Mexico’s electricity grid and fuel mix: implications of a fifteen-year planning horizon on emissions and air quality

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Abstract

Energy reform that required amendments to the Mexican Constitution in 2013 and implementing legislation aimed to increase the efficiency, economic competitiveness, and decarbonization of Mexico’s electricity sector. Emissions inventories were developed for the 2016 base year and a capacity development pathway established by Mexico over a 15-year planning horizon to 2031. Between 2016 and 2031, steep declines in generation from fuel oil-fired thermoelectric, turbogas, and coal plants in favor of a buildout of natural gas combined cycle and clean energy technologies were predicted to drive reductions in emissions of sulfur dioxide (SO 2 ), fine particulate matter (PM 2.5 ), carbon dioxide (CO 2 ) and nitrogen oxides (NO x ) of 68%, 61%, 13% and 7%, respectively, with an increase in carbon monoxide (CO) of 4%. Retirement of fuel oil-fired thermoelectric and coal generation contributed to substantial reductions in 24 h average PM 2.5 concentrations in Mexican and U.S. border states even with rising demand. In contrast, little change in maximum daily average eight-hour ozone concentrations was predicted with expansion of natural gas combined cycle generation, which is a source of NO x and CO. Mexico’s electricity sector planning process has been highly dynamic since the reform. Insights indicate how changes in national strategies could affect emissions and air quality outcomes.

1. Introduction

Mexico initiated transformational changes to its electricity sector during the last decade aimed at increasing its efficiency, economic competitiveness, and decarbonization. 1-4] Energy reform was part of the Pacto por Mexico implemented under the administration of Enrique Peña Nieto that required ratification of amendments to the Mexican Constitution in December 2013. 1] Secondary implementing legislation included the Electricity Industry Law and Federal Electricity Commission (CFE) Law in 2014 and Energy Transition Law in 2015. 2–4] The reform unbundled electricity generation, transmission, distribution, and supply activities of the CFE and transformed it to a productive state enterprise. 2, 5] Private participation in electricity generation and trade was allowed in a new wholesale electricity market and for supply services. 6, 7] The Energy Transition Law and General Climate Change Law established minimum targets for clean energy power generation of 30% by 2021 and 35% by 2024. 4, 8, 9] Pursuant to these goals, Mexico introduced an obligations market for the acquisition of clean energy certificates by suppliers and qualified consumers representing generation from clean power sources. 3, 4, 10, 11] and auctions for long-term clean energy capacity projects. 12] Mexico’s national strategies for its electricity sector have been highly dynamic. No changes to the Mexican Constitution have been made regarding energy reform; however, the administration of Andrés Manuel López Obrador that began in December 2018 has emphasized energy sovereignty,
prioritization of CFE over the private sector, and use of fossil fuels over renewable energy sources [13]. On 9 March 2021, Mexico altered provisions of the 2014 Electric Industry Law [14] and mandated an order of dispatch regardless of economic merit that prioritizes hydroelectric, nuclear, thermoelectric, and combined-cycle plants owned by CFE over privately owned wind, solar, and combined-cycle plants. Although a temporary injunction was issued shortly thereafter in an amparo (constitutional writ of protection) proceeding [15], these developments raise concerns for Mexico’s international trade agreements, emissions profiles, and clean energy generation commitments [16, 17].

Decreasing the reliance of national electricity systems on fossil fuels is integral to achieving reductions in carbon emissions and improvements in air quality and public health. Generation of electricity and heat accounts for 30% of global greenhouse gas emissions, a share which is similar in Mexico (193.2 Mt CO2e or 28% of the 679.9 Mt CO2e of greenhouse gas emissions in 2018) [18]. Fossil fuel combustion is a source of sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and mercury and other heavy metals. Emissions from Mexico’s thermoelectric plants that burn heavy fuel oil or coal impact local and regional air quality [19–22] and have been associated with increased adult [23] and infant mortality and reduced life expectancy [24]. Blackman et al [25] found that transport of PM2.5 pollution from power plants operating along the U.S.-Mexico border can exacerbate cross-border health outcomes including respiratory symptoms and asthma.

