

# Multilevel and multiregional analysis of the electricity metabolism across sectors

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## Abstract

This paper presents a novel improvement of MuSIASEM (Multiscale Integrated Analysis of the Societal and Ecological Metabolism) by incorporating a new regional analysis of the electricity metabolism across levels. An analysis of Mexico illustrates this toolkit and shows that the industry sector had economic energy intensity (EEI) with 40.3 MWh/MMXN reached a higher value than the commerce and services sector with 0.84 MWh/MMXN. Regarding the economic labor productivity (ELP) indicator (AV/h), the industrial sector with 208.5 TMXN/Kh reached a higher value than the commercial and services sector with 114.3 TMXN/Kh. Regarding the exosomatic metabolic rate (EMR), the household sector got 59.3 KWh/Kh whereas the economic sector reached 2,486.4 KWh/Kh. Disaggregation of the EMR indicator into economic sectors shows that the industrial sector got 8.4 KWh/Kh and the commercial and services sector reached 0.10 KWh/Kh. The lack of complete data for the agricultural sector does not allow us to calculate EEI, ELP, and EMR indicators accurately.

Considering the analysis of indicators by regions, regarding the EEI rate, the Central region had the lowest value with 12.7 MWh/MMXN, followed by the Noreste with 21.4 MWh/MMXN and Occidental with 29.4 MWh/MMXN, so they require less electricity to produce more added value. In terms of the ELP indicator, regions with higher values were Noreste with 182.3 MMXN/Mh, Central with 177.5 MMXN/Mh, and Norte with 127 MMXN/Mh, so these regions produce more added value per hour of work. About the EMR, regions in the northern part of the country had higher values: Noreste with 337 KWh/Kh, Baja California Sur with 334 KWh/Kh, Baja California with 328 KWh/Kh, Norte with 313 KWh/Kh and Noreste with 274 KWh/Kh, so these regions consume more electricity per hour.

This innovative approach is useful for governance because it helps to understand and reduce asymmetries across regions, resulting in more social equality and a better economic equilibrium across sectors and regions.

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## 1. Introduction

There is an increase in the importance of analyzing the economy from a biophysical perspective [1–3] and going beyond the use of the neoclassical economic model of supply and demand, which discards energy, work, and resources [4,5].

Therefore, this article deepens into the costs of both energy and work, since recent studies incorporating these factors are evidencing serious consequences when studying the limits of economic growth [6,7]. Showing inequalities in the contemporary economic model [8,9].

We think it is necessary to develop and apply an analysis that makes it possible to demonstrate the costs not incorporated in the equations of neoclassical economics, such as MuSIASEM [10,11], and that allows strategic planning of a country like Mexico, which has a great ethnic and social diversity [12].

We used the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) methodology [13,14] since MuSIASEM allows the analysis of socioeconomic variables and constraints based on population and environment [15,16].

We should note that there are no studies at the regional level of MuSIASEM inside a country. They exist to compare countries [17–21], to analyze the evolution of a country [22–24] or those that exist focus on a specific region [25,26]. For this reason, this work focuses on performing a multilevel and multiregional analysis of Mexico, since there are no multilevel-multiregional works within a country, just as there is no MuSIASEM analysis for Mexico.

Mexico is an interesting country since it has a free trade agreement with the US and Canada, as well as is a country that is examining a transformation in its government [27,28], and has great bio-cultural wealth, also being considered a country within the global South.

We organized the article as follows:

In section 2, you can find information such as the study area, data sources, and methods. Section 3 describes the results of the analysis. In section 4, you can find the discussion of the analysis, and finally, you can find the conclusion in section 5.

2. Study area, data sources, and methods

2.1 Study area and data sources

The study area considered in this paper is Mexico, the second most populous country in Latin America, after Brazil. By 2020, its population reached about 126 million inhabitants [29] In terms of electricity consumption, Mexico ranked sixth in Latin America with 2.01 MWh per capita, after Chile, Uruguay, Argentina, Venezuela, and Brazil. Regarding the economic indicator GDP, in Mexico in 2018 was \$9,687 U.S. dollars per capita [30].

2.2 Data sources

The work done here relies mainly on the analysis of economic, demographic, and electric consumption variables and their relations using MuSIASEM indicators across levels, sectors, and regions.

The year analyzed is 2018, and we chose it because of the availability of the data from the Economic Census [31], electricity consumption [32], and Population and Housing Census [29].

Economic Census bases its framework for the collection, analysis, and presentation of economic statistics on the 2018 North American Industrial Classification System [31]. **Table 1** describes the sectors that were taken into consideration for this analysis and their respective description.

Classification of electricity consumption by sectors (household, industry, commerce, and services) was based on the tariff scheme from CFE [33] (**Table 2**).

**Table 1.** Economic sectors. In *Italic* thematic areas were included in the 2019 Economic census. Source: Own elaboration based on data from [31].

Sector	Description
Agriculture	<i>Fishing, aquaculture, agriculture, forestry, breeding and exploitation of animals, and hunting</i>
Industry	<i>Construction, manufacturing industries</i>
Commercial and services	<i>Retail and wholesale trade. Health and social assistance services. Professionals, scientists, and technical services. Financial and insurance services. Educational services. Mass media information services. Cultural and sports entertainment and other recreational services. Postal transport and storage. Temporary accommodation and food and beverage preparation</i>

	<i>services. Other services except for government activities.</i> Corporate.
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**Table 2.** Classification of electricity consumption by sectors. Source: Own elaboration based on data from CFE [33].

Sector	Code	Description
Agriculture	9, 9M, 9CU, 9N, RABT, RAMT	Low and medium voltage water pumping service for agricultural irrigation. Nightly incentive rate for pumping water for agricultural irrigation and with a single charge. Agricultural Irrigation in low and medium voltage.
Household	1, 1A, 1B, 1C, 1D, 1E, 1F, DAC, DB2, DB1	Domestic with and without subsidy.
Commercial and services	5, 5A, 6, 7, APBT, APMT, 2, 3	Public lighting service, service for pumping drinking or sewage water for public service, temporary service, low and medium voltage public lighting. General service.
Industry	DIT, DIST, GDBT, GDBTH, GDBTO, HS, HSF, HSL, HSLF, HT, HTF, HTL, HTLF, GDMTH, PDBT, GDMTO	Industrial demand in transmission and sub-transmission. Great Demand (greater than 25 kW-month) in medium voltage. Hourly rate for general service in high voltage.
	HM, HMC, OM, OMF	Hourly rate for general service in medium voltage.
	PDBT	Small Demand (up to 25 kW-month) in low voltage.

Data analysis considered nine control regions as defined by SENER [34]. These regions are: Baja California, Baja California Sur, Central, Noreste, Norte, Noroeste, Occidente, Oriente, and Peninsular (**Fig. 1**).



**Figure 1.** Control regions. Source: Own elaboration based on data from SENER (2020)

2.3 Methods

Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) is an approach based on integrating various concepts related to complex system theory that makes it possible to perform a check on the feasibility and desirability of patterns of metabolism of socio-economic systems by providing a characterization at different levels and scales [3,14]. The concept of societal metabolism considers a set of transformation processes in a society that is necessary for its reproduction and sustenance over time [20]. MuSIASEM methodology allows for relate economic, energy, and population variables on various hierarchical levels combined with multi-regional analysis, which provides information about the way the society evolves and self-organizes. The development of this methodology allows the analysis of a large amount of data from national statistics of the economic sectors, demography, and from electricity, to get a diagnosis of how these systems are organized and how they interact. This research presents a tool to plan and solve unequal development of the different regions of Mexico.

In this work, data is organized from the most general to the most specific levels. The country is at the first level (N+1). The second level corresponds to the economic and household sectors (N+2). And the last level corresponds to the economic and household sectors distributed by region (N+3). We organized the variables and indicators of the MuSIASEM methodology according to these levels (Tables 3 and 4).

**Table 3.** MuSIASEM variables

Level N+1 Mexico	Level N+2 Sectors	Level N+3 Sectors and regions
THA: Total human activity. Total human time for one year. Population * 24 h * 365 days. Unit: hours (h)	HApwi: hours allocated to different economic sectors  HAhh: hours allocated to the household sector	HApwi: hours grouped by different economic sectors and regions.
TET: Total electrical energy throughput by country in one year. Units: kilowatt hour (KWh)	ETpwi: electrical energy throughput in the different economic sectors  EThh: electrical energy consumption	ETpwi: electrical energy throughput grouped by different economic sectors and regions.

	per capita in the household sector	
AV: Added value generated by an economy in one year by country. Units: MXN	AVi: added value grouped by different economic sectors.	AV: added value by regions

**Table 4.** MuSIASEM indicators

Level N+1: Mexico	Level N+2: Sectors	Level N+3: Sectors and regions
EEI: Economic energy intensity. Electrical energy consumption per unit of added value. TET/AV. Units: MWh/MMXN	EEIi: Economic energy intensity grouped by different economic sectors  ELPpwi: Economic Labour Productivity. AV/HApwi. Units: MMXN/Mh	EEIi: EEI grouped by different economic sectors and regions  ELPpwi: ELPpw grouped by different economic sectors and regions
EMRsa: Exosomatic metabolic rate. Electrical energy consumption per hour of human time is available to society. TET/THA. Units: KWh/Kh	EMRpwi exosomatic metabolic rate per hour in the economic sectors. ETpwi/HApwi  EMRhh exosomatic metabolic rate per hour in the household sector. EThh/HAhh	EMRpwi: EMRpwi grouped by different economic sectors and regions
AVhour: added value generated per hour of human activity in society. AV/THA Units: MMXN/Mh		AVhour: added value per hour of human activity grouped by region

### 3. Results

#### 3.1 Level N+1: Mexico

Considering that Mexico 2020 had a population of 126 million inhabitants [29], total human activity (THA), which is the time available for conducting different activities, was 1,103,882 Mh. The total electrical energy throughput (TET) in 2018 was 220,653 GWh, which only considers basic users' consumption and therefore does not include the users' consumption of the Wholesale Electricity Market or self-supply [32]. In economic terms, the added value (AV) for the year 2018 was 9,983.8 BMXN [31], and AV per capita was 79.2 TMXN.

