Energy 37 (2012) 122–132

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina☆

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A R T I C L E I N F O

Article history:
Received 21 January 2011
Received in revised form
1 July 2011
Accepted 5 July 2011
Available online 31 July 2011

JEL classification:
O11
O13
O54
Q01
Q57
Q58

Keywords:
Argentina
Energy intensity
Energy mix
Economic development
Societal metabolism
Integrated analysis

A B S T R A C T

The link between energy consumption and economic growth has been widely studied in the economic literature. Understanding this relationship is important from both an environmental and a socio-economic point of view, as energy consumption is crucial to economic activity and human environmental impact. This relevance is even higher for developing countries, since energy consumption per unit of output varies through the phases of development, increasing from an agricultural stage to an industrial one and then decreasing for certain service based economies.

In the Argentinean case, the relevance of energy consumption to economic development seems to be particularly important. While energy intensity seems to exhibit a U-Shaped curve from 1990 to 2003 decreasing slightly after that year, total energy consumption increases along the period of analysis. Why does this happen? How can we relate this result with the sustainability debate? All these questions are very important due to Argentinean hydrocarbons dependence and due to the recent reduction in oil and natural gas reserves, which can lead to a lack of security of supply.

In this paper we study Argentinean energy consumption pattern for the period 1990–2007, to discuss current and future energy and economic sustainability. To this purpose, we developed a conventional analysis, studying energy intensity, and a non conventional analysis, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting methodology. Both methodologies show that the development process followed by Argentina has not been good enough to assure sustainability in the long term. Instead of improving energy use, energy intensity has increased. The current composition of its energy mix, and the recent economic crisis in Argentina, as well as its development path, are some of the possible explanations.

1. Introduction

The link between energy consumption and economic growth, as well as the relevance of energy flows for economic development, has been widely studied in the economic literature from both theoretical and empirical standpoints [1–17]. Understanding this relationship is particularly important from both environmental and socio-economic viewpoints, as energy consumption is crucial to economic development and human environmental impact. This is even more important in developing countries, since energy consumption per unit of output varies through the phases of development, increasing from an agricultural stage to an industrial one and then decreasing for certain service based economies [18,19].

Furthermore, the relevance of the energy sector increases in a frame of instability of energy markets and energy supply as the one faced worldwide from 2007 on. As stated by the International Energy Agency (IEA) [20] as a result of the global financial crisis, both supply and demand sides of the energy sector were affected. One of the key variables of the impact of the financial crisis has been the lack of investment. The IEA clearly remarks how the effects of instability will have far-reaching and potentially grave effects on energy security, climate change and energy poverty. The problems are likely to appear in the medium and long term, as weaker fossil-energy prices, slower economic growth and fiscal

☆ An earlier version of the paper was presented at the 7th Biennial International Workshop Advances in Energy Studies: *Can we break the addiction to fossil energy?* held in Barcelona from 19 to 21 October 2010.

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0360-5442/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2011.07.011

austerity measures will cut down energy investment in clean energy projects and energy efficiency, with the corresponding impact on greenhouse gas emissions. Moreover, cutbacks in investment will delay access by poor households to electricity and modern energy, which will deepen the impact of poverty in different regions of the world. In developing countries, the impact of the instability of energy markets over the development process is even higher both from a material dimension as well as from a financial one. The volatility of energy markets and the increase in energy costs deeply influences the economic sustainability of those countries highly dependent on energy imports.

In the particular case of Argentina, energy supply problems appeared from mid 2004. Energy supply restrictions were common during the period 2004–2007 and reduced during 2008 and 2009, when the rate of growth of GDP was lower. However, during winter 2010, industries faced power shutdowns both as a result of a very cold winter and the return to the economic growth path which tightened supply. According to information of the Centro de Investigaciones de la Unión Industrial Argentina (CEU)[1] (Research Center of the Argentinean Industrial Union), industrial activity displayed an inter annual decrease of 2.3% in July 2010 as a result of the shortages in natural gas (NG) supply and the requirements of more expensive substitute fuels. This reflects one of the main characteristics of Argentina, its high dependence on hydrocarbons which accounted for 86 % of Total Primary Energy Supply (TPES) in 2009,[2] with NG accounting for 52%, while New Renewable Energy Sources (NRES) have not yet succeeded in the Argentinean energy market; despite it is a naturally well-endowed country [21].

In this context we have performed a study of the energy system in Argentina from a conventional and a societal metabolism perspective. The core characteristics of Argentina previously mentioned, such as its energy system composition and its political and economic instability, deserve a deep analysis of the energetic metabolism. Particularly, the evolution and current composition of energy supply are mainly due to a bad management of the energy resources, highly related to past energy policies. Since the early nineties, the liberalization and deregulation processes lead to an overexploitation of non renewable energy resources and to an abandonment of energy policy and planning [21,22]; more recently re-reforms have deepen the managing problems of energy sources [23]. Both aspects seem to have lead to a bad use of energy sources compromising the Argentinean energy, economic and environmental future, and claiming for a change of the energy model.

The main reason to perform a study from the metabolism perspective is that this kind of analysis allows to combine extensive variables and intensive variables with information coming from different fields (monetary, demographic, and biophysical), in order to discuss the evolution of society over time, its development constraints, as well as the allocation of scarce resources, such as natural resources or human time. Furthermore, the purpose of using such methodology is to complement the conventional perspective of the intensity of use of energy (very common in conventional energy economics) and to provide new insights to two different kinds of debates: the one on socio-economic development, and the one on environmental pressure of energy consumption. This frame also allows differentiating the material or energy use of different productive and non productive sectors of the system (i.e. scaling down), which leads to more complex and deep conclusions. In the Argentinean case, the recent evolution of the energy sector and energy policy, as well as the iteration of growth and de-growth periods, had social and economic impacts in different sectors, which definitely may require a deeper study of the energy use at the sector and sub-sector level.

The structure of the rest of the paper is the following: Section 2 studies the relationships between energy consumption and Gross Domestic Product (GDP) from a conventional point of view and briefly presents the structure of the energy system and the energy mix. Section 3 presents the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting methodology to analyze the relation, data and the main results at different hierarchical levels. Finally, Section 4 discusses the results and draws some conclusions from both a methodological and analytical point of view.

2. Conventional analysis: the role of energy intensity

2.1. Theoretical aspects

According to the hypothesis of *dematerialization*, there is a reduction in material and energy consumption along the economic growth path. For environmental economists this hypothesis supports the theory of the Environmental Kuznets Curve (EKC), which states the existence of an inverted-U-shaped relationship between economic growth and environmental degradation, implying that environmental degradation increases with economic activity up to a *turning point* after which income increases associate to higher environmental quality [24]. If this hypothesis were correct, the solution to natural resources depletion and environmental problems would be *growth and wait*.

To some extent, the EKC hypothesis is based in the concept of *intensity of use* [25], which means that the consumption of energy and materials can be mainly explained by income. In this sense, as previously stated, there is a positive relationship between economic growth and energy consumption and the latter increases at the same rate than the former up to a level, the turning point, after which economic growth and energy consumption will not be linked and further increases in output will not require increases in consumption.

