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The Role of CSP in Brazil: A Multi-Model Analysis

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Abstract. MESSAGE, TIMES and REMIX-CEM are potential tools for modelling a larger penetration of variable renewable energy (VRE) into the Brazilian power system. They also allow devising the opportunities that concentrated solar power (CSP) plants offer to the power system and to the wider energy system. There are different opportunities for CSP in Brazil in the short and medium term, consolidating this technology as a feasible alternative for greenhouse gas (GHG) mitigation in Brazil. This work verified that CSP is a cost-effective option only under very stringent mitigation scenarios (4DS and 2DS) and when carbon capture and storage (CCS) is not available. Still, according to the findings of REMIX-CEM-B, CSP can provide firm energy and dispatchable capacity in the Northeast region of Brazil, optimally complementing wind and PV generation. Moreover, CSP can offer additional flexibility to the Northeast power system, especially during winter and after 2030.

INTRODUCTION

Although renewable energy sources (hydropower in particular) contribute to the major share of Brazil's electricity supply, the remaining hydropower potential in the country is limited due to environmental and social constraints. Hence, fossil fuels, specially coal and natural gas, are likely to play a larger role in the Brazilian electricity system [1,2]. Building wind and solar photovoltaic (PV) power plants is an alternative for Brazil. In the Northeast region of Brazil, current wind power installed capacity is 5.4 GW and the prospects, considering all wind farms contracted until the end of 2014 by regular auctions, is to install at least an additional 12.6 GW by 2019. Although the current PV installed capacity in the Northeast region of Brazil is negligible (4.6 MWp), this technology shows promising expansion prospects in the country in the long term. Recent auctions held in Brazil contracted a total capacity of 642 MWp of centralized PV in the Northeast subsystem to begin operation between 2016 and 2017. A significant deployment of distributed generation (DG) based on PV systems is also expected in the medium to long term. The paradigm shift from conventional hydro-thermal generation based power system to variable renewable energy (VRE) based system brings various technical challenges at the planning and operation stages that must be overcome. The impacts caused by a large VRE penetration are such that a full re-assessment of power system expansion and operation planning, especially in setting frequency response and operational reserve services, is required.

Due to its technical characteristics, the deployment of concentrated solar power (CSP) plants in the Northeast Brazil is an attractive option to provide some of the additional flexibility that the Brazilian power and energy system will certainly need. The Brazilian Government is interested in developing CSP plants under the current auctions

scheme. For example, at the end of 2014, eight CSP projects, with a total capacity of 240 MW, were registered to participate in an auction called by the Government. However, there was no CSP plant contracted. The common perception is that, in a business-as-usual scenario, Brazil remains unable to adopt the CSP option in the short and medium terms and should focus on research and development (R&D).

The objective of this study is to assess the role of the CSP option as part of the future Brazilian energy system and to understand CSP capabilities to provide an extra source of flexibility to the Brazilian power system.

METHODOLOGY AND DATA

Participating Models and Model Coupling

Three modeling teams have produced six core scenarios for the Brazilian energy mix up to 2050 under different CO₂ price and technology availability scenarios. The Energy Planning Program (PPE/COPPE), from the Federal University of Rio de Janeiro (UFRJ), used the Integrated Energy Planning Model MESSAGE-Brazil. The Institute of Energy Economics and the Rational Use of Energy (IER), from the University of Stuttgart, used the TIMES-TiPS-B (The Integrated MARKAL EFOM System - Power System Model for Brazil) planning tool. Finally, the Department of Systems Analysis and Technology Assessment of the Institute of Engineering Thermodynamics, from the German Aerospace Center (DLR Stuttgart), used REMIX-CEM-B (Renewable Energy Mix - Capacity Expansion Model).

