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Why Catalonia will see its energy metabolism increase in the near future: an application of MuSIASEM[1]

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Abstract: This paper applies the so-called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to the economy of the Spanish region of Catalonia. By applying Georgescu-Roegen's fund-flow model, it arrives at the conclusion that within a context of the end of cheap oil, the current development model based on the growth of low productivity sectors such as services and construction must change. The change is needed not only because of the increasing scarcity of affordable energy carriers, or because of the increasing environmental impact that the present development represents, but also because of an ageing population that demands labour productivity gains. This will imply industry requiring more energy consumption per worker in order to increase its productivity, and therefore its competitiveness. Thus, we conclude that energy intensity, and exosomatic energy metabolism of Catalonia will increase dramatically in the near future unless major conservation efforts are implemented in both the household and transport sectors.

Keywords: Catalonia, exosomatic energy, energy metabolism, economic development, hierarchical levels, multi-scale, integrated analysis

JEL codes: O11, O13, O52, Q01, Q57, Q58

1. Introduction

This paper applies the so-called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach (Giampietro 2003) to study energy consumption by different compartments of an economy at three hierarchical levels. The case study is of Catalonia, an important region in the north-east of Spain, and focuses in the period from 1990 – 2005. The approach, an application of Georgescu-Roegen's fund-flow model (Georgescu-Roegen, 1971), 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.

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

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heat. By energy metabolism we understand the study by which energy is used by society to keep it running and to allow for 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. 2002).

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 less 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 remained more or less stable through the period, leading to stagnation in the economic labour productivity, 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 industry will require more energy consumption per worker in order to increase productivity of labour 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.

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.

2. Study area, methods and data sources

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 2005), representing 15.9% of the Spanish population. Catalonia is a well developed region, with an 18.7% of contribution to Spanish GDP (INE 2007). Catalonia also represents a big share of primary energy consumption in Spain, with 18.7% in 2004 (ICAEN 2006 and IEA 2007). 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.

2.1. 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 the Catalan economy into two sectors, Paid Work sector (PW) 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 its 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. At the same time, the paid work sector can be split into three main subsectors, which correspond to economic sectors, ie, 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. These three levels are not expressing a top-down hiearchy, since the three of them co-evolve, at different rythms. That is why we have to carry out the analysis at the three levels.

In MuSIASEM we mainly use three variables: primary energy consumption, human time allocated to different activities, and added value generated (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 woirk sector (ET_{PW}), in the household sector (ET_{HH}) or in each if the subsectors (ET_{AG}, ET_{PS}, and ET_{SG}).

Table 1: Variables used in MSIASM

Acronym	Name of the variable	Description	How is calculated?
TET[2]	Total Energy Throughput	Total primary energy used in an economy in one year, measured in Joules [J].	Statistical sources
THA	Total Human Activity	Total human time a society has available for conducting different activities, measured in hours [h].	Population times 8,760 hours
GDP	Gross Domestic Product	Added value generated by an economy in one year, measured in euros or dollars [€] (or $).	Statistical sources

With these data, obtained from statistical sources, we generate a series of indicators we will use for comparison. These are energy intensity, exosomatic metabolic rate, economic productivity of labour, and energy efficiency of production. **Table 2** summarises them.

Table 2: Indicators used in MSIASM

Indicator	Definition [unit]	Calculation	What does it measure?
EI_i	Energy Intensity [MJ/€]	= TET/GDP	Energy consumption per unit of added value (GDP)
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
ELP/EMR_i	Energy Efficiency of Production [€/GJ]	= GDP_i / ET_i	Added value generated per unit of energy consumption in sector i

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 the 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. The same can be said of the three subsectors, with their equivalent EMR_{AG}, EMR_{PS}, and EMR_{SG}.

Another ratio that we use is the economic productivity of labour (ELP) which is defined as GDP divided by the total of working hours (HA_{PW}). We also use ELP at the three subsectors by using

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

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 particiular sector or in the economy, and is expressed in euros per Giga Joule (€/GJ).

2.2. 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 still provisional.