The intensity of use concept, as well as the EKC, is supported by three main arguments: *scale* effects, *composition* effects and *technology* effects [26]. While the first effect implies an increase in energy and materials consumption (and environmental degradation) as a result of more economic activity, the other two effects imply a reduction. The composition effect refers to the change in the share of each economic activity out of the total activity, from agriculture (with low energy intensity in most countries, not in Argentina), to industrial activities (higher energy intensity), and finally back to a low energy intensive activity as services. On the other hand, the technology effect relates to higher levels of income to higher technology development, and this to lower energy use per unit of output. A fourth effect could be remarked though: changes in consumption patterns which imply an environmental quality demand in relation to development increases [27,28]. Therefore, as a joint result of these effects, developed economies should decrease their use of energy per unit of output and they should be dematerializing, while developing economies should be materializing or increasing their energy consumption.

However, there are different arguments which confront this theory. One of the most cited considerations is the one stated by Jevons [29], usually known as the Jevons' Paradox which suggest that economy-wide rebound effects are very important and that energy plays a key role in driving productivity improvements and economic growth. Therefore, instead of reducing energy consumption, technological progress will increase energy demand. See Herring [30] and Polimeni et al. [31] for a complete analysis of the topic.

[1] Information available at the web site of the Union Industrial Argentina: http://www.uia.org.ar/index.do.

[2] Information available at the web site of the Secretaría de Energía (Secretariat of Energy): http://energia3.mecon.gov.ar/contenidos.

In the frame of this analysis, conventional studies have focused in examining the evolution of energy intensity of different economies over time, defined as the ratio between Total Primary Energy Supply (TPES), as an indicator of national energy consumption, and Gross Domestic Product (GDP). In a similar way, some authors have carried out empirical studies of the EKC in its simplest way, using TPES and GDP as the only variables [31–33]. Other authors have developed more complex analyses in order to empirically validate the EKC hypothesis, including other variables in the estimation, as well as using different environmental pollutants to measure human pressure through energy and material use, reaching different and not concluding results [34–41]. However, these estimations and their results have been very criticized as they are highly dependent on the samples and econometric tools used to carry out the studies [42,43].

Nevertheless, if most of the previously stated arguments were correct, and in a frame of *income determinism* [44] a reduction in energy intensity should be expected in developed and developing economies and an increase should be observed in underdeveloped ones. Some authors insist that this has been the case of many developed economies, especially European countries, as a response to the second oil crisis at the end of the seventies, and as a result of an active energy policy particularly oriented to reduce energy dependency and consumption in the industry and household sectors [45,46]. On the other hand, some other authors defend that this outcome has been achieved by changes in the quality of the fuels used instead of a reduction in energy consumption per unit of GDP [47,48].

In continuation in the next section, we will study the evolution of energy intensity in Argentina and other Latin American countries in order to discuss energy intensity patterns in the region. As stated by Mendiluce et al. [52] different economy-wide energy efficiency indicators have been developed and applied for evaluating and explaining country comparisons in energy performance. Energy efficiency is measured with both physical-based indicators and monetary-based indicators. According to these authors, the most widely used monetary indicator is energy intensity (energy consumption per gross domestic product), which is considered to be a good measure of the energy efficiency of the economy. This is the reason why this indicator has been widely used in the energy literature in order to measure the results of improvements in energy efficiency in the end-use devices and structural changes in the economy [49–53].

However, as we consider that this conventional analysis of the intensity of use of energy does not take into account some non-linearities of the development process, we want to discuss the results of this methodology. Therefore, we present it with the aim of comparing the main results with a metabolism perspective, included in Section 3, which, as previously mentioned is considered to be more useful in this particular case.

2.2. Energy intensity in Argentina

In this section we explore the evolution of energy intensity in Latin America and the Caribbean and particularly in Argentina in the period 1970–2008. For energy data we used information from OLADE/SIEE,[3] and for monetary data we used statistics from United Nations Statistics Division.[4]

2.2.1. Evolution over time and international comparison

Fig. 1 shows the evolution of energy intensity for Latin America and the Caribbean and for five Latin American countries. Final energy intensity of total energy sources is calculated according to information from OLADE. Energy intensity of final energy consumption may be lower, as it happens in this case, than energy intensity of Total Primary Energy Supply, because of energy conversion processes or losses occurring in the energy sector [53–55]. For this reason, some level differences can be found between Fig. 1 and the rest of the figures for the Argentinean case. However, this figure has been included only with comparison purposes as it presents energy intensity of final consumption for a group of some Latin American and Caribbean countries.

The first thing to point out is the increase in energy intensity experienced in Latin America between 1979 and 1989 (black solid line). This increase can be partially explained as an accounting artifact during the regional financial crisis at the beginning of the 1980s, often known as the *lost decade*. This financial crisis was the result of a high level of sovereign debt induced by both internal and external factors, to the extent that foreign liabilities exceeded earning power, and the countries involved were not able to face their obligations, which translated in devaluations against the dollar. The deterioration in the terms of trade resulted in recessions, reduction in imports, unemployment, inflation and a reduction in the purchasing power mainly for the middle classes. Brazil performed differently as energy intensity decreased up to 1979 and then it increased slightly. The case of Brazil can also be seen as the result of an accounting artifact. While energy consumption maintained its positive trend with a slight stagnation in 1978–1986, GDP in dollar terms fell, but the reduction was not as important as in the other cases. Brazil experienced two devaluations in that period (December 1979 and February 1983). Therefore, the slight increase in energy intensity in Brazil may have been due to a strong currency during the financial crises rather than to a successful reduction in energy consumption.

Average primary energy consumption per unit of GDP in Argentina fluctuated around 6.79 MJ per $US dollar during the period of analysis, except between 1980 and 1990. Argentina has not become more efficient in energy terms; energy intensity in 2007 presented the same value than in 1979. Furthermore, as in many other Latin American countries, energy intensity increased in Argentina during the eighties. The main reason for this increase was the contraction of economic activity, although the bulk of the change was due to the devaluation of local currency against the US dollar. In 1980 the GDP (in U$S) decreased 27% in relation to 1979, while GDP in national currency at 1990 prices reduced only 5%. This implied a 41% growth of energy intensity, a level that was maintained until 1990 when it decreased 24% in relation to 1989. Once again, this can be seen as an accounting artifact.

These problems of the Argentinean economy (rise in fiscal imbalances and expanded domestic debt) exploded as hyperinflation in 1989, when consumer prices rose 4923.6 per cent per year. The National Government responded with contractive economic policies, such as a privatization of most of state companies and public services, defense of competition, and changes in the tax system. However, one of the most important economic decisions was the Convertibility Law of March 1991, which established the convertibility of the Austral with the U.S. dollar at 10.000:1 [56]. Therefore, the increase in GDP in $US dollars in 1989–1990 can be attributed to the convertibility adopted instead of to a real increase in economic output.

After that period, energy intensity fluctuated while final energy consumption showed a positive rate of growth except for the period 1999–2001 and for 2004. Once more, this situation cannot be explained by a more efficient energy consumption pattern, but

[3] The Latin American Energy Organization (OLADE) is a public governmental organization working for energy development in Latin America and the Caribbean. The Energy-Economic Information System (SIEE) of OLADE has Energy-Economic Information (electricity and hydrocarbons), with historic series from 1970 to today, this information is available at: www.olade.org/siee.

