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Catalonia's energy metabolism: Using the MuSIASEM approach at different scales ☆

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ABSTRACT

This paper applies the so-called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), based on Georgescu-Roegen's fund-flow model, to the Spanish region of Catalonia. It arrives to the conclusion that within the context of the end of cheap oil, the current development model of the Catalan economy, based on the growth of low-productivity sectors such as services and construction, must be changed. The change is needed not only because of the increasing scarcity of affordable energy and the increasing environmental impact of present development, but also because of the aging population. Moreover, the situation experienced by Catalonia is similar to that of other European countries and many other developed countries. This implies that we can expect a wave of major structural changes in the economy of developed countries worldwide. To make things more challenging, according to current trends, the energy intensity and exosomatic energy metabolism of Catalonia will keep increasing in the near future. To avoid a reduction in the standard of living of Catalans due to a reduction in the available energy it is important that the Government of Catalonia implement major adjustments and conservation efforts in both the household and paid-work sectors.

1. Introduction

In recent years, interest on the links between energy consumption and economic development has seen a revival outside the academic world, especially because of these three factors: (a) the spike in oil prices that started in 2007, (b) the continuous growth in oil demand by emerging economies and (c) the emergence, of the peak oil hypothesis (Hubbert, 1956; Campbell and Laherrere, 1998) by the media. The period analysed (1990 through 2005) was characterised mainly by economic growth, not a recession like the one we are facing nowadays. However, we would like to remind the reader that oil prices during that period were always lower than oil prices we had in May 2009, over 60 dollars per barrel. This means that the recent downturn in oil prices and other commodities from their maximums of over 140 dollars per barrel in July 2008 does not compromise the main conclusions drawn here, due to the fact that economic structures of most economies have not changed, yet. Therefore, in the near future as the main economies start to recover, we may see again rising industrial production in developed and developing countries, driving up demand and prices for oil and raw materials.

Providing this will be the context, national and provincial governments interested in their dependence on oil will need to commission studies on the matter. Examples of this need can be given as of the case of the so-called Hirsch Report (Hirsch et al., 2005) by the Department of Energy of the USA, which alerted the consequences of Peak Oil in America's GDP. Another case is the study by the Irish government on oil dependency (Forfás, 2006), which introduced a 'vulnerability index' to oil price increases with Ireland as the fifth most vulnerable economy in the world, followed by Spain. Lastly, a document by the Office of the Prime Minister of Sweden (Comission on Oil Independence, 2006) where the road map to achieve an economy independent from oil by the year 2020 was outlined.

Most of the work done relies mainly in economic variables, with energy intensity as the main one. However, such an approach, which links GDP growth to energy consumption only explains partially how economies evolve by consuming energy. Attempts at using different methodologies to approach the issue

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abound, for instance, Alcántara and Duarte (2004) use structural decomposition analysis to compare energy intensities of EU countries, showing how different sectors affect the aggregate indicator.

Another study analysing the energy consumption in Spain, Roca and Alcántara (2001), showed how there was no environmental Kuznets curve for energy intensity in Spain and highlighted the importance of both the residential and the transport sector in driving the high energy demand in Spain. Alcántara and Padilla (2003) used input–output analysis to identify "key" sectors in final energy consumption, where they highlighted, among other results, the importance of the domestic or residential sector. Llop and Pie (2008) also used input–output to analyse the effect of energy policies such as energy taxing and improving efficiency. Climent and Pardo (2007) used multivariate cointegration analysis to investigate different decoupling factors affecting the relationship between GDP and energy consumption, and showed a positive unidirectional causality from energy consumption to GDP. Another suggesting area of research is that of analysing energy balances from a historical perspective, as was done by Cussó et al. (2006) for an agrarian region in Catalonia, for which they calculated the energy return on investment (= EROI calculated in biophysical terms—that is: energy investment and energy return).

We believe standard economic analysis of energy intensity and consumption should be complemented by analyses as the ones mentioned above. However, to better understand exosomatic energy metabolism we suggest introducing the human time variable into the equation. Exosomatic metabolism is a term introduced by Georgescu-Roegen (1975) to indicate the conversion of energy input to perform human activities, which is under human control, but that is taking place outside the human body. In contrast, endosomatic energy metabolism refers to the physiological conversion of food energy into human activity. By introducing human time, we can find some benchmark values in terms of energy consumption per hour of activity, which can also be coupled with labour productivity in order to inform decision makers about the different outcomes of development options. In fact, when considering the exosomatic metabolism, it is the level of technical capital supporting an hour of labour – the ratio exosomatic energy consumption per hour – that will determine labour productivity. This type of analysis is what we are presenting in this work.

The research that led to this paper was a project commissioned by the Generalitat de Catalunya, a regional government in Spain with competences in energy policy among other issues due to the high degree of devolution currently in place in Spain. In that project, we applied the so-called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach (Giampietro and Mayumi, 1997, 2000a, 2000b; more systematically investigated by Giampietro, 2003) to study energy consumption by different compartments of the economy at three hierarchical levels. The case study is Catalonia, a region in the north-east of Spain, and focuses on the period of 1990–2005. The approach, an application of Georgescu-Roegen's fund-flow model (Georgescu-Roegen, 1971, 1975), combines demographic (total and working population), economic (added value generation) and biophysical (exosomatic energy consumption) information at three different hierarchical levels to generate a number of intensive variables that can be used for characterising the exosomatic energy metabolism of the system and therefore for comparison with other economies. There have been some applications of this methodology for countries such as Ecuador (Falconí-Benítez, 2001), Spain (Ramos-Martín, 2001), Vietnam (Ramos-Martín and Giampietro, 2005), China (Ramos-Martín et al., 2007), Chile, Brazil and Venezuela (Eisenmenger et al., 2007), the UK (Gasparatos et al., 2009), Romania, Bulgaria, Poland and Hungary (Iorgulescu and Polimeni, 2009).

However, focusing at the national level does not allow seeing the particular characteristics different regions may have. As Hernández et al. (2004) point out for Spain, there is a strong asymmetry across regions in regard to CO_2 emissions due to their energy systems and we would defend the same occurs in terms of primary energy consumption. This is why our paper is the first attempt at using MuSIASEM at a sub-national level. It is true, however, that focusing at sub-national level has its own limitations. The most important being the different metabolic profile shown by a particular region may be the result of the role that region plays at national level. This fact could explain why certain regions are more specialised in financial services, whereas others are in industrial production or information technologies' services, and so on. Despite this shortcoming, we believe the application of this methodology at the sub-national level has many advantages.

The framework of the analysis is based upon what is called 'Societal Metabolism'. The economic process implies the transformation of both materials and energy into final goods and services. This process means the parallel generation of wastes be it material or in the form of heat. By energy metabolism we understand the study by which energy is used by society to keep it running and to allow further development. The concept of social metabolism has been used in different fields of analysis, such as ecological economics (for instance, Martínez-Alier, 1987); industrial ecology (Ayres and Simonis, 1994); material and energy flow analysis (Adriaanse et al., 1997; Fischer-Kowalski, 1998; Matthews et al., 2000); economic structural analysis (Duchin, 1998) and social ecology (Schandl et al., 2004), and goes back to the basic rationale of energy analysis (Cottrell, 1955), or to the concept of metabolic flow, introduced by Georgescu-Roegen (1971). As Haberl (2006, p. 96) mentions "ecological problems associated with socio-economic energy metabolism are central for sustainable development", this is so because not only energy metabolism determines land use (for growing food, fiber and fuels), but also because the current "temporary emancipation from land" (Mayumi, 1991) that fossil fuels are providing may end in a foreseeable future, therefore constraining human activities and also future options.

The analysis shows how economic growth is linked to exosomatic energy consumption, with a correlation over 90%. We also see how structural change in the economy (with reduced activity in primary and secondary sectors) has implied a change in the metabolism of the society, although new 'diffuse' sectors, such as households or transportation have increased their metabolism faster than the average. At the same time, energy controlled by workers – during an hour of work across the different sectors – remained more or less stable through the period, leading to stagnation in the economic labour productivity – the amount of added value generated per hour of work across the different subsectors – whereas energy per hour of 'non-working time' has been increasing above the average, as a result of the increase in the material standard of living, converging to EU-15 values.