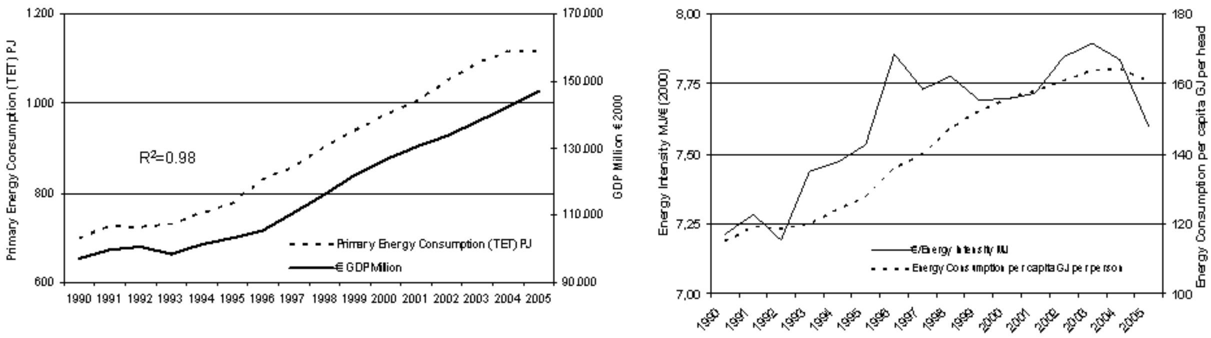
Regarding demographic data, we use national statistics for both total population (INE 2007b), and labour statistics such as active population, employment (INE 2005b). With this information we assume a total of 46 weeks of effective working time in a year which we combine with the average working hours 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 hours in the AG sector, 38.1 hours in PS, and 36.6 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 Statitistics Institute on its regional accounts (INE 2007). 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

Figure 1: Evolution of TET and GDP (left) and Energy Intensity and Energy Consumption per capita (right) in Catalonia, 1990-2005



The first result we see at the level of the Catalan economy is the high correlation between energy consumption and GDP, as seen in Figure 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 1,120 PJ in 2005.

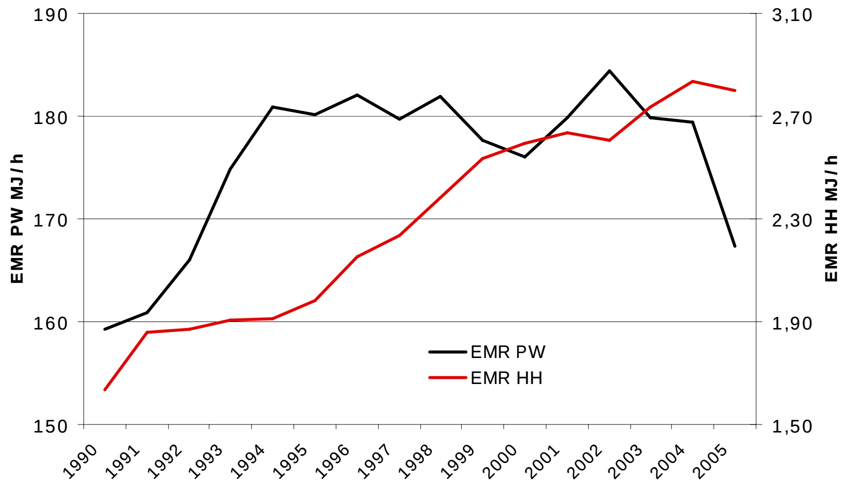
Therefore, both energy intensity and energy consumption per capita grew in the period. The former worsened from 7.21 MJ/€ in 1990 to 7.60 MJ/€ in 2005, closer to the EU-15 average of 7.91 MJ/€ in 2004, but well below the figure for Spain, 9.42 MJ/€. The latter jumped from 115 GJ per head in 1990 to 160 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 all senses, 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} we described before was due to the behaviour of both the production side (PW) and the consumption side (HH). We now see what happened with their metabolic rates and the distribution of time. In contrast with what happened in other surrounding economies, Catalonia saw how energy consumed by an hour of work (EMR_{PW}) did grow very little, going from 159 MJ/h in 1990 to 167 MJ/h in 2005. Figure 2 shows the value staying around 180 MJ/h from 1993 to 2002 and going down afterwards.