These models differ from each other in terms of their modelling approach, sectoral scope, geographical coverage, time resolution, availability of technological options, dispatch details, etc. A comparison of model features and a detailed SWOT analysis (strengths, weaknesses, opportunities and threats) can be found in [3]. MESSAGE-Brazil is an integrated energy planning tool, that includes not only the power sector but also all other energy conversion chains. A detailed description of MESSAGE-Brazil is presented by [1,2,4]. TIMES-TiPS-B was developed specifically for this study to model the long-term expansion of the Brazilian power sector. In the sequence, instead of using REMIX-CEM in its original application as detailed power sector specific capacity expansion model [5,6], the tool was applied as dispatch model to optimize system operation of a portfolio of technologies (calculated by the expansion tools) to supply the total electricity demand of the Northeast region of Brazil in a reliable and cost effective way. The optimization of dispatch was made only for the Northeast region of Brazil because it is the electrical subsystem that has the largest penetration of VRE generation. Due to its capability of optimizing solar field, thermal storage and back-up boiler size as well as unit commitment and dispatch patterns of each candidate CSP plant, REMIX-CEM was a key tool. To achieve the objectives a soft linked multi-model analysis was used (See Fig. 1).

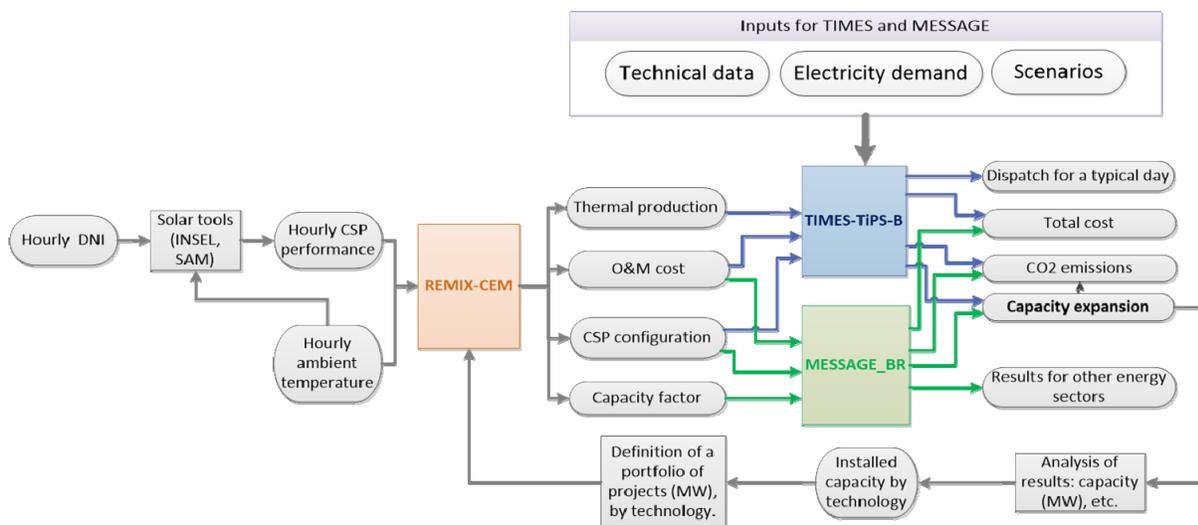


FIGURE 1. Interactions between MESSAGE-BRAZIL, TIMES-TiPS-B and REMix-CEM-B in the Brazilian application

Main Data and Assumptions

For the purpose of this exercise, the capacity expansion was simulated in MESSAGE-Brazil and TIMES-TIPS-B for ambitious greenhouse gases (GHG) mitigation scenarios. The least-cost expansion results (2DS_GEN) were fed into REMIX-CEM-B, which optimized the power operation dispatch. At this stage, it was analyzed whether the operational requirements were achieved with the investment portfolio provided to REMIX-CEM-B.