The analysis demonstrates that economic energy intensity (EEI) was 24.7 MWh/MMXN. Regarding exosomatic metabolic rate (EMRsa) at the country level was 199.9 KWh/Kh and finally added value per hour (AVhour) was 8.1 MMXN/Mh.

#### 3.2 Level N+2: Sectors

According to data from INEGI [31], human activity in the household sector (HAhh) reached 1,039,858 Mh represented by 94.2% and 64,025 Mh correspond to the economic sectors (HApw) equivalent to 5.8%. In terms of electrical energy throughput, the household sector (EThh) got 61,614 GWh, which makes up 27.9% and the economic sectors (ETpwi) reached 159,039 GWh, represented by 72.1% [32].

Regarding the exosomatic metabolic rate, the household sector (EMRhh) reached 59.3 KWh/Kh, whereas that in the economic sectors (EMRpwi) was 2,486.4 KWh/Kh. These demonstrate economic sectors consume more electricity per hour of human activity than the household sector.

Data analysis by sectors shows that the industrial sector had the highest electricity consumption with 143,498 GWh, which represents 90.2% of the paid sector. Regarding AVi, the industry sector ranked second with 3,557 BMXN (39.8%) after the commercial and services sectors. The HApwi dedicated to the industry sector was 17,064 Mh (26.7%) occupying the second place after the commerce and services sector. Considering EEIi, with 40.3MWh/MMXN, the industry sector ranked second after the commerce and services sector, which indicates it requires more energy to generate a unit of added value in comparison with the commerce and services sector. Considering the ELPpwi indicator with 208.5 TMXN/Kh, the industry sector ranked second after the agricultural sector. And finally, the EMRpwi indicator with 8.4 KWh/Kh reached the second place after the agricultural sector. Although the industrial sector consumes the largest amount of energy, it is not the main generator of added value, nor is it the one that generates the most employment.

The commercial and services sector has the lowest electricity consumption with only 4,508 GWh, which represents 2.8% of the paid work sector. This sector generated the highest AVi with 5,355 BMXN (60%) and accounted for the highest number of working hours (HApwi) with 46,869 Mh (73.3%). Regarding the EEIi indicator, this sector got the lowest value of 0.84 MWh/MMXN. Regarding the ELPpwi and EMRpwi indicators with 114.3 TMXN/Kh and EMRpwi with 0.10 KWh/Kh respectively, the commercial and services sector got the lowest values among the other sectors.

The agricultural sector had second place in electricity consumption in the paid sector with 11,032 GWh (6.9%). Considering that this sector only included fishing and aquaculture, the generation of added value (AVi) was 17 BMXN (0.2%) and the human activity (HApwi) was 30 Mh representing 0.05% of the total in the paid sector. In terms of economic energy intensity (EEIi), the agricultural sector reached the highest value with 632.8 MWh/MMXN. This indicator cannot be representative because the electricity consumption data includes the entire agricultural sector while the added value data only includes fishing and aquaculture as mentioned before. Regarding economic labor productivity by sectors (ELPpwi), the agricultural sector reached 572.8 TMXN/Kh which makes up the highest value of this indicator compared to the industry, commerce, and services sectors. In terms of the exosomatic metabolic rate (EMRpwi), the highest value was presented in the agricultural sector with 362.5 KWh/Kh. As was explained before for the case of EEIi, EMRpwi lacks sufficient data to be calculated accurately.

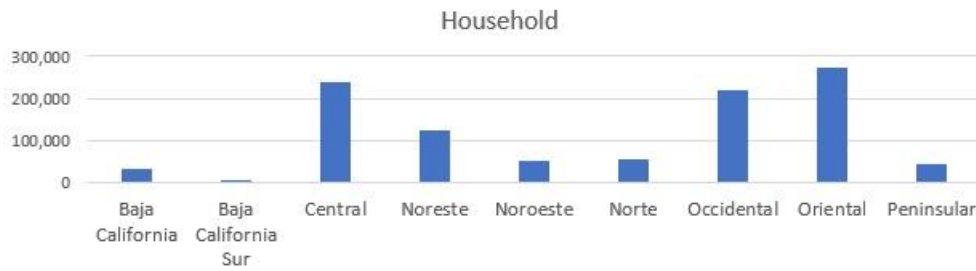
### 3.3 Level N+3: Sectors and regions

#### 3.3.1 MuSIASEM variables by sectors and regions.

##### 3.3.1.1 Human activity in the household (HAhh) and economic sectors (HApwi)

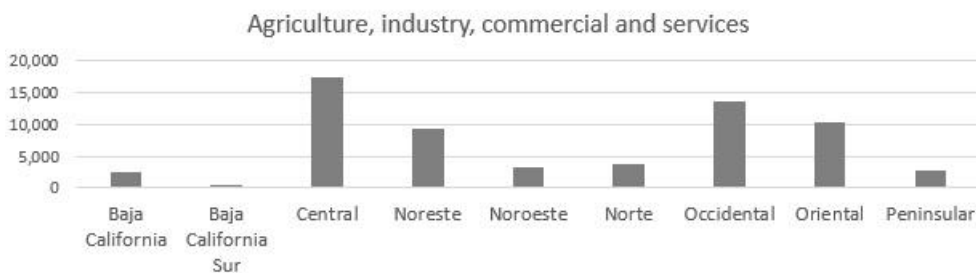
Regarding human activity allocated in the household sector (HAhh), the control region with the highest value of HAhh was Oriental, with 274,895 Mh (26.4%), followed by Central with 239,456 Mh (23%), Occidental with 218,127 Mh (21%), and Noreste with 123,983 Mh (11.9%). The regions with lower values of HAhh were Norte with 55,443 Mh (5.3%), Noroeste with 49,104 Mh (4.7%), Peninsular with 41,946 Mh (4%), Baja California with 30,519 Mh (2.9%) y Baja California Sur with 6,445 Mh (0.6%) (**Fig. 2**)





**Figure 2.** Human activity in the household sector (HApw) (Mh) by regions.

Taking into consideration all economic sectors (agriculture, industry, commercial, and services), the region with the highest values of HApw was the Central with 17,509 Mh (27.4%), followed by: Occidental with 13,734 Mh (21.5%), Oriental with 10,423 Mh (16.3%) and Noreste with 9,390 Mh (14.7%). HApw for the remaining control regions (Baja California, Baja California Sur, Noroeste, Norte, and Peninsular) reached values below 4,000 Mh, which makes up 20.2% of the total HApw (**Fig. 3**).

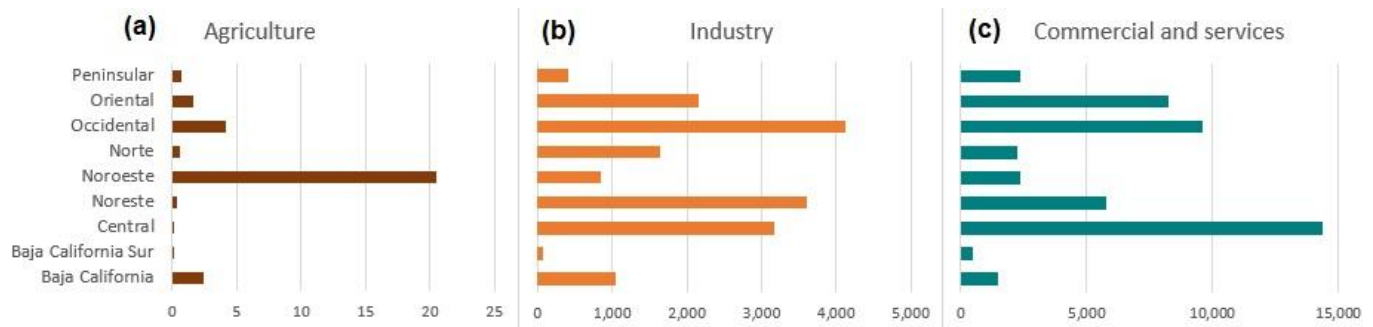


**Figure 3.** Human activity in economic sectors (HApw) (Mh) by regions.

Now we consider each economic sector grouped into control regions. Regarding the agricultural sector, the Noroeste region has the highest HApwi values, with approximately 20 Mh represented, representing 67.3% of the total hours allocated in this sector. Followed by regions: Occidental with 4.1 Mh (13.5%), Baja California with 2.4 Mh (8.1%) y Oriental with 1.6 Mh (5.3%). The remaining regions add up to 1.7 Mh, which makes up 5.7% of HApwi in the agricultural sector (**Fig. 4a**).