[4] Available at: http://unstats.un.org/unsd/default.htm.

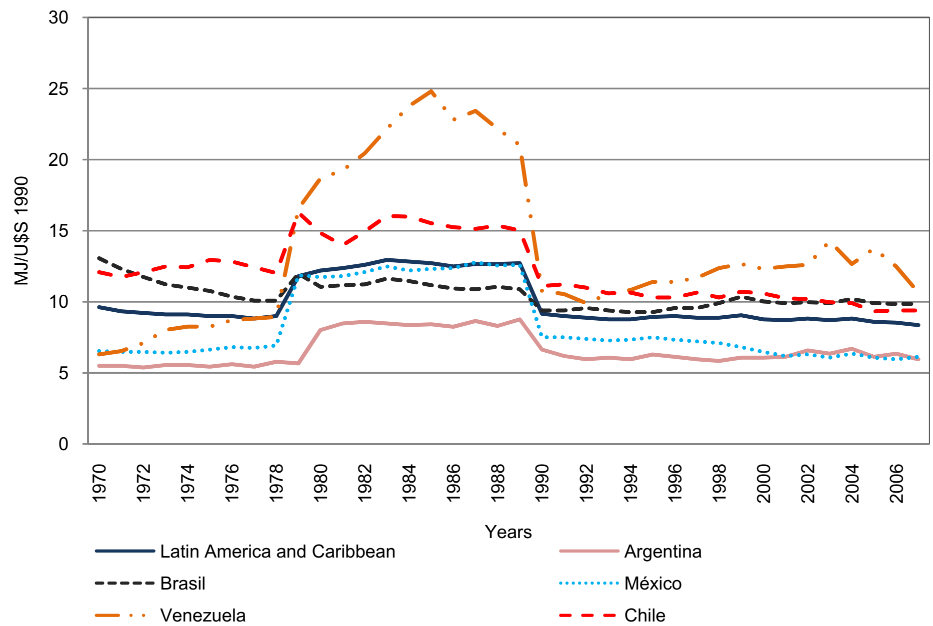

Fig. 1. Energy intensity of final energy consumption of Latin America and Caribbean region and countries. 1970–2007. Source: Own elaboration based on OLADE/SIEE (Latin American Energy Organization /Energy Environmental Information System).

rather by the joint effect of changes in the monetary policy and the effect of economic growth.

In 2002, in a context of a new socio-economic crisis, the Government abandoned the fixed exchange rate regime. The consequences of this policy were very different for both social and economic development. On the one hand inflation, inequality in functional income distribution and poverty all increased, and therefore energy consumption decreased [56–60]. From 2004 onwards, economic growth speeded up to *Chinese growth rates*. However, energy consumption fluctuated up and down as a result of supply restrictions due to national energy crises which translated in power shutdowns. This situation is mainly explained by tight supply due to economic growth and lack of investment in energy infrastructures in the previous period [61,62].

As a final comment to Fig. 1 we would like to stress the differences shown by high energy intensity countries such as Chile (probably due to its large mining sector) and low energy intensity countries such as Argentina, despite their huge energy reserves and exports.

2.2.2. An evolutionary perspective

In order to study the continuity of the energy intensity trend we use a phase diagram for the recent history of the country. The phase diagram methodology represents energy intensity of the year t and that of the year $t-1$, making it possible to check the continuity of a particular trend, or the existence of alternate phases of increased and decreased energy intensity around certain *attractor points*. The latter hypothesis corresponds to the theory of punctuated equilibrium [63,64] as applied to Spain by Ramos-Martin [65].

The phase diagram in Fig. 2 shows that in the period 1970–2007 the Argentinean economy had two attractor points. The flip in the attractor point during the eighties was due to the economic and financial crises and the following reduction in GDP measured in US dollars. However, after the reorganization of the economy during the nineties, near the end of the period under analysis, primary energy intensity is higher than at the beginning, as we could already see at Fig. 1. Therefore as previously mentioned, Argentina did not improve its energy efficiency.

Finally, Fig. 3[5] shows the joint evolution of energy intensity and TPES. We found that, in spite of the reduction in energy intensity in some periods of the series, total energy consumption displays a positive trend.

To this respect, we did not find data support for dematerialization in Argentina in the period under study. Instead, the Argentinean economy seems to be materializing. A decrease in energy intensity, energy consumption per unit of output, did not imply a decrease in total energy consumption. From an environmental standpoint the evolution of total energy consumption or throughput constitutes a key point, as the impact is due to the environmental pressure of primary energy consumption.

2.3. Changes in the primary energy mix

At the beginning of the nineties the Argentinean energy system shifted from public planning toward a market oriented configuration [46]. The system was deregulated and most of public companies were privatized between 1989 and 1992. Energy chains were structured in a way that horizontal and vertical integration was formally forbidden and natural gas and electricity transport, transmission and distribution were structured as regional regulated monopolies [21,22].

Argentina is highly dependent on hydrocarbons, mainly Natural Gas (NG) and Crude Oil. In 2007 hydrocarbons represented 90% of Total Primary Energy Supply (TPES), with natural gas accounting for

[5] For energy intensity analysis we used both data from OLADE and own estimations based in information from United Nations Database and national sources according to their availability. For comparative analysis between Latin America countries, as well as the 1970–2007 study of Argentinean energy intensity, we used data from OLADE. For the rest of the paper we used own estimations based on UN. The results may seem different, mainly for two reasons. In the first place, GDP from OLADE is higher to that reported by United Nations, which we used throughout the paper. In the second place, energy intensity in OLADE database is calculated as the ratio between final consumption and GDP while we used TPES and GDP. However, as the purpose of this analysis is to study energy intensity trends, which are almost the same for both estimations, level differences are not relevant for the conclusions.

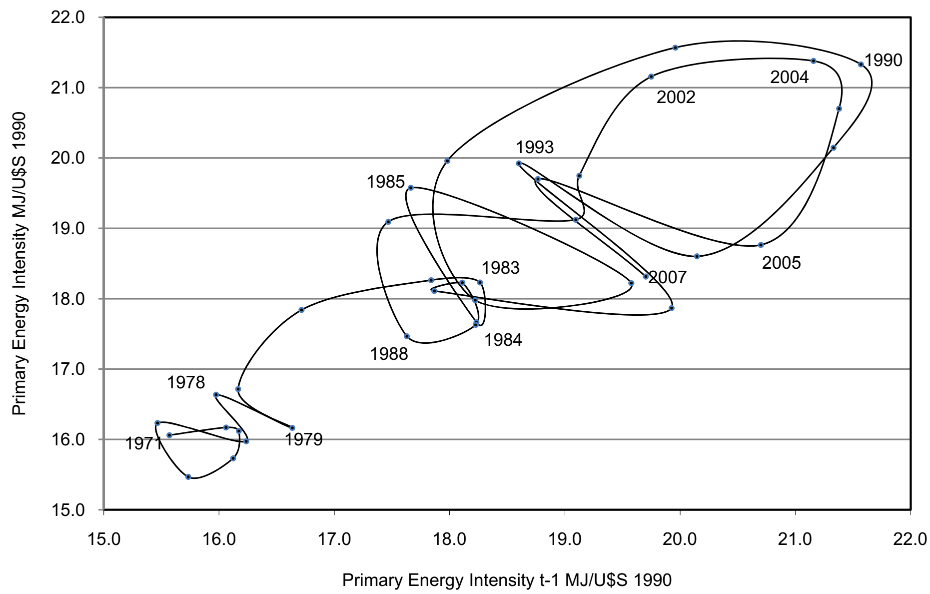

Fig. 2. Phase diagram for Argentina. 1970–2007.