National planning for energy transitions and investments in infrastructure is needed to achieve climate and air quality objectives. Cory [26] suggests that electricity sector planning involve both short-term actions (5–10 years) and long-term strategies (50 years) to allow for course corrections, flexibility to adopt emerging technologies, evolution of market and policy structures, and removal of critical-path barriers. The long-life of fossil fuel technologies can continue reliance on carbon intensive pathways [26]. For example, Shearer et al [27] found that continued development of coal-fired capacity in India had the potential to ‘lockout’ low carbon infrastructure, which was inconsistent with its national electricity sector plan and climate commitments. National policies can result in differential outcomes for pollutant emissions. Alhajeri et al [28] found that reductions in crude oil and heavy fuel oil and growth in natural gas and gas oil use between 2015 and 2030 would not achieve lower emissions for all air pollutants and recommended greater penetration of renewable energy in Kuwait.

This study examined the emissions and air quality impacts of Mexico’s electricity sector between a 15 year time horizon from 2016 to 2031 that reflected capacity planning for the National Electric System (SEN). A bottom-up approach was used to develop plant-level estimates of CO2, NOx, CO, SO2, volatile organic compound (VOC), and PM2.5 emissions in 2016, which was the base year of the National Collaborative Emissions Modeling Platform developed by the U.S. Environmental Protection Agency (EPA) and U.S. states [29]. Previous studies in Mexico have used bottom-up methods that apply emission factors from the EPA AP-42 compilation [30] with activity rates based on fuel consumption or generation [21, 23, 31–33]. Emission inventories have recently been developed for thermal power plants in China, Vietnam, Kuwait, and Brazil using a similar bottom-up approach, but with emission factors that had different levels of specificity including industry average values in the AP-42 compilation, regional or global estimates, or direct measurements from continuous emissions monitoring systems [28, 34–36]. Mexico issued regulatory requirements in 2012 [37] for suppliers to provide annual estimates of emissions per megawatt-hour (MWh) by technology based on operating parameters, including fuels, for inclusion in the Costs and Reference Parameters for the Formulation of Investment Projects in the Electricity Sector: Generation (COPAR). We applied COPAR emission factors [38] with plant-level annual electricity generation in 2016 reported by Mexico's Ministry of Energy (SENER).

SENER is required to issue annually the Program for the Development of the National Electrical System (PRODESEN) which serves as the primary planning instrument for the generation, transmission, and distribution of electricity within the SEN. The PRODESEN incorporates an Indicative Program for the Installation and Removal of Power Plants (PIRCE) that projects capacity expansions and decommissioning over the following 15 years. In support of our work, future generation and emissions were estimated based on the PRODESEN 2017–2031 [39]. The Comprehensive Air Quality Model with extensions (CAMx) was used to examine the effects of fossil fuel generation in 2016 and 2031 on ozone and PM2.5 concentrations in Mexican and U.S. border states. Six PRODESEN [39, 40–44] have been issued since the reform; none are binding and as such changes can occur between years. Our findings provide insights on how changes in priorities for Mexico’s electricity sector could affect emissions and air quality.

2. Methods

2.1. Base year generation and emissions estimates

Electricity demand in Mexico has increased on average 1.6% per year since 2000 [45]. Total installed capacity across Mexico’s SEN was 73 510 MW in 2016 with 52 331 MW corresponding to conventional fossil fuel plants (coal, natural gas combined cycle,
fuel oil or gas-fired thermoelectric, turbogas, internal combustion) and the remaining to clean energy from renewable (solar, wind, bioenergy, geothermal, hydroelectric) and other (nuclear, efficient cogeneration) technologies [39]. Figure 1 compares nationwide 2016 generation from conventional fossil fuel and clean energy technologies based on the PRODESEN 2017–2031 [39]. Mexico’s electricity generation was 317 062 GWh in 2016 with 252 289 GWh (80%) from conventional fossil fuel technologies, primarily combined cycle (50%), conventional thermoelectric (13%), and coal (11%) plants. The largest contributions from clean energy generation were from hydroelectric (10%), nuclear (3%), and wind (3%) power.

Locations of fossil fuel generation by primary fuel type, shown in figure 2, were based on facility-level mappings between PRODESEN [39, 41], North American Cooperation on Energy Information [46], and 2008 Mexico National Emissions Inventory (INEM) [47] data. Natural gas, coal, and fuel oil-fired electricity generating units (EGUs) contributed approximately 72%, 14%, and 13%, respectively, to fossil fuel generation in 2016.

