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A becoming China and the assisted maturity of the EU: Assessing the factors determining their energy metabolic patterns

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ABSTRACT

This paper presents a multiscale integrated analysis comparing changes in the energy metabolic pattern of China and the European Union between 2000 and 2016. The MuSIASEM method is used to explore and illustrate the entanglement over different factors, across dimensions and levels of analysis. Demographic factors observed at the level of the whole are linked to changes in the economic structure, the pattern of energy uses and the level of outsourcing (imports). When analyzing these issues for the selected case studies we found that: (i) due to their lower dependency ratio and higher workloads China presents now about 1260 h in paid work per capita, while the EU presents just 720; (ii) economic structure in China evolved rapidly moving almost 300 h per capita per year from agriculture to service, construction and industrial sectors, while it remained quite stable in the EU; (iii) the metabolic pattern of China changed dramatically by expanding its capital goods in all sectors (almost 4 times in agriculture and more than doubling in industry and services) while the EU just increased them around 10%. The quick industrialization of China (going from 20 to 60 MJ/h in paid work sector) required an extraordinary investment in the construction sector, which arrived to allocate almost 3 times more workforce and 5 times more cement per capita than the EU (already industrialized). The simultaneous reading of all these changes confirms known trends and identifies a few challenges. The apparent decoupling of economic growth from resource consumption in the EU economy is due to the outsourcing of industrial production (identified and quantified at the level of subsectors). The trajectory of economic development of China, still in the phase of industrialization, spells troubles in terms of future consumption of natural resources and pollution. The metabolic perspective used in the comparison enables to identify policy-relevant factors determining both temporary comparative advantages and dangerous locks-in. On the methodological side, the paper illustrates a few innovative features introduced in the MuSIASEM accounting framework improving the characterization of demographic and other societal aspects affecting the overall energy metabolic patterns of societies.

1. Introduction

Nowadays, China has a prominent position in any discussion over sustainability at the global level [1]. Due to its large population size and the outstanding pace of its economic growth, China is rapidly becoming a key player in the global economy. Despite having still a quite low level of energy consumption per capita, it has become the largest energy consumer in the world [2]. The explosion of its consumption of energy is associated with a similar explosion of consumption of materials – e.g. China has consumed more cement in 3 years (2011–2013) than the USA in the last century [1]. This metabolic change required massive economic investments that generated a critical lock-in on the consumption of primary energy sources – e.g. the required investments of coal power plants will have to be repaid by operating them for decades - that jeopardizes the 1.5 °C policy targets [3]. Finally, China is going through a quick transformation, into an urban society. This is another transformation that forces a deep change in its economic structure: the economy of China will soon require a much larger fraction of services, according to the expected trend observed in other developed countries [4–6].

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When looking at the situation of the EU (an already a rich developed economy), we find the opposite combination: high level of energy uses per capita are quite stable - the value of energy use per capita in 2015 is more or less similar to the value in 1995 [7] - and a demographic structure typical of an aged society. The post-industrialization of its economy is already a fact.

It is obvious that the existence of these significant structural and functional differences between the economy of China and the EU are very relevant for informing energy policy [8] and more in general for an effective framing of sustainability issues – e.g. the new European Green Deal [9]. If we want to compare the use of energy in China, and the EU, we should be able to answer the following questions: Why energy is used in the economy? What type of secondary energy is used (electricity, fuels, process heat)? By whom? To do what? How are various functions of the economy expressed? What are the main factors driving energy use variations? When moving to a local level of observation, how effective are the uses of different forms of energy carriers in relation to specific tasks? By answering these questions, we can identify causal relations between economic growth and changes in the level of energy uses, changes in the size and the demographic structure of the population, the effects on the material standard of living, the structural adjustment of the economy reshaping the relative size of economic sectors, and environmental impacts associated with the activities of the economy. However, the analysis of the entanglement over these changes cannot be done unless we "translate" the meaning of these terms – economic growth, energy uses, demographic characteristics, standard of living, relative change in the size and activity of the economic sectors, environmental impacts – into an integrated quantitative representation of the relations over these concepts across different levels and dimensions of analysis [10,11].

The concept of Social-Ecological Systems (SES) [12–15] is used in this analysis to face this epistemological challenge. This concept has emerged in the field of Ecological Economics in relation to the need for complementing conventional economic narratives with novel narratives when characterizing the performance of an economy [16]. This integration is obtained by adopting the concept of the metabolic pattern of Social-Ecological Systems (SES) [12–15]. The MuSIASEM accounting scheme (briefly illustrated below) is used to generate this integrated quantitative representation of the relations over demographic variables, economic structure, technological performance and effect of outsourcing on the characteristics of the energy metabolic pattern.

The study analyzes changes in the energy metabolic pattern of the economy of the EU28 (still including the UK) and China during the period 2000–2016. We describe the changes across multiple levels: (i) the overall energy metabolism of the China and EU (level n). At this level, the characteristics of the whole society are affected both by extensive variables (size of the population, total consumption of resources) and intensive variables (overall consumption per capita). These characteristics observed at the level of the black-box do not allow an analysis of the typology of metabolic pattern expressed by the socio-economic process; (ii) the metabolic characteristics of their macro-economic components: 'paid work sector' and 'household sector' (level n-1). At this level, we can study the effect of yearly workload, unemployment, inactivity or demographic variables as the dependency ratio over the metabolic pattern of nations. Moreover, we can also study the difference balance in the priority given to the investments in the market economy and in supporting the non-market economy through metabolic indicators. Data show that China is investing heavily in the capital goods of its commodified economy, taking advantage of the cheap supply of labor, but this reduces the possibility of developing quickly an internal economic demand in its households. In comparison, the EU has a higher and an stable level of capital goods both in the paid work and in the household sector (around six times higher than China). The better protection and extensive preparation of its workers makes the cost of its labor more expensive; (iii) the metabolic characteristics of the elements of the paid work sectors (level n-2) can be used to study internal drivers of the evolution of their economic structure. At this level we can see the modernization of China reflected in the expansion of its industrial and construction sectors; and a massive shift of human activity from agriculture to service sectors; and (iv) the metabolic characteristics of specific sub-sectors (level n-3) where finally we can study the effects of both changes in the technology and the level of externalization of the economy (outsourcing). These characteristics are studied by plotting changes in key factors of the end-use matrix over the chosen period. The proposed method of accounting does not make predictions but it can be used to explore the option space generated by the complex set of relationships across scales and dimensions. The rest of this paper is organized as follows. Section 2 describes the methodology employed and the statistical data used. Section 3 provides the results: a holistic vision on the pattern of metabolic changes that took place in the period in EU28 and China; Section 4 reflects and discusses the findings, and Section 5 concludes.

2. Methodology

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

A Social-Ecological System can be defined as the complex of functional and structural components operating within a prescribed boundary that is controlled in an integrated way by the activities expressed both by a given set of ecosystems (outside human control in the biosphere) and a given set of social actors and institutions operating in the economy (under human control in the technosphere) [17]. In this framing, the performance of an economy is associated with the expected characteristics of the "emergent property" of the social-ecological system determined by the interaction of lower-level functional components (e.g. economic sectors) embedded in the biosphere. These functional components are made up of structural elements – i.e. expressing the physical processes taking place in their constituent components. The emergent property of an economy is represented by its ability to reproduce and adapt according to its internal values and aspirations while interacting with its context [11]. Using the concept of metabolism, we can describe the structural and functional organization of society in the same way we describe the structural and functional organization of a biological organism [18,19].

For example, by adopting this analogy, we get an effective way of describing the differences in the metabolic pattern of China and the EU. China is an "adolescent" metabolic system still growing in size: it is still building the required structural elements needed to be able to express an enlarging profile of functions. EU is an "old lady" no longer growing in size (actually shrinking because of age). In this analogy, the EU is just maintaining and adapting the existing set of functions to changes in its boundary conditions. This different narrative flags the need for a novel approach to the quantitative analysis of the use of energy in social-ecological systems – we cannot compare the efficiency in the use of food energy of a "12-year-old" and a "90-year-old" person.

Economic narratives tend to miss these types of differences. In fact, they use econometric analysis extrapolating in the future the validity of existing sets of relations, although metabolic systems are becoming systems [20] changing their characteristics in time. This entails that the validity of the parameters used in econometric analysis tends to expire in time. There are other methods used currently in sustainability analysis to study the exchanges of material flows associated with the economic process: (i) Life-cycle assessment focusing on the characterization of the performance of specific processes or products. This solution generates the risk of losing the big picture and lacks the specific contextualization that would be required to reflect the specific purposes of the analysis [10,21]; (ii) Input-output analysis [22–28] or Material and energy flow accounting (MEFA) providing a representation of flows based on a pre-analytical definition of a given scale of analysis. The lack of an integrated representation across scales entail missing relevant systemic aspects of the metabolic pattern as the changing profile of human time allocation within the structure of the economy. These changes are related in an impredicative way with changes in demographic and technical factors (e.g. the strength of the exosomatic hypercycle or the bio-economic pressure) [11]. In general, all these methods do not make a distinction between funds and flows elements [29,30] when coming to the representation of extended production functions – i.e. the specific processes generating the invariant ratio between inputs and outputs. The missing of the relevance of flow-fund relations carries the risk of generating misleading indicators based on flow-flow relations such as the economic energy intensity or the material/resource intensity that are unable of distinguishing between industrialized and subsistence metabolic patterns (energy and material use are strongly correlated with value added generation!) [11,31,32]. However, these methods can be used in combination with MuSIASEM for characterizing supply systems and for studying resource footprints of imports [33–35]. In particular LCA coefficients can be used for characterizing production processes at lower levels and IO tables are essential for interrelating materials and products among sectors and countries [36–41].

The concept of metabolic pattern, implemented in terms of relational analysis, allows studying how the changes in the profiles of inputs and outputs affect each other in an impredicative way, by looking at changes in the processes of transformation taking place across various levels of organization [11,42,43]. This method of accounting studies the metabolic characteristics in terms of "expected" profiles of input/output ratios, whose robustness as external referents is given by the entanglement of relations over the characteristics of its functional and structural elements [44–49]. The State-Pressure approach is then used to establish a link between what is going on inside the system and the requirement of primary flows (on the supply and sink side expected from the context) [50–52].

More specifically we use here one of the tools developed in MuSIASEM called the end-use matrix [10,53]. This tool allows to study: (i) the relative size of the functional and structural elements across scales (their size in absolute terms and their size in relation to each other at different levels); (ii) the metabolic characteristics of functional and structural elements (their energy consumption per type of energy carrier in absolute terms and their energy consumption per unit of size); (iii) the effects of the combination of functional and structural elements associated with the identity of the society. By organizing the accounting in this way, it becomes possible to answer the list of questions provided above.

The metabolic pattern of a Social-Ecological System is determined by the activity of its constituent components divided in: (i) primary sectors - the catabolic part in biophysical terms, taking advantage of favorable gradients provided by nature to supply the required biophysical inputs (secondary inputs) to the rest of society. Using the category used by national statistics these sectors are: Agriculture, Forestry & Fishing and Energy & Mining; and (ii) the rest of sectors - the anabolic part in biophysical terms, using secondary inputs supplied by the primary sectors to maintain and reproduce the society. Using the category used by national statistics these other sectors include: Manufacturing & Construction, Service & Government and the Household sector (HH).