The conclusion is that within a context of the end of cheap oil, it seems clear that a change in the economic growth model is necessary, not only because of the increasing scarcity of affordable energy carriers, but also because of the increasing environmental impact that the present development model represents. Moreover, since the level of energy consumption per worker will remain high in order to increase productivity of labour (due to the reduced work supply determined by an ageing society) and therefore competitiveness, one can conclude that major conservation efforts have to be implemented in both the household and transport sectors, if a huge increase in energy consumption wants to be avoided or in alternative, a sensible reduction of the existing level of material standard of living.

Table 1
Variables used in MSIASM.

Acronym	Name of the variable	Description	How is calculated?
TET-flow[a]	Total energy throughput	Total primary energy used in an economy in one year, measured in Joules (J).	Statistical sources
THA-fund	Total human activity	Total human time a society has available for conducting different activities, measured in hours (h).	Population times 8760 h
GDP-flow	Gross domestic product	Added value generated by an economy in one year, measured in euros or dollars (€) (or $).	Statistical sources

[a] When applied to a sector or subsector i, we call it ET_i, HA_i, and GDP_i.

The structure of the rest of the paper is the following: Section 2 presents the study area, methods and data sources. Section 3 presents the main results at the different hierarchical levels under analysis. Finally, Section 4 discusses those results and draws some conclusions from an energy policy perspective, as well as from a methodological point of view.

2. Study area, methods and data sources

2.1. Study area

Catalonia is a north-eastern region in Spain with borders with France that is characterised by its industrial base. Population increased from 6 million in 1990 to 6.9 million in 2005 (INE, 2005a), representing 15.9% of the Spanish population. Catalonia is a well-developed region, with an 18.7% of contribution to Spanish GDP (INE, 2007a). Catalonia also represents a big share of primary energy consumption in Spain, with 18.7% in 2004 (IEA, 2007; ICAEN, 2006). It has a huge petrochemical compound in Tarragona and it is totally dependant on imports of energy carriers. The time period analysed goes from 1990 through 2005.

2.2. The methodology

The methodology multi-scale integrated analysis of societal and ecosystem metabolism (Giampietro and Mayumi, 1997, 2000a, 2000b; Giampietro, 2003) – has been developed by integrating various theoretical concepts from different fields: (i) non-equilibrium thermodynamics applied to ecological analysis – Odum (1971, 1983, 1995) and Ulanowicz (1986, 1995); (ii) complex systems theory (Kauffman, 1993; Morowitz, 1979; Rosen, 1958, 2000; Zipf, 1941) and (iii) bioeconomics (Georgescu-Roegen, 1971).

The "metabolism of human society" is a concept used to characterise the processes of energy and material transformation in a society that are necessary for its continued existence. We use here the distinction between "endosomatic" and "exosomatic" metabolism as introduced by Georgescu-Roegen (1975), who was building on the original idea of Lotka (1956). They indicate flows of energy and materials transformed under human control within socio-economic processes both inside (endosomatic) and outside (exosomatic) the physical body of the members of a given society. To study the biophysical roots of economic processes Georgescu-Roegen (1975) proposed the adoption of a fund-flow model for representing in biophysical terms, the socio-economic process of production and consumption of goods and services. If we consider Giampietro et al. (2009), "flow" coordinates are elements that enter but do not exit the production process or, conversely, elements that exit without having entered the process (e.g. a new product). Flow coordinates include matter and energy in situ, controlled matter and energy, and dissipated matter and energy. Fund coordinates (capital, labour and Ricardian land) are agents that enter and exit the process, transforming input flows into output flows. Fund coordinates can only be used at a specified rate and must be periodically renewed. Therefore, fund coordinates entail an overhead (for their own maintenance and reproduction) and do entail a constraint on the relative rate of their associated flows with them (a range of value for the pace of conversion they control).

Within MuSIASEM scheme qualitative differences in energy forms are not addressed using thermodynamic concepts such as exergy or enthalpy. Rather, the time dimension of energy transformation in energy sector and its relation to other economic sectors is used to focus on crucial qualitative factors which the traditional biophysical and thermodynamic analysis has not dealt with sufficient attention. MuSIASEM is an attempt to incorporate these qualitative differences in the intensity of flows into a simple scheme that can be used to analyse societal metabolism for sustainability issues.

2.3. Description of the variables

We have considered the Catalan economy as a nested hierarchical system, composed by different compartments that operate simultaneously at different hierarchical levels, but whose behaviour affects each other. Within the context of MuSIASEM this means dividing first the Catalan economy into two sectors, paid-work (PW) sector responsible for added value generation, and the sector responsible for the consumption of such added value, the household sector (HH) which includes all the dependant population, non-paid work as well as non-working time of the active population. Both sectors consume energy for their own maintenance and development, but the PW sector is also responsible for guaranteeing the continuous supply of primary energy the whole society needs, through the energy sector. Then, after this first split, the paid-work sector can be split into three main subsectors, which correspond to economic sectors, i.e. the productive sector (PS, which includes energy, building and manufacturing), services and government (SG) and the primary sector (AG, including agriculture, husbandry, forests and hunting). Thus, *level n* is formed by the Catalan economy as a whole, *level* $n-1$ would represent the division between the activities of production and consumption, and *level* $n-2$, the sectoral level within production. These three levels are not expressing a top-down hierarchy, since the three of them co-evolve, at different rhythms. That is why we have to carry out the analysis at the three levels.

In MuSIASEM, we mainly use three variables: primary energy consumption (a flow), human time allocated to different activities (a fund) and added value generated (a flow) (see Table 1). These variables can be used both at the level of the whole economy (or level n), or at sector (level $n-1$) or subsector level (level $n-2$). For instance, we use the total energy throughput (TET) of Catalonia to account for total primary energy consumption, but we also use the primary energy used in the paid-work sector (ET_{PW}), in the household sector (ET_{HH}) or in each of the subsectors (ET_{AG}, ET_{PS}, and ET_{SG}).

With these data, obtained from statistical sources, we generate a series of indicators we will use for comparison (benchmarks). These are the flow/fund ratios of GDP per hour, exosomatic

Table 2
Indicators used in MSIASM.

Indicator	Definition (unit)	Calculation	What does it measure?
Flow/fund indicators			
GDP_{hour}	GDP per hour in the society	= GDP/THA GDPp.c/8760	GDP per hour of human activity in the society
EMR_{SA}	Exosomatic metabolic rate, average of the society (MJ/h)	= TET/THA	Energy consumption per hour of human time available to the society
EMR_i	Exosomatic metabolic rate (MJ/h)	$= ET_i/HA_i$	Energy consumption per working hour in sector i
ELP_i	Economic labour productivity (€/h)	$= GDP_i/HA_i$	Added value per hour of working time in sector i
Flow/flow indicators			
EI_{AS}	Energy intensity (MJ/€) for the whole economy	= TET/GDP	Energy consumption per unit of added value (GDP)
ELP_i/EMR_i	Energy efficiency of production (€/GJ) for an economic sector	= GDPi/ETi	Added value generated per unit of energy consumption in sector i

metabolic rate and economic productivity of labour (ELP) (see Table 2).

By dividing GDP_{hour} by EMR_{SA} at the *level n*, and by dividing homogeneous assessments of the ratios flows/funds at *level* $n-i$—e.g. by dividing ELP_i by EMR_i – it is possible to calculate another relevant set of indicators – energy intensities for the whole economy and for individual sectors or subsectors.

It should be noted that the first set of indicators (GDP_{hour}, EMR_{SA}, EMR_i, ELP_i) refer to a given ratio flow/fund, and therefore they can be used as benchmarks, since they have as external referent an "expected typology of metabolic system". On the contrary the indicators of energy intensities refer to a ratio over two flows and, therefore, do not map onto expected values of typologies.

Coming to the analysis of benchmarks (the flow/fund ratios) an increase in EMR_i reflects an increase in the level of capitalisation of the selected sector, that is an increase in the material standard of living in case of the household sector (Pastore et al., 2000), or it is a proxy variable for investment in capitalisation (machinery and tools) in the paid-work sector (Hall et al., 1986). The same can be said of the three subsectors, with their equivalent EMR_{AG}, EMR_{PS}, and EMR_{SG}.

Another flow/fund ratio that we use is the economic productivity of labour which is defined as GDP divided by the total of working hours (HA_{PW}). We also use ELP at the three subsectors by using sectoral GDP as well as sectoral employment and average working hours, for instance $ELP_{AG} = GDP_{AG}/HA_{AG}$.

The economic energy efficiency of the paid-work sector, the ratio between ELP and EMR, measures the amount of added value a unit of energy is producing in a particular sector or in the economy, and is expressed in euros per Giga Joule (€/GJ).