MESSAGE-Brazil and TIMES-TIPS-B consider an exogenous useful energy demand vector as input, which was calculated based on homogenized growth rates according to [7]. The daily load profiles, by region, were harmonized across models using hourly values from 2013 provided by the National Operator of the Power System (ONS). The power generation chain within the expansion models is based on the structure of MESSAGE-Brazil. For further details see [2,4]. Within the power sector, all models included hydropower plants, nuclear plants, wind farms, solar facilities (PV and CSP) and thermal power plants fueled with sugarcane bagasse, fuel oil, diesel, coal or natural gas. Carbon capture (CCS) facilities are only included in MESSAGE-Brazil as add-on options into existing coal fired thermal power plants and as a capture ready option to be installed in new coal fired power plants. The power plant data base was updated and validated. All models used a general annual discount rate of 10% p.a. Data for wind speed, direct normal irradiation, global horizontal irradiation and ambient temperature for each region were considered according to the model's need. MESSAGE-Brazil used this information to input an availability resource profile in the required time and spatial resolution, while TIMES-TIPS and REMIX considered hourly series. REMIX-CEM used these hourly data in a more detailed temporal and spatial resolution to model the performance of VRE in high potential locations ("hot spots") in the Northeast region and their interaction with conventional thermal, hydro and CSP generators [8,9]. The thermal production profile of the solar field and hourly power generation for maximizing the energy yield of each CSP power plant was provided by DLR based on simulations conducted using the INSEL model [6,8], except for a hybrid biomass-CSP plant (CSP-BIO), whose simulation was executed in SAM model according to [10].

Four types of parabolic trough CSP power plants were considered (See Table 1). Back-up fossil boilers were considered for the first three conventional CSP plants to guarantee a more flexible operation. Although under real situations those power plants can operate using a fossil back-up system, a restriction of no electricity production from fossil back-up was set in the expansion planning tools. This restriction simplified the modeling of the use of the back-up system during the operative stage and also encouraged the expansion of technologies that produce electricity from solar origin only. Data for power plants (See Table 1) were previously calculated to set a standard performance within expansion tools. The dispatch tool calculated specific endogenous values for some parameters.

As MESSAGE-Brazil model was assembled in an integrated form to assure inter-sectorial consistency, the opportunity cost for each energy source was calculated considering the whole energy conversion chain. On the other hand, for TIMES-TIPS-B and REMIX-CEM-B the fuel costs were important input data, that were harmonized with fuel cost calculated by MESSAGE-Brazil whenever possible. Minimum installed capacity restrictions were implemented based on the existing and contracted (until December 2014) power plants. Finally, following the guidelines of the 10-year Expansion Plan (PDE 2022) new power plant and power line projects were also considered in the long term. Specific costs and parameters for operational restrictions by technology (ramp-up, ramp-down, minimum up-time, minimum down-time, minimum and maximum load rate, etc.) in the dispatch model were provided by DLR following the standard REMIX-CEM data base values. For a more complete description of these parameters and values see [6,8,11].

TABLE 1. Technical characteristics of the modeled CSP power plants

Technical specification	CSP-4hTES	CSP-8hTES	CSP-12hTES	CSP-BIO
Gross capacity of turbine (MW)	150	150	150	33
Solar multiple	1.6	1.9	2.2	1.2
Thermal energy storage (full load hours)	4	8	12	0
Back-up system capacity (% of gross cap.)	100%	100%	100%	30%
Back-up fuel	Fossil	Fossil	Fossil	Biomass
Max. share annual generation by back-up system	0%	0%	0%	49%
Total land area (km ²)	4.1	4.9	5.5	0.84 ^a
Gross efficiency @ max. load	39.3%	39.3%	39.3%	34.2%
Annual electricity production (GWh)	413	491	554	139
Capacity factor	31.5%	37.4%	42.2%	51.4%

Notes: ^a Total project area, including the crop, equals 51 km² [10]. TES: Thermal energy storage

Specific operational restrictions for some power plants in the Northeast region were implemented in REMIX-CEM-B when possible. Restrictions to existing and new transmission capacities between regions were implemented in REMIX-CEM-B according to ONS mid-term planning. Additionally, restrictions to minimum and maximum annual imports and exports between Northeast and other regions were set based on historical values. Typical capacity credits were considered by TIMES-TiPS-B within capacity balance equation. REMIX-CEM-B considered a spinning reserve requirement of 1.5 times of the largest generator which must be hold available in each time-step of the dispatch optimization and able to be deployed within 5 minutes to maintain the power balance in case of a frequency drop.