According to the analyzed data, the highest numbers of human activity (HApwi) in the industry sector, were presented in the following control regions: Occidental 4,127 Mh (24.2%), Noreste Mh (21.1%) 3,608, Central 3,165 Mh (18.5%), Oriental 2,159 Mh (12.7%) and Norte 1,640 Mh (9.6%). The following regions: Baja California, Baja California Sur, Noroeste, and Peninsular reached together HApwi 2,365 Mh, representing 13.8% of this sector (**Fig. 4b**).

In the commercial and services sector, the amount of human activity (HApwi) is higher in the following regions: Central with 14,345 Mh (30.6%), Occidental with 9,603 Mh (20.5), Oriental with 8,263 Mh (17.6%) y Noreste 5,581 with Mh (12.3%), which together represent a percentage of 81.1% of the human activity allocated in this sector. Regions that present a lower quantity of human activity in the same sector are Baja California, Baja California Sur, Noroeste, Norte, and Peninsular. These, add up to 8,877 Mh equivalent to 8.9% of HApwi in the commercial and services sector (**Fig. 4c**).

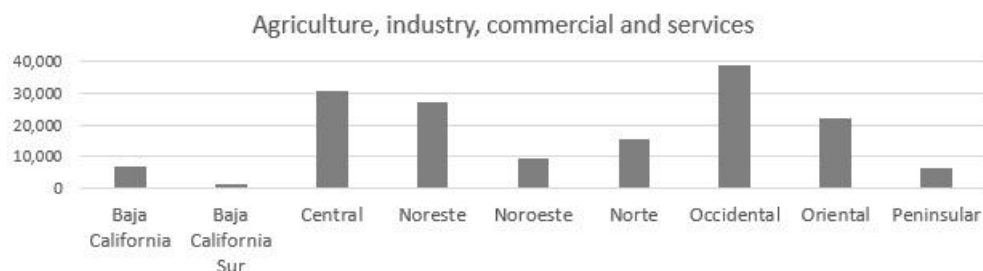


**Figure 4.** Human activity is grouped into different economic sectors (HApwi) (Mh) by region. (a) Agriculture, (b) Industry, and (c) Commercial and services.

### 3.3.1.2 Electrical energy throughput in economic sectors (ETpw) and in the household sector (EThh)

#### Electrical energy throughput in economic sectors (ETpwi)

According to data from CFE [32], the industry sector has the highest electricity consumption because of the use of automated processes and mechanization, and this is revealed in the behavior of the ETpwi indicator. When ETpwi is analyzed by regions, it is observed that the Occidental region reached the highest value with 38,768 GWh (22.6%), followed by Central with 30,855 GWh (17.8%), Noreste with 27,120 GWh (16.6%), Oriental with 22,318 GWh (16.1%), Norte with 15,312 GWh (8.4%) and Noroeste with 9,604 GWh (8.0%). The regions that presented the lowest consumption values were Baja California with 7,098 GWh, Baja California Sur with 1,525 GWh, and Peninsular with 6,439 GWh, which represented 10.6% of the energy consumed in the paid sector (**Fig. 5**).



**Figure 5.** Electrical energy throughput in economic sectors (ETpw) (GWh) by regions

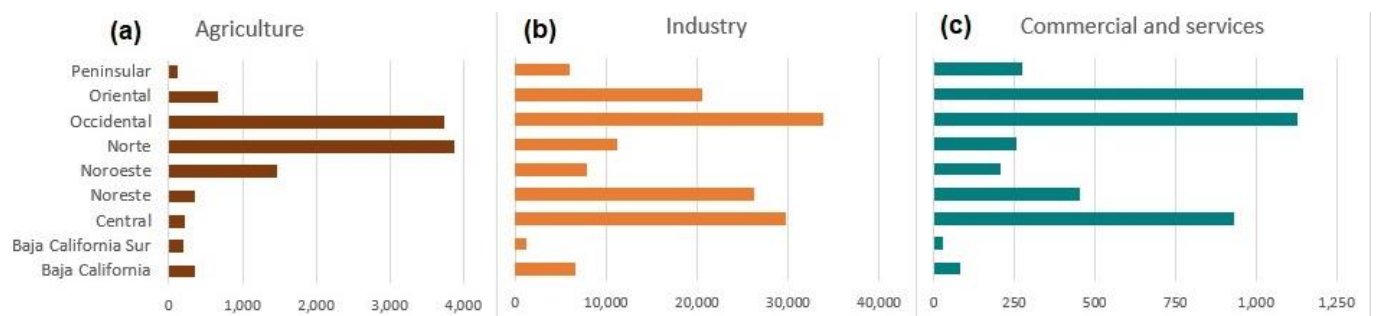
When focusing on each economic sector disaggregated by control regions, we can notice that in the agricultural sector stand out four regions with the highest electrical consumption: Norte with 3,877 GWh (35.1%), Occidental with 3,740 GWh (33.9%), Noroeste with 1,467 GWh (13.3%) and Oriental with 672 GWh (6.1%). In this same sector, the regions with the least energy consumption were Baja California with 357 GWh, Baja California Sur with 2,016 GWh, Central with 223 GWh, Noreste with 363 GWh, and Peninsular with 125 GWh; whose added percentage of electric consumption was 11.5% (**Fig. 6a**).

Regarding the electrical consumption of the industry sector, the following control regions are highlighted: Occidental with 33,899 GWh (23.6%), Central with 29,699 GWh (20.7%), Noreste with 23,304 GWh (18.3%) y Oriental with 20,498 GWh (14.3%). The remaining control regions presented lower electricity consumption as follows: Baja California with 6,660 GWh (4.6%), Baja California Sur with 1,291 GWh (0.9%), Noroeste with 7,928 GWh (5.5%), Norte with 11,180 GWh (7.8%), and Peninsular with 6,038 GWh (4.2%) (**Fig. 6b**).

And finally, the electricity consumption of the commercial and services sector was higher in the Oriental region with 1,148 GWh (25.5%), Occidental with 1,128 GWh (25%), Central with 933 (20.7%) and Noreste 451 GWh (10%). In less extent, regions with lower electricity consumption were Baja California with 81



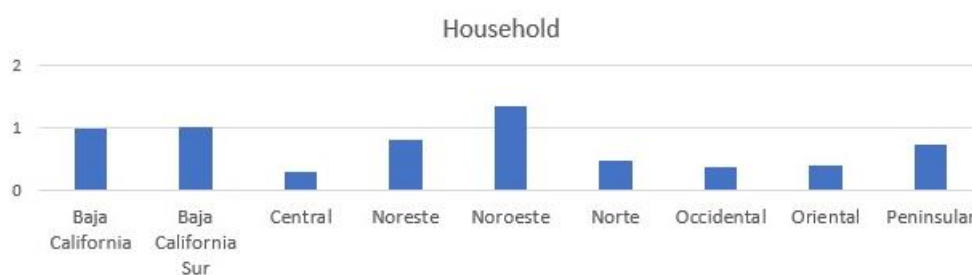
GWh, Baja California Sur with 28 GWh, Noroeste with 208 GWh, Norte with 255 GWh, and Peninsular with 276 GWh (**Fig. 6c**).



**Figure 6.** Electrical energy throughput is grouped into different economic sectors (ET<sub>pwi</sub>) (GWh) by region. (a) Agriculture, (b) Industry, and (c) Commercial and services.

### Electrical energy throughput per capita in the household sector (E<sub>Thh</sub>)

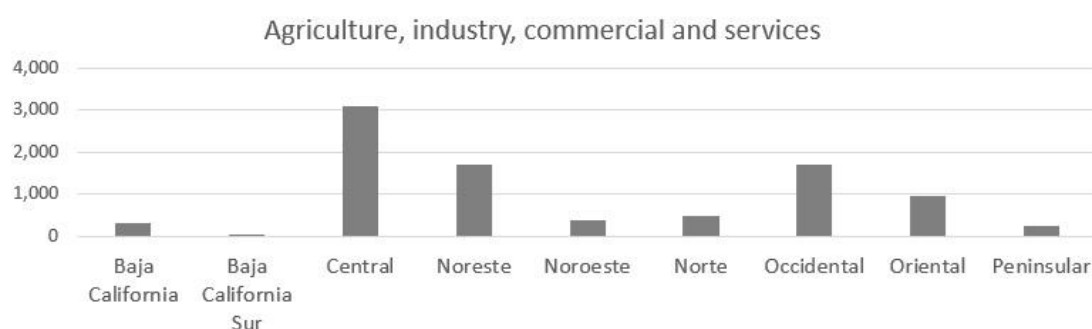
The data on electricity consumption per capita in the household sector by regions shows that the highest values were reached in: Noroeste with 1.34 MWh, Baja California Sur with 1.1 MWh, Baja California with 0.99 MWh, Noreste with 0.80 MWh and Peninsular with 0.74 MWh. Regions with less electricity consumption per capita were Norte with 0.48 MWh, Oriental with 0.4 MWh, Occidental with 0.37 MWh, and Central with 0.29 MWh (**Fig. 7**).



