x. However emissions of NO_x may be higher in some engine types [30].

Microalgae cultivation and processing have been advancing around the world, and certainly could be used in Brazil in an interesting way due to its high net energy conversion factor [28]. High average solar radiation associated with the possibility of feeding microalgae with waste from industrial processes could represent a new frontier for this biomaterial. If inserted in a biorefinery concept microalgae could be cultivated in the effluents of the alcohol distilleries – the vinasse – fed with clean CO_2 from the fermentation process to improve the energetic yields. Bottlenecks hampering microalgae oil's potential development are mainly technological and economic, but also cultural, since possible investors in sugar–ethanol subsector know little about its possibilities. On the other hand, the few existing experimental photobioreactors operating in a pilot scale within interested companies and in research institutions offer somewhat optimistic views on Brazilian microalgae perspectives and the development of this resource seems promising on the 2030 horizon considering technology learning and market pushes from R&D investments.

3.2.3. Biogas

Biogas may be used either directly as a gas fuel generating heat energy, or as a fuel for thermoelectric stations. In Brazil biogas has generally been seen as a byproduct with few utilities. However, since the implementation of the Clean Development Mechanism (CDM), along with the availability of landfill sites with biogas recovery opportunities, plus negative externalities caused by the direct discharge of organic waste, namely from livestock industries, there have been increased investments in the production biogas from organic waste. The conversion of biogas into useful energy is still in its infancy in Brazil, but evidences point to a wide-scale usage of such energy source into the next decades. Advantages of producing biogas from waste, and further converting its energetic potential into electricity involve mainly the primary objective of offsetting organic waste discharge pollution, namely in water bodies; the possibility for decentralized electricity generation as a rural complement; an offset in electricity purchase from the utility; and reduced greenhouse gas emissions with possible carbon credits allocated through the CDM.

The potential for biogas production from bovine and swine industries is probably the most promising in terms of energy, economic, social and environmental gains. As shown by the example of the biogas to electricity demonstration facility built by the Itaipu hydroelectric initiative in the Colombari Swine Industry,[3] in southern Brazil, where a thermoelectric generator powered by the biogas obtained exclusively from swine manure provides 32 kWh, more than all its electricity needs. Exceeding electricity is then injected into the public grid, generating a substantial income for the site owner. Current stats from the National Electric Energy Agency (ANEEL) show that by April 2011, there were 13 biogas thermoelectric plants in operation in Brazil with a total installed potency above 69 MW [14]. Other significant possible biogas sources are sugar vinasse coming from ethanol/sugar industry; and urban waste landfills. These recoveries would contribute modestly towards the increase in energy supply, but would play a considerable role in reducing environmental impacts caused by the discarding of such wastes, besides providing possibilities for economic gain through CDM projects or economically advantageous fuel switching. Perspectives for energy generation from landfill biogas are further detailed in Table 5.

Biogas technologies are available at relatively low costs, but still manure and other organic wastes are hardly seen as possible resources, except for when used as a soil conditioner. The immediate discarding of manure into rivers or water bodies has worked for decades as a way of eliminating the waste from individual sites, resulting in externalities such as the eutrophication of important water bodies in regions with high concentrations of swine production. The above mentioned social program developed by the Itaipú hydroelectric plant, for example, was motivated by the critical eutrophication sites and consequent damaging of the hydroelectric turbines due to excessive organic matter in the water that originated from upstream manure disposal. The incentives for biogas units were provided by the hydroelectric plant itself, in order to reduce their turbine maintenance costs, working as a consequent solution for local waste management with extra benefits of electricity production and providing a source of income for surrounding communities. Bottlenecks preventing the full use of biogas potentials are mainly the lack of technical knowledge; cultural inertia; capital constraints for large-scale projects; and the lack of inspection and penalties for possible environmental damages of organic matter disposals.