Scenario Description

A baseline scenario (6DS) plus five capacity expansion trajectories were calculated by MESSAGE-Brazil and TIMES-TiPS-B which include a combination of mitigation scenarios and CSP constraints. The core baseline scenario considers business-as-usual assumptions at national level and includes climate and energy policies enacted prior to 2010. Mitigation scenarios are progressively stringent. Mitigation policy in climate change scenarios were implemented in the models through CO₂ price applied to all GHGs, with values related to a 6°C, 4°C and 2°C global warming scenarios of [12] (namely, 6DS, 4DS and 2DS scenarios – Table 2).

TABLE 2. CO₂ price paths by scenario (\$₂₀₁₃ /t CO₂)

CO ₂ price paths	Year			
	2020	2030	2040	2050
6DS	0	0	0	0
4DS	30	40	50	60
2DS	50	100	140	170

Source: Based on [12]

The core scenarios are divided into two different sets: scenarios with CO₂ price and scenarios with CO₂ price plus a constraint of minimum CSP installed capacity until 2050 (Table 3) (scenario for CSP capacity contracted by auctions). In all core and sensitivity scenarios, the optimization tools allocated the CSP constraint's minimum value into the four considered CSP technologies according to a total minimum cost criteria.

A sensitivity analysis was made for the scenarios listed in Table 4. A constraint for minimum electricity production from CSP was tested to compare the economic effectiveness of this constraint with that for the minimum CSP installed capacity. Finally, some sensitivities on the technology portfolio were analyzed for each scenario: a) when CCS is not available; b) when low-cost biomass is an option to hybridize CSP plants; and 3) when solar water heating (SWH) is considered. A total of seven sensitivity scenarios were analyzed.

TABLE 3. Brief description of the core scenarios used in this study

Core scenarios	CO ₂ price path	CSP constraint	Simulated by
Baseline	6DS		MESSAGE-Brazil and TIMES-TiPS-B
4DS	4DS	No constraint	
2DS	2DS		
6DS_CAP	6DS	Minimum CSP installed capacity:	TIMES-TiPS-B
4DS_CAP	4DS	1.5 GW in 2020, 10 GW in 2030,	
2DS_CAP	2DS	18 GW in 2040, 30 GW in 2050	

TABLE 4. Brief description of the sensitivity analysis scenarios

Sensitivity scenario	CO ₂ price path	Description of the sensitivity scenarios and constraints	Simulated by
6DS_GEN	6DS	Min. electricity generation from CSP: 15 TWh in 2030, 45 TWh in 2040 and 110 TWh in 2050	MESSAGE-Brazil
4DS_GEN	4DS		
2DS_GEN	2DS		
4DS_w/o CCS_CSP BIO	4DS	CCS is not an investment option. Hybrid CSP-BIO power plant added as a technological option	MESSAGE-Brazil
2DS_w/o CCS_CSP BIO	2DS		
2DS_SWH	2DS	SWH is a technological option.	TiMES-TiPS-B
2DS_CAP_SWH	2DS	Combination of 2DS SWH and 2DS CAP scenarios	

RESULTS

The results for the different models/scenarios are analyzed only for the power sector. According to the results of MESSAGE-Brazil, in the baseline scenario 6DS the primary energy consumption increases more than two folds from 2010 to 2050 (2.18 times increase). Figure 2 presents results of the expansion of power generation until 2050 calculated by both expansion tools. Power generation in 6DS would be largely based on coal.

Figure 3 presents the results for power generation in the sensitivity scenarios. CSP is a cost-effective expansion option only in very stringent mitigation scenarios. In case of MESSAGE-Brazil, this happens by 2040 only in the “2DS_w/o CCS_CSP BIO” with high CO₂ price (140 US\$/t CO₂ in 2040), when CCS is not available as an option and when CSP power plants use low-cost biomass for its hybridization. In a similar fashion, TIMES-TiPS-B showed that CSP is a cost-effective option by 2050 with medium CO₂ price (above 60 US\$/t CO₂) (when imports from Itaipu hydro power plant were modeled as a flexible option to cover load peaks). Additional simulations with TIMES-TiPS-B, modeling Itaipu imports as base load, showed that CSP is a cost-effective option by 2050 with high CO₂ price (above 100 US\$/t CO₂). This last consideration looks like the most realistic situation.