Individual contributions varied with 83 of 355 EGUs accounting for 95% of combined fossil fuel generation across Mexico.

Estimates of NO\(_2\), CO, SO\(_2\), VOC, PM\(_{2.5}\), and CO\(_2\) emissions were developed using a bottom-up approach according to the following:

\[ E_{i,j} = A_j \times EF_{i,j} \]

where \(i\) and \(j\) represent the emitted pollutant and plant, \(A\) is plant-level generation (MWh), and \(EF\) represents the plant-specific emission factor (kg MWh\(^{-1}\)). Electricity generation in 2016 for each of the 355 plants was obtained from the PRODESEN 2017–2031 [39]. However, the PRODESEN 2017–2031 provided only aggregate emission factors by technology and plant capacity or fuel based on COPAR data. We applied instead plant-level emission factors directly from the COPAR 2015 [38] which was available within the public domain. A total of 89 plants that accounted for 57% of total nationwide generation were included in the COPAR. The information in the COPAR did not allow us to track how individual plant-level emission factors were derived. Median and maximum values of emission factors across COPAR plants by technology and fuel were shown in table S1 (available online at stacks.iop.org/ERL/16/074050/mmedia). Median emission factors were applied by technology and fuel for 266 plants (43% of generation) that were not included in the COPAR.

Table S1 indicates that all coal and most fuel oil-fired plants were included in the COPAR 2015. However, natural gas and diesel-fired generation was less complete. The most significant gap was for natural gas combined cycle plants which constituted a large share of nationwide generation. Natural gas combined cycle plants that were included in the COPAR were operated by either the CFE or independent energy producers (PIEs). Of those not included, four were owned by CFE, the largest of which was the Manzanillo power station (10 412 GWh), and the remaining 38 were PIEs, self-supply, cogeneration, or industrial sources (76 062 GWh).

Stack exit release parameters were not available through the PRODESEN 2017–2031 or COPAR.
Stack parameters from the 2008 INEM were matched to 156 EGUs identified in the PRODESEN that comprised 85% of total electricity generation during 2016. For the remaining 199 EGUs that accounted for 15% of generation representative values by combustion category (table S2) were developed based on INEM records.

2.2. Estimates of generation and emissions in 2031
The PIIRCE development plans within the PRODESEN 2017–2031 established the chronological sequence of capacity additions and retirements by state with consideration of factors such as gross domestic product (GDP), fuel price, demand and consumption, and the trajectory of clean energy goals [39]. Projections of electricity generation were available only nationwide for 2031. Statewide estimates of fossil fuel generation in 2031 were developed by scaling existing 2016 to projected 2031 statewide capacity in addition to nationwide 2016 and 2031 generation by technology.

Estimates of 2031 generation applied a similar approach for each clean energy technology. Generation for states that had no changes in capacity by 2031 was set equal to 2016 generation. Excess nationwide generation for 2031 was calculated as the difference between projected 2031 and existing 2016 generation. This additional generation was spatially apportioned across all states that had capacity increases in linear proportion to each state’s contribution to the overall nationwide increase in capacity and then added to the state’s 2016 generation to estimate generation in 2031. All clean energy technologies were assumed to have negligible emissions.

Statewide estimates of conventional fossil fuel generation in 2031 were applied with an analysis of EGU-level infrastructure based on the PIIRCE plans and our 2016 emissions inventory to estimate emissions in 2031. Emissions from a given conventional fossil fuel technology were assumed unchanged between 2016 and 2031 if statewide generation was unchanged, while reductions in generation were associated with an across-the-board downscaling of emissions at existing 2016 EGU locations. Specific existing facilities were retired when inferred from changes in statewide capacity. Increases in statewide generation between 2016 and 2031 were assumed to be new capacity buildout. Emissions from the buildout were estimated using median emission factors grouped by state and technology shown in table S1. Statewide emissions increases were spatially allocated among all EGUs during 2016 with similar technology; if no activity occurred during 2016, emissions were allocated to the state’s centroid. It was conservatively assumed that expansion of future capacity would apply technology with similar emission rates as that of the 2016 base year infrastructure in Mexico.