52%. Fig. 4 shows natural gas increasing the share since mid seventies. The evolution of the energy mix, due to the differences in energy quality, is an important determinant of energy intensity and energy consumption evolution. As we have previously mentioned, one of the most important critics to the dematerialization hypothesis emphasizes the relevance that fuel substitution had in developed countries in order to reduce energy intensity [18,19]. The energy mix is important in our case because we have analyzed primary energy intensity instead of using final energy. We have done so because it is primary energy sources that ultimately have an impact upon the environment.

The share of natural gas increased significantly after the discovery of the field Loma la Lata at Cuenca Neuquina (one of the most important NG basins of the country) in 1977 [66]. The role of natural gas increased as a result of the energy policy the purpose of which was security of supply. Moreover, as can be seen in Fig. 4, the share of renewable energy sources is nearly zero, basically due to the lack of an active renewable energy policy [21,22,62]. Finally, the high relevance of natural gas in the Argentinean energy system is mainly due to electricity generation, as the share of thermal installed capacity increased significantly in recent years (see Table 1). In 2008 57.4% of the installed generation power corresponded to thermal technologies, with the majority of thermal power plants using any fuel but NG [21,22].

3. Multi-scale integrated analysis of societal and ecosystem metabolism

3.1. Methodology

The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism developed by Giampietro and Mayumi [67,68] and

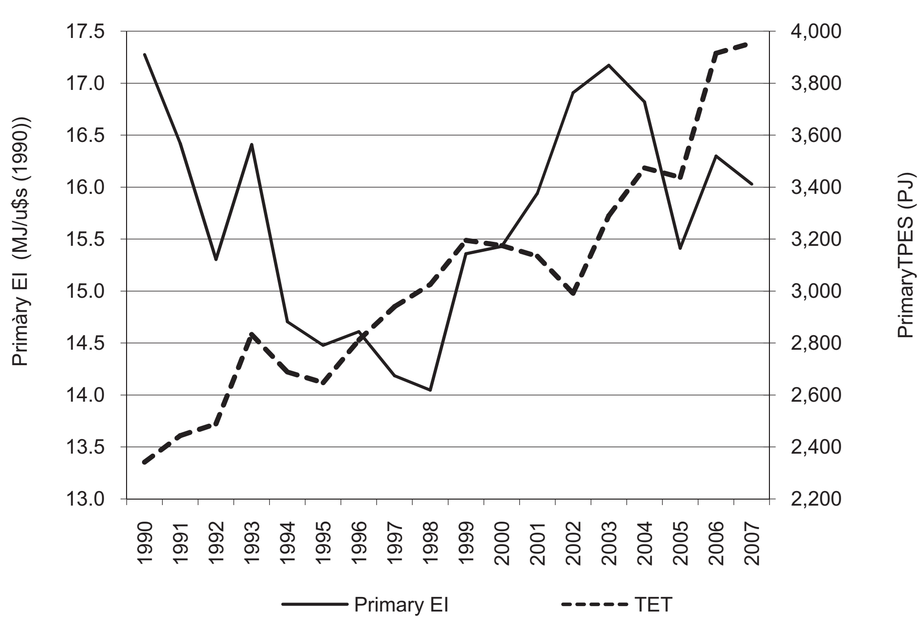

Fig. 3. Evolution of energy intensity and total primary energy supply in Argentina. 1990–2007.

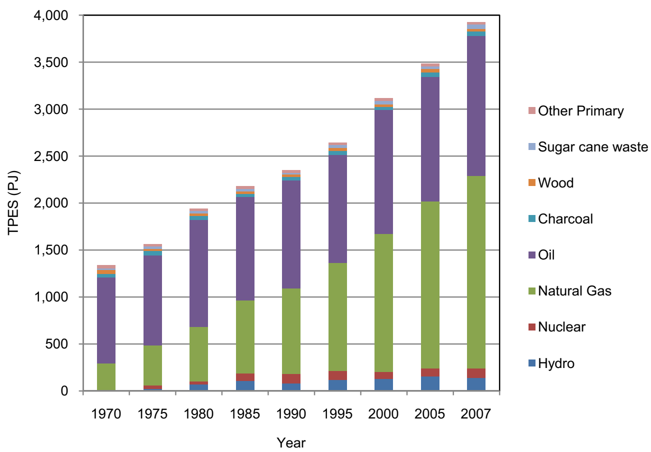

Fig. 4. Evolution of TPES in Argentina 1970–2007. Source: Own elaboration based on Secretaría de la Energía de la Nación.

Giampietro [69] integrates different fields of study with the purpose of a wide analysis of the social, economic and ecological system. This method has been applied to study the energy metabolism of different countries and regions such as Spain, Catalonia, Ecuador, Vietnam and China [65,70–76]. The *metabolism of human societies* is a notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence [73]. In some way this methodology is an application of Georgescu-Roegen's [77] flow-fund model, which is also a representation of an economic–social–biophysical system.[6]

The division of the human time allocation between the dissipative side of the society and the hypercycle (following Ulanowicz [78]) is achieved through the division of the activities between the fraction generating value added, called here Paid Work (PW) and the fraction responsible for consumption and non-paid work, called here Household sector (HH).

MuSIASEM works at different hierarchical levels. We use here three hierarchical levels of study: the national (level n); the division between productive and consumption activities (PW and HH) (level $n-1$); and the disaggregation of the PW sector, which includes the Productive Sector (PS), including energy, building and manufacturing; Service and Government (SG); and Primary Sector (AG), including agriculture, husbandry, forests and hunting.

3.2. Description of variables

Variables can be divided into two main groups: extensive variables, which can be summed up and characterize the size of the system; and intensive variables (indicators or benchmark values) which characterize changes in the system. Within the extensive variables we find:

GDP: Gross Domestic Product
THA: Total Human Activity: Total human time a society has available for conducting different activities (endosomatic and exosomatic consumption), measured in hours (h). (Population times 8760 h)
HA_{PW}: Human Activity paid work: Human time in the productive sector in one year, measured in hours (h).
HA_{HH}: Human Activity households: Human time in the household sector in one year, measured in hours (h).

[6] For a complete description of the fundaments of the MuSIASEM see [69,72,73,77].

Table 1
Composition of the Installed generation power. 1992–2008.