**Figure 7.** Electrical energy throughput per capita in the household sector (E<sub>Thh</sub>) (MWh) by regions.

### 3.3.1.3 Added value (A<sub>Vi</sub>)

In 2018, the control region that contributed the most in added value (AV) was the Central with 3,108 BMXN, representing 34.8% of the total, followed by the Noreste with 1,712 BMXN (19.2%), Occidental with 1,692 BMXN. (18.9%) and Oriental with 941 BMXN (10.5%). The following regions generated the remaining 16%: Baja California with 293 BMXN, Baja California Sur with 52 BMXN, Noroeste with 386 BMXN, Norte with 490 BMXN, and Peninsular with 255 BMXN (**Fig. 8**).

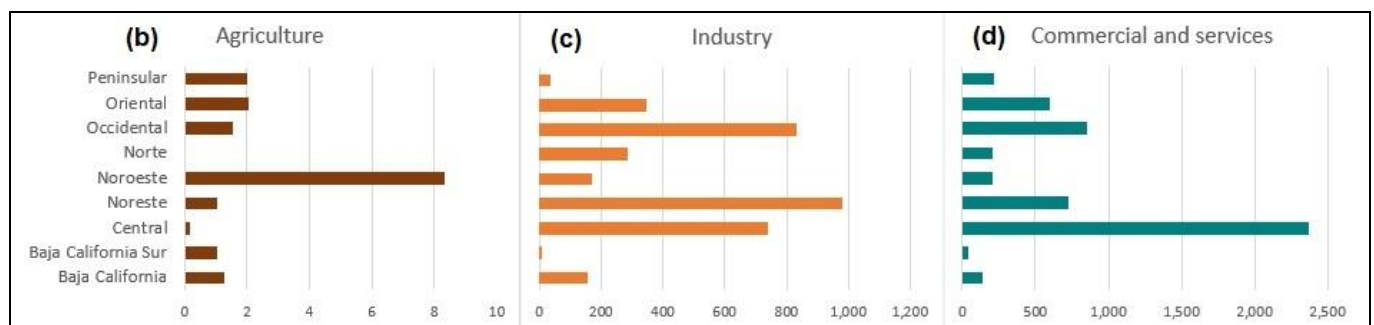


**Figure 8.** Added value (AV) (BMXN) by regions.

The added value of the agricultural sector had the highest values in the following regions: Noroeste with 8.3 BMXN (47.7%), Oriental with 2.04 BMXN (11.7%), Peninsular with 2.02 BMXN (11.6%), and Occidental with 1.6 BMXN (8.9%). The regions that contributed the least in this sector were Baja California with 1.3 BMXN (7.2%). Noreste with 1 BMXN (5.9%), Baja California Sur with 1 BMXN (5.9%), Central with 0.2 BMXN (0.9%) and Norte with 0.05 BMXN (0.3%) (**Fig. 9a**).

Regarding with industry sector, regions with the highest contributions in added value were Noreste with 981 BMXN (27.6%), Occidental with 835 BMXN (23.5%), Central with 737 BMXN (20.7%), Oriental with 345 BMXN (9.7%) and Norte with 287 BMXN (8.1%). The remaining regions contributed to a lesser extent in this way: Noroeste with 171 BMXN (4.8%), Baja California with 155 BMXN (4.4%), Peninsular with 38 BMXN (1.1%), and Baja California Sur with 8.5 BMXN (0.2%) (**Fig. 9b**).

In commercial and services sector, it stands out the contribution of the Central region with 2,371 BMXN (44.3%), Occidental with 856 BMXN (16%), Noreste with 730 BMXN (13.6%), and Oriental with 594 BMXN (11.1%). Regions that contributed to a lesser extent were Peninsular with 215 BMXN (4%), Noroeste with 207 BMXN (3.9%), Norte with 203 BMXN (3.8%), Baja California with 138 BMXN (2.6%), and Baja California Sur with 43 BMXN (0.8%) (**Fig. 9c**).



**Figure 9.** Added value grouped into different economic sectors (AVi) (BMXN) by regions. (a) Agriculture, (b) Industry, and (c) Commercial and services.

### 3.3.2 MuSIASEM indicators by sectors and regions.

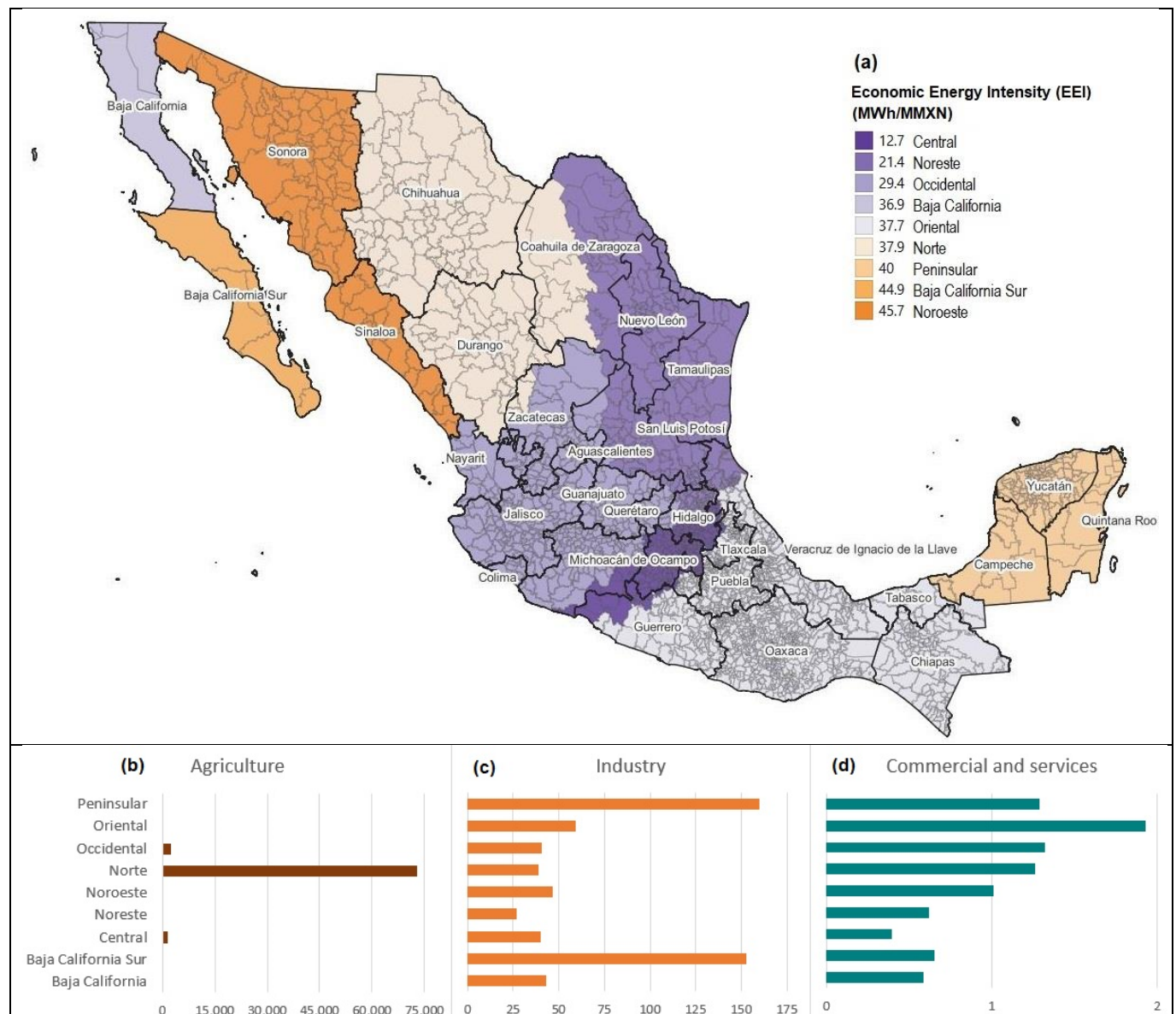
#### 3.3.2.1 Economic Energy Intensity (EEIi)

Considering all economic sectors distributed by regions, the Central region had the lowest value of EEI with 12.7 MWh/MMXN, followed by Noreste with 21.4 MWh/MMXN, Occidental with 29.4 MWh/MMXN, Baja California with 36.9 MWh/MMXN, Oriental with 37.7 MWh/MMXN, Norte with 37.9 MWh/MMXN, Peninsular with 40 MWh/MMXN, Baja California Sur with 44.9 MWh/MMXN and finally the highest value in Noroeste region with 45.7 MWh/MMXN. (**Fig. 10a**).

Analysis of EEIi indicator shows that in the agricultural sector, Norte region stands out from other regions with 72,967 MWh/MMXN, followed by regions: Occidental with 2,416 MWh/MMXN and Central with 1,424 MWh/MMXN. Values of EEIi were smaller in Noreste with 355 MWh/MMXN, Oriental with 330 MWh/MMXN, Baja California with 285 MWh/MMXN, Baja California Sur with 199 MWh/MMXN, and Noroeste with 177 MWh/MMXN (**Fig. 10b**).

Regarding the industry sector, two regions had the maximum values of EEIi, they were Baja California Sur with 153 MWh/MMXN and Peninsular with 160 MWh/MMXN, followed by Oriental with 60 MWh/MMXN, Noroeste with 46 MWh/MMXN, Baja California with 43 MWh/MMXN, Central, Occidental and Norte with 40 MWh/MMXN each, and the lowest value correspond to Noreste with 27 MWh/MMXN. (**Fig. 10c**).