Figure 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



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 productive sectors, but rather to provide the new working force with the necessary equipment. In fact, working population (HA_{PW}) went up from 3,880 million hours in 1990 to 5,760 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 inmigrated population, the majority of which were not only in working age, but actually working. 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 once the arrival of new immigrants stabilises productive sectors should increase their energy consumption in order to climb up the ladder of added value, by incorporating new technology. This will allow increases in productivity to materialise.

Once we have seen that the increase in EMR_{SA} is not driven by a higher capitalisation of productive sectors, one can say that along with the increase in active population, the household sector was another important driver of energy consumption increase. In fact, EMR_{HH} 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 experienced in recent years. The interpretation of the result is that a huge part of the increase reflects a capitalisation process within the household sector. This is just the process of converging with the European Union in material standard of living (ie appliances and consumption patterns[3], including a greater use of the plane and the car for travelling).

However, one cannot solely blame the household sector for EMR_{SA} increase. It is true that most of energy consumption still happens in the production side of the economy, and that the difference between EMR_{HH} and EMR_{PW} is still huge, but the increase in EMR_{HH} is worrysome 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. So the share of ET_{HH} is growing at the expenses of the share of ET_{PW}.

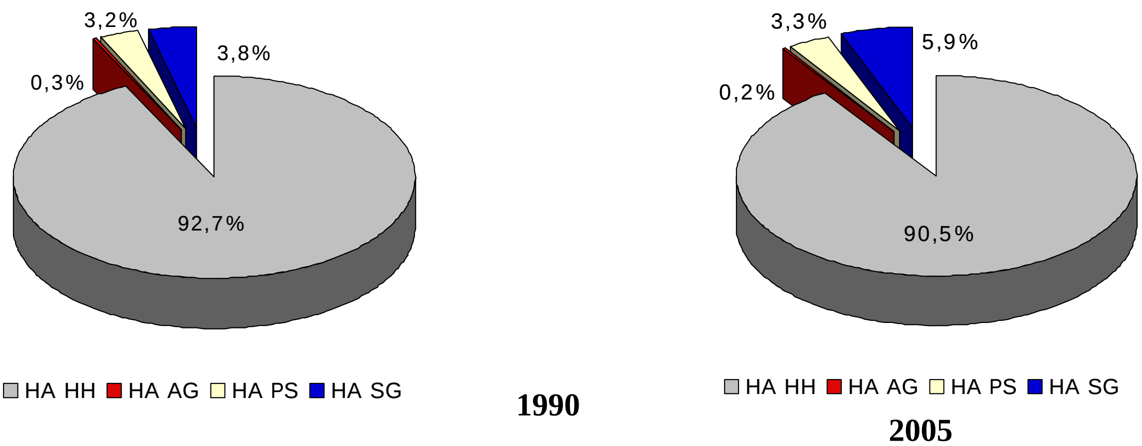
In fact, HA_{HH} grew from 49,400 million hours in 1990 to 55,100 million hours in 2005, at a mere 0.7% a year, far below the yearly growth rate 2.5% for working population. This result is positive in the short term, since it allows overcoming the problem of an ageing population, but it is only a question of time that the problem will surge again 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.

3.3 Level n-2: Evolution of the productive sectors

The massive entrance of inmigrant population to the labour market has gone hand in hand with a change in the structure of the labour market. According to Ramos-Martin et al. (2008) agriculture lost 1% of working population in 2005 when compared with 1990, industry lost 9 percentual points, and services gained 10%.

In order to see how this structural change explains EMR_{PW} as presented in the previous section, we need to introduce the exosomatic metabolic rates of each sector. This is what we do in Figure 4. EMR_{PW} depends then, on the behaviour of each individual EMR_i and the profile of distribution of working time among sectors (Figure 3).