2.4. Data used in the analysis

Energy data has been obtained from the Energy Balances of Catalonia for the period 1990–2005 as provided by the Catalan Institute for Energy (ICAEN, 2006). Data for years 2004 and 2005 are provisional.

In reference to demographic data, we use national statistics for both total population (INE, 2007b) and labour statistics such as active population and employment (INE, 2005b). Applying this national data to Catalonia we assume a total of 46 weeks of effective working time in a year which we combine with the average working hours per week by economic sector found at the INE Population Census 2001 (INE, 2002). This source gives us working hours by sector and age group. The result is a weighted average working week of 40.4 h in the AG sector, 38.1 h in PS and 36.6 h in SG. We use these values with data on employment by sector in order to get the amount of hours worked in every sector.

Regarding Added Value, we recall data generated by the National Statistics Institute on its regional accounts (INE, 2007a). We have built a homogeneous series for the period 1990–2005 taking year 2000 as base year.

3. Presentation of results

3.1. Level n: catalonia

The first result can be seen in the Catalan economy is the high correlation between energy consumption and GDP, as shown in Fig. 1 (left side). In the period of analysis (1990–2005) GDP grew in Catalonia at a yearly rate of 2.6%, from 97,000 million euros to 147,000 million euros. This represented an increase in GDP per capita from 16,000 euros in 1990 to 21,000 in 2005, with a yearly growth rate of 1.8%. Population grew faster, about 1 million in the period, reaching 6.9 million in 2005. Primary energy consumption rose faster than GDP or population, at about 3% a year, going from 699 PJ in 1990 to 1120 PJ in 2005 (see Table 3 for main data and results).

Therefore, both energy intensity and energy consumption per capita grew in that period. The former worsened from 7.21 MJ/€ in 1990 to 7.60 MJ/€ in 2005, closer to the EU-15 average of 7.91 MJ/€ in 2004, but well below the figure for Spain, 9.42 MJ/€. The latter jumped from 115 GJ per head in 1990 to 160 GJ per head in 2005, almost the same value than the EU-15 (167 GJ per head).

Finally, the exosomatic metabolic rate, average of the society (EMR_{SA}), went up from 13.1 MJ/h in 1990 to 18.4 MJ/h in 2005. This means Catalonia has grown in every sense, but we need to see what goes on in every compartment to draw some conclusions and explain why we believe energy consumption will keep increasing.

3.2. Level $n-1$: production and consumption

The increase in EMR_{SA} as we described before was due to the behaviour of both the production side (PW) and the consumption side (HH). At the level $n-1$, we can check what happened with their metabolic rates and the distribution of time. In contrast with what happened in other surrounding economies, in Catalonia the energy consumed per hour of work (EMR_{PW}) did grow very little, going from 159 MJ/h in 1990 to 167 MJ/h in 2005. Fig. 2 shows the value staying around 180 MJ/h from 1993 to 2002 and going down afterwards.

This small growth means that, even though ET_{PW} grew at a yearly rate of 2.8%, from 618 PJ in 1990 to 964 PJ in 2005, the increase in energy consumption for production was not directed to increase the level of capitalisation of the productive sector, but rather to provide the new working force with the necessary equipment. In fact, working population (HA_{PW}) went up from 3880 million hours in 1990 to 5760 million hours in 2005, with a yearly growth rate of 2.5%. This growth was induced by two facts, the entrance of more women to the labour market, as well as new

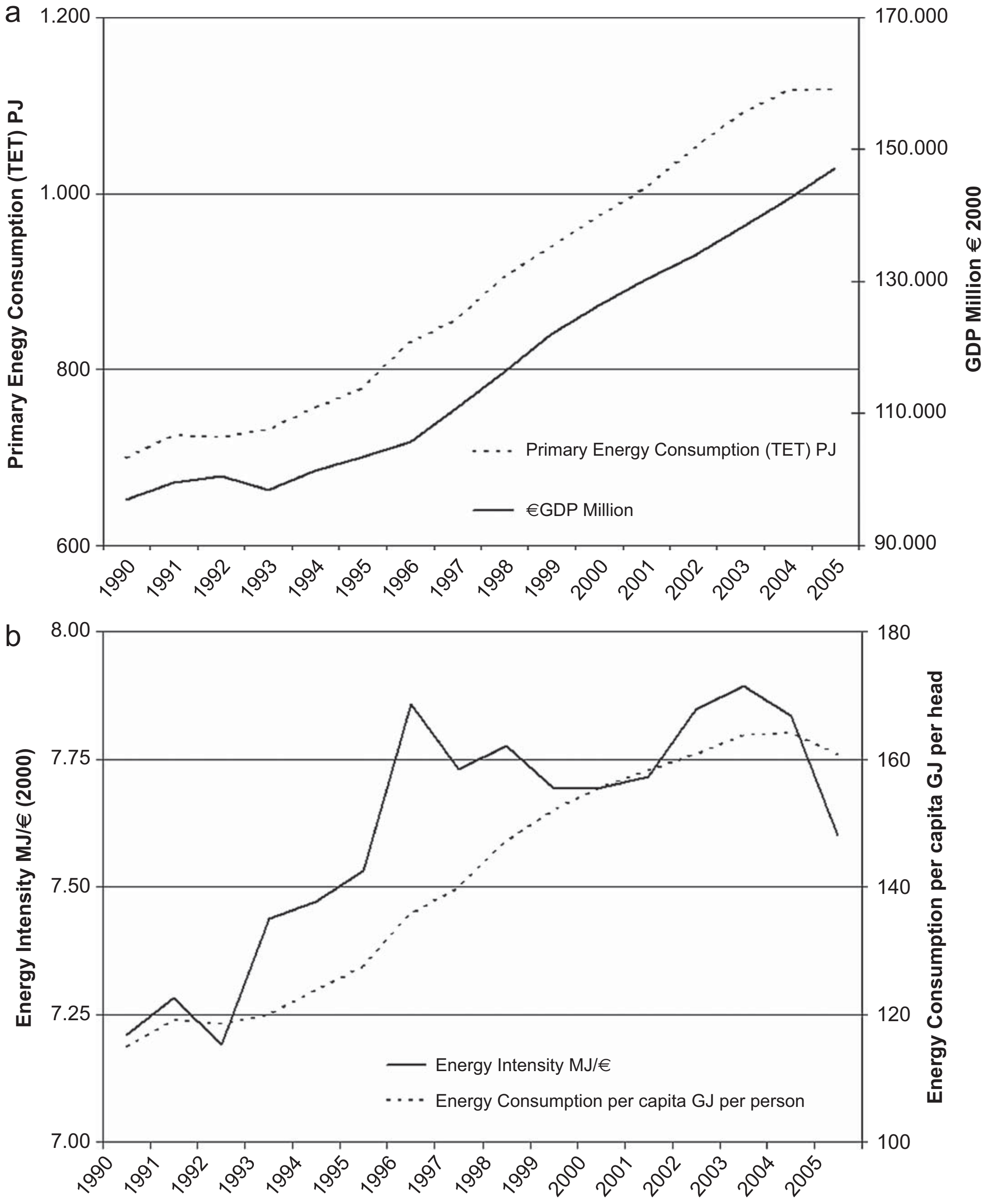

Fig. 1. Evolution of TET and GDP (above) and energy intensity and energy consumption per capita (below) in Catalonia, 1990–2005.

immigrated population, the majority of which were not only in working age, but actually employed. This increase in working population was a response of the Catalan economy to a stagnant productivity of labour. So, in order to increase output, the economy just hired more people, even though it allocated them in low-productivity sectors (construction and services).

One can foresee that the integration of new immigrants in the Catalan economy should entail an increase in the energy consumption of the productive sector. As discussed earlier this is required in order to climb up the ladder of added value generation per hour of work, by incorporating new technology. This is a step required to make it possible to achieve increases in labour productivity.

However, we have seen that the increase in EMR_{SA} in Catalonia has not been driven by a progressive capitalisation of the productive sector, but rather by: (i) an increase in active population (simply by an increase in the number of hours of work); and (ii) the increase in energy consumption of the household sector. In fact, EMR_{HH} – the pace of exosomatic energy consumed per hour of human activity in the final consumption sector – went up from 1.64 MJ/h in 1990 to 2.80 MJ/h in 2005, with a yearly growth rate of 3.4%. It is true that this value is still low when compared with other European economies, but what is relevant here is the rapid increase of this value experienced in recent years. The interpretation of the result is that a huge part of the increase in the ability of the Catalan economy of consuming more exosomatic energy reflects a biophysical capitalisation process which took place within the household sector. Looking at this change in terms of benchmark we can see that Catalonia is just converging with the European Union in material standard of living (i.e. appliances and consumption patterns,[1] including a greater use of the plane and the car for travelling).