Year	Thermal		Hydro		Nuclear		Total
	MW	%	MW	%	MW	%	MW
1992	6541	49.30	5721	43.12	1005	7.57	13,267
1993	6601	47.18	6384	45.63	1005	7.18	13,990
1994	7132	46.17	7309	47.32	1005	6.50	15,446
1995	7698	47.13	7629	46.71	1005	6.15	16,332
1996	7874	46.02	8230	48.10	1005	5.87	17,109
1997	8449	46.41	8748	48.06	1005	5.52	18,202
1998	9226	48.81	8668	45.86	1005	5.31	18,899
1999	9582	49.11	8925	45.74	1005	5.15	19,512
2000	10,789	52.07	8925	43.07	1005	4.85	20,719
2001	12,414	55.55	8925	39.94	1005	4.50	22,344
2002	12,812	56.09	9021	39.50	1005	4.40	22,838
2003	12,953	56.37	9021	39.26	1005	4.37	22,979
2004	12,927	56.13	9100	39.51	1005	4.36	23,032
2005	12,882	55.28	9415	40.40	1005	4.31	23,302
2006	13,094	54.48	9934	41.33	1005	4.18	24,033
2007	13,245	54.27	10,156	41.61	1005	4.11	24,406
2008	15,065	57.44	10,156	38.72	1005	3.83	26,226

Source: Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima (CAMMESA) (Information available at: www.cammesa.com.) (Administration Company of the Wholesale Electricity Market).

$$HA_{PW} = \sum HA_i$$

$$HA_i = W{*}PO_i{*}HsS_i$$

where HA_i: total human activity for the activity i; W: working weeks per year; PO_i: population in the activity i; HsS_i: weekly hours of work in the activity i.

$$THA = HA_{PW} + HA_{HH}$$

TET: Total Exosomatic Throughput: Total primary energy dissipated in a socio-economic system for supporting consumption and production activities in one year, measured in Joules (J).
ET_{PW}: Exosomatic Throughput paid work: Total primary energy used in the paid-work sector in one year.
ET_{HH}: Exosomatic Throughput households: Total primary energy used in the household sector in one year.

$$TET = ET_{PW} + ET_{HH}$$

Within indicators or intensive variables we have:

$EMR_{SA} = TET/THA$: Average Exosomatic Metabolic Rate: Energy consumption per hour of human time available to the society.
$EMR_{PW} = ET_{PW}/HA_{PW}$: Paid Work Exosomatic Metabolic Rate: Energy consumption in the paid-work sector per working hour available.
$EMR_{HH} = ET_{HH}/HA_{HH}$: Household Exosomatic Metabolic Rate: Energy consumption in the household sector per household hour available.
$ELP_i = GDP_i/HA_i$: Economic Labor Productivity: Added value per hour of working time in sector i.
$ELP_i/EMR_i = GDP_i/ET_i$: Energy Efficiency of Production: Added value generated per unit of energy consumption in sector i, measured in U.S. dollars/Joules.

3.3. Data used in the analysis

The main data sources have been national statistics when available, international sources otherwise. As in the energy intensity analysis, energy data has been obtained from the Energy Balances of the Secretaría de Energía de la Nación 1990–2007.[7] For the demographic data we used national statistics from the Instituto Nacional de Estadísticas y Censos (INDEC)[8] and International Labor Organization (ILO) – LABORSTA.[9] Regarding monetary data we used statistics from United Nations Statistics Division.[10]

For level *n*, we calculate primary energy consumption, excluding non-energy use, which can be defined as:

$$PEC = TFC_{PS} + ESOU_{PS} + L$$

where PEC: primary energy consumption; TFP_{PS}: total final consumption primary sources; $ESOU_{PS}$: energy sector own use; *L*: loses.

For level $n-1$ we use Total Final Consumption plus the energy sector, non-energy use. For level $n-2$ we allocated energy sector consumption and transformation loses to each of the final consumption sectors according to their share in final energy consumption.

Following Ramos-Martin [65] and Ramos-Martin et al. [73] ET_{HH} has been computed as residential energy consumption plus 25% of transport energy consumption; the remaining 75% of transport energy consumption has been allocated to services and government sector. The reason for this distribution is that we assumed that 50% of mobility is for transporting goods; 50% of the remaining half corresponds to compulsory mobility (i.e. commuting) and the other 50% corresponds to voluntary mobility which we incorporate to household energy consumption. In the same line, the Gross Value Added (GVA) generated in the transport sector has been allocated to SG.

For monetary information at the level $n-2$ we used Gross Value Added (GVA) by economic activity at constant (1990) prices in US dollars from *United Nations Statistics Division*; *National Accounts Estimates of Main Aggregates*.[11]

THT and HA_i were based on estimations and projections of population and active population evolution from INDEC. To compute the occupation rate by industry we extrapolated INDEC data for the census (Censo Nacional de Población y Vivienda 1991 y 2001). In order to complete the information we used data from *ILO-LABORSTA* and *CEPAL-CEPALSTAT*. We assumed a total of 48 weeks of working time in a year. We combined this information with the average working hours per week by economic sector from *ILO-LABORSTA*. The average working hours per week during the period of analysis has been 48.5, 43.27 and 38 for the AG, PS and SG, respectively.

3.4. Results

The main data and results can be seen in Table 2.

3.4.1. Level n: Argentina

The first result we found is a high correlation between energy consumption and GDP during 1990–2007, which can be seen in Fig. 5. During the period of analysis, energy consumption and GDP had a similar evolution as well as similar cyclical changes. Both variables almost doubled their values in the period under analysis. However, the rate of growth for TET was higher than for GDP, except in 1996/1997, 2003/2004 and 2007, with the consequent impact over energy intensity and EMR_{SA}. This increase in the level of energy consumption per hour of activity was directed to both increasing the level of capitalization at work and at home as we will see later.

The second result is that energy intensity (Fig. 3) has an N shape. There are three turning points for energy intensity. The first turning point is in 1999. Energy intensity remains growing even when energy consumption decreases, mainly attributable to the Argentinean economic crisis. Between 1999 and 2002 GDP decreased more than energy consumption, which can be due to energy indivisibility, for this reason energy intensity displays a growing trend. The second turning point can be found in 2003 where the rate of growth of energy consumption increased, and exceeded the rate of growth of GDP.

Thirdly, population growth was constant during the period, and was followed by energy consumption as shown in Fig. 6. That is, increases in energy consumption had been devoted, partially, to cover population growth with a minimum of energy consumption.

The average exosomatic metabolic rate of the society (EMR_{SA}) exhibits a positive trend, which oscillates between 8.20 and 11.47 MJ/h. From this information, energy consumption per hour in Argentina is larger than two of its neighbors. According to Eisenmenger et al. [72] in 2000 Brazilian and Chilean EMR_{SA} was 5.21 MJ/h and 7.60 MJ/h respectively, while it was 9.25 MJ/h in Argentina, and 11.21 MJ/h in Venezuela. However, these disparities can be found all around the world, as world average rate is 7.8 MJ/h, while OECD is 22.3 MJ/h and, in 1999, the Chinese EMR_{SA} was 4.1 MJ/h [79]. The differences can be mainly explained through the study of the components of the exosomatic metabolic rate at lower hierarchical levels. On the one hand, energy consumption is very unequal between developing and developed regions, because of the productive sector and cultural factors. On the other hand, the evolution of population forces different evolution of the EMR_{SA}, which can be clearly seen in the Chinese example. In that country, even when EMR_{SA} doubled from 1980 to 1999, the exosomatic energy consumption per hour was low, comparatively to other countries, emphasizing the role of demographic fund variables and their reproduction.