Figure 3: Distribution of time use between production and consumption in Catalonia, years 1990 and 2005



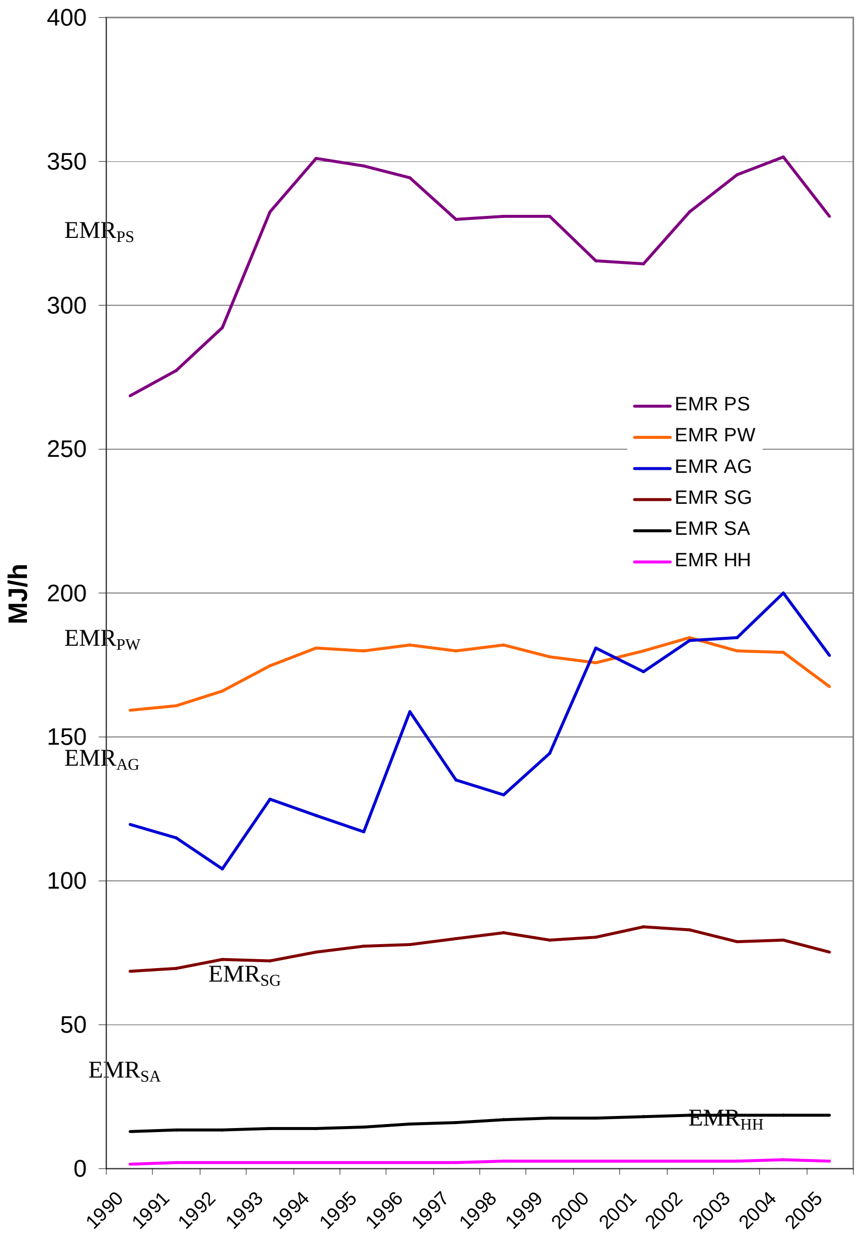
The first result we want to highlight from Figure 4 is the huge difference in the exosomatic metabolic rates the different sectors show. This is due to the difference in the capital that is needed to perform the different activities. Therefore it is understandable that agriculture needs more energy per hour of work than say, services. The sequence for Catlonia 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 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

[3] According to the INE Survey on Life Conditions, in year 2005 76,5% of Catalan households had a private car, 58,9% a personal computer, 98,8% a 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.

analysed EMR_{PS} increased very little, from 268 MJ/h in 1990 to 331 MJ/h in 2005, but due to the fact that industry 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 in said period.