[1] According to the INE Survey on Life Conditions (INE, 2007c), in year 2005 76.5% of Catalan households had a private car, 58.9% a personal computer, 98.8% a

Table 3
Main data and results.

Level n

Variable(unit)	GDP (million € year 2000)	Population (THA) (hours)	TET (MJ)	Energy intensity (MJ/€)	Energy consumption per capita (GJ/hab)	GDP per capita (GDP/hab)	EMR_{SA} (MJ/h)
1990	96,978	5.33E+10	6.99E+11	7.21	115.00	15,948	13.13
1991	99,612	5.33E+10	7.26E+11	7.28	119.19	16,364	13.61
1992	100,556	5.34E+10	7.23E+11	7.19	118.61	16,493	13.54
1993	98,421	5.34E+10	7.32E+11	7.44	119.98	16,134	13.70
1994	101,206	5.34E+10	7.56E+11	7.47	123.94	16,588	14.15
1995	103,339	5.35E+10	7.78E+11	7.53	127.51	16,928	14.56
1996	105,654	5.35E+10	8.30E+11	7.86	135.89	17,292	15.51
1997	110,813	5.37E+10	8.57E+11	7.73	139.84	18,091	15.96
1998	116,325	5.39E+10	9.05E+11	7.78	147.16	18,922	16.80
1999	122,066	5.41E+10	9.39E+11	7.69	152.08	19,769	17.36
2000	126,455	5.48E+10	9.73E+11	7.70	155.62	20,222	17.76
2001	130,400	5.57E+10	1.01E+12	7.72	158.27	20,513	18.07
2002	133,845	5.72E+10	1.05E+12	7.85	160.86	20,501	18.36
2003	138,041	5.83E+10	1.09E+12	7.89	163.81	20,753	18.70
2004	142,497	5.96E+10	1.12E+12	7.84	164.18	20,952	18.74
2005	147,070	6.08E+10	1.12E+12	7.60	160.93	21,173	18.37

Level $n-1$

Variable (unit)	HA_{PW} (hours)	HA_{HH} (hours)	ET_{PW} (MJ)	ET_{HH} (MJ)	EMR_{PW} (MJ/h)	EMR_{HH} (MJ/h)	ELP_{PW} (€/h)
1990	3.88E+09	4.94E+10	6.18E+11	8.09E+10	159.30	1.64	24.98
1991	3.94E+09	4.94E+10	6.34E+11	9.17E+10	160.82	1.86	25.27
1992	3.80E+09	4.96E+10	6.30E+11	9.28E+10	166.01	1.87	26.48
1993	3.64E+09	4.98E+10	6.37E+11	9.48E+10	174.89	1.90	27.02
1994	3.65E+09	4.98E+10	6.61E+11	9.53E+10	180.84	1.91	27.69
1995	3.78E+09	4.97E+10	6.80E+11	9.85E+10	180.09	1.98	27.37
1996	3.98E+09	4.95E+10	7.24E+11	1.07E+11	182.01	2.15	26.58
1997	4.15E+09	4.95E+10	7.46E+11	1.11E+11	179.77	2.24	26.71
1998	4.33E+09	4.95E+10	7.87E+11	1.18E+11	181.86	2.38	26.89
1999	4.58E+09	4.95E+10	8.13E+11	1.26E+11	177.63	2.54	26.66
2000	4.79E+09	5.00E+10	8.44E+11	1.30E+11	176.01	2.59	26.39
2001	4.85E+09	5.08E+10	8.72E+11	1.34E+11	179.85	2.63	26.89
2002	4.96E+09	5.22E+10	9.14E+11	1.36E+11	184.46	2.60	27.00
2003	5.25E+09	5.30E+10	9.45E+11	1.45E+11	179.89	2.73	26.29
2004	5.37E+09	5.42E+10	9.63E+11	1.54E+11	179.43	2.84	26.55
2005	5.76E+09	5.51E+10	9.64E+11	1.54E+11	167.33	2.80	25.54

Level $n-2$

Variable (unit)	HA_{AG} (hours)	HA_{PS} (hours)	HA_{SG} (hours)	ET_{AG} (MJ)	ET_{PS} (MJ)	ET_{SG} (MJ)	EMR_{AG} (MJ/h)	EMR_{PS} (MJ/h)	EMR_{SG} (MJ/h)	ELP_{AG} (€/h)	ELP_{PS} (€/h)	ELP_{SG} (€/h)
1990	1.42E+08	1.73E+09	2.01E+09	1.70E+10	4.64E+11	1.38E+11	119.74	268.35	68.38	10.89	19.88	23.30
1991	1.59E+08	1.69E+09	2.09E+09	1.83E+10	4.70E+11	1.46E+11	114.80	277.44	69.83	9.26	20.60	23.21
1992	1.41E+08	1.59E+09	2.06E+09	1.47E+10	4.66E+11	1.50E+11	104.29	292.18	72.75	13.03	21.58	24.02
1993	1.29E+08	1.41E+09	2.11E+09	1.65E+10	4.68E+11	1.52E+11	128.36	332.45	72.33	13.37	23.56	23.60
1994	1.36E+08	1.38E+09	2.14E+09	1.67E+10	4.84E+11	1.61E+11	122.83	351.18	75.01	12.68	24.89	23.89
1995	1.48E+08	1.41E+09	2.22E+09	1.73E+10	4.92E+11	1.71E+11	116.95	348.70	77.10	11.70	24.80	23.71
1996	1.37E+08	1.51E+09	2.33E+09	2.17E+10	5.20E+11	1.81E+11	158.89	344.09	77.97	14.19	23.27	23.57
1997	1.50E+08	1.62E+09	2.38E+09	2.03E+10	5.36E+11	1.90E+11	135.23	330.03	79.93	12.71	22.27	23.92
1998	1.62E+08	1.70E+09	2.46E+09	2.11E+10	5.64E+11	2.02E+11	129.92	330.99	82.09	11.18	21.94	23.96
1999	1.58E+08	1.74E+09	2.68E+09	2.28E+10	5.78E+11	2.13E+11	144.52	331.09	79.53	11.03	21.80	23.49
2000	1.30E+08	1.90E+09	2.76E+09	2.35E+10	5.98E+11	2.22E+11	180.69	315.27	80.22	14.62	20.51	24.03
2001	1.40E+08	1.96E+09	2.75E+09	2.42E+10	6.16E+11	2.32E+11	172.69	314.56	84.21	13.86	20.60	24.87
2002	1.33E+08	1.97E+09	2.86E+09	2.43E+10	6.53E+11	2.37E+11	183.45	332.29	82.83	15.35	20.68	24.67
2003	1.37E+08	1.94E+09	3.18E+09	2.54E+10	6.69E+11	2.50E+11	184.77	345.14	78.85	14.60	21.32	22.91
2004	1.30E+08	1.92E+09	3.32E+09	2.60E+10	6.73E+11	2.64E+11	200.05	351.43	79.37	15.51	21.87	22.72
2005	1.49E+08	2.01E+09	3.59E+09	2.66E+10	6.67E+11	2.70E+11	178.21	331.14	75.06	13.13	21.04	21.90

Source: own elaboration from ICAEN (2006), INE (2002), INE (2005b), INE (2007a, 2007b).