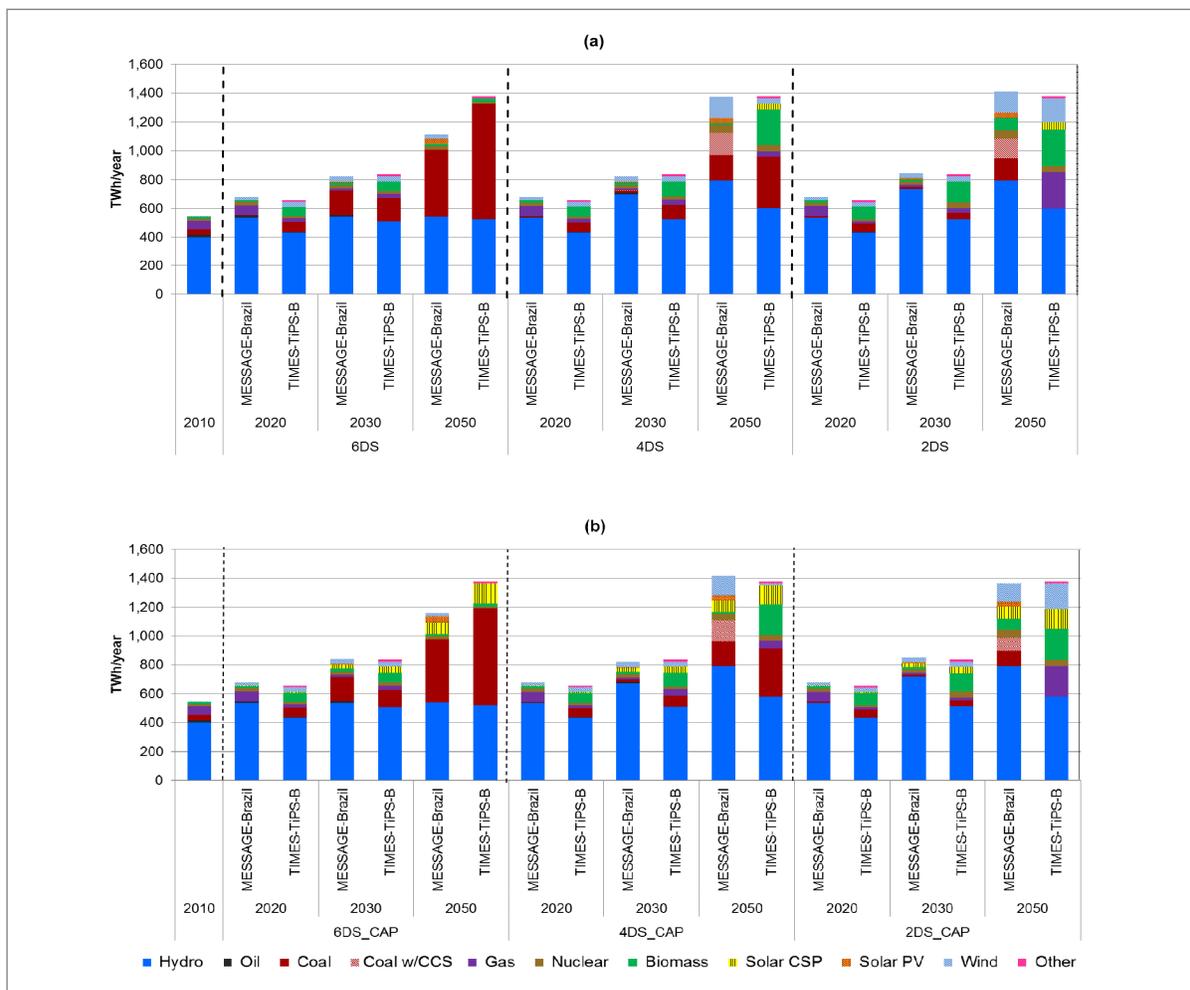


FIGURE 2. Power generation calculated for the core scenarios. Panel (a) for scenarios 6DS, 4DS and 2DS. Panel (b) for scenarios 6DS_CAP, 4DS_CAP and 2DS_CAP.