Finally, in the commercial and services sector, the Oriental region had the highest value of EEI with 1.9 MWh/MMXN, followed by regions Norte, Occidental, and Peninsular with 1.3 MWh/MMXN each, Noroeste with 1 MWh/MMXN, Baja California Sur with 0.7 MWh/MMXN, Noroeste and Baja California with 0.6 MWh/MMXN each, and Central region with 0.4 MWh/MMXN (**Fig. 10d**).



**Figure 10.** (a) Economic energy intensity (EEI=TET/AV) (MWh/ MMXN) by regions and grouped into different economic sectors (b) Agriculture, (c) Industry, and (d) Commercial and services.

### 3.3.2.2 Economic Labour Productivity (ELPpwi)

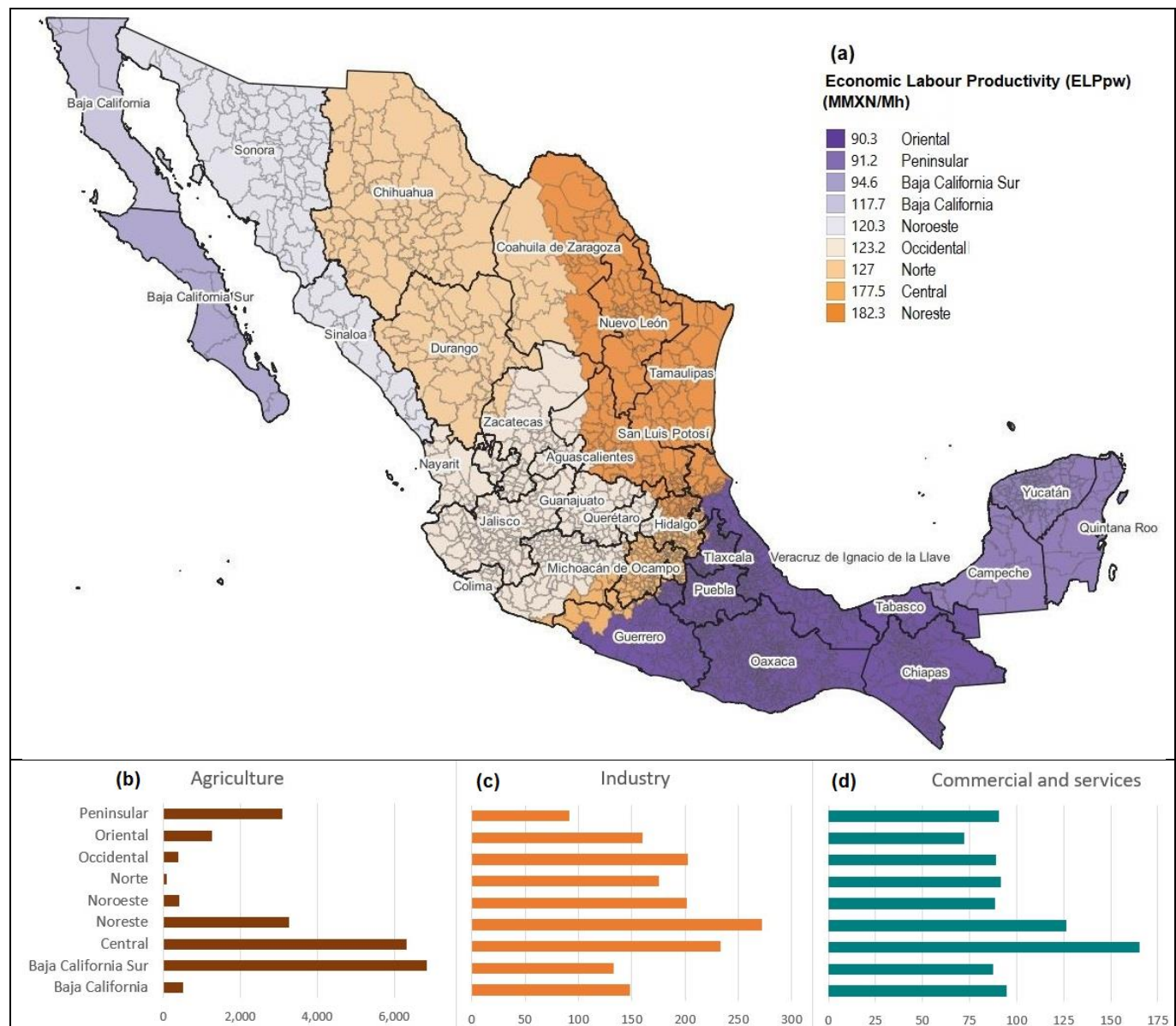
Regions with the highest ELPpw were: Noreste with 182.3 MMXN/Mh, Central with 177.5 MMXN/Mh, Norte with 127 MMXN/Mh, and Occidental with 123.2 MMXN/Mh. Followed by regions with smaller value of ELPpwi: Noroeste with 120.3 MMXN/Mh, Baja California with 117.7 MMXN/Mh, Baja California Sur with 94.6 MMXN/Mh, Peninsular with 91.2 MMXN/Mh and Oriental with 90.3 MMXN/Mh. (**Fig. 11a**).

Considering the ELPpwi values by regions, it is observed the highest values in the agricultural sector correspond to the following regions: Baja California Sur with 6,852 MMXN/Mh, Central with 6,320 MMXN/Mh, Noreste with 3,271 MMXN/Mh, and Peninsular with 3,098 MMXN/Mh. Lower values correspond to the regions: Oriental with 1,267 MMXN/Mh, Norte with 87 MMXN/Mh, Occidental with 376 MMXN/Mh, Noroeste with 406 MMXN/Mh, and Baja California with 506 MMXN/Mh (**Fig. 11b**).



The highest values of ELPpw in the industrial sector were presented in the Noreste and Central regions (with 272 and 233 MMXN/Mh respectively), followed by Noroeste and Occidental with 202 MMXN/Mh each, Norte with 175 MMXN/Mh, Oriental with 159 MMXN/Mh, Baja California with 149 MMXN/Mh. The lowest values were presented in Baja California Sur and Peninsular with 133 and 92 MMXN/Mh respectively (**Fig. 11c**).

Finally, considering data on commercial and services sector, the Central and Noroeste regions stand out with 165 and 126 MMXN/Mh, respectively. The following regions had intermediate values: Baja California with 94.7 MMXN/Mh, Norte with 91.4 MMXN/Mh, Peninsular with 90.3 MMXN/Mh, Occidental with 89.1 MMXN/Mh, Noroeste with 88.3 MMXN/Mh. The lowest values were presented in Baja California Sur with 87.5 MMXN/Mh, and Oriental with 71.9 MMXN/Mh (**Fig. 11d**).

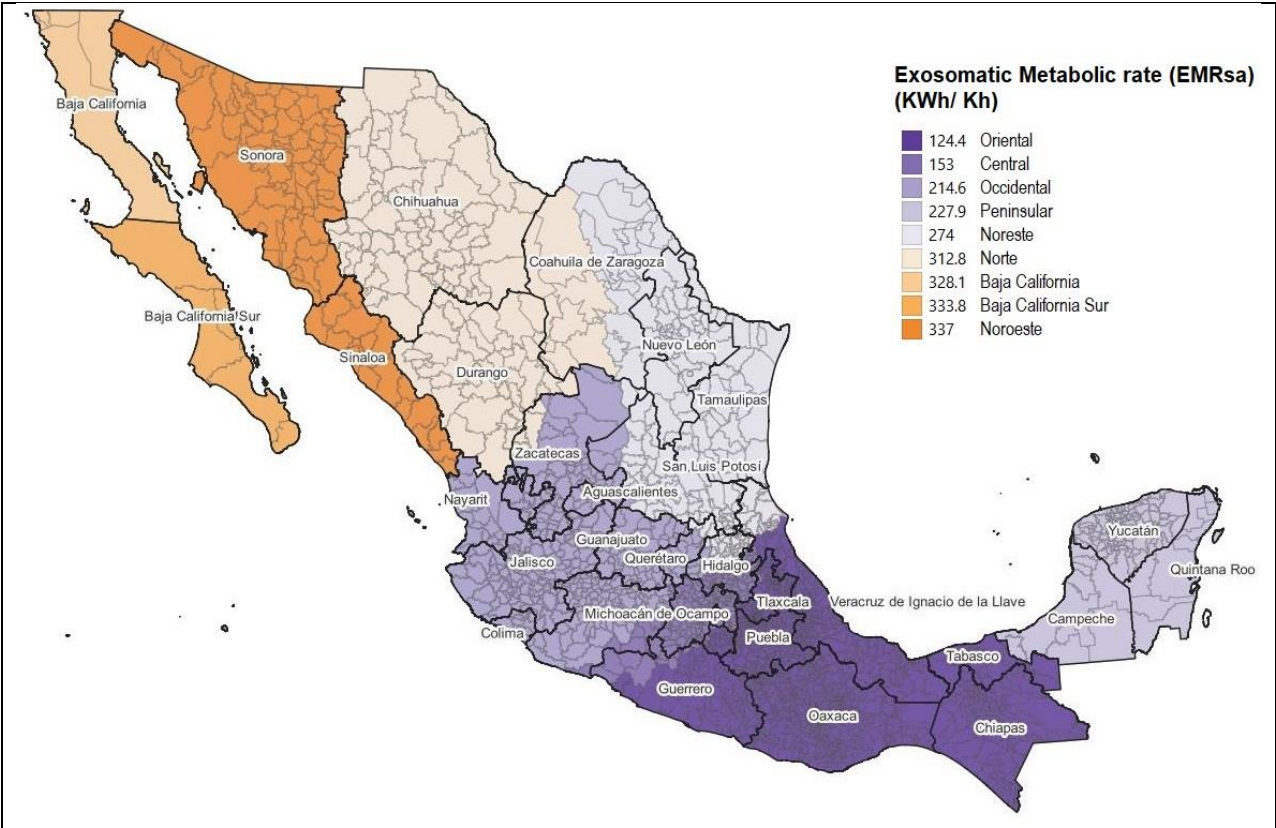


**Figure 11.** (a) Economic labour productivity (ELPpw=AV/HApw) (MMXN/ Mh) by regions and grouped into different economic sectors (b) Agriculture, (c) Industry, and (d) Commercial and services.