2.3. Air quality modeling configuration and analyses
This study adapted a 2016 CAMx air quality modeling platform from the Texas Commission on Environmental Quality [48] that was based on the U.S. National Collaborative Emissions Modeling Platform.
Figure 3. Annual 2016 and projected 2031 emissions (tons) of NO$_x$, CO, SO$_2$, VOC, PM$_{2.5}$, and CO$_2$ from conventional fossil fuel generation in Mexico by technology and fuel type.

[29]. The horizontal grid domain shown in figure S1 included most of Canada, the continental United States, and almost all of Mexico. The vertical grid structure included 29 vertical layers between 30.8 and 17 800 m AGL. CAMx v.7 [49] was applied with meteorological fields from the Weather Research and Forecasting Model v.3.81 [50] over a time period spanning 15 December 2015–1 January 2017, which included the model ‘spin up’ period. Boundary and initial conditions were obtained using GEOS-Chem version 11-02rc [51]. Carbon Bond version 6 revision 4 was applied as the gas-phase mechanism [52–57]. The CF2 (coarse-fine) scheme with the SOAP2.2 [58] module for secondary organic aerosol chemistry/partitioning and ISORROPIA [59, 60] for partitioning of inorganic aerosol constituents were used as the aerosol chemistry options. A plume-in grid algorithm was applied for elevated point sources with NO$_x$ emissions of ≥ 5.0 tons per day, which included 61 EGUs representing >90% of Mexico's nationwide EGU NO$_x$ emissions.

The point source emissions inventories for Mexico's electricity generation (NAICS 221110) and upstream and midstream oil and gas sectors (NAICS categories 211110 and 325110) were replaced with our emissions estimates. The 2016 and 2031 inventories were prepared for input to CAMx using version 3 of the Emissions Processing System (EPS3) [61] to support atmospheric transport modeling.

CAMx simulations applied a zero-out emissions approach to conventional fossil fuel plants collectively as well as aggregated separately by fuel type in 2016 to investigate the effects on maximum daily average eight-hour (MDA8) ozone concentrations and 24 h average PM$_{2.5}$ concentrations in Mexican and U.S. border states. An additional CAMx simulation was conducted with the 2031 emissions estimates.

3. Results and discussion

3.1. Base year emissions profiles

Figure 3 summarizes nationwide emissions by technology and fuel in 2016. Annual emissions of NO$_x$, SO$_2$, and PM$_{2.5}$ were approximately 527 000, 859 000 and 29 000 tons, and for CO$_2$ were 138 million tons in 2016. Emissions of CO and VOC were approximately 83 000 and 3200 tons, respectively. Contributions to pollutant emissions from fossil fuel plants varied by technology and fuel. Figure 4 shows the spatial distributions NO$_x$, SO$_2$, CO, VOC, CO$_2$, and PM$_{2.5}$ emissions by fuel in 2016. Natural gas combined cycle (44%), coal (36%) and fuel oil-fired (7%) thermoelectric generation contributed 87% of NO$_x$ emissions. Natural gas combined cycle generation contributed 49% of CO$_2$ emissions followed by coal and fuel oil-fired generation with 18% each; it accounted for 85% of CO emissions. The primary contributions to
Figure 4. Spatial distributions of 2016 annual (a) NO\textsubscript{x}, (b) SO\textsubscript{2}, (c) CO, (d) VOC, (e) CO\textsubscript{2}, and (f) PM\textsubscript{2.5} emissions (tons) by fuel type from conventional fossil fuel generation in Mexico. Note differences in scales between plots and identification of selected facilities with relatively higher emissions contributions.
Figure 4. (Continued.)
SO$_2$ were from fuel oil-fired thermoelectric generation (60%), coal (27%), and internal combustion of fuel oil (5%). Fuel oil combustion dominated as a source of PM$_{2.5}$ (62%) emissions, as Mexico’s three coal plants have electrostatic precipitators [62].