3.4.2. Level n − 1: production and consumption

As previously mentioned, total energy consumption has a smooth positive trend, which can be explained by the behavior of the two compartments in which the economy can be split, the production side (PW) and the consumption side (HH). Both ET_{PW} and ET_{HH} increased steadily, almost doubling in the period. At the same time population growth was directed only to the non-working fraction (HA_{HH}), whereas working population (HA_{PW}) decreased almost 50% in the period (see Table 2). This combination of increasing ET_{PW} and reduction of HA_{PW} resulted in an increase in the level of capitalization at work, as we will see.

This is actually what we see when looking at the intensive variable EMR, measuring exosomatic energy consumption per hour of activity. At level *n*, EMR_{SA} increased 39% between 1990 and 2007. In the same period, the increase in EMR_{HH} was about 44%, while EMR_{PW} increased 128%. Fig. 7 shows the growth of EMR_{SA}, EMR_{PW} and EMR_{HH}. It can be seen that EMR_{PW} has grown much faster than EMR_{HH}. This result is not as good as it may appear at first sight. The increase in the level of capitalization of workers can be explained not only by the increase in ET_{PW} that we showed before, but particularly by the dramatic reduction in HA_{PW}, that is, in working population in economic sectors, with a sharp decrease after 1996.

[7] Available at: energia.mecon.gov.ar.

[8] Economically active population by industry and by occupation (rate). Available at: http://www.indec.gov.ar/.

[9] Statistics of working hours – Hours of work, by economic activity (Per week). Available at: http://laborsta.ilo.org/.

[10] Data from National Accounts Main Aggregates Database, Series of Gross Value Added by Kind of Economic Activity at constant (1990) prices – US dollars, available at: http://unstats.un.org/unsd/default.htm.

[11] It is important to point out that there may be a methodological mistake as we computed GVA instead of GDP. However, this is the only available information at sectorial level in US dollars at constant prices.

Table 2
Main data and results.

Variable	Level n							Level $n-1$						
	GDP (MMU$S1990)	THA (Gh)	TET (PJ)	EI Prim (MJ/U$S)	EC pc (GJ/hab)	GDP pc (U$S/hab)	EMR_{SA} (MJ/h)	HA_{PW} (Ghs)	HA_{HH} (Ghs)	ET_{PW} (PJ)	ET_{HH} (PJ)	EMR_{PW} (MJ/h)	EMR_{HH} (MJ/h)	ELP_{PW} (U$S/h)
1990	135,555	285,408	2342	21.33	71.87	4161	8.20	31,511	253,897	1025	468	32.53	1.84	4.30
1991	148,823	289,330	2444	20.14	73.98	4506	8.45	31,146	258,184	1035	492	33.24	1.91	4.78
1992	162,626	293,241	2489	18.60	74.35	4858	8.49	31,164	262,077	1057	495	33.93	1.89	5.22
1993	172,627	297,117	2833	19.93	83.52	5090	9.53	30,582	266,535	1256	638	41.08	2.39	5.64
1994	182,821	300,933	2688	17.87	78.26	5322	8.93	31,003	269,929	1198	571	38.65	2.12	5.90
1995	182,857	304,665	2647	18.11	76.12	5258	8.69	30,389	274,276	1217	581	40.06	2.12	6.02
1996	192,463	308,313	2812	18.23	79.89	5468	9.12	24,138	284,175	1261	597	52.23	2.10	7.97
1997	207,256	311,894	2940	17.63	82.57	5821	9.43	23,716	288,178	1320	595	55.65	2.06	8.74
1998	215,373	315,407	3025	17.47	84.02	5982	9.59	24,371	291,037	1345	614	55.20	2.11	8.84
1999	208,019	318,852	3195	19.09	87.78	5715	10.02	24,223	294,629	1341	669	55.35	2.27	8.59
2000	205,755	322,227	3175	19.12	86.31	5594	9.85	23,871	298,356	1294	677	54.20	2.27	8.62
2001	196,617	325,488	3134	19.75	84.35	5292	9.63	22,653	302,835	1231	645	54.33	2.13	8.68
2002	176,934	328,637	2991	21.16	79.74	4716	9.10	21,656	306,981	1206	611	55.69	1.99	8.17
2003	191,605	331,739	3290	21.38	86.88	5060	9.92	22,084	309,655	1305	660	59.08	2.13	8.68
2004	206,514	334,860	3473	20.70	90.87	5402	10.37	20,647	314,214	1496	695	72.47	2.21	10.00
2005	223,060	338,067	3438	18.76	89.08	5780	10.17	23,316	314,752	1498	703	64.26	2.23	9.57
2006	240,199	341,383	3915	19.70	100.45	6164	11.47	23,316	318,067	1931	835	82.83	2.62	10.30
2007	246,684	344,762	3954	18.31	100.47	6268	11.47	23,316	321,446	1934	877	82.96	2.73	10.58

Variable	Level $n-2$														
	HA_{AG} (Ghs)	HA_{PS} (Ghs)	HA_{SG} (Ghs)	ET_{AG} (PJ)	ET_{PS} (PJ)	ET_{SG} (PJ)	EMR_{AG} (MJ/h)	EMR_{PS} (MJ/h)	EMR_{SG} (MJ/h)	ELP_{AG} (U$S/h)	ELP_{PS} (U$S/h)	ELP_{SG} (U$S/h)	ELP/EMR_{AG} (U$S/MJ)	ELP/EMR_{PS} (U$S/MJ)	ELP/EMR_{SG} (U$S/MJ)
1990	3453	13,298	14,761	83	409	533	24.06	30.79	36.09	3.33	3.83	4.96	0.14	0.12	0.14
1991	3312	13,145	14,689	92	406	538	27.70	30.88	36.60	3.61	4.29	5.48	0.13	0.14	0.15
1992	3570	13,145	14,448	99	413	546	27.60	31.40	37.80	3.32	4.77	6.10	0.12	0.15	0.16
1993	3057	12,993	14,533	124	467	665	40.47	35.95	45.79	4.00	5.15	6.43	0.10	0.14	0.14
1994	2989	13,145	14,869	128	462	609	42.87	35.12	40.93	4.39	5.38	6.66	0.10	0.15	0.16
1995	3016	12,504	14,869	135	468	614	44.75	37.42	41.32	4.60	5.78	6.50	0.10	0.15	0.16
1996	2774	6901	14,463	144	481	635	52.03	69.74	43.91	4.94	11.15	7.04	0.09	0.16	0.16
1997	2774	6962	13,980	140	531	649	50.56	76.20	46.43	4.96	12.09	7.82	0.10	0.16	0.17
1998	2774	7000	14,596	134	523	688	48.48	74.69	47.13	5.40	12.38	7.79	0.11	0.17	0.17
1999	2774	6870	14,578	139	492	710	50.04	71.60	48.71	5.53	11.78	7.66	0.11	0.16	0.16
2000	2774	6695	14,402	133	490	670	48.07	73.24	46.54	5.43	11.75	7.78	0.11	0.16	0.17
2001	2018	4727	15,908	126	485	620	62.23	102.64	38.97	7.55	15.62	6.76	0.12	0.15	0.17
2002	2018	4430	15,209	126	471	609	62.28	106.40	40.05	7.38	14.62	6.40	0.12	0.14	0.16
2003	2018	4468	15,597	152	527	626	75.38	117.94	40.11	7.88	16.73	6.47	0.10	0.14	0.16
2004	2018	4545	14,083	244	559	693	121.04	122.93	49.22	7.76	18.47	7.59	0.06	0.15	0.15
2005	2018	4694	16,604	241	566	691	119.68	120.62	41.59	8.63	19.38	6.91	0.07	0.16	0.17
2006	2018	4694	16,604	196	930	806	97.12	198.03	48.53	8.85	21.20	7.40	0.09	0.11	0.15
2007	2018	4694	16,604	179	989	767	88.56	210.64	46.19	9.72	22.73	7.98	0.11	0.11	0.17

Source: Own elaboration.