3.3. Wind energy

At present there are 51 wind power plants installed in Brazil with an associated potency of 936,782 kW of wind energy; another 18 are under construction; and another 103 plants are expected to be built in the following years. When all 172 plants are running together, their potential will add up to over 4841 MW of installed power [14]. The wind energy auction promoted by the ANEEL in August 2010 negotiated the buying of energy from 70 wind generation plants at an average cost of US$73.9/MWh for that time. For the first time in Brazil, wind energy has been sold less expensively than biomass and small hydro energies, indicating its increasing competitiveness. The governmental Program for Incentive of Alternative Energy Sources (PROINFA) established by the law 10.438 in April 2002, is ongoing since 2003, and has wind energy generation as a main focus, subsidizing the contraction of wind generated electricity into the public grid [31]. Recent data, however, indicate that the program has been functioning below its initial expectations hindered by delays in environmental licensing of several wind plants. Unlike new technologies in many industries, wind turbines cannot command a higher price based on quality features and still capture market share, demand-pull and supply-push policies must exist simultaneously for innovation to occur [32].

Sources greatly differ on mapping Brazilian potentials for wind energy generation, mainly due to model assumptions, and consideration or not of constraints. The Atlas for Brazilian Potential on Wind Generation [33] presents an estimate of 143 GW of potential wind energy to be harvested onshore in the country, half of that being on the North East Region. Muylaert and Freitas [34] pointed that from the economic and technical point of view, it was possible, without undermining the Brazilian power production system, to install at least 12,000 MW between 2006 and 2010. The Atlas also presents an interesting complementary correlation between wind potential and hydroelectric power supply, in which the typical low rainfall season in May–September season matches precisely with the highest wind season in the northeastern region. Over viewing the wind development in Brazil, one may note a gradual overcoming of cultural inertia, technological and political constraints. As learning curve effects couple with the PROINFA mechanism pulling costs down, it is more likely that environmental

[3] More information on the Colombari Project can be found in Itaipu's oficial renewable energy platform website: http://www.plataformaitaipu.org/projeto/granja-colombari.

Table 4
Potential for nuclear power generation in Brazil in 2030.

Scenario	Volume of reserves t U_3O_8	Total potential MW	Thermo nuclear units
1	66,200	7800	4
2	177,500	20,800	17
3	309,370	36,400	33

Adapted from [10].

concerns are more easily and addressed and widespread deployment is achieved within the 2030 range.

3.4. Nuclear energy

At present Brazil has only two operating thermonuclear power plants, with a total installed capacity of 2007 MW running in the southwest of the state of Rio de Janeiro. This accounts for a 1.4% of the total energy supply in Brazil, and 2.4% of its electrical matrix [14]. The Decanal Energy Plan [15] indicates the addition of the third Brazilian nuclear power plant by 2015, and maintenance of only 3 plants into 2019. Brazilian uranium reserves have been proven to be vast; around 309 thousand tons of U_3O_8 had been confirmed by 1993, from which 80% would have exploration costs under US\$80/kg U_3O_8, in a prospection covering only 25% of national territory. Current studies point to a probability of reserves reaching 800 thousand tons U_3O_8 in all Brazilian territory. The National Energy Plan projects the participation of nuclear energy in Brazil in the 3 scenarios: scenario 1 sets a storyline in which uranium resources directed to electricity production would be limited to the known resources with an exploration cost under US\$40/kg U_3O_8; scenario 2 would limit resources for electricity between US\$40 and US\$80/kg U_3O_8; and scenario 3 would consider all resources available for production costs under US\$80/kg U_3O_8 [10]. With such assumptions it has been possible to estimate the total electricity generating potential, excluding the existing installed capacity, and possible number of units considering an average 1000 MW per unit, as shown in Table 4.

On May 2010, the final license for building Brazil's third nuclear power station was conceived by the National Commission of Nuclear Energy [35]. This event marks an important advance in the Brazilian nuclear energy program, since the project for the building of the 3 units is ongoing since 1974, when an agreement was set with the German Nuclear Agency, and had its completion pending due to the lack of licenses since then. The works for the building of the new unit have begun in the Southwest region of Rio de Janeiro state, adjacent to the 2 currently operational plants. The new plant is expected to be functioning by 2015, with a total installed capacity of 1405 MW. Such delay in its licensing emphasizes the bottlenecks hampering the increase of nuclear participation in Brazilian energy provision, mainly, public acceptance – NIMBY syndrome – and regulatory aspects, in which the development of radioactive waste management is a crucial factor.