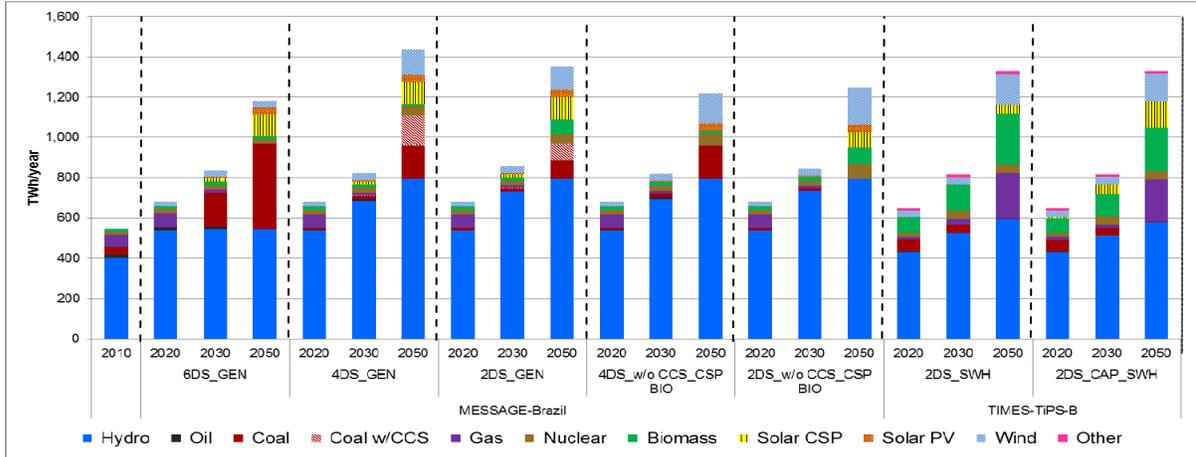


FIGURE 3. Power generation for the sensitivity scenarios

The left panel of Fig. 4 presents the electricity cost and emission factor in power sector for different scenarios, while the right panel shows the CSP expansion, by type of technology, until 2050. In a “2DS_w/o CCS_CSP BIO” scenario the CSP technology becomes a cost-effective option for Brazil, due to the use of low-cost biomass for CSP hybridization. In 2DS_GEN scenario the CSP expansion is based on two traditional technologies (4h and 8h of thermal energy storage – TES) as the result of total minimum cost expansion for the wider energy system. After 2035, CSP_8h TES plants provide cheaper electricity than CSP_4hTES plants.