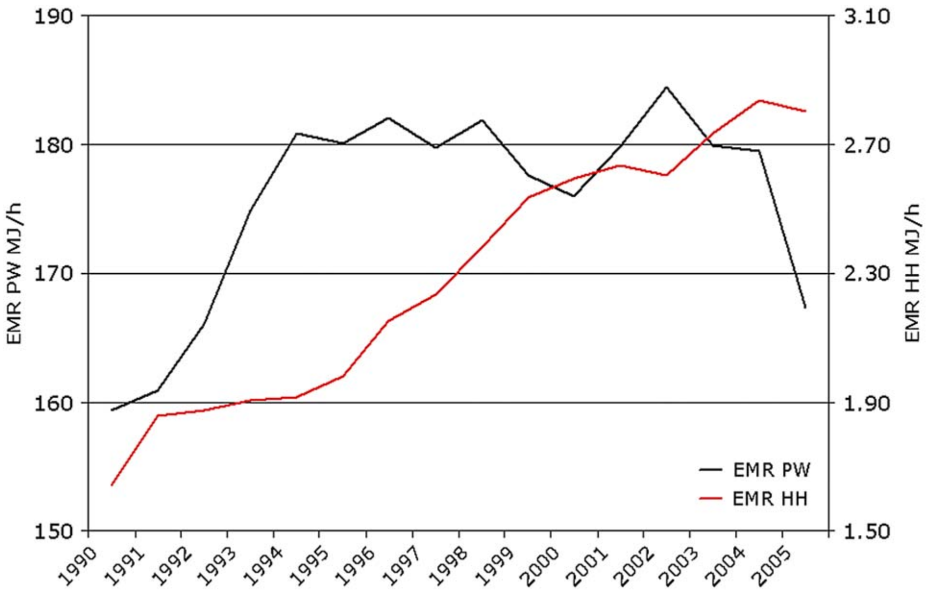

Fig. 2. Exosomatic metabolic rate (energy consumption per hour) of sectors generating added value (EMR_{PW}) and sectors consuming added value, households (EMR_{HH}), in MJ/h.

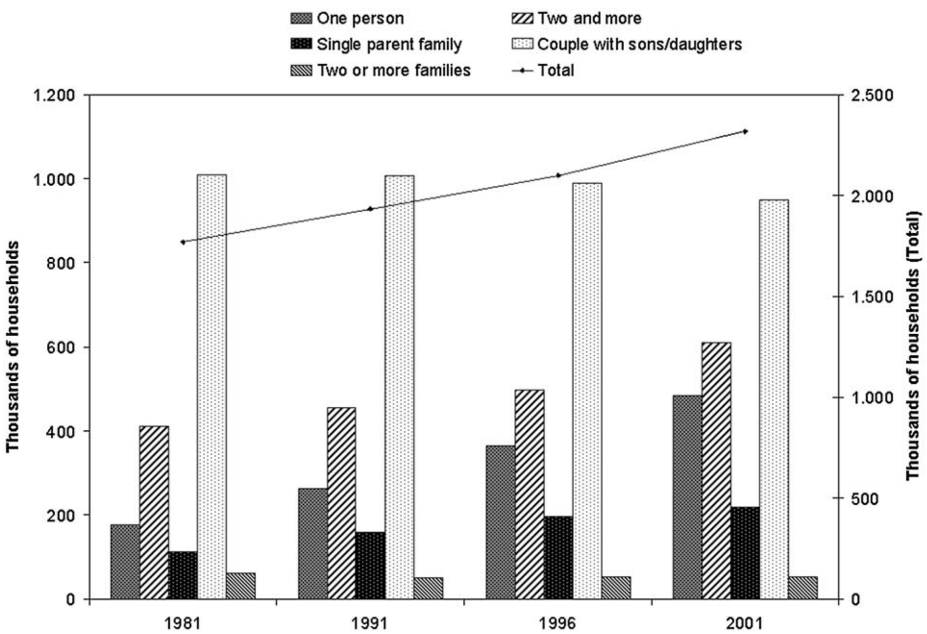

Fig. 3. Household typologies.

On the other side, the household sector has also experienced a change in its composition in the last decades. As Fig. 3 shows, traditional families (couple with sons/daughters) decreased over time, while non-familiar households (one person and two or more people) and single parent households increased over time. The total amount of households has increased about 31% between 1981 and 2001.

Fig. 4 shows the aggregate allocation of time of the different household typologies to different activities. We obtain these figures by combining the activities of the member of the different household typologies (from the use of time survey) with the number of households in each typology. Fig. 5 shows the share of these activities within each household typology.

A first conclusion from these figures is that, we cannot overcome the effects on energy consumption of the increasing size of the household sector by using better technology. If we have 10,000 people living within a typology of "large households" [= two families in the same household] that suddenly decide to live in the typology "single" [= one person] this will necessarily increase the energy consumption of this sector, no matter how efficient are the appliances that will be used in the one-person household. This is to say that qualitative changes in the composition of this compartment of the socio-economic system

(*footnote continued*)
washing machine, 98.5% telephone, and 99.5% colour TV. These figures represent an increase with respect to one year before, regardless of the larger number of households.

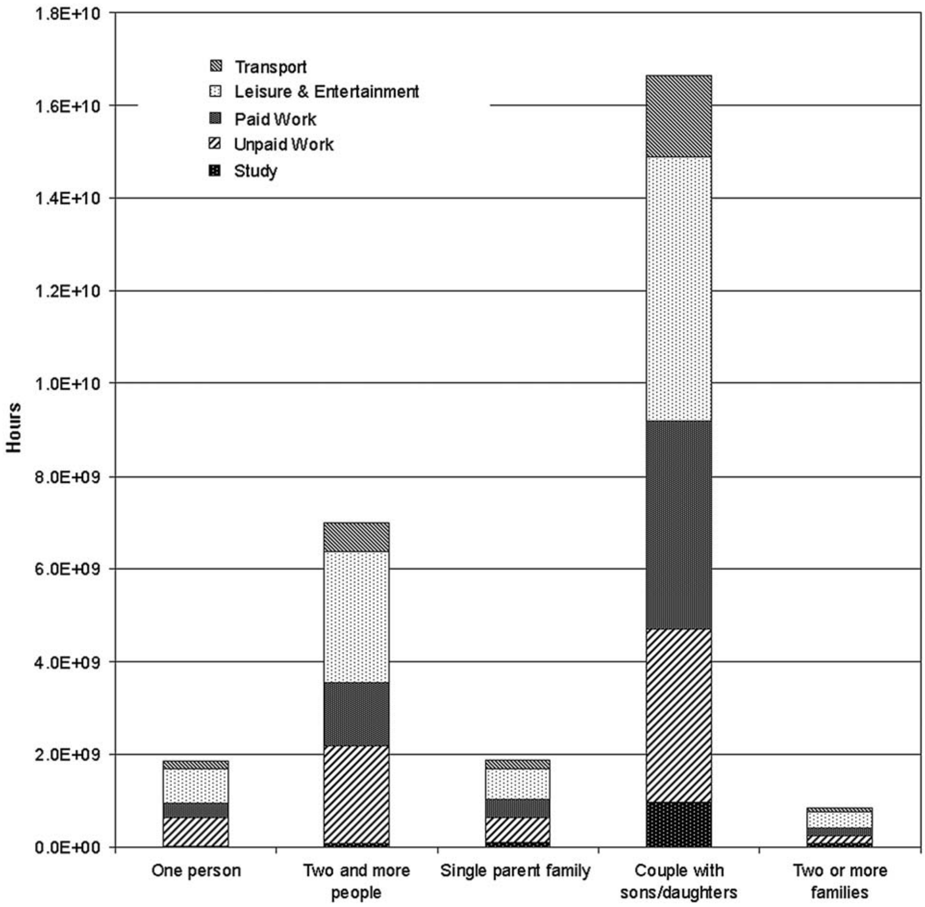

Fig. 4. Aggregate allocation of time by household typologies.

play an important role in energy-consumption terms. Qualitative changes are determined by demographic changes, life styles, geographic distribution, typology of residential structures and transport infrastructures. The analysis of household metabolism, based on the characterization on typologies can result very useful. For instance, non-familiar and single parent households present a higher share of time allocated to Leisure & Entertainment and Unpaid Work, while familiar households present a higher share of transport, study and paid-work activities. All these activities entail different exosomatic metabolic rates: The energy consumed in unpaid work, paid work and study mainly depend on the metabolism of the buildings in which activities are carried out. The energy consumed in transportation depends on the transportation systems and on the spatial organization of the city.

One has to recall here that most of the energy consumption of a developed economy still happens in the production side of the economy, so that the household sector is responsible only for a minor part of EMR_{SA} increase. However, in spite of the big difference between EMR_{HH} and EMR_{PW}, the increase in EMR_{HH} is worrisome since ET_{HH} is growing at a yearly rate of 4% (from 81 PJ in 1990 to 154 PJ in 2005) in a sector that represents more than 90% of total human time. Moreover, the share of ET_{HH} is growing at the expenses of the share of ET_{PW}.