### 3.3.2.3 Exosomatic Metabolic Rate in the household sector (EMRhh) and in the economic sectors (EMRpwi)

Considering exosomatic metabolic rate for both household sector and economic sectors (EMRsa), it is observed that regions in the northern part of the country had higher values: Noroeste with 337 KWh/Kh, Baja California Sur with 334 KWh/Kh, Baja California with 328 KWh/Kh, Norte with 313 KWh/Kh and

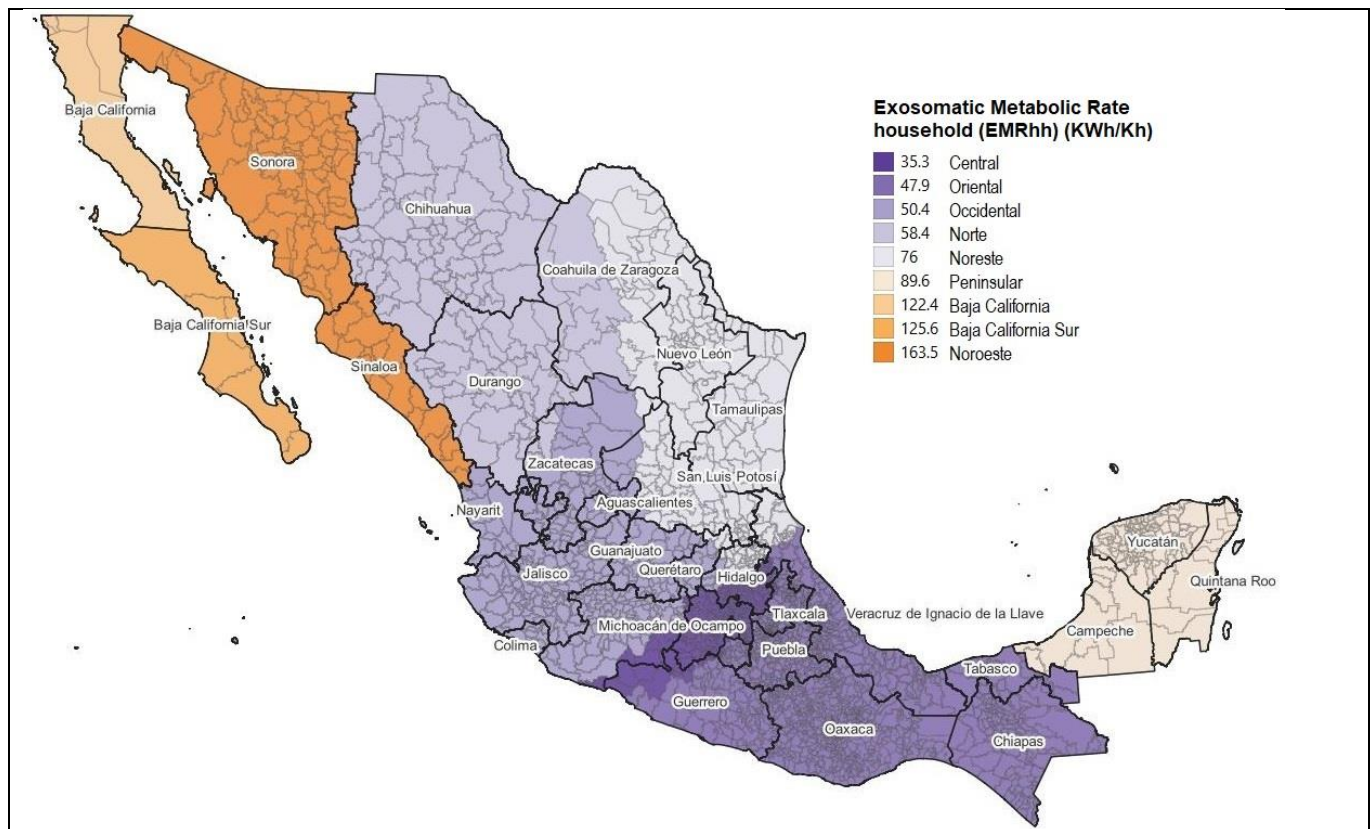
Noreste with 274 KWh/Kh. While the following regions registered lower values of EMRsa: Oriental with 124 KWh/Kh, Central with 153 KWh/Kh, Occidental with 215 KWh/Kh, and Peninsular with 228 KWh/Kh. (Fig. 12).



**Figure 12.** Exosomatic metabolic rate by regions (EMRsa=TET/THA) (KWh/Kh)

**Exosomatic Metabolic Rate in the household sector (EMRhh)**

The data show that the highest values of EMRhh occurred in the following regions: Noroeste with 163.5 KWh/Kh, Baja California Sur with 125.6 KWh/Kh, Baja California with 122.4 KWh/Kh, Peninsular with 89.6 KWh/Kh, Noreste with 76 KWh/Kh. EMRhh was lower in the following regions: Norte with 58.4 KWh/Kh, Occidental with 50.4 KWh/Kh, Oriental with 47.9 KWh/Kh and Central with 35.3 KWh/Kh (Fig. 13).



**Figure 13.** Exosomatic metabolic rate in the household sector ( $EMR_{hh} = EThh/HA_{hh}$ ) (KWh/Kh) by regions.

### Exosomatic Metabolic Rate in economic sectors ( $EMR_{pwi}$ )

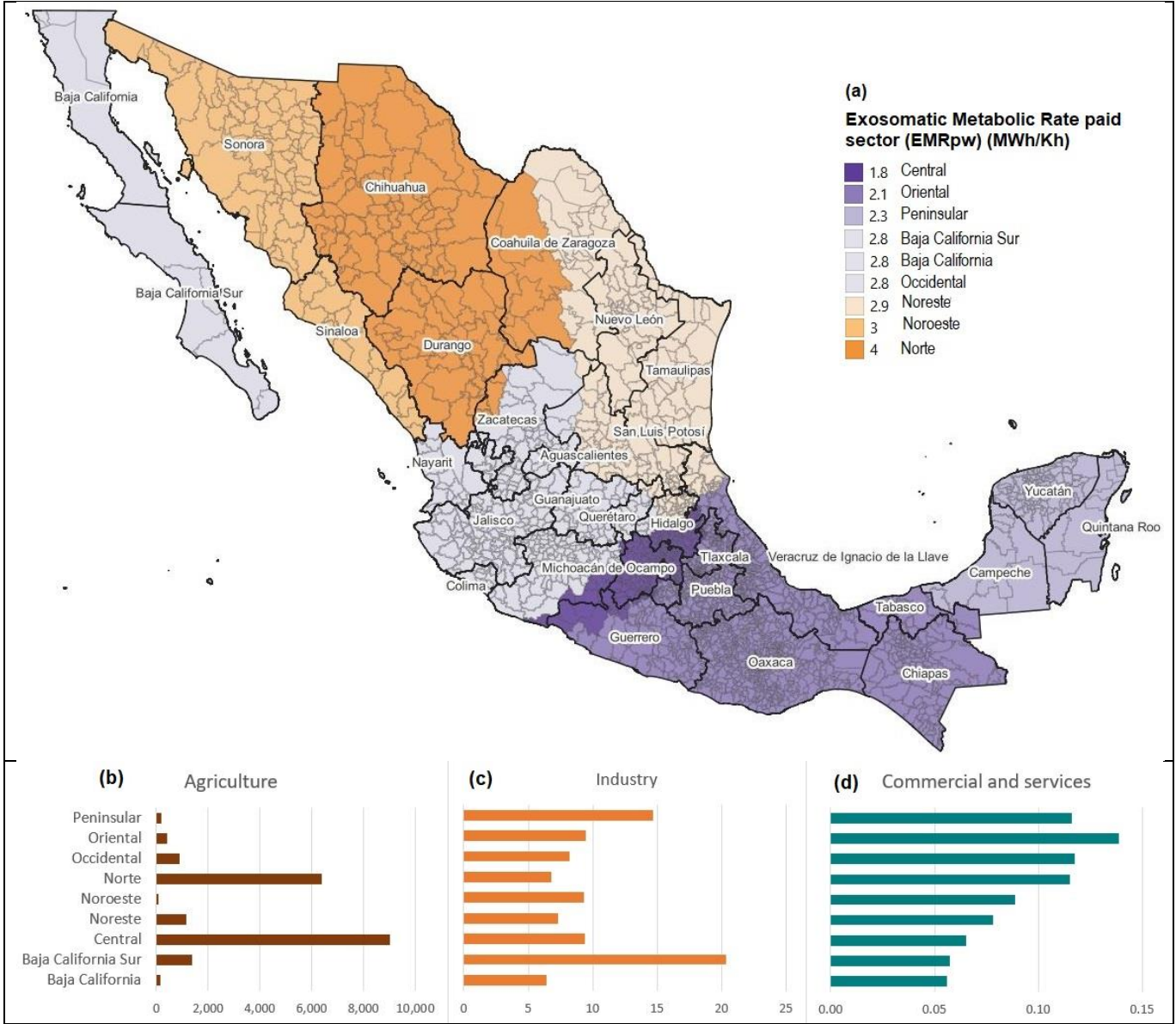
Analysis of Exosomatic metabolic rate in the economic sectors by regions ( $EMR_{pwi}$ ) indicates that the next regions reached higher values: Norte with 4 MWh/Kh, Noroeste with 3 MWh/Kh, Noreste with 2.9 MWh/Kh, and Occidental with 2.8 MWh/Kh. Baja California and Baja California Sur with 2.8 MWh/Kh each. The regions with the lowest values were Peninsular with 2.3 MWh/Kh, Oriental with 2.1 MWh/Kh, and Central with 1.8 MWh/Kh (**Fig. 14a**).