Another interesting issue is to see how EMR_{PS} followed the economic cycle, in other words, it increased faster in economic booms and went back 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.

Figure 4: Evolution of EMR_i



4. Discussion and conclusion

4.1 Distribution of time among activities

When focusing on human time allocation (Figure 3) one realises the small amount of time the society dedicates to generate added value. The share of human time allocated to the PW sector[4] was 9.5% in 2005, up from its 7.3% in 1990. The increase may be driven by two factors. On one hand the 1 million population increase was due to inmigrants, most of them in working age, and actually working. On the other hand, the country has seen a massive entrance of women in the labour market, actually 60% of the new active population. This situation may change in the future if more stringent immigration policies are put in place, a fact that would hit harder economies such as Catalonia, with an ageing population that badly needs either a higher female activity rate, more immigrants, or both.

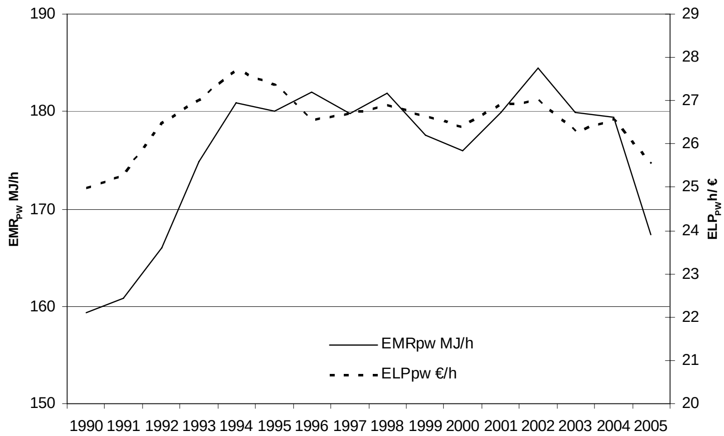
Regarding the distribution of active population among sectors, the picture is similar to other European economies, with services dominating the labour market. Most interesting is the new active population (totalling 1.1 million) that were directed mainly to services (940,000) and construction (140,000), while active population in both agriculture or industry remained stable. This result is not particularly good, since these two sectors are characterised by being non-tradable, and therefore closed to international competition, a fact that explains its low productivity. Therefore, if population is ageing and we face a higher dependency rate in the future, productivity gains must be obtained, meaning more energy has to be consumed per hour of work in order to drive a technological change.

4.2 Link between economic growth and energy consumption

If we follow 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 (ELP). This is explained by the fact that an increase in EMR_{PW} means both the use of more machinery and tools (ie 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., 1984), Ecuador (Falconi 2001) and Spain (Ramos 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 Figure 5).

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 productive 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.

Figure 5: Link between EMR and ELP in Catalonia (1990-2005)



[4] 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 sociocultural, like women participation in the labour market.

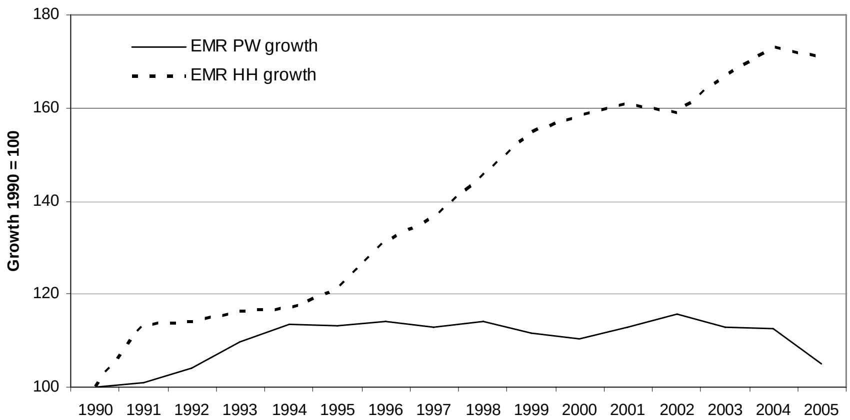
The ageing population mentioned in the previous section implies that Catalonia faces the challenge of increasing dramatically its productivity of labour while keeping its energy intensity at current (EU-15 average) values. Something that can only be done if undergoing a tremendous structural change that 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 the period was 3%. However, Figure 6 shows how EMR_{PW} has grown very little in the period, while EMR_{HH} has been the main driver of rising energy consumption. In fact we have already pointed how the increase in TET was mainly directed to increasing 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.