In fact, HA_{HH} grew from 49,400 million hours in 1990 to 55,100 million hours in 2005, at a mere 0.7% a year, far below the yearly growth rate of 2.5% for working population. This result is positive in the short-term, since it allows overcoming the problem of an ageing population,[2] but it is only a question of time that the problem will surge again (when today workers become pensioners) and Catalonia will face another bottleneck unless it increases dramatically the ratio of active population, the productivity of labour, or adopts a permanent policy of welcoming foreign workers (see Fig. 6).

3.3. *Level n−2: evolution of the productive sector*

The massive entrance of immigrant population to the labour market has gone hand in hand with a change in the structure of the labour market. According to Ramos-Martín (2009) agriculture lost 1% of working population in 2005 when compared with 1990, the productive sector lost 9 percentage points, and services gained 10%.

To see how this structural change explains changes in EMR_{PW} as presented in the previous section, we need to introduce the exosomatic metabolic rates of each sector. This is what is done in Fig. 7. EMR_{PW} depends on the behaviour of each individual EMR_i,

[2] As shown in Ramos-Martín (2009) life expectancy at birth in Catalonia increased from 74.3 years in 1974 to 80.8 years in 2004. These improvements occurred mainly in population over 60 years. The outcome has been the ageing of the total population.

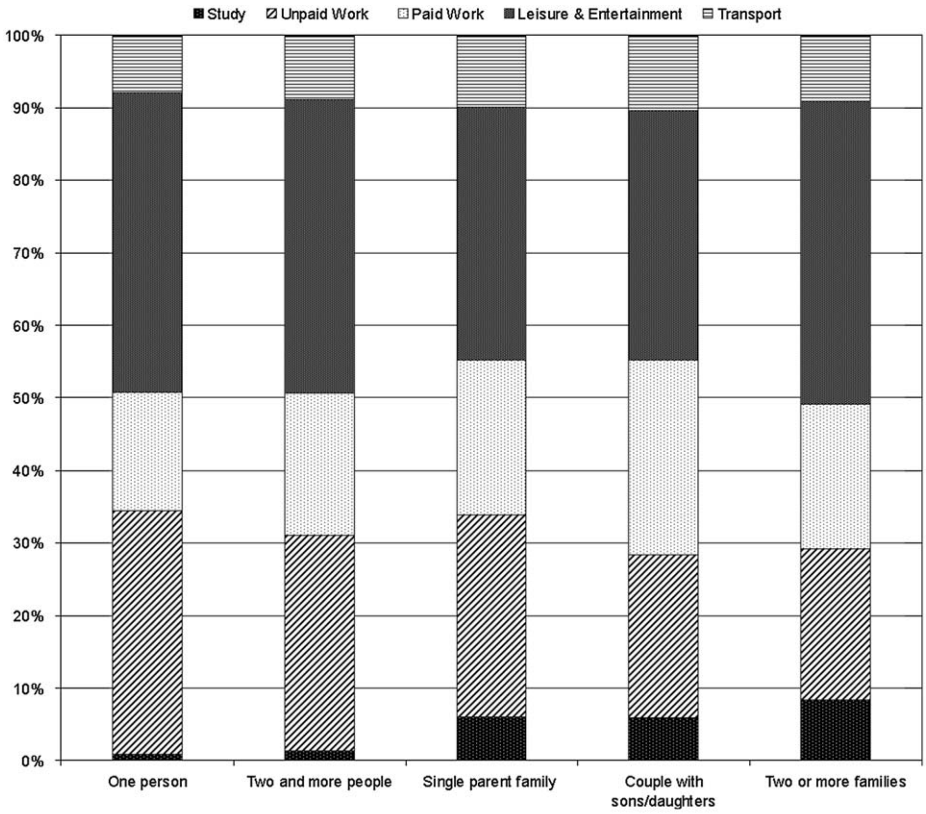

Fig. 5. Allocation of time by household typologies.

and the profile of distribution of working time among sectors (Fig. 8).

The first result we want to highlight from Fig. 7 is the huge difference in the exosomatic metabolic rates the different sectors show. This is due to the difference in the capital that is needed to perform the different activities. Therefore, it is understandable that agriculture needs more energy per hour of work than say, services. The sequence for Catalonia was $EMR_{PS} > EMR_{AG} > EMR_{SG} > EMR_{HH}$. With data for 2005, EMR_{PS} was 333 MJ/h (which includes the construction and energy sectors), whereas it was 178 MJ/h in agriculture, 75 MJ/h in services and 2.8 MJ/h at the household sector. Only when looking at this lower level we can explain why EMR_{PW} evolved the way it did, and which sector was responsible for what. During the period analysed EMR_{PS} increased very little, from 268 MJ/h in 1990 to 331 MJ/h in 2005, but due to the fact that the productive sector lost 9% in the working force, this implied moving a large fraction of active population from energy-intensive sectors (331 MJ/h) to the services sector (75 MJ/h), a fact that explains why energy intensity did not increase more in Catalonia over the considered period.

Another interesting issue is to see how EMR_{PS} followed the economic cycle, in other words, it increased faster than the others during economic booms and went down in crisis. Something similar to what happened in agriculture, with the difference that in this case one must also account for draught periods such as 1996 which forced the use of more fertilizer. On the other hand, EMR_{SG} was decreasing since 2001, a fact that may be reflecting just the structural change going on in the electricity generation model that is shifting towards gas-fired combined cycle power plants that show higher efficiency in conversion (meaning less primary energy per unit of electricity delivered) of electricity, the main energy carrier for non-transport services.

4. Discussion and conclusion

4.1. Distribution of time among activities

When focusing on human time allocation (Fig. 8) one realises how small is the fraction of human activity which is dedicated in a developed society to generate added value. The share of human time allocated to the PW sector[3] was 9.5% in 2005, up from its 7.3% in 1990. The increase may be driven by two factors: (i) the 1 million population increase was due to immigrants, most of them in working age, and actually employed; and (ii) a massive entrance of women in the labour market, actually 60% of the new active population. However, this situation may change in the future if more stringent immigration policies are put in place, and if the additional incorporation of women into the labour market was a once-and-for-ever event. This implies a serious problem for Catalonia, with an ageing population that will badly need both more immigrants, and an additional increase in the incorporation of women in the work force.

Regarding the distribution of active population among sectors, the picture is similar to other European economies, with services dominating the labour market. Most interesting is the new active population (totalling 1.1 million) that were directed mainly to services (940,000) and construction (140,000), while active population in both agriculture or the productive sector remained stable. This fact is not particularly good, since these two sectors –

[3] The variable human activity allocated to paid-work activities may change depending on different factors, such as demographic ones (population structure); social and ethical, like fixing the minimum working age at 16, or retirement at 65; or socio-cultural, like women participation in the labour market.

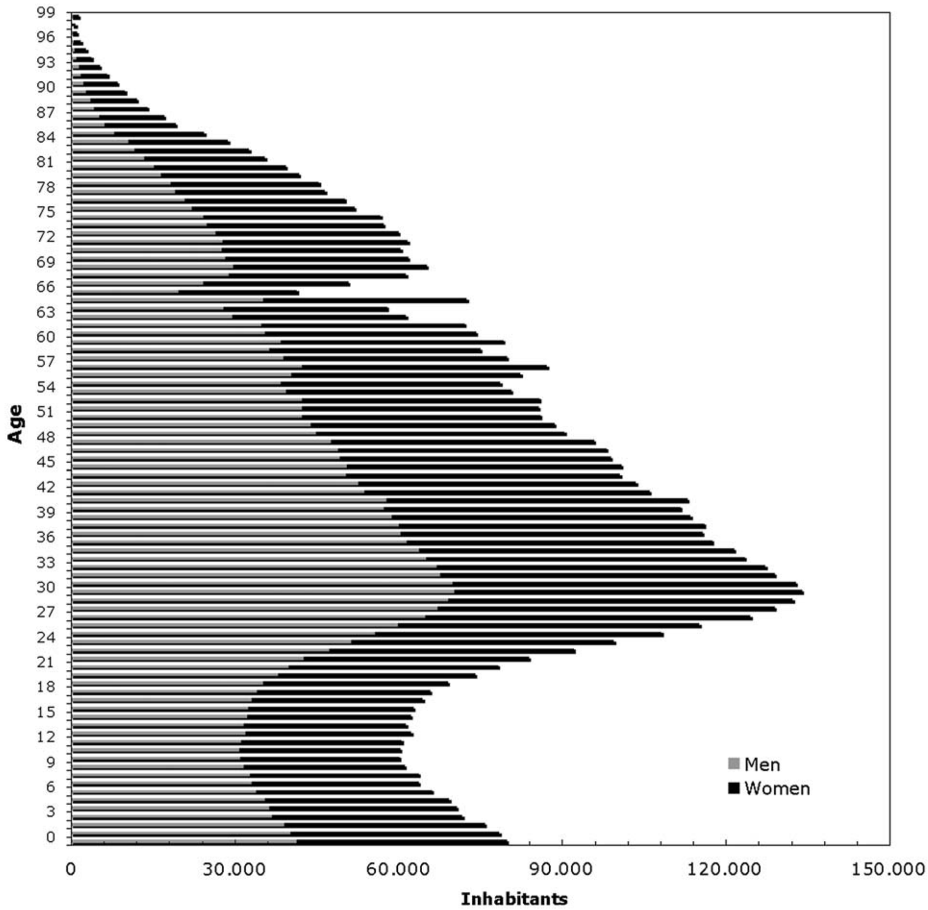

Fig. 6. Population pyramid for Catalonia 2003.