3.5. Energy recovery from urban waste

Brazil's legislation on solid waste management consists firstly on a federal directive named National Policy for Solid Waste, established by the law 12.305 in august 2010, through which the national government obliges different state laws to comply with the same text and welfare objectives. According to it, the waste management around the country should follow the hierarchical order of priority actions as follows: non-generation, reduction, reusing, recycling, solid waste treatment, and final disposal in environmentally sound manners. Where energy recovery from burning any category of solid waste is seen as a waste treatment stage, considering the energy provision as a sub product of thermal destruction treatment in specific incinerators joint with thermoelectric turbines. The recovery of energy from solid waste has clear social, economic and environmental advantages, if providing a useful and environmentally sound destiny for residuals that are still being generated; are beyond reduction; are not reusable; and are unrecyclable, or unworthy to recycle. In other words, to be directed for energy recovery, such waste should provide more welfare benefit having their energetic potential recovered then if being directed to upper hierarchical levels, treated with another method, or directed towards disposal in lower hierarchical levels.

Article 37 of the policy, relates to energy recovery of solid waste, stating: "(...) it should be disciplined in a joint implementation between the ministry of environment and ministry of mines and energy (...)." Hence, the directive is not technically detailed on standards, but is safeguarded by the need for authorization from technical entities present in ministries above mentioned. With such it assures that such facilities will fit into strict environmental laws, such as emission monitoring; and avoids risky electrical operation, according to specific laws from each ministry. A proponent project would, therefore, have to provide evidence for the advantages of such activity related to other treatment options or landfilling and fit into existing regulations.

Brazilian legislation therefore allows for the construction of Waste to Energy (WTE) facilities, but lacks side policies or instruments to incentive actual diffusion of the technology. There are emission reduction targets stated in the country's National Climate Change Plan [23], above mentioned legislation on solid waste management, and laws regulating electricity systems, but a WTE project that deals with the three spheres will be hindered by the need for independent approvals, leading to new costs and time consuming processes which act as un-incentives. The few initiatives that have created demonstration projects, owe much to their own efforts directed towards the legalization of such projects within the municipal levels and regional electricity supply companies, allowing for flows of electricity between incinerators and public grid.

An integration of legislative framework should, therefore, join licensing schemes within concerned governmental ministries, local administrative levels and public opinion. These could be coupled to positive incentives, such as financing mechanisms for best practices implementation, stimulating innovations with positive externalities simultaneously to negative incentives, discouraging projects causing negative externalities. Such mechanisms may however source a series of side effects, and should be carefully designed based on more thorough regional studies. Further discussion and a guide for literature on policy mechanisms and technology advances can be found in Jaffe et al. [36]. Regarding public opinion, awareness raising actions in different spheres are likely to remove old paradigms of incinerators as mere waste burners, disseminating the understanding of waste as potential secondary energy sources, within the context of climate change, costs/constraints of primary resources, lack of space and other onuses related to other disposal and treatment options. All the above should supposedly lead to the deployment of high standard incinerators, turning into reality the potential shown in Table 5.

Moreover, governmental assessments for waste treatment/disposal options are much fixed in the paradigm of Cost-Benefit Analysis (CBA). However, understanding the series of advantages and disadvantages, possible incommensurability of values, and some subjectiveness inherent to different solid waste destination options that compete with incineration with energy recovery, the decision into directing waste towards a recovery plant, or not, could best be done if based in a social multicriteria analysis (SMA). It thereby should take into account all onuses and bonuses associated to all options without trying to translate different incommensurable values into one singular monetary

Table 5
Potential for electricity generation with urban waste.