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) tend to fix future energy consumption. Energy that will be more expensive, and that will be purchased with added value generated by an ageing population and work force. Therefore, the urgent need to increase productivity of labour that will drive up energy consumption in the PW sector in the short run.

Figure 6: EMR_{PW} and EMR_{HH} growth over time



4.4 On the evolution of the subsectors al level n-2

We have seen the huge differences in EMRi among sectors in Section 3.3. Therefore in order to see the real impact of a transition towards the service sector that many suggest, one should know the share each energy carrier represents in the consumption for each sector. This is what was done in Ramos-Martin et al. (2008). According to those authors, the first energy carrier used by industry is natural gas, followed by electricity and oil products, whereas SG (that in our case includes 75% of transportation) consumes 60% of its snergy from oil products, followed by electricity and natural gas. Therefore, a shift of working population from industry 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 in terms of energy dependency or CO_2 emissions is relativised. In the case of agriculture the improvement of moving 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 the case of the household sector (which includes 25% of the transport sector energy consumption), 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} has a very high impact in terms of energy dependency and its relative impact upon the environment is higher than an increase in industry. 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 production by the different sectors. That is, to see how much added value is generated by a GJ of primary energy consumed. This is obtained by calculating ELPi/EMRi, as shown in Table 3 for all the productive sectors combined (PW) and for the three economic sectors considered at level n-2.

It is interesting to notice that what we have said befote regarding the evolution of the productivity of labour can also be seen in terms of the energyc efficiency of production. The first result is that, by large, the service sector is the one that generates more added value per unit of energy. Moreover, it is shocking that industry 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 turn warning lights on for policy makers especially in a context of increasing fossil fuel scarcity and parallel oil-price hikes. It is urgent that Catalonia squeezes its use of energy carriers, be it with technological improvements, or with structural changes directing activity towards services, although keeping in mind that the first option must always be to conserve energy and reduce demand.

Table 3: 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

4.5 On the model of development

The main conclusion of the paper is that the growth model for Catalonia, heavily depends on the consumption of energy, with a correlation between GDP and primary energy consumption of 98% in the past 15 years (Figure 1), cannot be sustained in the future. This is due not only to the environmental impact associated with fossil energy consumption and the associated greenhouse gas emissions, but also because of the increasing dependency on foreign and expensive energy carriers.

During the period analysed, the huge increase in energy was not reflected in qualitative changes of the development model, but just a mere replication of the current trends, therefore, just growth. In fact, the increase in energy consumption was not directed to inducing a structural change towards less energy intensive activities, while generating more added value. In contrast, it was directed to provide new active population with the necessary means to conduct their 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, but the lack of innovation and investment in new technologies will make productivity improvements harder to get, being the first limiting factor Catalonia will face in the near future.

This result is more worrying when we consider population is getting older, meaning a lower share of active population will be in charge of generating added value in the future. Therefore the solution is to encourage substitution of cariers for electricity generation (phasing out coal power plants) to improve the ration final energy / primary energy, or to limit energy consumption at the household level (the sector which will see the main increase in activity in the future), or improving its productivity of labour, or both. However, limiting consumption in diffuse sectors such as households or transport is very unpopular and very costly, and improving productivity of labour will require increasing the amount of energy consumed by hour of work and a structural change towards less intensive sectors. This is what drives us to conclude that we foresee energy consumption, and therefore Catalonia's exosomatic energy metabolism to increase in the near future.

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