services and construction – are mainly non-tradable – i.e. closed to international competition – a fact that explains its low productivity. Therefore, if population keeps ageing, entailing a higher dependency ratio in the future, productivity gains must be obtained through the adoption of more technology, meaning that more energy will have to be consumed per hour of work.

4.2. Link between economic growth and energy consumption

If we consider Cleveland et al. (1984), we could say there is a link between energy consumption per hour of work (EMR) and the resulting economic productivity of labour. This is explained by the fact that an increase in EMR_{PW} means both the use of more machinery and tools (i.e. computers), the production of which has consumed energy and also because this machinery consumes energy for running. It is true that this approach has the limit of not accounting for energy-efficiency improvements, but in any case data for the USA (Cleveland et al., 1984; Hall et al., 1986), Ecuador (Falconí-Benítez, 2001) and Spain (Ramos-Martín, 2001) among others, show there is a link between more energy consumption per hour of work and higher productivity of labour. This link is also observed in the case of Catalonia (see Fig. 9). For further analysis in regards to the Jevons' Paradox look at Polimeni et al. (2008).

The stagnation of EMR_{PW} around 180 MJ/h over a long period of time, and its decline after 2002 reflected that the increase in energy consumption in the paid-work sectors (ET_{PW}) was directed at absorbing new active population and not to increase their level of capitalisation, with the consequent stagnation in the economic productivity of labour, as we already have said.

The ageing population mentioned in the previous section implies that Catalonia faces the challenge of dramatically increasing its productivity of labour while keeping its energy intensity at current (EU-15 average) values. Something that can only be done if undergoing a tremendous structural change that moves away from energy-intensive industries and focuses in non-transport services with higher economic efficiency (Euros per GJ, see Section 4.4).

4.3. On the evolution of the two sectors at level n−1

The yearly increase in the overall primary energy consumption for Catalonia in this period was 3%. However, Fig. 10 shows how EMR_{PW} has grown very little in the period, while EMR_{HH} has been the main driver of rising energy consumption. As already pointed out in Section 3.2 the increase in TET was mainly directed to increase material standard of living and even the increase in ET_{PW} was used to cover for the increase in active population (HA_{PW}) and not to increase the level of capitalisation.

This implies that recent increase in the material standard of living in Catalonia (EMR_{HH}) is going to be very expensive in the near future, because of the link between EMR and ELP. More household capitalisation (more appliances, but also more mobility needs) tends to fix future energy consumption. If this energy will become more expensive, the added value required to buy this energy, will be generated by an ageing population and work force. Therefore, Catalonia faces the urgent need to increase productivity of labour. This may very well end up by increasing the energy consumption in the PW sector.

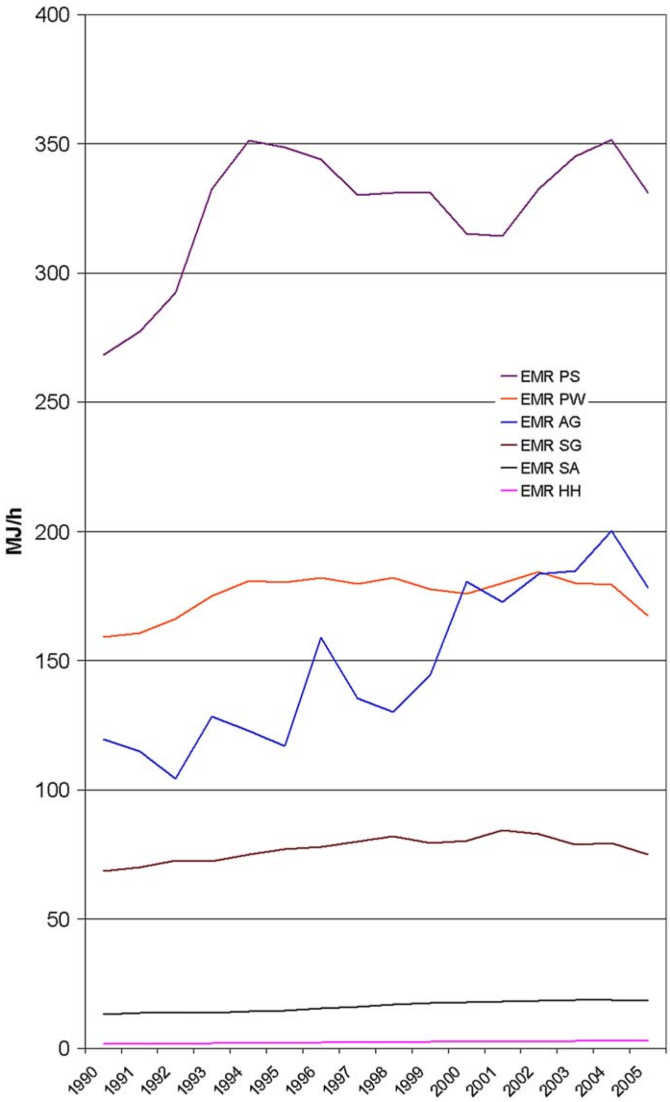

Fig. 7. Evolution of EMR_i.

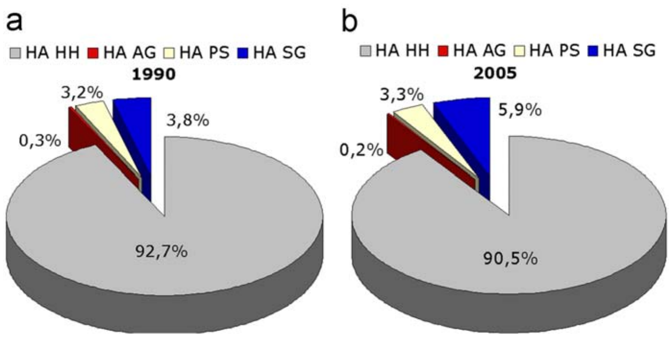

Fig. 8. Distribution of time use between production and consumption in Catalonia, years 1990 and 2005.

4.4. *On the evolution of the subsectors al level n−2*

According to Ramos-Martín (2009), the first energy carrier (e.g. electricity, liquid fuels, delivery of natural gas to possible end uses) used by the productive sector is natural gas, followed by electricity and oil products, whereas SG (that in our case accounted for 75% of energy in transportation) consumes 60% of its energy from oil products, followed by electricity and natural gas. Therefore, a shift of working population from the productive sector to services will lower energy demand per hour of work, but will also change the share of the different carriers, increasing the consumption of oil products (in relative terms). If we add the fact that EMR_{SG} is growing above the average (mainly due to the transport sector), the initially positive result of a change in the share of the SG sector over PW both in terms of energy dependency and CO_2 emissions is relativised. In case of agriculture the improvement generated by the moving of active population to the services sector is clear, not only because agriculture has a higher metabolic rate, but also because oil products are its main energy carrier, with over 90% of consumption.

In case of the household sector (which includes 25% of the energy consumption in the transport sector for the use of private cars), oil products represent more than half the energy carriers it uses, followed by natural gas with around 30% and electricity. With these figures any increase in EMR_{HH} will have a very high impact in terms of energy dependency and its relative impact upon the environment is higher than an increase in the productive sector. So, even though EMR_{HH} is very low at 2.8 MJ/h in 2005, the share of human time allocated is huge, representing more than 90%, therefore this translates in an absolute consumption (154 PJ) which is already 16% of the energy consumed in the PW sectors combined, and is rising at a faster pace, than the overall economy.