This fact may imply that the increase in EMR_{PW} may not be fully translated in an increase in the productivity of labor if knowledge goes abroad with the loss of working hours. Actually, the decrease of HA_{PW} was due to emigration because of economic reasons, and ELP_{PW} grew, but not as much as EMR_{PW} did.

Finally, contrary to what happened to its neighbors [72], economic labor productivity grew between 1990 and 2007, particularly in 1991/1992, 1996/1997 and 2003/2004. The growth, however, was much lower than that of EMR_{PW}, showing that part of the increase in capitalization of workers could not be exploited because of the loss of skills implied by the decrease in working population.

3.4.3. *Level $n-2$: evolution of the productive sector*

In order to understand the previous results we need to break down the productive sectors into the three compartments, agriculture, forestry and husbandry (AG), industry, energy and mining (PS) and services and government (SG).

The first result to highlight is that the dramatic decrease in HA_{PW} that we saw before was not evenly distributed. While working time in services and government increased over the period of time, it decreased 50% in the primary sector and more than 66% in the secondary sector. So, the drainage of workers hit particularly industry and agriculture. Therefore, it is reflecting not only a mechanization process in agriculture, but may also indicate a structural change toward a service economy, as well as an industrial decline.

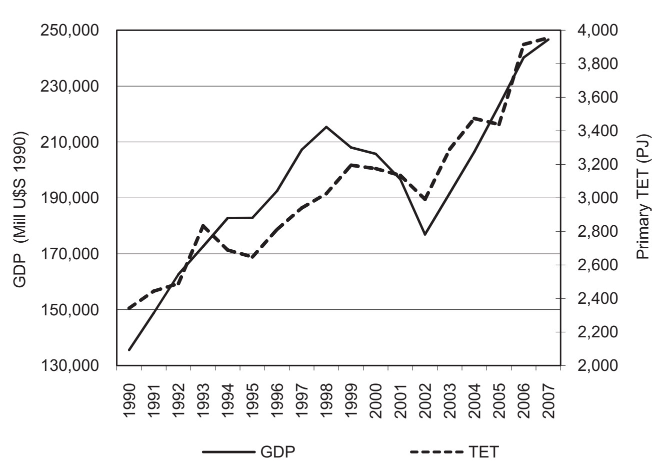

Fig. 5. TET and GDP evolution. 1990–2007.

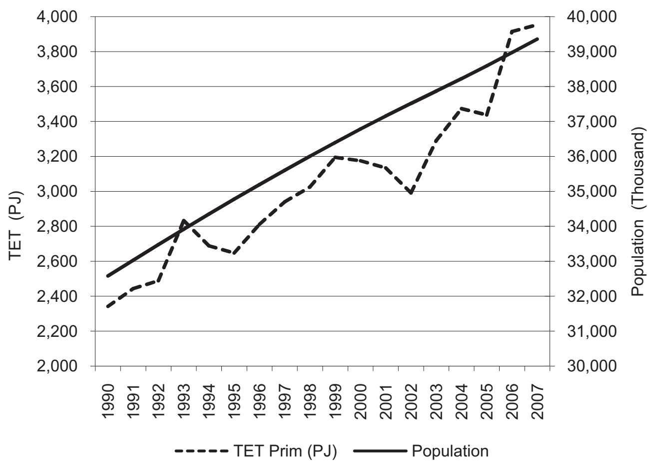

Fig. 6. Population and TET evolution. 1990–2007.

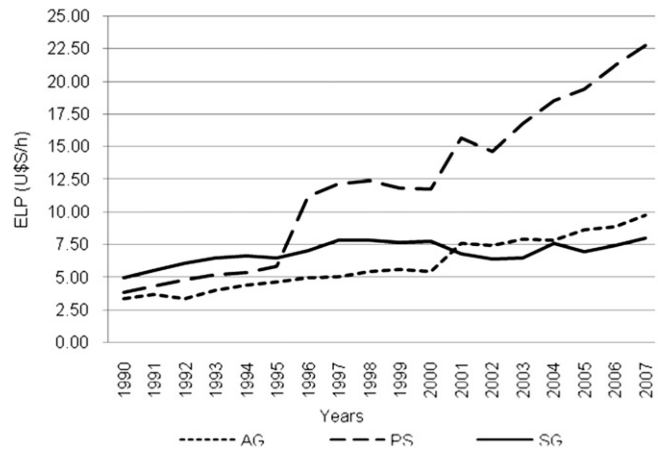

Fig. 9. ELP_{AG}, ELP_{PS}, and ELP_{SG} evolution. 1990–2007.

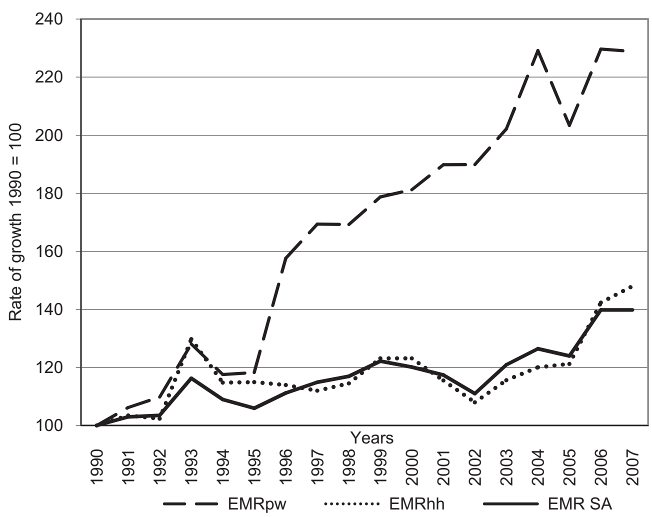

Fig. 7. EMR_{SA} EMR_{PW} and EMR_{HH} growth. 1990–2007.

At the same time ET_{AG} and ET_{PS} doubled in the period, but ET_{SG} only increased 50%. The combination of the evolution of the two variables is what we get in Fig. 8, with the rates of exosomatic metabolism of the three sectors. The capitalization of the services sector increased a bit, reflecting the fact that energy consumption in the sector increased faster than working population. However, the real change happened in EMR_{AG} (growing 300% in the period) and EMR_{PS} (growing 600% in the period), where the increase in energy consumption occurred while working population was decreasing dramatically.