The 'end-use matrix' describes the interactions taking place inside the black-box across various hierarchical levels of analysis and dimension [11,42,54]. It builds on Georgescu-Roegen fund-flow model [29], considering human activity as a fund (element preserving its identity through the time duration of the analysis), and energy throughput and value-added as flows (elements appearing or disappearing during the time duration of the analysis) [11]. The end-use matrix, described in detail by Velasco-Fernández et al. [53], characterizes in quantitative terms the relations between flows and funds across scales (i.e. temporal, space), levels (i.e. institutional, geographical) and dimensions (i.e. depending on the choice of the analyst, it can include energy, water, materials, wastes, money, human activity, land) [32,43]. An analysis across hierarchical levels in the form of end-use data arrays. The society as a whole is considered the focal level (n). The next lower level (n-1) distinguishes between the "paid work" and the "household" sectors. One level further down (n-2) we have the constituent components within the market as main paid work sectors: agriculture, industry, construction, transport and service & government. At level n-3, we can observe the characteristics of industrial subsectors. At level n-1, the household sector includes energy use in residential and private mobility and all the human activity out of the market (e.g. sleeping, commuting or 24 h of retired, children and unemployed people). In that sense, when analyzing its metabolic pattern, we can capture relevant changes in material standard of living: introduction big appliances or the use of private cars and motorcycles. Note that the household sector (defined at level n-1 as the difference between population times their yearly hours (8,760) minus the registered hours in paid work) is not further sub-divided into this work. However, this is possible as illustrated in the characterization of Barcelona's metabolism [55]. In that sense, we get two limitations in the accounting presented here: (i) we are not considering the HA of tourists, foreign workers developing their activities in second regions or paid work hours not registered in official statistics (e.g. informal economy), even though their energy use is considered in the accounting; and (ii) we are not distinguishing among the different human activities taking place in the household sector.

Each of these compartments is characterized with the following indicators: exosomatic energy throughput (ET), human activity (HA), exosomatic energy metabolic rate (EMR), gross value added (GVA) and economic job productivity (EJP). When referring to level n (average society), we get the total energy throughput (TET) and total human activity (THA). Energy throughput is a generic indicator making references to a quantity of energy flow type transformed by a metabolic component. It could be expressed in terms of exosomatic (e.g. electricity, process heat, fuel) or endosomatic (e.g. vegetables, meat) energy carriers, or their equivalent expressed in gross energy requirements (e.g. thermal equivalent) [33,56]. In this study, ET is expressed in thermal joules of Gross Energy Requirement equivalent (GER) as there are already too many complexifications in the analysis. Human activity refers to the actions carried out by people, here considered as a fund (population is preserved) and quantified in hours. EMR is defined as the quantity of exosomatic energy transformed per hour of human activity. This indicator is basically driven by the use of power capacity [57,58] and in that sense, we use it as a proxy of the level of capitalization of the sectors: how much technical capital or capital goods (machinery, devices and infrastructure in a wide sense) is used to perform a certain activity. This indicates the level of mechanization and modernization of a society, which is related to its energetic (and resource) dependency on its environment. The effects of efficiency over the metabolic performance of a society are far from clear due to it is mixed with other effects as the Jevons paradox [21,59], the operation load or the utilization factor of the power capacity [10,60]. Economic job productivity (EJP) indicates the value-added generated per hour of paid work, it is, a measure of the labor productivity in monetary terms.

In this system of accounting the definition of constituent components is being mutually exclusive. This means that the extensive variables describing their size must maintain closure across different levels of analysis:

$$TET \text{ (level n)} = \Sigma ET_i \text{ (level n-1)} = \Sigma ET_j \text{ (level n-2)} = \ldots = \Sigma ET_k \text{ (level n-x)}$$

$$THA \text{ (level n)} = \Sigma\, HA_i \text{ (level n-1)} = \Sigma\, HA_j \text{ (level n-2)} = \ldots = \Sigma\, HA_k \text{ (level n-x)}$$

This entails forced metabolic relations over the size of the constituent components and their metabolic pace according to the following equations of congruence across levels:

$$TET\ (\textit{level n}) = THA \times EMR_{AS}\ (\textit{level n}) = [HA_{HH} \times EMR_{HH}] + [HA_{PW} \times EMR_{PW}]\ (\textit{level n-1})$$

For example, at the level n:

$$TET/THA = EMR_{AS} \text{ (average society, level n)}$$

$ET_{HH}/HA_{HH} = EMR_{HH}$ (household, level n-1)

$ET_{PW}/HA_{PW} = EMR_{PW}$ (paid work, level n-1)

The metabolic pace of the society (EMR_{AS}) observed at the *level n* depends on four distinct factors that can only be observed at the *level n-1*: the human activity of the household sector and the paid work sector (HA_{HH} and HA_{PW}) and the pace of energy metabolism in the household sector and the paid work sector (EMR_{HH} and EMR_{PW}). This same set of expected relations can be used to move the analysis further down the hierarchy (see Table 1).

2.2. Variable and data sources

All data used is secondary data from the statistical offices of the European Union and China for the years 2000–2016. EU data includes all members of the European Union (EU28), while Chinese data do not include Hong Kong, Macao and Taiwan. Tables 2 and 3 show the variables in the analysis and the data sources.

Both European and Chinese statistics for energy, labor and economic statistics about value-added are based on the ISIC classifications and hence largely comparable. However, while in Chinese statistics the consumption of energy carriers in the private transport (private cars and motorcycles) is included within the household sector; in Eurostat statistics, it is included in the services sector (transport). Therefore, data from Eurostat Energy Balances [62] were recalculated, isolating fuel consumption of private cars and motorcycles from the transport services sector and adding it to residential energy consumption. For more detail go to Appendix A.

For each component, the quantities of energy carriers metabolized (electricity, process heat and fuel) are assessed (in joules per year) as well as the monetary value added (in chain-linked volumes (2005) euros (€) and yuan (¥) per year). Due to the different currencies, this can only be compared across scales inside the same region, but not between them. Total energy throughput (TET) of each component is reported as 'primary Gross Energy Requirement equivalent' (GER in J thermal energy) by converting the given mix of energy carrier consumption (electricity and fuels) into a notional quantity of thermal joules, using the partial substitution method [69] and assuming a conversion efficiency of 38,6% provided by the World Energy Council [70] for electricity and considering one to one for fuels. The energy metabolic rate (EMR, in J/h) of each component is obtained by dividing the total energy throughput by its size.

When considering the results, one has to take into account the reallocation of data for EU countries affecting the households and transport service sector that could introduce differences with other similar analyses [8,71,72]. Additionally, as the reliability of China statistics has repeatedly been questioned [73,74] the results should be considered indicative.

Table 1
Levels and sectors of analysis.

n	n-1	n-2	n-3
China/ EU28	Paid Work (PW)	Agriculture, forestry & fishing (AFF)	
		Industry (IN)	Energy & Mining (EM)
			Food & Tobacco (FT)
			Textile & Leather (TL)
			Pulp, Paper & Print (PPP)
			Wood & Wood Products (WWP)
			Chemical & Petrochemical (CP)
			Non-Metallic Minerals (NM)
			Basic Metals (BaM)
			Machinery (Ma)
			Transport Equipment (TE)
			Non-Specified Industry (NS)
		Construction (CO)	
		Transport Services (TS)	
		Services and Government (SGnT)	
	Households (HH)		

3. Results: analyzing the energy performance of China and EU28 across scales

3.1. Looking at the regional level

The characteristics useful to study the overall energy metabolic characteristics of EU28 and China are shown in Fig. 1; total human activity expressed in gigahours per year, the total energy throughput expressed in Exajoules of thermal GER, and the energy metabolic rate (the coefficient of previous indicators). This figure shows three relevant facts. The first is that China's energy use has doubled from 44 to more than 120 EJ, surpassing EU28 in 2006. It has become the world's largest energy user, also overcoming the US in the year 2009 [75]. Second, this increase is due to the skyrocketing energy metabolic rate (EMR) of China going from 4 to more than 10 MJ/h (+150%) and not due to a population increase (just +9%). Finally, the European Union presents a stagnant energy use around 70 EJ. This is due to its EMR slightly decreased (−4%), while its population grew in a similar amount (+5%).

To examine the drivers of the difference in overall metabolic rates of the EU and China (level n), we open this 'black box' and observe the constituent elements household and paid work sector at the lower level (n-1) in the next section 3.2.

3.2. Household and paid work sectors

3.2.1. Implications of the socio-demographic characteristics

When looking at the metabolic pattern of a society it is crucial to identify its socio-demographic characteristics. This is because the energy metabolic rate (EMR) in the paid work sector is generally many times higher than that of the household. In 2014 in China EMR_{HH} was 1.7 MJ/h, while EMR_{PW} was 58 MJ/h: a difference of 34 times. Therefore, the relative size of these compartments must be analyzed carefully. It is affected both by demographic and socio-economic factors. China allocates around 14,5% of human activity to paid work (1260 h per capita per year, ±20 h during the analyzed period), almost double than the European Union with just 8,5% (750 ± 25 h). The most relevant factors determining this difference are the workload (hours per worker per year) and the dependency ratio (the number of children and elderly relative to those in working-age, between 15 and 64 years old). Other factors to be considered are unemployment, inactivity and the effect of holidays and other social regulations. It should be noted that here we define inactive as people between 15 and 64 age that do not contribute in the paid work sector as they are students, housekeepers, pensioners, disabled, pure rentiers or just NEETs (Not in Employment, Education or Training) [76]. The fraction of human activity invested in the Paid Work sector indicates the structural pressure on the productive population: the given supply of paid work has to sustain the material standard of living of the whole population.

China's dependency ratio - shown in Fig. 2 - has decreased during the first part of the period of study (around 80% during the 60s until 36% in 2010) and afterward it has increased until 40% in 2018. The reduction is produced by the "child dependency ratio" going from around 70% in the 60s to 25% determined by the important reduction of natality from the one-child policy introduced in 1979 and replaced at the end of 2015 by the two-child policy. On the other hand, the "elderly dependency ratio" increased slightly from 6% in the 60s to 10% 2000s and more

Table 2
Main variables and data sources for the EU energy metabolic pattern analysis.

Variable	Database	Data sources	Brief description
Human Activity (HA)	*Total employment domestic concept* (hours worked)	*National accounts employment data by industry (up to NACE A*64)*	Employment covers all persons engaged in some productive activity (within the production boundary of the national accounts). Employed persons are either employees (working by agreement for another resident unit and receiving remuneration) or self-employed (owners of unincorporated enterprises).
	household hours	*Population on 1 January* [61]	Difference between total paid work hours and total available human time in hours per year (i.e. population multiplied by 8760).
Monetary Value-Added	Gross Value Added	*National accounts aggregated by industry (up to NACE A*64)*	Chain linked volumes (2005), million euro
Energy throughput	Energy products by final use	*Eurostat Energy Balances* [62]	Data on final energy consumption by sector, excluding non-energy use and allocating distribution losses to the Energy Sector. Household and Transport sector have been recalculated; see Appendix A for details.

Table 3
Main data sources for the analysis of the China energy metabolic pattern analysis.