Characteristics of waste	2020	2030
Volume (millions of tons/year)	62.7	92.2
% of organic matter	56.0	47.5
% of recyclable matter	39.0	47.5
Potential for electricity generation (MW)[a]		
Biogas in landfills	1700	2600
Anaerobic digestion	980	1230
Incineration	3740	5280
Optimized combined cycle	5980	8440

Adapted from [10].
[a] Considering an 80% capacity factor.

evaluation scheme. Ideally, such management would direct all wastes towards options where whichever would add onto public welfare more than they cause onuses. A key conflict of interests however lays on the key point that waste incineration should be aimed at all materials that would provide more welfare benefit in that destination than in another, and no other material, as mentioned above. The incineration industry, however, would rather have as much energy rich material flowing into it as possible with the lowest cost, which logistically would surely extrapolate the limits of the options providing the most welfare. In such there is a conflict of interests between public interests on environmental soundness and social welfare, and the private interests of an energy recovery industry.

3.6. Carbon capture and storage

Up to date CCS plans in Brazil have only been announced by Petrobras, Brazil's largest energy company, which means the participation of such technology in future Brazilian emission patterns still depends entirely on one company. With growing concern on how climate change might affect its business, and more recently, the findings of new oil and gas mega fields, the company has been engaged in restraining its GHG emissions, and CCS is one of the options chosen in its emission reduction strategies. CO_2 injection into geological media has been done by Petrobras since the 1980s in Northeastern Brazil, solely with the purpose of enhancing oil recovery. However, following an internal R&D program the company announced in 2008 plans for the development of CCS projects aimed towards emission reductions to be stored in several sites by 2017, amongst which are deep saline aquifers; coal seams with additional coal bed methane recovery; and depleted or depleting oil reservoirs [37]. However, from 2009 onwards there has been an apparent stagnation of such plans in a way that one may hardly estimate CCS perspectives in Brazil. It is known however that the company has been concentrating CCS R&D efforts into the pre-salt mega fields on the verge of commercial exploration, in which offshore platforms may re-inject large amounts of CO_2 separated in the process of commercialization of natural gas into saline aquifers, oil and gas fields, which would otherwise be vented. Carbon capture techniques – oxyfuel, post and pre combustion – are seen as focus points for R&D towards cost reduction, currently accounting for up to 80% of full CCS chain costs, but still the option for offshore CO_2 reinjection and sequestration is likely to be deployed in Brazil into 2030; since CO_2 has to be separated for natural gas commercialization; for avoiding long transportation costs; and possibly enhancing oil recovery, incurring lesser costs than full CCS chains applied in onshore industries or power plants.

Another concern hampering CCS deployment in Brazil is the lack of regulations involving the specificities demanded by such actions. Brazil still has no such laws to deal with long-term liability issues; underground property rights; underground royalties and other aspects. Câmara et al. [38] explores thoroughly this issue presenting a proposal for CCS regulatory framework and suggesting the development of its main regulatory mechanisms drawing much from existing oil & gas laws. The need for such framework is critical considering the large amounts of CO_2 present in the pre-salt fields on the verge of large-scale exploration.

3.7. Energy efficiency

Up to date, there are four main official law enforced efficiency programs in practice in Brazil. The National Electrical Conservation Program (PROCEL), in operation since 1985, focuses the technological aspect of energy conservation. Its main actions are related to the labeling, marketing and public lighting sub programs, achieving until 2008, accumulated savings of 4.37 billion kWh [39], enough to supply 2.5 million average Brazilian households for a year. The program works based on a market approach, promoting the adoption of more efficient products, such as refrigerators, CFLs, or chillers. By targeting one or more products (or end-uses), rather than end users, and developing strategies and incentives to increase market penetration rates of the efficient models, it seeks a long-term shift in market trajectory on a sustained basis.