The evolution of EMRs translated into different behaviors of the productivity of labor (Fig. 9). While ELP doubled in the case of services (despite the increase in working population), it grew 200% in agriculture and 450% in the secondary sector (because of the drainage of working population). It is also noticeable that productivity of labor has become higher than in the tertiary sector since 2001.

The results presented in the previous two figures need to be complemented by Fig. 10, where the energy efficiency of the three sectors is presented. This figure shows the ratio between ELP and EMR, which is the amount of US dollars of value added generated by consuming a MJ of energy in a particular sector. Here the results are striking. Despite the dramatic increases in energy consumption, and in energy per hour of work, this did not translate in a better use of energy over the period, and actually only the services and government sector was able to increase the generation of value added per unit of energy. This result is particularly alarming in the

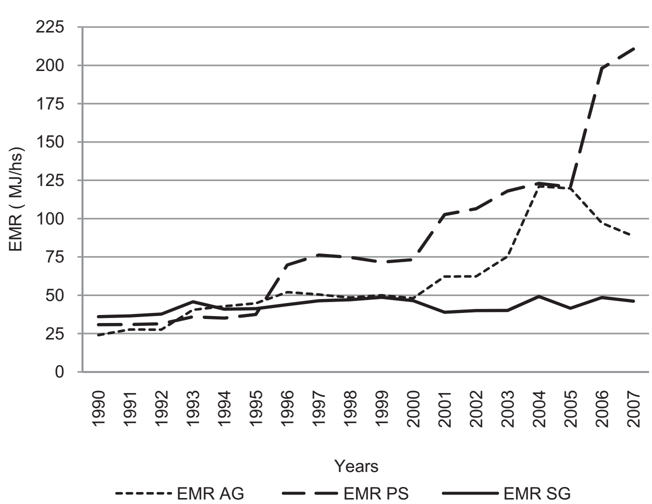

Fig. 8. EMR_{AG}, EMR_{PS}, and EMR_{SG} evolution. 1990–2007.

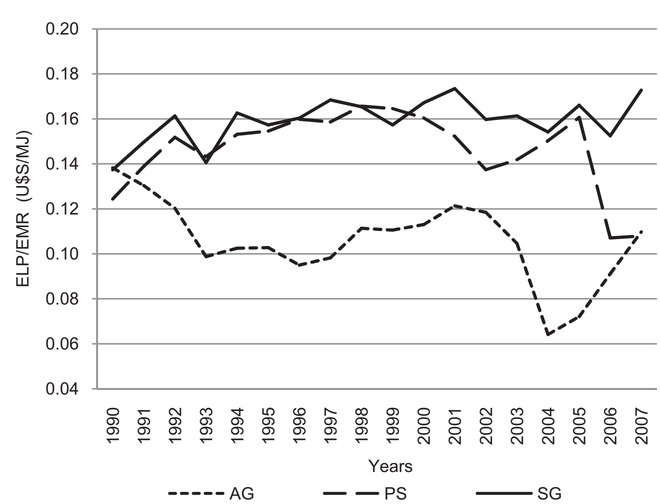

Fig. 10. ELP/EMR_{AG}, ELP/EMR_{PS}, and ELP/EMR_{SG} evolution. 1990–2007.

new context of expensive energy that the world is experiencing since the summer of 2008, and since the fossil-fuel reserves of Argentina are decreasing rapidly. The consequence to becoming more *inefficient* in the use of energy may be that Argentina will need to allocate more working hours to production, at the expenses of either leisure, dependent population, or both.

4. Concluding remarks

When analyzing the energy use or energy metabolism of societies, the use of integrated methodologies such as MuSIASEM complements the economic conventional view of focusing on energy intensity only. Expanding the vector of variables used allows us to study different dimensions of the reality such as economic productivity and competitiveness, quality of life and equality, and environmental impact of natural resources consumption, all of them at different hierarchical levels. As stated by Gowdy et al. [79] the relationship between human activity, energy use and economic production derived from this approach helps with comparing different economic systems and their different historical development.

In the Argentinean case, the erratic evolution of energy intensity may hide the fact that, on a longer time-window, energy efficiency did not increase, but instead shows that increases in energy consumption did not imply efficiency increases. According to Altomonte [80] the productive structure of the economies, the energy consumption composition by sector and the particular share of fossil fuels in the energy mix are the main reasons to explain the non desirable path of energy intensity in Latin America which also seems to be the case of Argentina.

Being an energy supplier, Argentina shows some of the characteristic behaviors of such kind of economy, such as high metabolic rates in the different productive sectors. This is significantly different to the results obtained by Eisenmenger et al. [72] for some other Latin American countries, and cannot only be attributed to the level of economic development but rather to some degree of *Dutch disease* that is harming local industry. The SG sector presents a high energy consumption level, similar to Venezuela (another fossil-fuel exporting country) and much higher than China, Brazil and Chile, which have more diversity in economic activities.

This aspect is important to understand the different evolution of the productivity of labor and the productivity of energy of a particular sector, such as industry. If we look at Fig. 9 we see that the productivity of labor has increased over time, reflecting the enhanced level of capitalization that was mentioned before. A standard economic analysis would stop here, however, by combining energy consumption, time use, and added value information, we can also see the energy productivity of industry, in Fig. 10, that is, the value added generated per MJ of energy consumed. Here, the evolution of the industry (PS) is not so impressive, and actually at the end of the period it even worsens. Therefore, we can say that the increase in labor productivity ($US/hour) occurs at the expenses of decreasing the efficiency of the use of energy. This was possible only because Argentina was a net exporter of energy, a situation that will change in the coming future, characterized by rising energy costs, making it difficult for Argentina to achieve further increases in labor productivity unless major restructuring of the economy occurs.

The resemblance between the energy consumption patterns of Argentina and Venezuela is actually worrying, since proven reserves differ a lot between the two countries. While Venezuela's proven reserves are 87.04 Gbbl of oil and 4708 Gm3 of natural gas, those of Argentina are only 2.59 Gbbl of oil and 446.16 Gm3 of natural gas, anticipating the fact that Argentina will become a net energy importer in the coming years while keeping an economic structure heavily dependent on exosomatic energy. Therefore, Argentina should get ready for rising energy bills in the coming years, in a context of increasing oil prices.

Acknowledgments

Marina Recalde would like to thank the Departamento de Economía of the Universidad Nacional del Sur, and Dr. Walter Pengue, GEPAMA-UBA and the EuropeAid Co-operation Office funded Alfa project "Sustainable Use of Photosynthesis Products & Optimum Resource Transformation (SUPPORT)", for the financial support for a research stay at the ICTA-UAB, where this study was mainly carried out. Jesús Ramos-Martin acknowledges support from: (i) the Consolidated Research Group on "Economic Institutions, Quality of Life and the Environment", SGR2009–00962; (ii) the EU funded project "Synergies in Multi-Scale Interlinkages of Eco-Social Systems" (SMILE, Contract 217213-FP7-2007-SSH-1), and (iii) the Spanish Ministry for Science and Innovation project HAR-2010-20684-C02-01. Gratitude is also extended to three anonymous reviewers for their comments which were very useful to improve this article.

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