Variable (abbreviation)	Database	Data sources	Brief description
Human Activity (HA)	Number of workers	*China Statistical Yearbook (2001–2016)* [63]	With the number of employed persons at Year-end in urban and rural areas, and the details of the sectors of level n-2 are depicted from the proportion of *the 2010 population census*.
	Working time (workload)	*China Labour Statistical yearbook (2001–2017)* [64], *The 2010 population census of the People's Republic of China*	Weekly working hours in the urban area by sector are from the series yearbook from 2001 to 2016. Since the survey only includes urban areas; we adjusted the number from the 2010 Population Census of China.
	Household hours	*China Statistical yearbook (2001–2017)* [65]	Defined as the difference of total hours (population multiplied by 8760) and working hours.
Monetary Value-Added	GDP	*China Statistical Yearbook (2001–2017)* [63]	Indices of gross domestic product from the yearbook, with the year 2000 as constant.
Energy throughput (ET)	Energy carrier	*China Energy Statistical Yearbook (2001–2017)* [66]	Total final consumption of energy carriers of the China Energy Balance table, with the exclusion of the non-energy use. Since it excludes the consumption of fuel of low calorific value, bio-energy and solar energy [67], we include the waste and biofuels data of rural energy from IEA statistic [68].

importantly during the second period arriving until 15% in 2018, due to the generalized improvement in life expectancy after the year 2000 going from 71 to more than 76 years old in the year 2016 [77]. Therefore, the dependency rate of China will probably increase significantly during the next decades, especially due to the increase of both the proportion of retirees (due to the one-child policy) and life expectancy (given by an improvement of the material standard of living during the 2000s [71]).

European dependency rates indicate an aging population (see Fig. 3). It presents a quite stable path going from 49 to 53% between the years 2000 and 2016. The "elderly dependency ratio" increased all along the period. It even surpassed in 2005 the "child dependency ratio", as a result of the constant increase of life expectancy from 78 to 81 years [78] and a fertility rate of around 1.6, half-point below the replacement rate [79]. This makes the European Union an old and aging region.

Comparing both regions, the European Union presents a higher dependency ratio than China, a difference that has been increasing from 3% (49% vs 46%) in 2000 to more than 14% (53% vs 39%) in 2016. This difference represents a temporary competitive advantage for China, which will become a disadvantage when the one-child courts reach retirement age increasing the elderly dependency ratio significantly.

As stated above, not only the relative size of the dependent populations in terms of age (children 0–14 years and elderly 65+) affect the profile of allocation of human activity in the metabolic pattern. The average working hours per worker per year is by far the most important, however also unemployment, and the fraction of inactive population in working age should be considered. For taking out the demographic effect over these other factors in the comparison, their assessment is expressed over the working-age population (between 15 and 64 years old) instead of the active or total population. The unemployment rate over the population between 15 and 65 years in Europe is about 6.5% (±1.5%, variation during the analyzed period) [80]. That is twice as much as China, which is about 3.5% (±1%) [81]. On the other hand, the economically inactive population between 15 and 64 age (students, pensioners, housekeepers, etc.) during the analyzed period (2000–2016) has been reduced from more than 31 to 27% in the European Union and increased from 17 to 24% in China [82]. In both cases, unemployment and inactivity in the working-age population are higher in Europe, which put more pressure over the workers to sustain this dependent population. Coming to the differences in workload per year, Chinese workers present lower vacation time and higher workloads with about 2220 (±40, variation during the analyzed period) paid work hours per worker per year, while European ones present 1730 (±45) hours. Current 996 debates in China [83] and campaigns against it (996.ICU) suggest that long working hours could be reduced soon. When considering unemployment, inactive population, vocational education time and higher workloads, we get that working-age population work per capita per year 1745 h in China and 1120 h in Europe. As it has been previously glimpsed, the differences between these workloads reflect that the European Union presents: higher social protection to workers (e.g. fewer workloads per week, unemployment allowance or more holidays); pensions for people with disabilities; and more assistance for having a higher proportion of tertiary education students.

Finally, adding up the demographic effects we get that China presents 1260 (±20, variation during the analyzed period) hours per capita per year in the paid work sector, almost the double than Europe with just 750 (±25) hours (see Fig. 4). As we shall see below, understanding

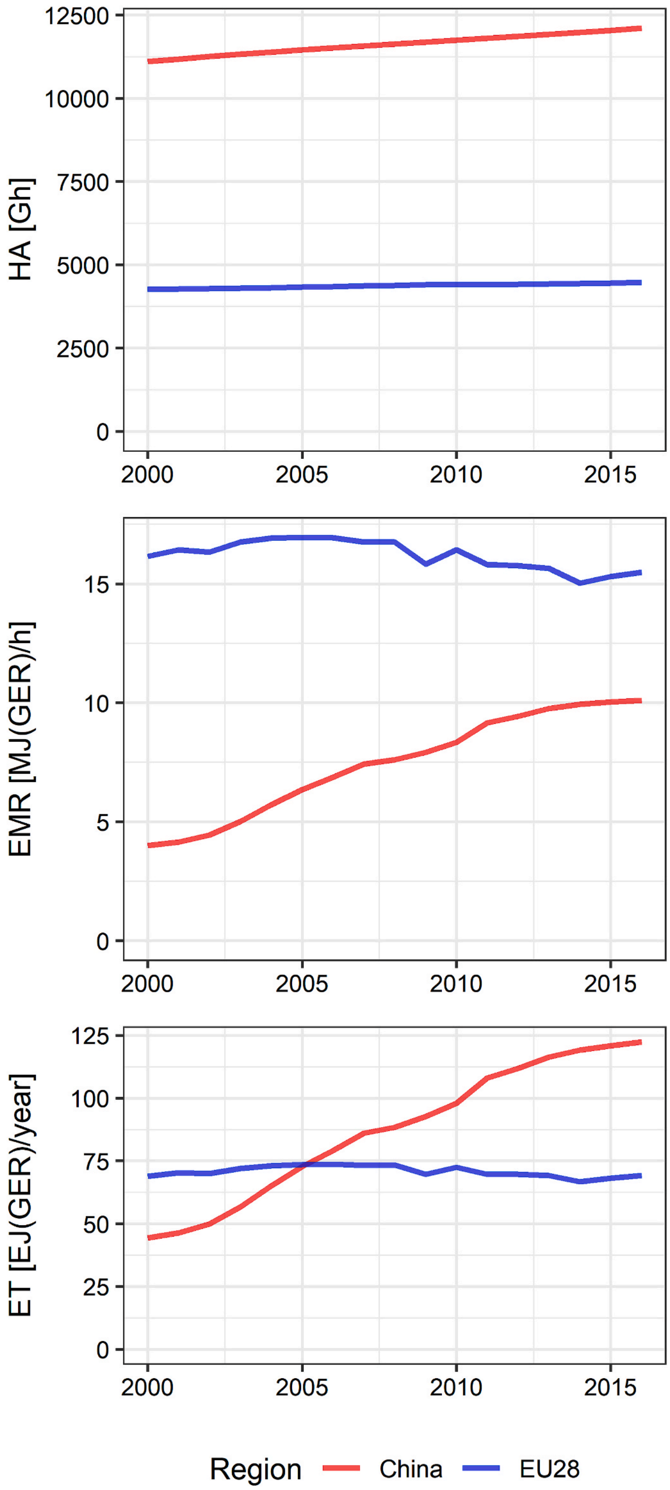

Fig. 1. Human activity (HA), energy metabolic rate (EMR) and energy throughput (ET) of China and EU28 at the level n (the whole) between 2000 and 2016.

better the connections of these issues with the energy performance of a society requires looking at how these hours of work are coupled to different energy metabolic rates inside the various sectors and subsectors.

3.2.2. Energy performance of the household and paid work sector

The metabolic characteristics of the household and paid work sectors of China and EU28 for the period 2000–2016 in energy terms are shown

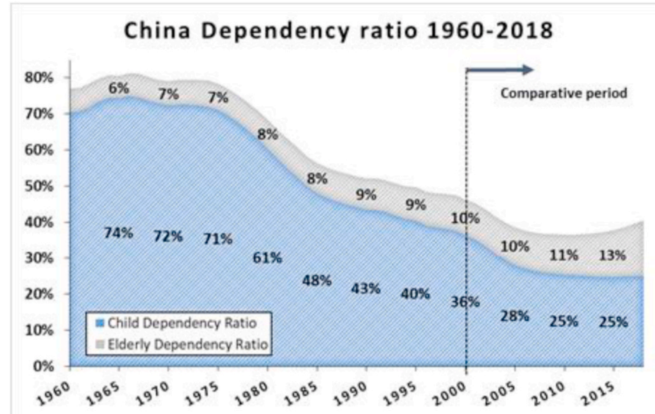

Fig. 2. Historical dependency ratios of China, (total, child and elderly) between years 1960 and 2018. The time duration of the analysis is longer than in EU to visualize the effect of the one-child policy. The period of the comparison begins in the year 2000 as indicated in the figure.

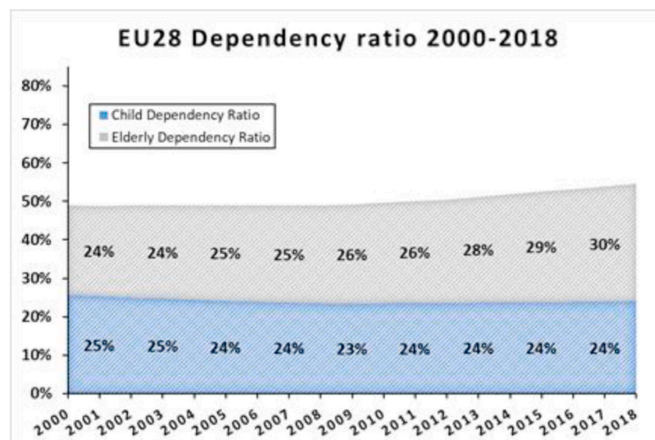

Fig. 3. EU28's dependency ratio (total, child and elderly) between years 2000 and 2018.

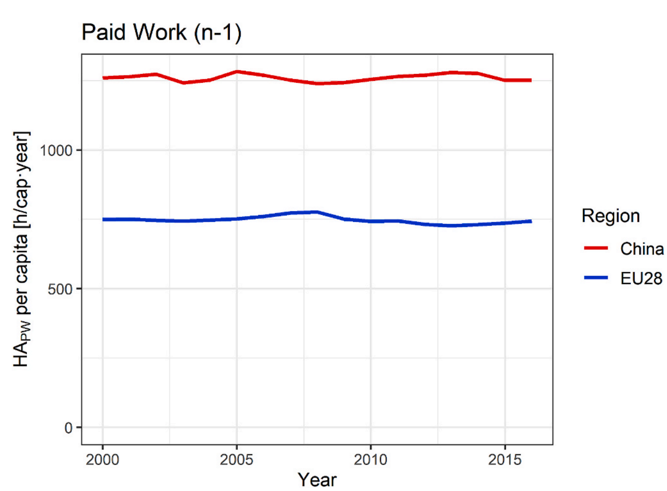

Fig. 4. Human activity per capita in paid work sector for China and EU28 between 2000 and 2016.

in Fig. 5, following the historical representation of the metabolic patterns of the paid work taking place in the market (not considering informal economy as in other analysis [55]) and human activity out of it.