Based on the law – 9.991 from July 2000 – public energy distribution companies are obliged to apply annually 0.75% of their net earnings in R&D for the electrical sector, and 0.25% into final use energy efficiency programs (PEE) passing to 0.5% in mid 2010. Energy generation concessionaries and private energy production companies are obliged to invest 1% in the same R&D programs, except for companies acting solely on small hydro; biomass; qualified cogeneration; wind; and solar energy sources. The law established 40% of generation companies 'R&D contribution would be meant for a National Fund for Technological and Scientific Development (FNDCT); 40% for R&D projects defined by ANEEL; and 20% meant for the Ministry of Mines and Energy Research and planning programs, realized through the energy research company (EPE). Distribution companies 'contribution division would differ slightly between receiving purposes and contain the mentioned compulsory investments in energy efficiency programs. The ANEEL presents data on accumulated investments in R&D until 2007, overcoming R$977 million, but data on accumulated energy savings coming R&D are diffuse, due to the segmented destiny of investments and possible incommensurability of values saved by each effort done in each benefitted institution. In the other hand, energy efficiency program results are quantifiable due to case-by-case baseline reduction methodology demanded by the ANEEL. Data presented show that up to mid 2007 over R$1.8 billion had been invested in such energy efficiency programs, resulting in a built up energy saving of 5484 GWh/year, equivalent to avoiding the construction of a 782 MW power plant working at 80% of its capacity.

National Policy for Conservation and Rational use of Energy, established by the decree nº 99.250, in May 1990, later altered by the law 10.295 in October 2001, defined that maximum levels of energy consumption or minimum levels of energy efficiency for all electrical appliances made in or commercialized in the country, would be set and updated based on pertinent technical indicators. Aside with taxes applied over non-compliance, the policy led to the creation of a sequence of programs for energy efficiency incentives, such as the Brazilian Labeling Program (PBE), which applies informative labels in electrical appliances showing their efficiency levels for companies who voluntarily require the label. With such consumers are empowered to evaluate and select optimized energy consumption as they please. Compiled results are again hardly quantifiable, considering unknown baseline references and unknown effectiveness on each consumer's decision. The National Program for Rational use of Oil Products and Natural Gas (CONPET) was also a sub product of such law; created in 1991 it comprises subprograms acting on fossil fuel efficiency concerning efficiency labeling for the transport sector and fossil consuming domestic appliances; and education on multiple spheres. Current data presented for the CONPET transport related savings show an average 17 million/l/year of diesel saved, avoided emissions over 45 kT/CO_2 since its beginning [40]. Data presented for CONPET household related efforts show that labeling plus education actions have the potential to promote 20% savings in household gas consumption [35]. Again values are hardly quantifiable due to impossibility of knowing the effects of labeling in each individual purchase.

Brazil has important mature programs with strong legal frameworks but there is still greatly unexplored potential. Policies and programs become effective in creating a virtuous cycle of energy generation, economic development and environmental sustainability as energy intensive institutions themselves implement and operate internal efficiency policies in a stable fashion, independent of changes of government, pushed by competitive advantages of doing so. In order to accelerate the trajectory of current efforts, it is recommended that energy efficiency goals are promoted through clearer, more relevant message "of improved economic prosperity and health" i.e., enhanced energy security (fewer power cuts, load shedding, industries getting closed); reduced vulnerability to energy prices; higher industrial and commercial competitiveness; and increased employment [41]. The extent to which such message is conveyed throughout all stakeholders from supply to demand side, will largely define the fulfillment of energy saving potentials in the country, where awareness raising through education may strongly reach final consumers in industrial, household and commercial levels, leading to quite different savings into 2030.

4. Conclusions

Brazilian energy sector's technological evolution in the coming decades will largely define its position between a transition economy and a developed country, as well as to what extent it will contribute to a global effort towards emission reductions. The analyzed studies in Sections 2.2–2.5 show scenarios with high emission perspectives into their different time ranges, and all agree with large potentials for low carbon technologies on offsetting significant emission fractions. The study analyzed in Item 2.4 [9] presents a thorough exploration of the industrial subsector's low carbon technological options, with a key conclusion that a good part of the low carbon technological advances have negative costs, creating abatement opportunities coupled with economic attractiveness. This is very likely true for much of the selected technologies presented in Section 3. But this alone has not been enough to prompt implementation of most such advances spontaneously. Throughout item 3 there are clear indications that investments into R&D and technological learning will improve the flexibility, performance, and competitiveness of new technologies [12], allowing them to perform significantly in the future, thus incentives towards such investments are market insertion policy recommendations. The Brazilian government has created a series of programs and actions for planning and fostering low carbon technological advances since the 1980s, but the extent to which they work is affected by a diversity of bottlenecks, mainly internal constraints as lack of incentives, cultural inertia, technological delay, capital constraints and a general lack of united political framework.