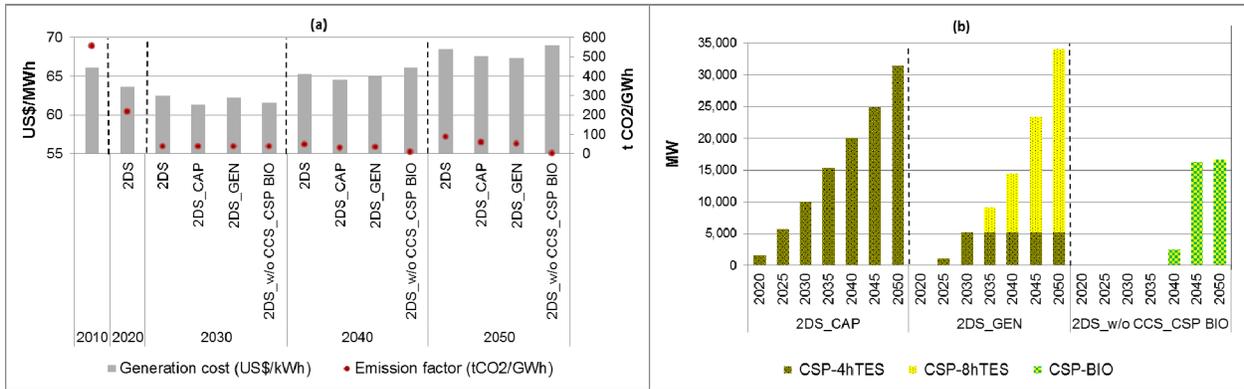
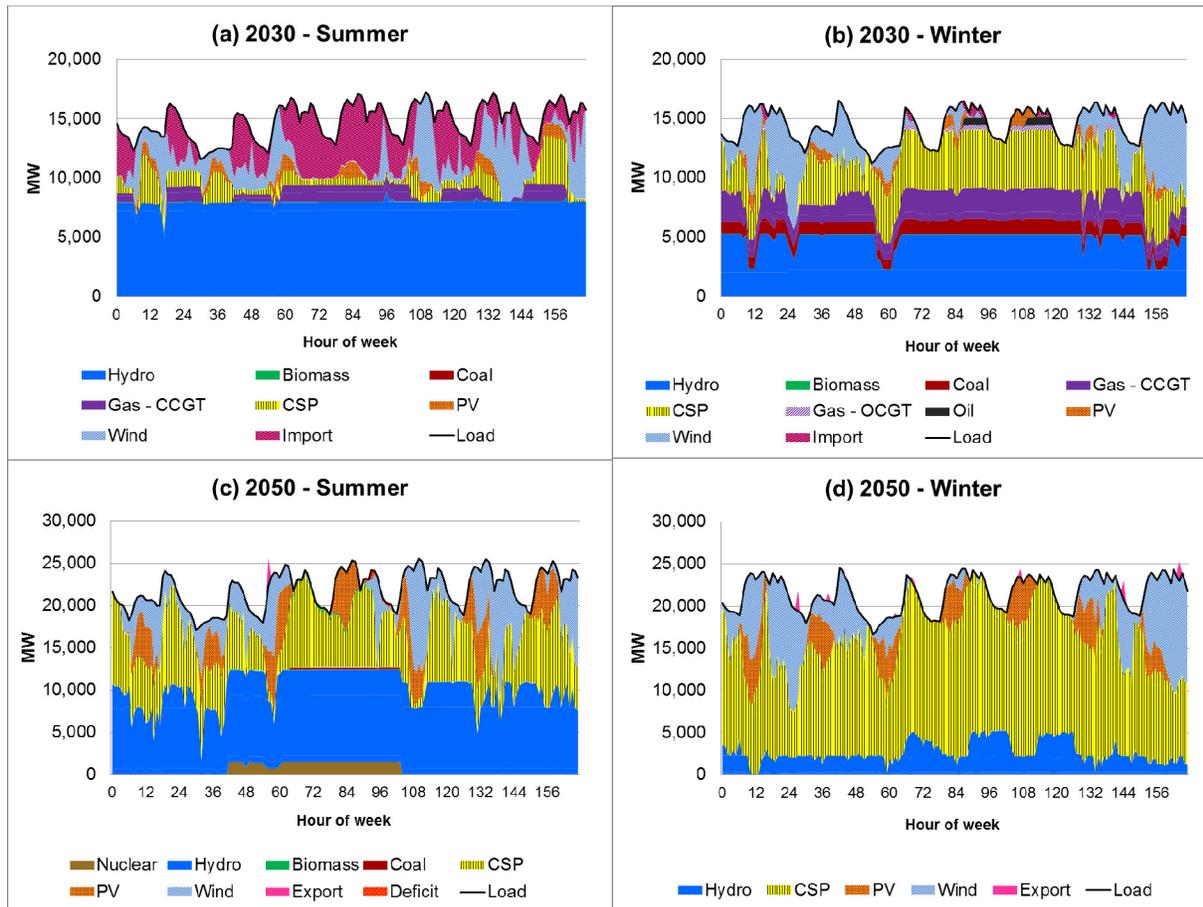


FIGURE 4. Panel (a): Electricity costs and grid emission factors in 2DS variations. Panel (b): CSP expansion in 2DS variations

The panel (a) of FIGURE 4 shows, until 2030, a decreasing generation cost in the Brazilian power system that is explained by the expansion of the least cost technologies, mainly based on large hydropower plants located in the Amazon Region, where lies the remaining hydropower potential. Additionally, expansion models have restricted freedom to decide about the expansion and operation of the power system during the first years of the period, when most of the investments are already in place. Nevertheless, from 2020 some efficient technologies expand in the system also lowering the generation cost. After 2030 the expansion of hydropower plants becomes more expensive due to social and environmental constraints and lower capacity factors. At this time, other technologies expand at higher cost, significantly based on coal.