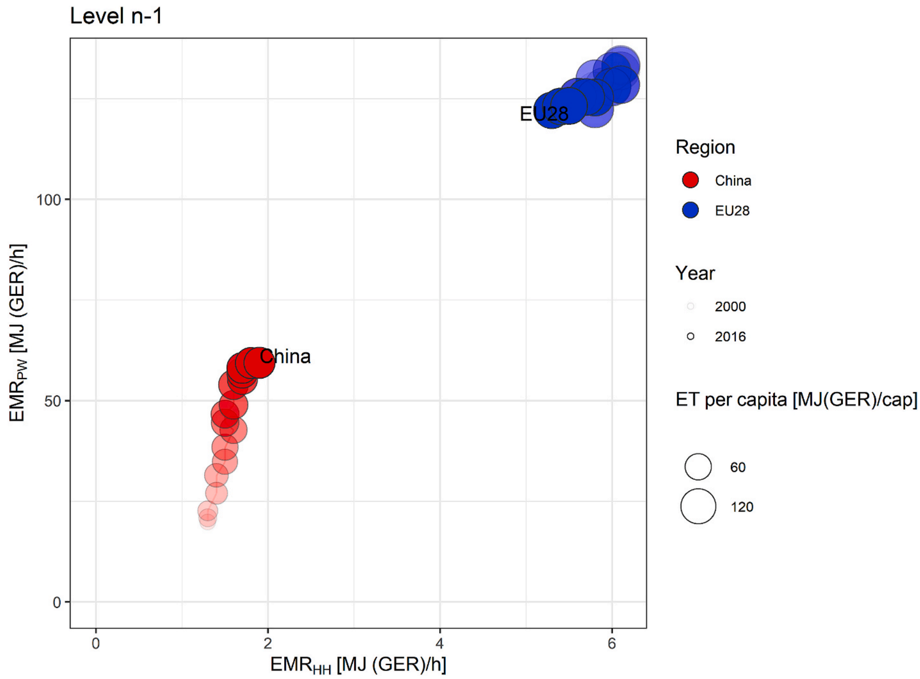

Fig. 5. Evolution in time (2000–2016) of the Energy metabolic rate (EMR) of household vs paid work for EU28 and China. Bubble size represents the energy use per capita (ETpc) expressed in joules of thermal equivalent.

This metabolic confrontation graphic was previously used in MuSIASEM analysis [71,84]. It shows the evolution of the introduction of power capacity [57,58] in the so-called production and consumption sectors (market vs families), which here are just identified as different compartments of the society metabolizing energy for different final causes [17,85–87]. However, this division could be also interpreted through the economic exchange modalities analyzed by Polanyi building in the works of Malinowski and Thurnwald [88]: while the paid work sector is driven by interchange and redistribution modalities, the household sector is dominated by reciprocity.

Following MuSIASEM rationale [71,89], the exosomatic energy metabolic rate (EMR) can be used as a proxy of the ability to boost the mechanical and cybernetic power capacity of human activity in generating useful work. When applying this rationale to paid work sector EMR becomes a proxy of the technical capitalization of the sector (i.e. mechanization and computerization making the activities more competitive in the market or more effective in public services), whereas in the household sector it is a proxy of the material standard of living (i. e. power capacity introduced to facilitate household chores and private mobility). This hypothesis has been validated in the analysis provided in Ref. [11].

It that sense, when looking at trajectories of changes on a plan determined by the EMR of the Paid Work sector (y-axis) and the EMR of the household sector (x-axis) in Fig. 5, we can see how the material standard of living of China has almost doubled during the analyzed period - EMR_{HH} went from 1 to 2 MJ/h. On the other hand, this value went from around 6 MJ/h in EU28 with a slight downward trend to 5.5 MJ/h in the last years. Part of this reduction is clearly generated due to the economic crisis in 2008 but analyzing this in more detail would require opening this sector to lower levels as done in other analysis [55]. When looking at the value of EMR_{HH} China presents similar values found in countries like Brazil (1.4 MJ/h), Chile (2.6 MJ/h) and Venezuela (2.1 MJ/h) in the year 2000 [90] or Bulgaria (1.4 MJ/h), Romania (1.8 MJ/h), Poland (2.4 MJ/h) and Hungary (3.1 MJ/h) in 2004 [91]. Even though Chinese households have experienced a large increase in access to appliances and automobiles, when compared to other countries there is still a long way to go. On the other hand, EU28 with higher values is still lower than Australia (6.8 MJ/h), Canada (8.8 MJ/h) and USA (10 MJ/h) in 2008 [92]. Differences among these high-income countries could be explained by their different urbanization types, where the urban sprawl and larger houses results in more intensive use of automobiles and heating/cooling than more compact European cities [93]. However, EU is a heterogeneous region where countries like Finland (9.8 MJ/h), Sweden (8.3 MJ/h) or Austria (7.3 MJ/h) present also a high EMR_{HH} (own elaboration data for the year 2016 following same data sources, methods and hypothesis of the current study). This heterogeneity has been already analyzed in previous MuSIASEM analysis following different data sources and hypothesis [42,72,94]. Needless to say, China's metabolic pattern includes even a greater heterogeneity among its regions [95,96].

When looking at the trajectories in the plan we can see that they are very different. While China presents an important growth going from 20 to 60 MJ/h in PW, Europe has a stable EMR_{PW} around 130 MJ/h that shows a slight decrease until 123 MJ/h. As a result, Europe metabolized six times more energy per hour in paid work than China in the year 2000, a difference that was reduced to just two times in 2016. When analyzing the metabolic patterns in paid work and household sectors all together, we can see that China is increasing its technical capitalization (the value of EMR) in both sectors, whereas EU28 is stagnant and, in some way, reducing it. Moreover, we can see that the transformation in China has been more intensively in the paid work sector (tripled during the period) and a little less in households (doubled). However, considering the size of the country these numbers are outstanding. The quick modernization of China has contributed significantly to the achievement of the Millennium Development Goals (MDGs) specifically in poverty reduction. When looking at poverty in terms of consumption or income, the poorest population in China are in rural areas. In that sense, the poverty reduction has been possible thanks to the price increase of agricultural products, technological progress and accumulation of capital (human and technical). In hour analysis we corroborate this observations trough metabolic indicators which indicate an increase in the level of capitalization in the agricultural (going from 1,5 to 5,7 MJ/h, +280%) and household sectors (going from 1,3 to 1,9 MJ/h, +46%), as well as in the EJP (going from 1,9 to 5,2 Yuan/h, +174%) and GVA in agriculture per capita (1495–2317 ¥ per capita, +42% during the period), while reducing the proportion of workforce allocated to the agricultural sector (614–325 h per capita, −47%): exosomatic energy (technical capital) substituting workers.

Comparing China with other countries we can see that after having achieved the result to get millions of Chinese out from poverty, economic policies have focused on getting competitiveness in the world market and rapid growth. This goal generates a clear trade-off between a further increase in material standard of living of the population and the need for keeping low labor costs to guarantee competitiveness. This problem can be identified when looking at the trajectory of China in Fig. 5 and at the evolution of the energy throughput per capita (ETpc), which has skyrocketed in China from 25 to 74 GJ per capita, while it has grown at a much more moderate rate in households going from 10 to 14 GJ per capita. On the other hand, Europe has experimented a stagnation in its energy use per capita both in the paid work and the household sector. ETpc in the paid work sector has slightly grown from 95 to 100 GJ per capita in the period before the 2008 crisis and decreased until 92 GJ per capita during the last years. Similarly, ETpc in the household sector has been fairly stable during the first part of the period over 49 GJ per capita, while decreasing during the last part of the period until 44 GJ per capita per year.

As one can see, the energy metabolic differences between China and EU28 have been reduced, but they are still relevant at the end of the period in the household (Europe presents more than three times higher EMR_{HH} and $ETpc_{HH}$ than China) and in the paid work sector (Europe presents two times more EMR_{PW} and 1,2 times higher $ETpc_{PW}$ than China). For a detailed explanation of these differences and evolutions, we need to go down one hierarchical level, where the metabolic characteristics of the main economic sectors in paid work can be observed.

3.3. Moving down the hierarchy: metabolic characteristics of the main paid work sectors

3.3.1. Human activity distribution

Fig. 6 shows the profile of the distribution of human activity per capita of China across the main economic sectors. Data show a huge reduction of the human activity allocated in the Agriculture, Forestry & Fishing sector, going from 614 to 325 paid work hours per capita between 2000 and 2016. Most of these working hours have moved to Service & government sector, which has grown from 327 to 487 h per capita during the same period. The year 2012 was the first that China allocated more time to services than to agriculture. The other sectors have also increased their working hours between 2000 and 2016, especially the construction sector going from 46 to 123 (with a peak of 134 h in 2013), the industrial sector from 239 to 261 (with a peak of 291 h in 2012) and transport services from 39 to 55 h per capita.

Fig. 7 shows the human activity per capita of the European Union allocated in the main economic sectors. As a general feature, the European Union presents a more stable distribution. However, a closer look reveals that there is a significant reduction in working hours per capita in the industrial and agricultural sectors, going from 140 to 110 and from 60 to 39 respectively. These hours are transferred to the service sector, which increased from 459 to 511 h per capita. On the other hand, the construction sector presented first an ascending trend going from 58 h per capita in 2000 to 67 in 2007 right before the economic crisis; and a second descending trend that goes to 53 h per capita in 2016 (5 h less than in 2000). The transport sector presents the most stable pattern around 28 h per capita per year.

3.3.2. Energy performance of the main paid work sectors (level n-2)

In this section we complement the relative allocation of human activity analyzed previously with the energy metabolic rates and the relative energy throughput per capita. These three indicators characterize biophysically crucial qualitative factors of societal metabolism. All these indicators are plotted historically in Fig. 8 for the period 2000–2016. As the exosomatic energy metabolic rate pattern indicates, all sectors of both regions increase their level of capitalization during the analyzed period. This economic transformation supposed in China the industrialization and modernization of the country. For example, it reduced the fraction of *Working poor* (defined at PPP$3.10 a day) from 66% of the workforce in 2000 to 10% in 2016 [97] or increased its Human Development Index from 0.59 to 0.75 [98]. On the other hand, this increase in the level of capitalization is just a step forward in their tertiarization pattern and technological investments for maintaining its competitiveness. Looking at each sector in more detail (Fig. 8), we can see how these metabolic transformations take place.

Agricultural Sector – in the EU, the human activity allocated in this sector has been reduced from 60 to 39 h per capita per year. This low labor force allocation in agriculture is possible not only because of the high level of technology used, but also due to the high level of externalization generated by the massive imports of feed for animal products [99]. In China we can see a similar trend, the level of capitalization of the sector increased from 1,5 to 5,7 MJ/h, but it is still more than ten times lower than in Europe (68 MJ/h in 2016). However, this capitalization has enabled to halve their human activity allocation to agriculture. More problematic is for China the option of massive imports of food due to the size of its population. A significant level of imports could easily saturate the supply capacity of the global market.

Industrial Sector – In the EU28, the EMR increased from 400 to 430 MJ/h during the analyzed period (+7%), arriving until 452 MJ/h after the readjustments prorogued by the crisis. However, this variation has

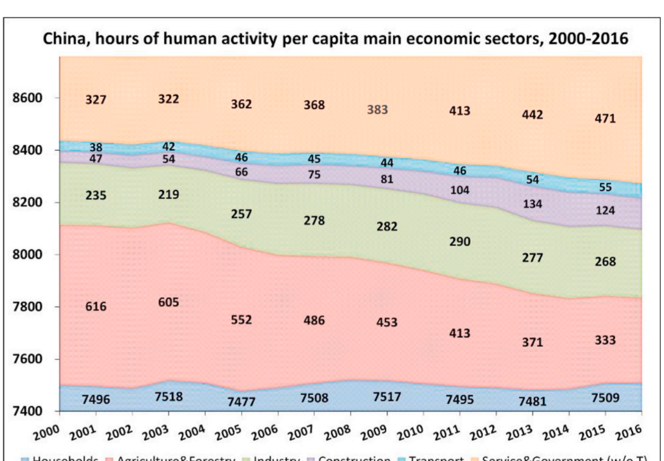

Fig. 6. Hours of human activity per capita over main sectors (level n-2) for China between 2000 and 2016.