Considering disaggregation by economic sectors and control regions shows that the agricultural sector has the highest  $EMR_{pwi}$  values among the other sectors. In this context, the Central and Norte regions stand out with 8,997 MWh/Kh and 6,365 MWh/Kh, respectively. Followed by Baja California Sur with 1,367 MWh/Kh, Noreste with 1,161 MWh/Kh. Occidental with 909 MWh/Kh, Oriental with 418 MWh/Kh, and finally Peninsular with 191 MWh/Kh, Baja California with 144 MWh/Kh, and Noroeste with 72 MWh/Kh (**Fig. 14b**).

Following the agricultural sector is the industry sector with  $EMR_{pwi}$  values that range between 20 and 6 MWh/Kh. Where the following regions presented the highest values: Baja California Sur with 20.3 MWh/Kh, Peninsular with 14.7 MWh/Kh, Oriental with 9.5 MWh/Kh, Central with 9.4 MWh/Kh, Occidental with 8.2 MWh/Kh, Noreste with 7.3 MWh/Kh, Norte with 6.8 MWh/Kh and Baja California with 6.4 MWh/Kh (**Fig. 14c**).

Finally, the lowest values of  $EMR_{pwi}$  were reached in the commercial and services sector. The regions with the highest values are Oriental with 0.14 MWh/Kh, Peninsular, Norte, and Occidental with 0.12 MWh/Kh each, Noroeste with 0.09 MWh/Kh, Noreste with 0.08 MWh/Kh, Central with 0.07 MWh/Kh, Baja California, and Baja California Sur with 0.06 MWh/Kh each (**Fig. 14d**).

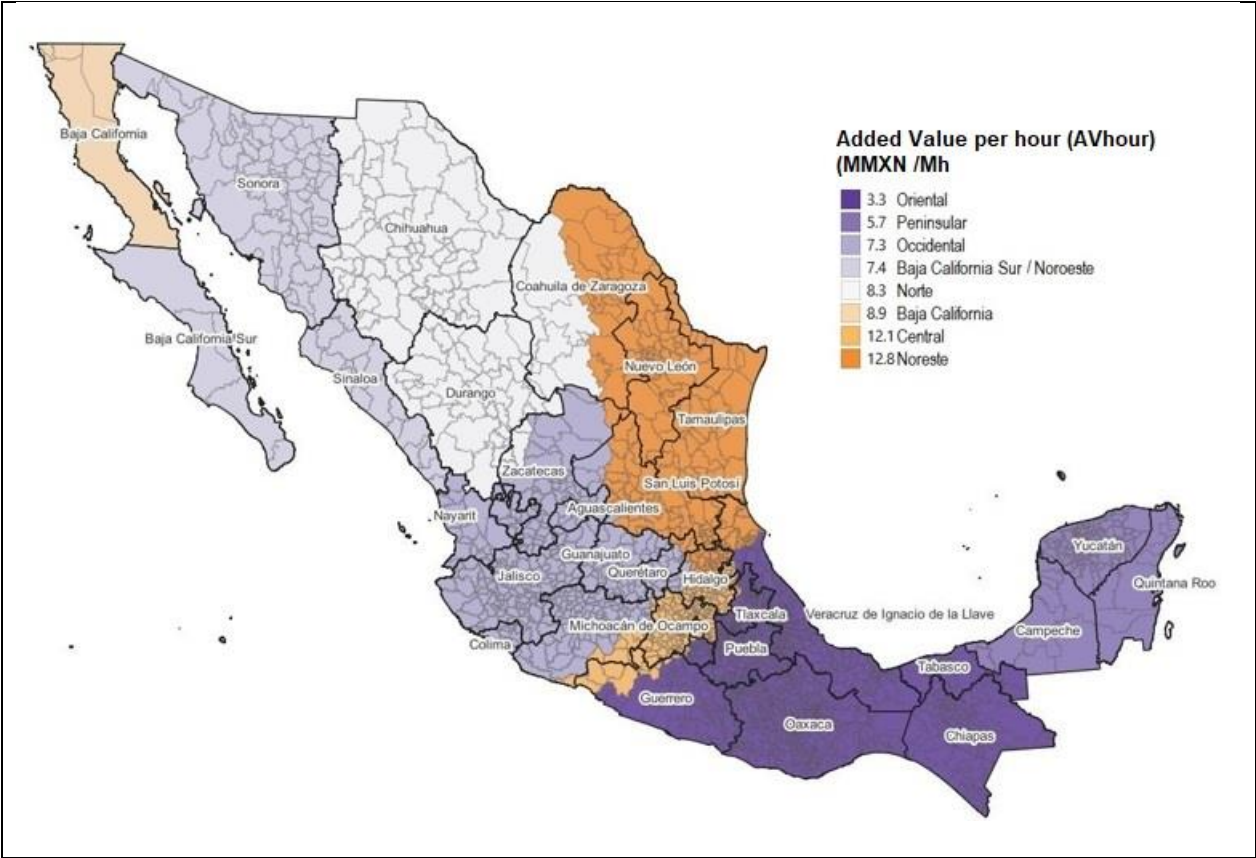




**Figure 14.** (a) Exosomatic metabolic rate (EMRpw=ETpw/HAPw) (KWh/Kh) by regions and grouped into different economic sectors (b) Agriculture, (c) Industry, and (d) Commercial and services.

3.3.2.4 Added Value per hour (AVhour)

Based on the data reported by official sources [29,31] the value generated per hour of human activity (AVhour) in 2018 was higher in the following regions: Noreste with 12.8 MMXN/Mh, Central with 12.1 MMXN/Mh, Baja California with 8,9 MMXN/Mh, and Norte with 8.3 MMXN/Mh. Lower values of AVhour were in Baja California Sur y Noroeste with 7.4 MMXN/Mh each, Occidental with 7.3 MMXN/Mh, Peninsular with 5.7 MMXN/Mh, and finally Oriental with 3.3 MMXN/Mh (**Fig. 15**).



**Figure 15.** Added value generated per hour of human activity (AVhour=AV/THA) (MMXN/Mh) by regions.

**Discussion**

Based on the analysis of the variables and indicators by sectors, we can state that the industrial sector had the highest electricity consumption, ranked second in added value generation after the commercial and services sector, and occupied second place in human activity. Regarding the economic energy intensity ( $EI = ET/AV$ ), the industrial sector ranked second after the commerce and services sector, which shows more energy is needed to generate a unit of added value in comparison with commerce and services sectors. Considering the economic labour productivity indicator ( $ELP = AV/HA$ ), the industrial sector ranked second after the agricultural sector. And finally, the exosomatic metabolic rate indicator for the industrial sector ( $EMR = ET/HA$ ) reached the second place after the agricultural sector. The industrial sector stands out that although it consumes the largest amount of energy, it is not the main generator of added value, nor is it the one that generates the most employment.

The commercial and services sector had the lowest electricity consumption. This sector generated the highest added value (AV) and accounted for the highest number of human activity (HA). Regarding the EI indicator, this sector had the lowest value, since the activities carried out required less electricity consumption compared to the industrial sector, which is compensated with greater human activity. Regarding the ELP and EMR indicators, the commercial and services sector had the lowest values compared to the other sectors. This is because of the high number of hours of HA allocated to the commercial and service sector.

The agricultural sector was the second sector in electricity consumption in the paid work sector. Considering that this sector only included fishing and aquaculture, the generation of added value (AV) and human activity (HA) were undervalued. In terms of economic energy intensity (EI), the agricultural sector reached the highest value. This indicator cannot be representative because the electricity consumption data includes the entire agricultural sector, while the added value data only includes fishing and aquaculture, as mentioned before. In terms of the exosomatic metabolic rate (EMR), the agricultural sector presents the highest value. Values of EI and EMR indicators lack sufficient data to be calculated accurately.