The necessity of policies which create both supply-push and demand-pull is recommended to overcome such obstacles, permitting insertion by improving attractiveness of new technologies. In discussing policy instruments, Galli and Teubal [42] point that markets are not necessarily formed in a spontaneous fashion, in the early phase of the diffusion of a new technology potential customers may not be able to articulate their demand (in terms of price/performance) and meet the supplier in the market place. Markets may therefore need to be created in a process where fragmented potential customers can formulate and articulate their demands [43]. Market-based instruments – such as pollution charges, subsidies, tradeable permits, and some types of information programs – can encourage the development of low carbon technologies by individual firms. Command-and-control regulations in the other hand, tend to force firms to share pollution-control burden, regardless of the cost. But holding all firms to the same target can be expensive and, in some circumstances, counterproductive [36] because costs and contexts vary within firms [44].

Moreover, the above review indicates that despite the existence of robust legislative programs, Brazilian investors whether private or public, often see the development of more sustainable, less carbon/waste/energy intensive systems as a burden. The overcoming of such conceptual barrier shall happen as the environmental dimension is incorporated *ex ante* into political, economic and technological decision making, based not only in short term economic profits, but also mid-long term benefits of reducing impacts over oneself, acknowledging the biophysical constraints to which social metabolisms are confined to.

Table 6
Authors' considerations: likeliness to be widely deployed and key bottlenecks for selected technologies until 2030.

Technology	Key bottlenecks	Likeliness of wide deployment by 2030
Run-of the river hydro power	Costs/susceptible to water level variations	Medium
Small hydroelectric plants	Initial investments/possible land use conflicts	High
Liquid biofuels	Land use conflicts/logistics	High
Solid biomass (electricity)	Lack of financial incentives/logistics/costs of new technology/cultural inertia	High
Solid biomass (iron/steel)	Lack of control over deforestation charcoal/higher costs for reforestation charcoal/logistics	Medium
Microalgae biofuels	Initial costs/need for R&D/cultural inertia	Medium
Biogas	Technological upgrade lag/costs	High
CCS offshore CO_2 reinjection	Costs/lack of regulation	High
CCS other	Higher costs/lack of incentives and regulation	Low
End use fuel efficiency	Costs of modern equipment	Medium
End use electricity efficiency	Costs of modern equipment	Medium
End use fuel switching (ethanol/natural gas)	Land use conflicts/lobby for C intensive fuels/oscillation in natural gas supply	Medium
Power generation efficiency and fuel switching	Costs/lack of incentives	Medium
Nuclear energy	Social conflicts/NIMBY syndrome/regulatory delays	Medium–high
Wind energy	Costs per MWh/lack of incentives/financing constraints	High
Solar photovoltaics	Costs per MWh/cultural inertia/lack of incentives and national production	Medium
Energy recovery from urban waste	Urban waste logistics/education for separation	High
Hydrogen technologies	Costs/lack of incentives and know-how	Low
Transport sector efficiency	Technological delay/costs	Medium
Transport sector fuel switching	Associated land use conflicts/fossil fuel lobby	High

The following technologies have been selected as the most meaningful for the Brazilian energy system's future. Table 6 shows a synthesis of the authors' considerations on their main bottlenecks and their likeliness of being widely deployed until 2030. The definition of main bottlenecks, and amongst low, medium or high likeliness of deployment for each technology was based upon informal interviews amongst authors, collaborators, and specialists.

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