Due to the variety of CSP technologies in the expansion in the 2DS_GEN scenario, which would be installed in Northeast region, the optimization of the dispatch of power plants within this electrical subsystem was calculated by REMIX-CEM-B. The main purpose of this stage was to understand the role of CSP in the hourly dispatch in the Northeast region. Another purpose of this exercise was to verify whether the Northeast electricity demand can be supplied by the expansion plan calculated by MESSAGE-Brazil and TIMES-TiPS-B tools for this region. The optimum dispatch for a typical week in summer and winter of 2030 and 2050 were calculated by REMIX-CEM-B. For example, the Fig. 5 presents the optimum dispatch using the expansion plan calculated by MESSAGE-Brazil.

REMIX-CEM-B restricted the use of biomass back-up to 20% of annual power generation, for each hour to take advantage of all CSP strengths: TES and back-up system.



Note: Summer considers from January to March and winter considers from July to September

FIGURE 5: Typical dispatch in the NE region. Panel (a): 2030- summer week; Panel (b): 2030 - winter week; Panel (c): 2050 - summer week; Panel (d): 2050 - winter week

DISCUSSION AND CONCLUSIONS

MESSAGE, TIMES and REMIX-CEM are potential tools to improve the modelling of large penetration of VRE in the Brazilian power system. These energy planning tools provide outputs to understand the opportunities that CSP offers to the power system and to the wider energy system. This modelling approach not only allowed improving VRE representation, but it proved to be a good approach to understand the role that CSP technology can play in the Brazilian energy and power sectors. Outcomes of this project were shared with Brazilian energy policy makers to highlight the strengths of CSP in Brazil and benefits of this modelling approach.

There are different opportunities for CSP in Brazil in the short to medium term, consolidating this technology as a feasible alternative for GHG mitigation in the country. This work verified that CSP is a cost-effective expansion option only in very stringent mitigation scenarios (4DS and 2DS). MESSAGE-Brazil showed that CSP is a cost effective option only by 2040 in the “2DS_w/o CCS_CSP BIO” scenario, characterized by high CO₂ price, when CCS is not available as an option and when CSP power plants use low-cost biomass for its hybridization. The share of CSP electricity in the national power matrix in 2050 in this scenario can reach 6%. Using low-cost biomass hybridization is a technical and economic feasible option for the country that would decrease the cost of the electricity generated by CSP plants. Additionally, TIMES-TiPS-B showed that traditional CSP power plants with TES and fossil back-up can be a cost effective option only by 2050 with medium CO₂ price. In the longer term, TES is a feasible option, especially when carbon tax policies are implemented. Results from REMIX-CEM-B showed

that CSP can provide firm energy and dispatchable capacity in the Northeast region of Brazil, optimally complementing wind and PV generation. In the same way, it was verified that CSP offered additional flexibility to the Northeast power system, especially during winter and after 2030. In all 2DS scenarios the emission factor of the power system remained below 100 t CO₂/GWh through the whole period of analysis.

Scenarios are largely dependent on the assumptions for the future evolution of main drivers, such as energy demand and fuel price. Although premises such as technology costs, performance and availability were harmonized across models, differences in model scope, time and spatial resolution, as well as the differences in electricity demand are the main reasons for divergences in results from both expansion tools. As MESSAGE-Brazil is an integrated planning tool and TIMES-TiPS-B focuses only on power sector, some divergence becomes evident in their results. Nevertheless, both expansion tools showed similar trends through 2050. Coal remains an important energy source while the share of VRE sources growth slowly in 6DS scenario. Both models showed that CSP is highly complementary with wind and PV generation in CAP and GEN scenarios. This was verified on an hourly resolution in 2030 and 2050 using REMIX-CEM-B.

REMIX-CEM-B showed (Fig. 5) some hours with deficit when optimizing the dispatch of expansion plans calculated by both expansion tools. In this sense, further study is necessary to repeat in an iterative way the loop showed in Fig. 1. In this case, the new expansion planning cycle should take into consideration the outcomes from REMIX-CEM-B, such as capacity factors by technology and the optimized configurations of CSP plants.

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