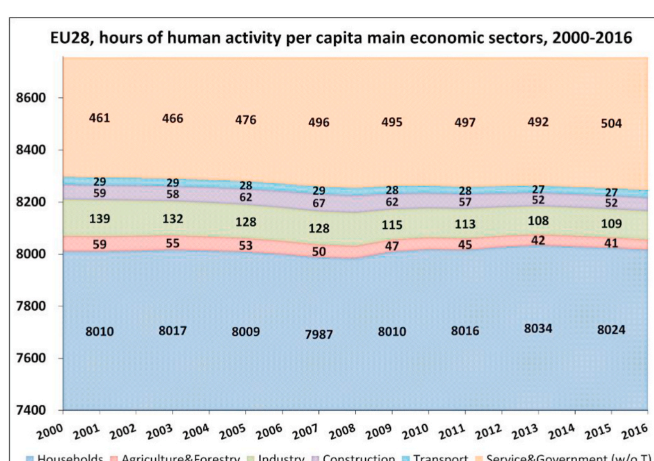

Fig. 7. Hours of human activity per capita over main sectors (level n-2) for the European Union between 2000 and 2016.

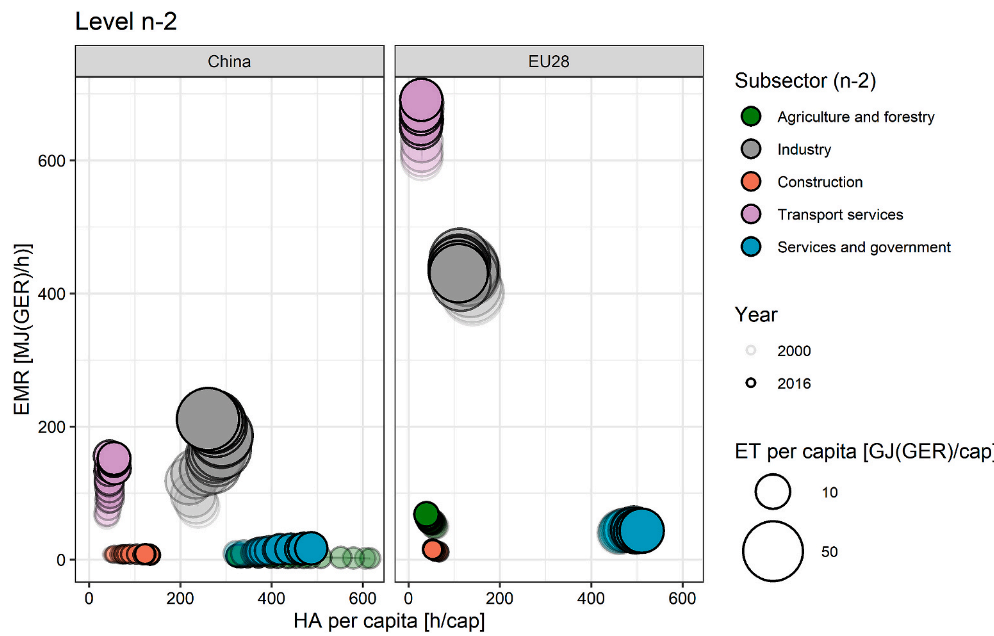

Fig. 8. Evolution in time (2000–2016) of the energy metabolic rate (EMRi) and human activity requirement expressed in hours per capita (HApc) of the main paid work sectors for EU28 and China. Bubble size represents the energy use per capita (ETpc) expressed in joules of thermal equivalent.

been more important in the relative size of the sector in terms of labor per capita (−21%) and energy throughput per capita (−16%). This pattern indicates that the European Union is: (i) still capitalizing their industries; and/or (ii) externalizing those generating less value-added. In the next section, we will see that both trends are taking place. On the other hand, the industrial EMR of China skyrocketed from 80 to 211 MJ/h (+164%), while its HApc oscillates over the 255 h per capita. The ETpc more than doubled going from 19 to 55 GJ. In other words, China initially expanded its industry in terms of both workforce and technical capital (and consequently its ET and ETpc). But 2012 onwards, labor decreased while capitalization is still increasing. This phenomenon indicates the externalization of some low productive industrial activities to other countries as shown in the next section.

Construction sector - In the EU28 the level of capitalization slightly increased from 12 to 15 MJ/h (+22%) as the ETpc (+14%), while its workforce per capita increased before the crisis (+16%) and decreased afterward (−21%). On the other hand, the Chinese workforce in construction almost arrive to be 7 times in absolute terms (182 vs 26 Mh) and almost triple in per capita (134 vs 52 h) the one of EU28 in 2013 and 2014, but with only a minor increase in EMR from 7.4 to 8 MJ/h (around half that of EU). In absolute terms, China triples the energy throughput in construction of EU28 in 2016, using 1359 PJ and producing 2.41 Gt of cement (1743 kg per capita) vs 0.17 Gt (330 kg per capita) of EU28 [100]. Updating the illustrative comparison of Vaclav Smil [1] with the apparent cement consumption of the US during the entire twentieth century (4.52 Gt), we get that China emplaced more cement (4.9 Gt) in new construction in just two years between 2013 and 2014 [100]. When comparing with the rest of the world, China is manufacturing almost 60% of the world production between 2011 and 2016 (see Fig. 9) having just over 18% of the population [101]. However, looking at the energy throughput per capita (ETpc) in this sector, in 2016 we find 1 GJ per capita versus 0.8 GJ in EU28, reflecting a different mode of construction in China: more manual and less mechanized that in the European Union (as its EMRs indicated before).

Transport sector - the EMR of EU28 increased from 601 to 687 MJ/h between 2000 and 2007. The crisis made that it decreased until 648 MJ/h in 2012 and then recover until 691 MJ/h in 2016. In the meanwhile, the HApc have been stable over the 28 h and the ETpc fluctuated between 29 and 32 GJ. In the case of China, it was the second most

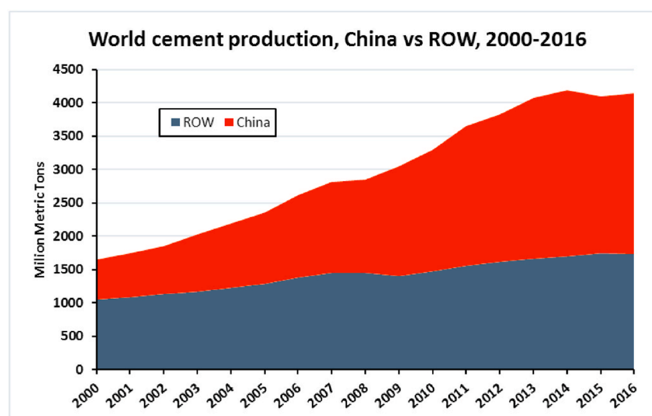

Fig. 9. World cement production spit between China and the Rest of the world (ROW) between 2000 and 2016. Source: US Geological Survey [100].

capitalized sector going from 64 to 152 MJ/h, while its HApc increased from 39 to 55 h (+16). Its ETpc went from 2.5 to 8.4 GJ.

Service and Government sector (excluding transport) - In EU28, the level of capitalization of this sector is quite stable going from 39 to 43 MJ/h and presenting a peak of 46 MJ/h. On the other hand, it is the only sector that increased its allocation of human activity per capita (+52 h) and energy throughput per capita (+4 GJ) during the period, showing an important step towards tertiarization of the European economy that explains the apparent dematerialization of its economy [53]. In the case of China, the level of capitalization more than doubled during the period going from 6.6 to 16 MJ/h. Adding the huge expansion of HApc (+165 h) and urbanization (+21% [102]), one can see how the industrialization of China occurs at the same time as the expansion of services and cities.

3.3.3. *Monetary performance of the paid work subsectors of China and EU28 (level n-2)*

Fig. 10 presents the relation between EMR and EJP in China. In general, all sectors except Construction had a clear upward trend in both ratios, more than tripling in the specific case of Industry. Moreover, we

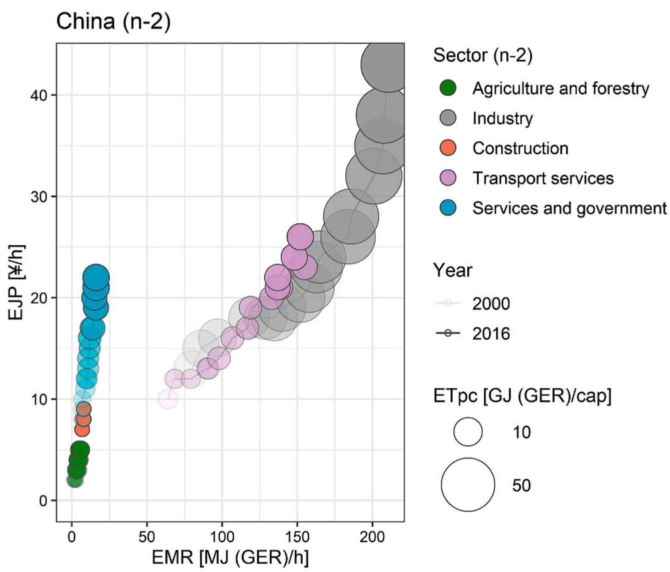

Fig. 10. Evolution in time (2000–2016) of the Economic Job Productivity (EJP) vs the Energy Metabolic Rate (EMR) of the main paid work sectors (n-2) for China. Bubble size represents the energy use per capita (ETpc).

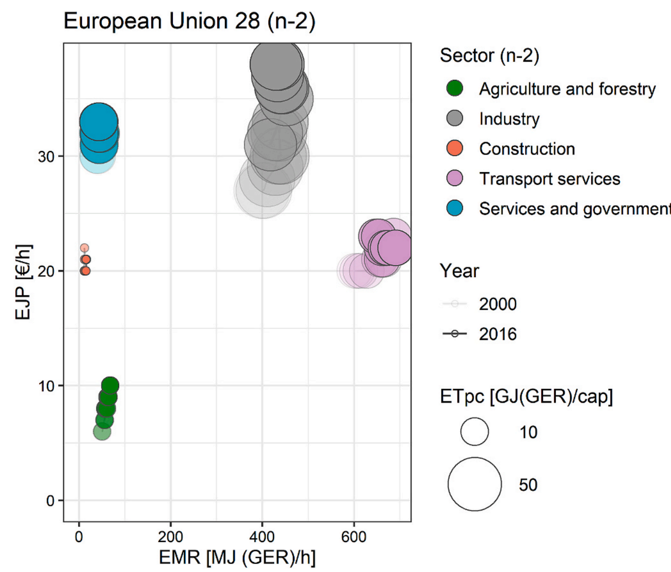

Fig. 11. Evolution in time (2000–2016) of the Economic Job Productivity (EJP) vs the Energy Metabolic Rate (EMR) of the main paid work sectors (n-2) for EU28. Bubble size represents the energy use per capita (ETpc).

can see how economic job productivity is correlated with the energy metabolic rate, as more technical capital increases labor productivity. When looking at the transport sector pattern, we can see an abrupt reduction of both ratios between 2012 and 2013, when the great recession arrived in China freezing its exports. For industry, this correlation became less intensive during the last period of the analysis. This could be due to different reasons: (i) moving from an industry that bases its competitiveness on production to one more oriented to quality, the first increase its labor productivity purely by mechanization, the second require also more human capital; (ii) the mix of industrial subsectors changed from more energy-intensive sectors (e.g. basic metals) to less intensive ones but with higher EJP (e.g. chemical industry), (iii) production chains move from concentrating energy-intensive processes (e. g. pulp production) for local consumption and export, to outsource it and concentrate on importing semi-finish products (e.g. paper) for allocating human activity to high-value processes in the production chain of the industry (e.g. paper products) [32].