The regions with the highest electricity consumption (Occidental, Central, and Noreste) are also those that provide the most added value. There is an imbalance in terms of energy generation and consumption, that causes losses in this process [28] since the energy must travel large distances from the regions with high electricity production (Noreste and Oriental) to regions that demand the most (Occidental and Central). With the establishment of the North American Free Trade Agreement (NAFTA) between the US, Canada, and Mexico, automobile and other manufacturing industries were installed in Mexican territory mainly in the Occidental, Noreste, Norte, and Central regions, which have high electrical consumption and the added value is less than that generated by commerce and services sector. Regarding human activity in the economic sectors, the regions with the highest values were the Central, Occidente, and Oriente, which are allocated in the commerce and services sector. The industrial sector offers a smaller number of jobs compared to the commerce and services sector.

On the contrary, the regions with the lowest electricity consumption in the paid sector were Baja California, Baja California Sur, and Peninsular whose economic activities are focused on industry, commerce, and services and the generation of added value was less than the regions mentioned previously. Because they are far from regions that generate the most electricity, the supply of electricity presents difficulties in its transmission, especially because they are regions that consume more electricity than they produce. Regarding per capita electricity consumption, these three regions plus the Noroeste region presented the highest values, which are related to the need for lower temperatures, especially in summer. In these regions, it would be important to install distributed energy generation plants to meet their own needs.

Regarding the economic energy intensity indicator ( $EEI=ET/AV$ ), the lowest values were reached by the Central, Occidental, and Noreste regions, which shows that they need less electricity to generate a unit of added value. In the Central region, the sector that contribute the most to added value (AV) are commercial and services, and the amount of energy required to develop this activity is less than that required in the industrial sector. The situation is different in the Occidental region where the industrial, commercial, and service sectors generate approximate values, and electricity consumption is the highest of all the regions. In the Noreste region, the industrial sector generated a high added value (AV) which corresponds to high energy consumption. On the contrary, we find the highest values of EEI indicator in the Peninsular, Baja California Sur, and Noroeste regions, which means more electricity is required to produce a unit of added value.

Considering the economic labour productivity indicator ( $ELP=AV/HA$ ) which is added value per hour of working time, it can be observed that the higher values were in the following regions Norte and Noreste, where the industrial sector generated higher added value compared to other sectors and the human activity were relatively low compared with commercial and services sector. The Central region also reached a high value of  $ELP_{pw}$ , and it was characterized by the highest number of hours and added value in the commercial and services sector. The lowest values were found in the Oriental, Peninsular, Baja California, and Baja California Sur regions. These regions are the ones that had a lower contribution in added value in the industrial, commercial, and services sectors.

Analyzing the exosomatic metabolic rate of the economic sectors ( $EMR=ET/HA$ ) which is the amount of energy used per unit of time in the paid sectors and considering the regions with higher values it can be observed this occurs in the regions where the industry is more developed (Occidental y Noreste), and the energy is more required because of the use of automated processes and mechanization. On the contrary, regions with lower  $EMR_{pw}$  (Oriental and Central) are characterized by having economic activities oriented towards commerce and services.

In terms of the exosomatic metabolic rate of the household sector ( $EMR_{hh}=E_{Thh}/HA_{hh}$ ), which is the electricity consumed per unit of time in the household sector can be considered an indicator of the standard of living. Greater consumption of electrical energy and home appliances is related to greater comfort of resting time at home [3,20]. It can be noticed the regions that are in the country's north, and the Peninsular region have hot summers and there is a need to use air conditioning which increases electrical consumption

[32]. On the contrary, regions with lower values of EMRhh coincide with those that have the poorest overall access to energy services (Oriental and Central).

It should further be noted that the electric generation of self-supply modality is an area without information, but it has been found that they have evaded taxes and have perhaps even carried out illegal operations within the electricity market [35,36] It would be optimal to have this information in the future, since it mainly includes the electric consumption of large industries, so the level of lack of information is significant to achieve a more complete analysis.

As part of this research, an analysis of the evolution of the variables and indicators over time was attempted, which was impossible because, in the first place, the economic census does not present all the data of the same variables in consecutive censuses. INEGI does not allow access to all data under the argument that it is information that compromises national security, as in the energy and mining sectors. All the data was not available for the same municipalities in consecutive Economic Census. Therefore, this work has allowed finding weaknesses in national statistics, as was clear in the Economic and Population and Housing Census do not occur in the same years and do not have the same periodicity, which makes difficult the analysis of indicators and relations among variables. Similarly, the data on electricity consumption also does not allow a study of the temporal evolution since the electric rates were changed and even though there are equivalences, the trends after and before 2018 do not seem to represent reality.

However, an analysis is presented for the first time showing how electrical metabolism works in different regions and levels in Mexico. For the strategic planning of the country, it is key to count on information on where, for what, how, and what produces added value, as well as energy and labor costs, since to plan the economy of regions with imbalances, is necessary to plan where to use necessary resources to reduce disparities, since, as can be seen in the analysis, there is an imbalance on where the industry and services and commerce sectors are mainly located.

We know that the economy also obeys logistical market issues, but these types of logistical operations do not apply when there is an internal economic imbalance within a country, and if this economic imbalance is to be reduced [28] With where agriculture is located, it is more complex because it also has to do with the availability of resources, much of the electricity used is because seasonal agriculture cannot occur in those regions that depend more and more on the pumping water and this makes up a vicious circle, the greater the scarcity of water, the greater the amount of energy is required.

The decisions on which activities to use resources, or create new jobs have consequences in determining a country's future development. Therefore, not only will there be an impact in the regions regarding whether to carry out certain activities, but also in terms of economic activities, there may be an imbalance benefiting only certain sectors.

We must consider the diversification of the economy since a society cannot only live on services, since in the past this decision has had consequences, such as what happened in the 2008 crisis [37], where the United States benefited the service sector over the others, bringing with it an impact on the new Internet corporations. But this situation also brought unemployment, since frequently services generate fewer jobs compared to industry[38]. Societies require food, so we cannot lose focus on the fact that not all activities must be based on business, but we must consider them as activities that can bring well-being to the population. Therefore, having analyzes that allow us to identify the imbalances between regions and between sectors is essential to seek a balance in the well-being of a country.

This work is important since statistics are integrated for the first time and that previously were only analyzed separately. We believe that above all they will be useful for the Secretary of Energy, the Secretary of Economy, and the Energy Regulatory Commission since there had been no integration of statistics in the way we developed them in this investigation. Therefore, economic, energy, and social decisions are disintegrated, and, in the future, it will be increasingly important to decide in an integrated manner since the effect of one decision has repercussions on other areas and vice versa.



## Conclusion

This work presents for the first time a multilevel and multiregional analysis of the electrical metabolism across residential and economic sectors, and it was possible through the application of the MuSIASEM methodology and the organization of the data in a geospatial way that allowed synthesizing a large amount of data to identify the regions and sectors with the highest Economic energy intensity (EEI), Economic labor productivity (ELP), Exosomatic metabolic rate (EMR) and Added value per hour (AVhour) values. This analysis makes up a tool for diagnosing economic development by region of the country and adequate planning to achieve a greater regional balance of the residential and economic sectors.

This work has also made it possible to see the weaknesses of national statistics, both in the economic census and in integrating energy economic statistics. We propose new statistical agendas that are necessary and useful for decision-making and to provide greater well-being to regions with inequalities and therefore reduce the country's regional and sectoral imbalance.

This work answers the questions of why, for what, how, and where Mexico uses its electricity.

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## List of Acronyms and Abbreviations

**AV** Added value

**AVhour** Added value per hour

**AVi** Added value disaggregated by agriculture, industry, commerce, and services sectors

**BMXN** Billion of Mexican pesos

**CFE** Comisión Federal de Electricidad

**CONACYT** Consejo Nacional de Ciencia y Tecnología

**EEI** Economic energy intensity

**EEIi** Economic energy intensity disaggregated by agriculture, industry, commerce, and services sectors

**ELPpw** Economic labor productivity in paid sector

**ELPpwi** Economic labor productivity in paid sector disaggregated by agriculture, industry, commerce, and services sectors

**EMRsa** Exosomatic metabolic rate

**EMRpw** Exosomatic metabolic rate in paid sector

**EMRpwi** Exosomatic metabolic rate in paid sector disaggregated by agriculture, industry, commerce, and services sectors

**EMRhh** Exosomatic metabolic rate in the household sector

**ETpw** Electrical energy throughput in paid sector

**ETpwi** Electrical energy throughput in paid sector disaggregated by agriculture, industry, commerce, and services sectors

**ETHh** Electrical energy throughput in the household sector

**GDP** Gross domestic product

**GWh** Gigawatt hour is a unit of energy equivalent to 1e+9 Watt-hour

**HApw** Human activity allocated in paid sector

**HApwi** Human activity allocated in paid sector disaggregated by agriculture, industry, commerce, and services sectors

**HAhh** Human activity allocated in the household sector

**INEGI** Instituto Nacional de Estadística, Geografía e Informática

**KWh** Kilowatt hour is a unit of energy equivalent to 1,000 Watt-hour

**MWh** Megawatt hour is a unit of energy equivalent to 1e+6 Watt-hour

**Mh** Million hours

**MMXN** Millions of Mexican pesos

**MuSIASEM** Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

**PLANEAS** Plataforma Nacional Energía Ambiente y Sociedad

**TET** Total electrical energy throughput by country in one year

**THA** Total human activity in one year

**TMXN** Thousand of Mexican pesos