Finally, we would like to say a word on the energy efficiency of economic production by the different sectors. That is, this analysis refers to the amount of added value generated by a GJ of primary energy consumed. As explained in Section 2.3, this value is obtained by calculating ELP_i/EMR_i. The results for the paid-work sectors combined and for the three economic sectors considered at level $n-2$ are shown in Table 4.

It is interesting to notice what said before regarding the evolution of the economic productivity of labour is also found in terms of energy efficiency of production. The service sector, by large, is the one that generates more added value per unit of energy. Moreover, it is shocking that the productive sector is less efficient than agriculture. The loss in competitiveness implied by the poor performance of ELP mentioned before can be seen by the fact that between 1990 and 2005 Catalonia has reduced the amount of added value generated by 1 GJ of primary energy. This result must be seriously considered by policy makers, especially in a context of increasing fossil-fuel scarcity and parallel oil-price hikes. It is urgent that Catalonia improves its ability in using energy carriers, be it with technological improvements, or with structural changes directing activity towards services. The final result must be to conserve energy and reduce demand.

4.5. *On the model of development*

The main conclusion of the paper is that, so far, the growth model for Catalonia heavily depends on the consumption of energy, with a correlation between increases in GDP and increases in primary energy consumption of 98% in the past 15 years (Fig. 1). Considering that with aging Catalonia will have to produce the same levels of GDP using a lower amount of work supply, it is obvious that "doing more of the same" is not an option. Additional reasons for an urgent need of change are: (i) the environmental impact associated with fossil-energy consumption (e.g. greenhouse gas emissions); and (ii) the increasing risk associated with the dependency on foreign energy in a sector becoming more and more volatile.

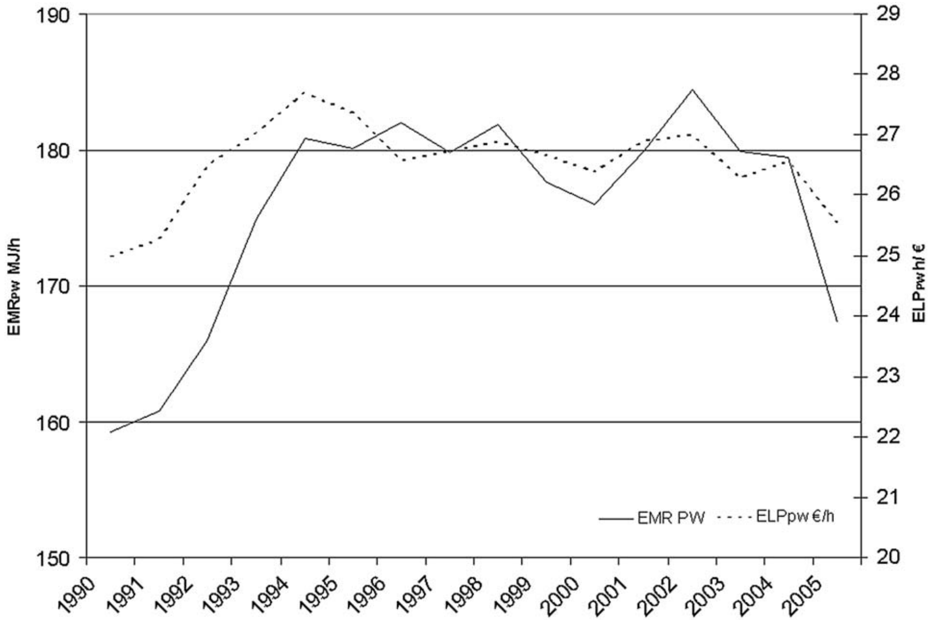

Fig. 9. Link between EMR and ELP in Catalonia (1990–2005).

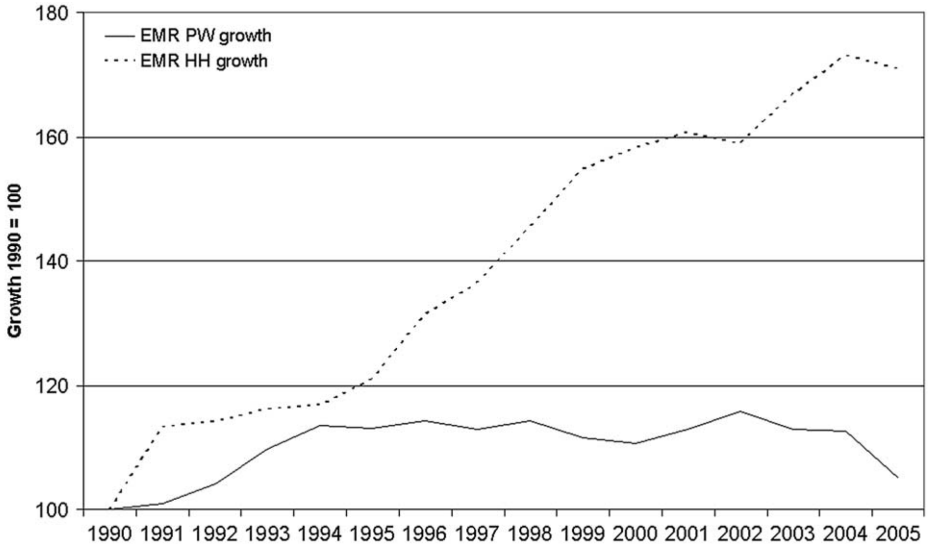

Fig. 10. EMR_{PW} and EMR_{HH} growth over time.

Table 4
Energy efficiency of production in euros per GJ.

	1990	2000	2005
$(ELP/EMR)_{PW}$	157	150	153
$(ELP/EMR)_{AG}$	91	81	74
$(ELP/EMR)_{PS}$	74	66	63
$(ELP/EMR)_{SG}$	341	300	292

During the period analysed, the huge increase in energy was not reflected in qualitative changes of the development model, but just a mere replication and amplification of the current trends. We can define an increase based on doing more of the same as just growth. The increase in energy consumption was not used to carry out structural changes in the economy towards less energy-intensive activities, while generating more added value. Rather, it was directed to provide to a larger active population the necessary means to conduct their "business as usual" activities, in terms of machinery, tools, and services such as transportation. This lack of structural change explains why the new active population was almost entirely allocated to construction or services, where there is less need of know-how. This has allowed Catalonia to absorb new population, and to generate an important amount of added value, by generating a dramatic increase in the value of real estate. However, in the long run and in case of financial and economic crisis, the lack of innovation and investment in new technologies may make productivity improvements harder to get. Actually, a shortage of investments in innovation may represent a key limiting factor Catalonia will face in the near future.

This result is more worrying when we consider population is getting older, meaning that a lower share of the total population will be employed in generating added value in the future.

Moreover, an old work force entails also little flexibility in terms of new ''know-how'' available. Looking at these challenges we can imagine different types of solutions. Technical solutions referring to the efficiency of the energy sector – for example encourage substitution within the existing set of processes of electricity generation (more combined cycle plants) to improve the ration final energy/primary energy. Another solution can be related to the consumption of the final sector – for example, improving the efficiency of energy consumption at the household level. More difficult would be the third field of intervention, how to improve the economic productivity of labour within the paid-work sector? In a situation of extreme uncertainty, in which we can expect that peak-oil and concern for environmental impact will lead a series of major structural changes in modern economies, it is difficult, if not impossible, to guess the final result of this major restructuring of developed economies. Some sectors will be dramatically changed (e.g. high input agriculture, the car sector). We can expect changes in life style (e.g. teleworking, increase in the size of households, increased use of public transportation), and also in the service sector (e.g. an increase in the transport on water and railroad, more ICT in place, etc). So we can see this upcoming restructuring not only as a threat for the Catalan economy, but as an opportunity if the investments in the Catalan economy are wisely directed on those economic activities. However, as noted earlier limiting consumption in diffuse sectors such as households or transport is very unpopular and very costly. Moreover, improving the productivity of labour going through a major restructuring of the main economic sector will require heavy investments and it is likely to increase the amount of energy consumed per hour of work.

In conclusion, within this general context, it will be crucial to be able to wisely assess the effects that investments done at the sectoral level will have at the level of the whole economy. This is why, a tool such as the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism can be used to characterise scenarios referring to different strategies of investments, having the goal to balance the goals of: (i) economic productivity and competitiveness; (ii) quality of life and social equity and (iii) environmental impact and request of natural resources.

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