In the case of the European Union (see Fig. 11), the only clear trend is the industrial one. It fluctuates around a certain level of EMR that doubles that of the last years of China but at the same time it increases significantly its EJP from 27 to 36€/h, surpassing that of Services and government in 2011. The EJP of Agriculture and forestry almost doubles (from 6 to 10€/h).

3.4. The metabolic characteristics of the industrial subsectors of China and EU28 (level n-3)

When characterizing the energetic part of societal metabolism, it is crucial to analyze the industrial sector and its subsectors moving to level n-3.

3.4.1. Human activity distribution

Industrial subsectors of China present a general decrease during the first three years of the analyzed period (2000–2003) especially important in the Energy & Mining subsector going from 51 to 46 h per capita (Fig. 12). From 2003 to 2012 the trend was reverted, mainly due to the Machinery subsector that went from 48 to 80 h per capita. During the last period (2012–2016) the overall tendency was to decrease, again with the Energy & Mining being the subsector that decreases the most (from 53 to 38 h per capita).

In the case of EU28 (Fig. 13), all its industrial subsectors present a

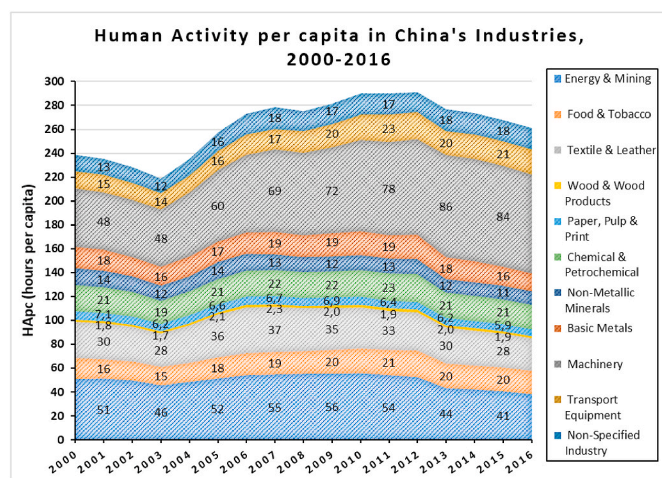

Fig. 12. Human activity per capita distribution over industrial subsectors (level n-3) for China between 2000 and 2016.

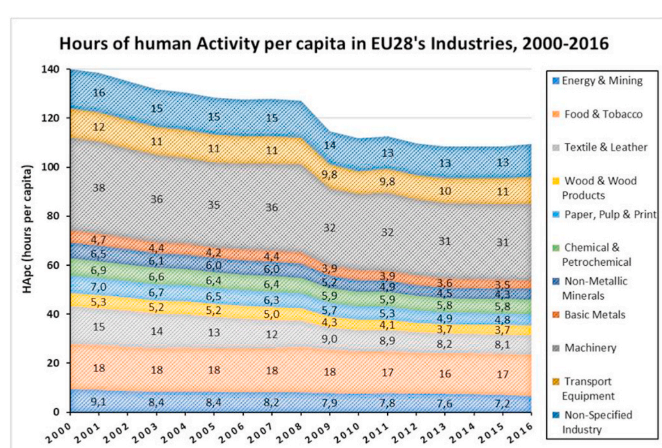

Fig. 13. Human activity per capita distribution over industrial subsectors (level n-3) for EU28 between 2000 and 2016.

sustained progressive reduction of hours of human activity per capita, being the Textile & Leather and the Machinery the ones that decrease more during the period (from 15 to 8 and from 38 to 31 h respectively). On the other hand, subsectors as Chemical & Petrochemical, Basic Metals or Transport equipment reduced by just over an hour. It should be noted that the crisis of 2008 provoked a sharp reduction in the human activity per capita in all industrial subsectors in just one year (2008–2009), especially relevant in Machinery (−4.4 h) and Textile & leather (−1.8 h), a reduction that has not been recovered.

3.4.2. Energy performance of the industrial subsectors of China and EU28 (level n-3)

When looking at the metabolic pattern of China in Fig. 14, we can see how all industrial subsectors have increased their level of capitalization. This increase in the power capacity is especially important in the heavy industry: Basic metals (+1021 MJ/h), Non-metallic Minerals (+406 MJ/h) and Chemical & Petrochemical (+296 MJ/h). These subsectors together with Wood & Wood products and Pulp, Paper & Paper products present a vertical pattern evolution in the figure, which indicates that its ETpc growth is driven by its important technical capitalization during the period (the size of the sector indicated by its HApc remains quite stable). On the other hand, Machinery, Transport Equipment, Non-Specified Industry, Food & Tobacco & Textile and leather present a horizontal pattern, where its EMR increase just between 20 and 45 MJ/h, while the HApc increased until 34 h in Machinery or increase from 30 to 38 h for after decrease until 27 h in Textile & Leather. The metabolic pattern of Textile & Leather and Energy & Mining (an increase of EMR (+44 and + 150 MJ/h) and ETpc (+1 and + 5 GJ) while decreasing HApc (−3 and −13 h)) seems to indicate that China is beginning to reduce some of its industrial activity. In the case of textiles due to its low economic job productivity (EJP), while in the case of Energy & Mining due to its local resources are unable to satisfy the huge demand of its industry [1,103,104].

In the case of EU28 two clear metabolic patterns can be identified in its industrial subsectors (Fig. 15). On one hand, the subsectors that concentrate more human activity and low levels of technical capitalization present at the same time important reductions in their workforce and a more moderate variation in their energy metabolic rates (horizontal evolution): Machinery, Food & Tobacco, Textile & Leather, Transport Equipment and Non-Specified industry. On the other hand, those subsectors with higher levels of technical capitalization increase them having small changes in the workforce: Energy & Mining, Basic Metals, Chemical & Petrochemical, Non-Metallic Minerals and Pulp, Paper & Print. However, there are some exceptions as Food & Tobacco just reducing its HApc 1.5 h or Wood & Wood products increasing its EMR in 118 MJ/h. Additionally, it is interesting to observe that some sectors present a reduction in their level of capitalization (e.g Basic Metals (−36 MJ/h) or Textile & Leather (−17 MJ/h)). In both cases, the moderated and sustained reduction on time could be associated with improvement of efficiency, technological changes or even structural changes on the composition of the subsector. Another interesting phenomenon observed is a sudden reduction of the EMR during the crisis of 2008 (2007–2009) recovered quickly just one or two years after (2011–2012). This phenomenon could be observed in Basic Metals (−429 MJ/h), Non-Metallic Minerals (−79 MJ/h), Chemical & Petrochemical (−76 MJ/h), Pulp, Paper and Print (−46 MJ/h), Food & Tobacco (−13 MJ/h) or Transport Equipment (-8 MJ/h). This illustrated one of the limitations of the energy metabolic rate (EMR) as a proxy of the level mechanization of an activity, as this sudden reductions are clearly not generated by a reduction of the installed power capacity, but due to the reduction of the utilization factor and operation load of the machinery [57] during the crisis (i.e., much of the machinery was just stopped not de-installed).

3.4.3. Monetary performance of the industrial subsectors of China and EU28 (level n-3)

At level n-2, the Chinese industry increased dramatically its Economic Job Productivity (EJP). In Fig. 16, one can see that all its subsectors at level n-3 at least doubled it. Wood & wood products and Food & Tobacco increased their EJPs the most and ended up having the largest ones. Energy & Mining, Chemical & Petrochemical, Non-metallic Minerals, and especially Basic Metals increase also its EJP, but as we can see thanks to the important increase of their exosomatic Energy Metabolic Rates (EMRs). The smallest EJP was Textile & Leather along the

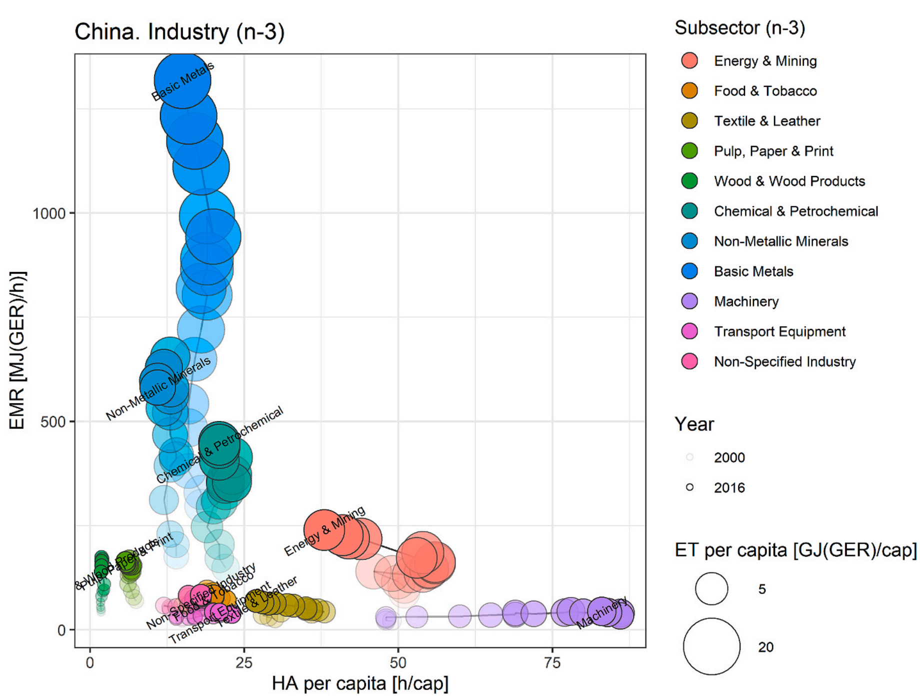

Fig. 14. Evolution in time (2000–2016) of the energy metabolic rate (EMRi) and human activity in hours per capita (HApc) of industrial subsectors of China. Bubble size represents the energy use in each sector by the population of the region (ETpc) in joules of thermal equivalent.