3.2. Fuel mix and generation in 2031

The PRODESEN 2017–2031 projected 16 GW of retiring capacity and 56 GW of additional capacity by 2031, resulting in a net increase in capacity from 73 GW to 113 GW [39].
Conventional thermoelectric plants accounted for 11 GW of retiring capacity with additional retirements from natural gas combined cycle and turbogas capacity. Figure 1 compares nationwide 2016 generation in the PRODESEN 2017–2031 with our estimates of generation in 2031. Between 2016 and 2031, steep declines in installed capacity and generation from Mexico's fuel oil-fired conventional thermoelectric facilities, turbogas, and coal plants occur in favor of a buildout of natural gas combined cycle and clean energy technologies. Conventional fossil fuel generation decreases by only 3% in 2031 relative to 2016, retaining its importance in meeting Mexico's electricity demand but almost entirely through the use of natural gas combined cycle technology. Figures S2 and S3 show Mexican states and the locations of statewide expansions and retirements of fossil fuel generation.

Installed capacity and generation from clean energy technologies approach those of conventional technologies by 2031. Among the states with marked increases in renewable generation (figure S3) are Tamaulipas, Nayarit, Veracruz, Oaxaca, Coahuila, Chihuahua, San Luis Potosi, Jalisco, and Yucatan.
These areas are geographically coincident with high quality renewable resource, including wind and solar, availability [39].

### 3.3. Emissions profiles in 2031

Estimates of annual nationwide emissions during 2016 and 2031 by technology and fuel are compared in figure 3. Decreasing reliance on fuel oil-fired thermoelectric and turbogas generation along with the retirement of the Carbón I coal plant near the Texas-Mexico border drive reductions in emissions but with variability in impacts between pollutants. Total annual nationwide emissions of SO$_2$ and PM$_{2.5}$ from Mexico’s electricity sector are estimated to decrease by 68% (588 000 tons) and 61% (18 000 tons), respectively, and VOC emissions by 21% (700 tons). CO$_2$ emissions decrease by 13% (18 million tons). Although retirement of approximately 2 GW of natural gas combined cycle capacity was planned by 2031 from the Dos Bocas, Gómez Palacio, Huinalá, and Valladolid Felipe Carrillo Puerto power stations that are among the oldest owned by CFE [63], the buildout of new capacity to meet growth in demand moderated reductions of CO$_2$ achieved from the fuel oil-fired thermoelectric and turbogas retirements. Natural gas combined cycle generation was the largest source of NO$_x$ and CO emissions in 2016; the shift toward its greater use as other fossil fuel generation is retired results in a decrease in NO$_x$ emissions by 7% (37 000 tons) but a slight increase in CO by 4% (3550 tons). The differential benefits of fuel switching were also shown by Sosa et al [21] who found that the use of natural gas instead of fuel oil at the Tula thermoelectric plant northwest of Mexico City would lead to substantial reductions in SO$_2$ and PM, but with no benefit for NO$_x$ and CO$_2$ and increases in CO emissions.

The COPAR did not include information regarding emission control devices with the reported plant-level emission factors. Natural gas combined cycle plants included in the COPAR that were owned by CFE began operation between 1971 and 2007 [63] and could represent different efficiencies. We assumed that emission rates for new natural gas combined cycle capacity and existing capacity in 2016 that remains in operation through 2031 would be similar to the median emission rates of CFE and PIE plants included in the COPAR. As such our findings are based on a conservative scenario that could be influenced by the implementation of best available control technology requirements to achieve lower emissions for Mexico’s new capacity buildout.
3.4. Contributions to air quality in Mexican and U.S. border states

Emissions from fossil fuel generation in Mexico influence air quality throughout the country as well as in U.S. states such as Texas, New Mexico, and Arizona and along the Gulf Coast. Figure 5(a) shows percentile differences in predicted MDA8 ozone concentrations from zeroing emissions from coal, natural gas, and fuel oil-fired facilities, respectively, relative to the 2016 base case. Spatial patterns of predicted average and maximum differences in MDA8 ozone concentrations from coal and natural gas generation are shown in figure 6. These indicate the relative contributions of generation by fuel type to air quality but are not intended to represent specific emission control strategies. Coal and natural gas generation had the largest contributions to MDA8 ozone concentrations among all fuel types with the exception of fuel oil-fired generation in Baja California Sur. Emissions from coal plants most frequently affected air quality within the immediate area and neighboring states downwind. These regions included Coahuila and western Texas from the Carbón I and II coal plants and Guerrero, Colima, Michoacán, Morelos, and México from the Petacalco plant. HYSPLIT forward trajectories shown in figure S4 initiated at each coal plant during March and September show seasonal differences in the spatial extent of downwind areas as the primarily south-southwesterly wind flow pattern in the spring shifts to south-southeasterly or easterly by the early fall. Contributions of natural gas generation to MDA8 ozone concentrations were widespread due to its geographic distribution throughout Mexico.