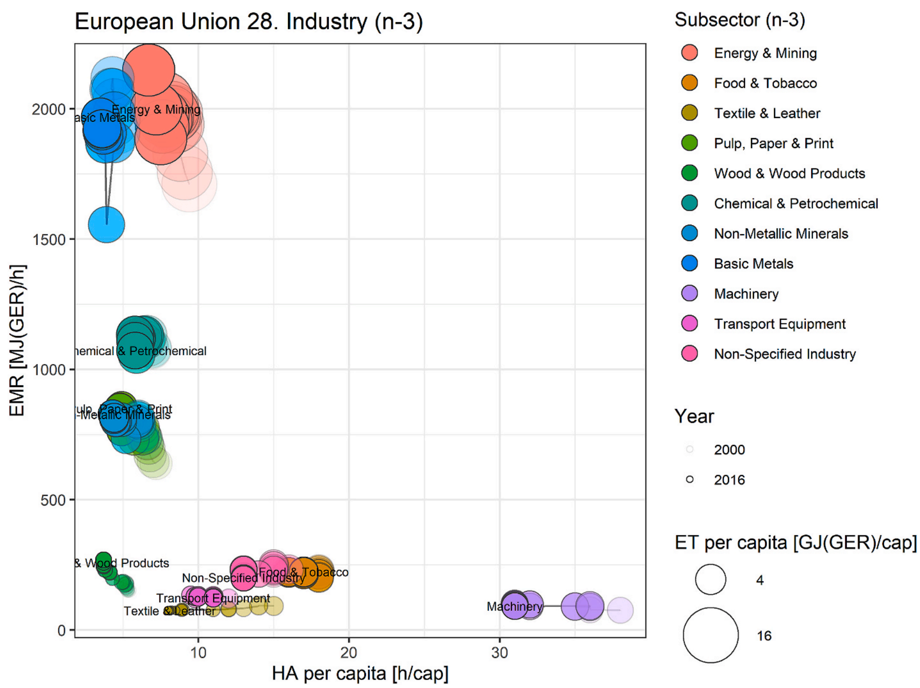

Fig. 15. Evolution in time (2000–2016) of the energy metabolic rate (EMRi) and human activity requirement expressed in hours per capita (HApc) of industrial subsectors of EU28. Bubble size represents the energy use in each sector by the population of the region (ETpc) expressed in joules of thermal equivalent.

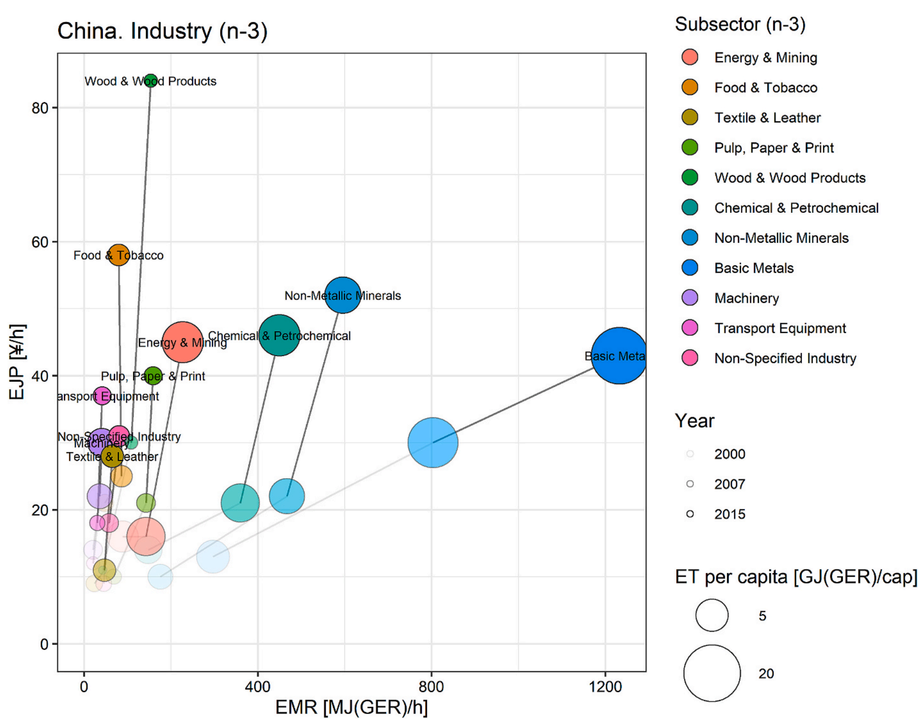

Fig. 16. Evolution in time 2000, 2007 and 2015 of the Economic Job Productivity (EJP) vs the Energy Metabolic Rate (EMR) of industrial subsectors (n-3) for China. Bubble size represents the energy use per capita (ETpc).

whole period, which at having the lowest EMR indicate that it is a labor-intensive industry. Again, this low profitability could explain the decreasing weight in jobs seen in Fig. 14.

Once observed the pattern of capitalization and economic job productivity, we can come back to Fig. 12 and analyze the decrease of HApc in industry between 2000 and 2013. This occurs while the level of capitalization (going from 80 to 118 MJ/h) and economic job productivity (going from 13 to 18 ¥/h) of the overall industry sector increased (Fig. 10). This reinforces what indicated previous analysis [71], namely, that the incorporation of China into the WTO forced an increase of competitiveness in its industry. This is confirmed when looking at the subsectors (Figs. 14 and 16), where all reduce the human activity per capita (from −1% in Machinery to −17% in the Paper, Pulp & Print subsector), at the same time that all of them increase their EMR (from +21% in Food & Tobacco to +77% in Non-metallic minerals) and the EJP (not available for 2003, but increasing from less than 1% in Energy

& Mining and +176 in Wood & Wood Products subsector between 2000 and 2007). The HApc expansion from 2003 to 2012 in the industry together with its EMR and EJP indicate that China became very competitive and expand its industrial contribution to the world market, just reducing the relative workforce in the less profitable subsectors as the textile industry. After 2012 we can observe a progressive reduction of HApc while EMR still increasing, which indicate that China enters in a tertiarization pattern as the EU.

In the case of the EU, the EJPs follow a more stable trend as can be seen in Fig. 17. Energy & Mining and Chemical & Petrochemical have the largest EJPs, the latter almost doubles during the period going from 50 to 79 €/h. Transport equipment and Machinery sectors increase EJP significantly with almost constant EMRs. Transport equipment and Basic metals increase EJP in general terms but in the 2008 crisis experimented a sudden decrease.

4. Discussion

Several of the results presented so far deserve a discussion, especially concerning the formidable process of becoming of China.

Looking at its demographic structure, we can see that the low dependency ratio of the Chinese population allows this country to allocate more human activity to its paid work sector than any other developed country. The Chinese paid work sector metabolizes more than 30 times as much energy per hour than the household sector. Besides, China has a lower level of unemployment, of the inactive population in the working-age, fewer holidays and much higher workloads per worker. This combination makes its economy very competitive in terms of labor costs due to the lower pressure felt by paid workers to the needs of their dependents. That is, this low pressure is not only determined by low dependency, but also by the low level of the material standard of living experienced by Chinese household sector (low EMR_{HH}), already detected in previous MuSIASEM analysis. On the contrary, the European Union has not only a value of EMR in its household sector six times higher than the one of China, but also higher social protection to workers (e.g. less workload per week, unemployment allowances and more holidays), more pensions, better assistance for people with disabilities and a higher proportion of tertiary education students. This combination makes easier for the EU economy to attract human capital and entrepreneurs.

The household sector of China presents a low metabolic rate when compared with other countries, but also when considered in relation to the metabolic rate of its own paid work (the difference is larger than in other countries). This indicates that China adopted a policy prioritizing the competitiveness of its economy, which translated into a strategy of investments in the paid work sector (increasing EMR_{PW}) aiming at a rapid growth based on exports to international markets, that only indirectly will generate an improvement of the local material standard of living (increasing EMR_{HH}) in time. Paradoxically, this generated a fragility in the paid-work sector of China, which presents an important dependence on foreign demand despite the huge potential of its domestic one already indicated by conventional economic analysis [105].

When comparing the changes in the paid work sectors of both regions, we can see that China's modernization is reflected in: (i) the expansion of its industrial and construction sectors; and (ii) a massive shift of human activity from agriculture to service sectors. These two trends are the reflection of the huge wave of urbanization in the society that took place during the last years, when China became the largest cement producer (almost 60% of the world). In fact, the construction sector of China has quadrupled its human activity during the period, arriving at almost triple the energy use of EU28 in 2016. This expansion in infrastructure has also allowed the transport sector of China to almost tripling its energy metabolic rate trough the massive introduction of exosomatic transport equipment (e.g. cars, motorbikes, trucks, trains, ships, planes). This acceleration of the societal metabolism of China is reflected in the expansion of the economic job productivity in all sectors and its overall energy and material use. In the case of Europe, the picture is less complex: the paid work sector has followed a standard tertiarization pattern. That is, an increase in the level of capitalization of all sectors, while reducing the human activity (paid work) in all of them except in the services. As the service sector presents high economic job productivity and low energy metabolic rate, the GDP of the EU countries has been growing at a higher pace than the increase in energy use. This fact is interpreted by European Environment Agency analysts [106] as

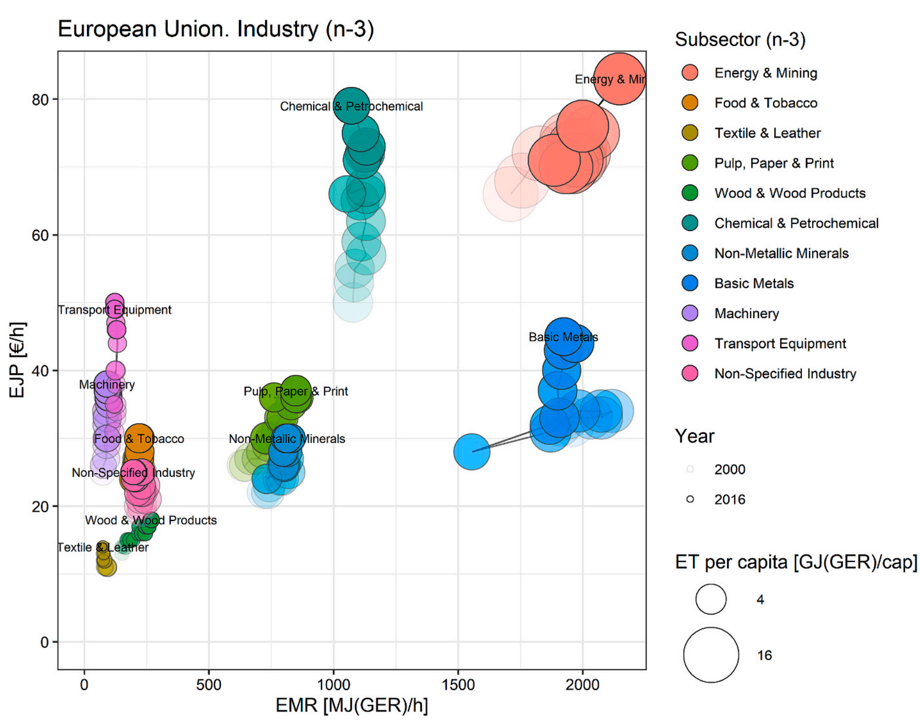

Fig. 17. Evolution in time (2000–2016) of the Economic Job Productivity (EJP) vs the Energy Metabolic Rate (EMR) of industrial subsectors (n-3) for EU28. Bubble size represents the energy use per capita (ETpc).

the result of the decoupling of economic growth from the use of resources (also known as the environmental Kuznets curve [107,108]). However, our analysis shows that this fact is simply due to the significant reduction of the process of production of goods in the energy-intensive sectors (e.g. Basic metals and Chemical & petrochemical), which is not associated with an analogous reduction of consumption of the relative goods in the society. The production of what is consumed is simply outsourced. This is here indicated by the important reduction of HApc in manufacturing in favor of services while increasing its EMR and EJP in both sectors, which is also confirmed by the trade pattern evolution collected by international trade goods statistics [109]. Same conclusion could be found in previous analysis using decomposition analysis [110]. An early attempt proposing a decomposition analysis using fund-flow model and MuSIASEM rationale, as well as the effects of trade over human activity budgets can be found in Deliverable 4.4 from EUFORIE project [111] and forthcoming publications derived from new advances within MAGIC project in relation to the nexus [32, 112].

Industrial subsectors' analysis shows how the industrialization and urbanization of China have translated into a massive technical capitalization of its heavy industry. However, despite this quick process of industrialization, the values of energy metabolic rates in most industrial subsectors of China are still half of those found in the EU. This indicates that Chinese industrial subsectors remain competitive due to low labor costs and that its technical capitalization should be expected to continue growing during the next years. This is not good news for the fight to reduce emissions. Strategic subsectors as Machinery or Transport equipment have increased importantly its number of jobs and energy use in China. However, the great recession arrived in 2012 translated into stagnation and reduction of its exportations. The effects of the recession could be observed in our analysis in two ways: (i) a reduction of human activity in almost all industrial subsectors; and (ii) a sudden reduction and recuperation of EMRs during 2012 that indicates a reduction in the utilization factor of the installed power capacity. These phenomena could be also observed in Europe. The only difference is that they occurred earlier between 2008 and 2009.

The multiscale integrated analysis of the energy metabolic pattern of China and the European Union provides a detailed characterization of the factors shaping the modernization of China and the post-industrialization of the European Union. Chinese modernization has been huge during the analyzed period. However, its metabolic rates are still low when compared with developed countries. This entails that we should expect them to continue to grow in the future. When considering the size of China, it is easy to conclude that this expected growth represents a huge sustainability issue when coming to the requirement of primary sources (energy sources, raw material, land) and primary sinks (problems of emissions and pollution). On the other hand, the tertiarization of the European Union is certainly benign for the environment but flags the setting of a senescent economy. The productive sectors have become increasingly insignificant in terms of both GVA (agriculture 2%, industry 23% and construction 5%) and working hours (agriculture 5%, industry 15% and construction 7%) compared to the service sector (76% in terms of GVA and 73% of HApw, data for the year 2016). The progressive liquidation of industry and construction sectors, following the contraction of the agricultural and energy sector during the industrial revolution, is driven by competition from the international market, notably from countries with cheap labor as China.

From the analysis presented here many other questions emerge. Assuming that China will arrive at the levels of tertiarization and externalization of Europe, who will produce food, energy and material products for its large population? It is not clear that if there are socio-economics systems in the world capable to produce and export to China a significant fraction of the huge amount of food required by China. How serious will be the international tensions in a globalized market in which the majority of trading countries try to externalize their biophysical constraints to other social-ecological systems? What will be the consequences of this massive externalization of environmental pressure on the poorer regions of the world? Will international institutions be capable to handle these conflicts? Will we move away from the strategy of free trade agreements accelerating competition, growth and environmental degradation? Or rather will we have a regression in which countries will be focusing on protecting their national economies from the threats of trade? Will the world be capable of working out a new international socio-environmental agreement having the goal of handling in a fair, socially responsible and ecologically friendly manner reverse the existing pattern of resource depletion and socio-environmental degradation?

In relation to the proposed methodology, this study presents several innovations when compared with previous MuSIASEM analysis. We improved methodological aspects [8] and enlarged the analysis to include 28 countries (here EU is considered as a whole region still including UK) and opening lower levels of analysis for the industrial sectors. So we combined the historic analysis (using moving bubbles characterizing the metabolic patterns) and the static multilevel characterization of the end-use matrix [94,113]. In the case of China, we update its metabolic analysis by moving to lower levels [71,84]. In relation to methodological aspects, we introduced new visualizations improving previous representations of the societal and demographic aspects affecting the human activity patterns [114]. These updates have made possible to advance the effectiveness of the biophysical characterization of the economy of a country across levels and scales (e.g. the relation of the EMRs with the HApc and the ETpc) [115].

5. Conclusions

From the methodological point of view, the analysis presented here improve previous applications and shows how MuSIASEM accounting scheme allows the generation of a coherent information space made up of non-equivalent representations of the biophysical functioning of the economic process carried out simultaneously at different levels and dimensions. In this way, it becomes easier to understand the role that relevant factors – observable only across different scales and dimensions - play in the expression of a complex phenomenon such as the evolution of large social-ecological systems. In particular, we illustrate that it is possible to study the entanglement over the changes taking place when considering socio-demographic variables, energetic and economic processes, as well as international trade. The coherent and integrated information space generated in this way allows a richer discussion of their connections and evolution in time.

In addition, we present an application of an analytical tool – the end-use matrix – developed within a holistic method called Multi-Scale Integrated Accounting of Societal and Ecosystem Metabolism. In this application, the end-use matrix has been used to characterize and compare in quantitative terms the energy metabolic pattern of China and the European Union across different levels and dimensions in the period 2000 and 2016. During this period China has experimented a formidable metabolic transformation associated with the industrialization and modernization of its society. In contrast, the EU does not have brought dramatic changes in the existing trends beyond the impact of the great recession that accelerated its tertiarization pattern. The characterization of the metabolic evolution of China can be summarized in the following points (in brackets the values of the EU in 2016 for comparison):

(i) an incredible boost of technical capital in all its sectors captured through the increase of the exosomatic energy metabolic rate across levels between 2000 and 2016. Here some of the more relevant: from 4 to 10 MJ/h at average society (EU 15 MJ/h) at level n; from 1.3 to 1.9 M/h in households (EU 5,5 MJ/h) and from 20 to 60 MJ/h in paid work (EU 125 MJ/h) at level n-1; from 1,5 to 5,7 MJ/h in Agriculture (EU 68 MJ/h), from 80 to 210 MJ/h in Industry (EU 430 MJ/h) at level n-2; and from 300 to 1320

MJ/h in Basic metals (EU 1925 MJ/h) or from 175 to 580 MJ/h in Non-metallic (EU 815 MJ/h) at level n-3.

(ii) the tremendous reallocation of human activity indicated in hours per capita per year among the main economics sectors during the analyzed period: from agriculture (decreasing from 614 to 325 h) to industry (increasing from 240 to 260 h), services (from 322 to 487 h), transport (40–55 h) and construction (from 46 to 123 h). In 2016, the values for these sectors in the EU were 40, 110, 510, 28 and 55 h respectively;

(iii) an extraordinary workload around 1260 h per capita per year (740 h in the EU) derived from: a low dependency ratio that remains during almost all the analyzed period below 40% (around 50% in the EU); a low unemployment rate always below 4% (around 6.5% in the EU); a low inactive population rate around 20% (around 30% in the EU); and short vacation time and long working hours resulting in an average workload of 2220 h per worker per year (around 1730 h in the EU).

In terms of policy relevance of these results, when comparing the values of China with the EU, we can expect that China will continue urbanizing and capitalizing its economy intensively for a while, expanding its energy and material requirements. On the other hand, it seems that the EU will continue with a similar post-industrial metabolic pattern: maintaining their current high resource demand, retaining activities with high economic job productivity and outsourcing low added value activities (mainly associated with primary and secondary sectors).

In the current status quo, we can expect that all these tendencies will continue increasing international tensions for controlling global markets. This fact evidences the lack of adequate international institutions for managing conflicts that can be expected because of: (i) the competition for high-value processes in global production networks, (ii) the generalization of natural capital grabbing practices and (iii) the increasing environmental pressure over primary sinks [116].

Credit author statement

Raúl Velasco-Fernández: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration. **Laura Pérez-Sánchez**: Software, Validation, Data Curation, Writing - Review & Editing, Visualization. **Lei Chen:** Investigation, Data Curation, Writing - Review & Editing. **Mario Giampietro:** Conceptualization, Writing - Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Correction of private transport applied to EUROSTAT statistics

Energy consumption in the household sector for EU28 has been calculated by summing residential consumption (from the Eurostat Energy Balances [62]) and fuel consumption by private cars (hypothesis: 80% of the total fleet) and motorcycles (hypothesis: 90% of the total fleet). The main data sources for this calculation are in Table A1. Details of the calculations can be found below.

Table A1
Data sources used for the transport and household recalculation.

Data	Data sources	Brief descriptions
$ET_{fuelTSEurostatij}$ $ET_{fuelHHEurostatij}$	*Eurostat*	Energy throughput of the transport and the households sectors
$nveh_{ijk}$	*Eurostat*	The stock of vehicles by category and NUTS 2 regions [tran_r_vehst]
x_{ijk}	*Eurostat*	Millions of kilometers [Mveh·km] (1990–2012) Motor vehicle movements on national territory, by vehicles registration [road_tf_vehmov] (2012–2016) Road traffic on the national territory by type of vehicle and type of road (million Vkm) [road_tf_road]
$Fecon_{ijk}$	*Odyssee-mure project*	Fuel economy of the fleet for each country and year (for k = moto constant value of 4l/100 km) [l/100 km]
GCV_{diesel} $GCV_{gasoline}$	*IEA-EUROSTAT-OECD Energy Manual (pag. 181)*	Gross calorific value diesel and gasoline [MJ/l]
$Per_{dieselijk}$	*Eurostat*	percentage of diesel cars in the fleet per each year, country (for k = moto, $per_{dieselijk} = 0$) [%] Passenger cars, by type of motor energy and size of the engine [road_eqs_carmot]

Indexes:

- Countries: 28 EU countries (i)
- Years: 1990–2016 (j)
- Modes of transport: cars and motorbikes (k)

Given the considerable amount of missing data, a European average of km per vehicle (average of the countries) was calculated for each year:

$$avx_{ijk} = \frac{x_{ijk}}{nveh_{ijk}}$$

$$avx_{EUjk} = \frac{\sum_i avx_{ijk}}{\text{number of countries with } x_{ijk}}$$

With this average (avx_{jk}) we can calculate x_{ijk} for those which we have not the data:

$$x_{ijk} = avx_{EUjk} \cdot nveh_{ijk}$$

The $nveh_{ijk}$ database has also a lot of missing data. There are countries for which extrapolations or interpolations (linear or exponential) have been made. For others, we have used values for similar countries or countries with similar trends.

Finally, ET_{fuel_ijk} (fuels consumed by cars and motorbikes) can be calculated:

$$ET_{fuel\_ijk} = \left[\left(GCV_{diesel} \cdot per_{diesel\,ijk}\right) + GCV_{gasoline} \cdot \left(100\% - per_{diesel\,ijk}\right)\right] \cdot x_{ijk}$$

And to conclude, the ET from the transport service sector and household has been rearranged. Having calculated the fuel consumption in private cars and motorcycles (HH), this value has been subtracted from energy use in the Transport Sector (Land Transport). It was assumed that 80% of the total fleet of cars and 90% of the total fleet of motorbikes are employed in the household sector.

$$ET_{fuelTS\_ij} = ET_{fuelTSEurostat_{ij}} - ET_{fuel_{ijmoto}} \cdot 90\% - ET_{fuel_{ijcar}} \cdot 80\%$$

$$ET_{fuelHH\_ij} = ET_{fuelHHEurostat_{ij}} + ET_{fuel_{ijmoto}} \cdot 90\% + ET_{fuel_{ijcar}} \cdot 80\%$$

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Glossary

MuSIASEM: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
HA: human activity per year (HApc indicates per capita)
GVA: gross value added
ET: energy throughput per year (ETpc indicates per capita)
EMR: exosomatic energy metabolic rate in the sector i
EJP: economic job productivity
AS: average society
HH: household sector
PW: paid work sector
GER: gross energy requirement