Fuel oil-fired facilities had the largest nationwide contributions to 24 h average PM$_{2.5}$ concentrations from Mexico’s electricity sector followed by coal plants in 2016 (figure 5(b)). HYSPLIT forward trajectories initiated at 500 m AGL at 1pm local time at three of Mexico’s largest oil-fired facilities, Tula, Tuxpan, and Mazatlán II, in figure 7 highlight large differences in seasonal long-range transport patterns across central and northern Mexico and the U.S. Gulf Coast for April compared to July 2016.

The changes in fuel mix and emissions between 2016 and 2031 had differential benefits for achieving reductions in MDA8 ozone and 24 h average PM$_{2.5}$ concentrations. Figure 8 indicates that reductions in MDA8 ozone concentrations in 2031 relative to the 2016 base case in Mexican and U.S. border states were typically less than 0.5 ppb, as natural gas combined cycle generation remains a source of
4. Conclusions

Analysis of the PRODESEN 2017–2031 showed that reductions in CO₂ emissions and improvements in air quality can be achieved while meeting rising electricity demand in Mexico. However, the relative benefits varied among criteria pollutants. In the PRODESEN 2017–2031 through 2020–2034, expansion of natural gas combined cycle technology remains critical for meeting future demand. Although this is a key transition from Mexico’s historical reliance on fuel oil and coal, its expansion contributes to CO₂, NOₓ, and CO emissions. Our analysis indicated that in contrast to the declines in PM₂.₅ concentrations, MDA8 ozone concentrations across Mexico experience little change between the 2016 and 2031 scenarios. Buildout of natural gas combined cycle with lower emitting technology and carbon capture could alter these outcomes. Growth in the use of natural gas in Mexico has been accompanied by increasing reliance on U.S. pipeline exports, which can be a source of methane emissions [64]. Mexico would benefit from a diverse energy mix that includes leveraging the enormous potential for renewable energy generation. The total share of clean energy generation has increased from 21.5% to 27.5% between 2017 and 2020 [44] toward a target of 30% by 2021. Hydroelectric power has been the largest source of renewable energy in Mexico and will be integral to achieving Mexico’s clean energy targets. National support could further promote the growth of other renewable energy resources such as wind and solar that to date have been developed almost entirely through private sector investment.

A future focus should be on harmonizing and reporting plant-level data for emission factors and emission controls in Mexico. An on-going need is the development of specific emission factors for Mexico and other countries as an alternative to the frequent use of AP-42 factors that represent U.S. benchmarks. Over time emission factors should reflect changes in technology, fuel composition, and emissions measurements and be developed with high spatial and temporal granularity for atmospheric modeling to support air quality planning and management decisions.

The methods of this study can be used to assess how changes in infrastructure or policy initiatives affect emissions and air quality outcomes. In addition to the attempt to alter the provisions of the 2014 Electric Industry Law in March 2021, other indications of shifts in national priorities are a concern for Mexico’s electricity sector. Both the PRODESEN 2019–2033 and 2020–2034 indicate no retirements of conventional fossil fuel generation. In addition, current national plans are to increase the output of existing state-owned Petróleos Mexicanos (Pemex)
refineries as well as to complete construction of a new refinery in Tabasco [63]. Fuel oil for electricity generation in Mexico has primarily been the surplus from Pemex refineries. It currently has a higher sulfur content [66] than the 2020 limit of 0.5% for marine fuel by the International Maritime Organization [67]. Consequently, it cannot be supplied for shipping operations without sulfur mitigation. The expectation would be continued or expanded use of surplus fuel oil for electricity generation. This would reflect a path backwards for Mexico as it has sought to decrease the use of fuel oil over the past 15 years and would have markedly different outcomes than the development pathway examined in this study.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no conflict of interest.

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