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The Physical Economy of France (1830–2015). The History of a Parasite?

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ABSTRACT

This article explores long-term trends and patterns of material use in France for a 185-year period. It is the first long-term study of material flows for France with national and yearly data for most of the period. Based on a material flow analysis (MFA) that is fully consistent with current standards of economy-wide MFAs and covers domestic extraction, imports, and exports of materials, we investigated the evolution of the French metabolism from industrialization to financialized capitalism. Over the whole period, there is a 9-fold increase in domestic material consumption, an expansion of material use per capita, and a spectacular addition of abiotic resources (fossil fuels and minerals) to biotic materials. Using a world-ecology framework, we exhibit a specific metabolic path: that of a state benefiting from successive world-systems for its economic development through massive material imports.

Introduction

What are the material characteristics and peculiarities of the French economy for two hundred years? How does it fit into the material flows structuring the world-system? What are the differences and similarities compared to other economically similar countries? In line with the article by Schandl and Schulz (2002) broadly presenting and over a long period the metabolism of the United Kingdom, and other national studies published since, this research proposes the first description of the social metabolism of France on almost two centuries.

Over the last twenty years, material flow analysis (MFA) has produced ever-increasing results to examine societies' metabolism (Fischer-Kowalski et al., 2011). In addition to the global overview (Krausmann et al., 2009; Schaffartzik et al., 2014), there are a number of long-term studies for the following countries: United Kingdom (Schandl and Schulz, 2002), Austria (Krausmann et al., 2008), Czechoslovakia (Kovanda and Hak, 2011), Japan (Krausmann et al., 2011), United States (Gierlinger and Krausmann, 2011), Spain (Infante-Amate et al., 2015) and Russia/USSR (Krausmann et al., 2016). Other researches, based on international databases (FAO, BGS, USGS, IEA, UNSD), usually start only in the 1970s. For France, the only available works are diluted in larger reviews: the study of the United Nations (UNEP, 2016) summarizes the French economy from 1970 on one single page through eight graphs; Schaffartzik et al. (2014) use decennial data from international organizations since 1950.

Our work is the first long-term study of material flows for France. It is based on new series concerning the physical aspects of domestic extraction and foreign trade. Unlike other studies, our database is built from yearly and national data for most of the period (1888–2015 for foreign trade and 1948–2015 for domestic extraction).

Nevertheless, this work is not limited to a production of graphs. Material flows accounts have sometimes been criticized for not providing socio-historical determinants of their data (Giampietro, 2008). One added value of this article is to propose a historical interpretation of these material flows in a theoretical framework inspired by the notion of world-ecology. It relies on the assumption that each phase of the world-system is accompanied by a certain Earth-system regime, a reorganization of ecosystems, energy and material flows at global scale (Moore, 2015). We want to illustrate that the dialogue between the MFA and the historical discipline allows a mutual enrichment of both approaches.

Let us take a concrete example. Economic history of France often

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gives the image of a rather slow process of industrialization, guided by protectionism and, at least, less dependent on international trade than the United Kingdom. Historians generally distinguish several phases with a weak international insertion before 1860 (Cobden-Chevalier treaty), expanding at the end of the 19th century, before experiencing a decline from the First World War to the 1950s, and a clear reopening from the 1960s (Broder, 1977; Verley, 1988; Lévy-Leboyer, 2006). This historiography echoes the representation of economic and political actors of the 19th century, opposing a protectionist France to the liberal United Kingdom (Todd, 2015). MFA illustrates how this narrative is based on a partial vision of France's foreign trade, focused on exports of industrial products but not taking into account the great mass of material flows involved in world trade. Our work shows that the French way to industrialization, from its very early stage on, can only be understood in the light of its very particular and very beneficial integration into material flows at a European and even global scale.

The first section briefly describes the usual MFA method and data sources. The second section presents our time series for extraction, trade and domestic material consumption over the period 1830–2015. We explain the choice of our time intervals and discuss the different phases of the metabolic transition in France. Finally, the third section undertakes a more in-depth analysis of these flows by examining economic and political developments.

1. Methods and Data

We follow the basic principles and current international standards of economy-wide MFA. We provide the most common indicators (Eurostat, 2013): domestic extraction (DE), physical trade balance (PTB = Imports − Exports) and domestic material consumption (DMC = DE + PTB). Unused extraction and indirect flows associated with imports and exports were not accounted for. The database provides material flow data at a medium level of aggregation, discerning a maximum of 61 material groups. Data and indicators are presented for four main material groups: biomass, fossil energy carriers, metallic ores, and non-metallic minerals. Furthermore, a distinction between biotic (biomass) and abiotic (mineral and fossil) resources is made. As for Russia (Krausmann et al., 2016) and the United Kingdom (Schandl and Schulz, 2002), the statistical territory of metropolitan France has undergone several changes over the period – these however do not produce any radical discontinuity[1].

1.1. Data Quality and Reliability

France has a long tradition in building national statistics, and the reliability of sources can be considered as high. After the French Revolution, the French State puts in place a control of the territory and its populations which involves the construction of national statistics entrusted to the *Départments*. These send the production statistics to the associated Ministries (Agriculture, Maritime Fisheries, Mines) whose duty is to aggregate them at the national level. Trade data have been collected at the borders by the customs since the very beginning of our period.

Statistics for the PTB are of very good quality compared to other long-term studies that settle for aggregate and inaccurate data provided by international institutions. We have used decennial summaries from customs directories since 1888. To provide annual series, we completed the period 1830–1888 with seven ten-year averages.

The quality of DE data is more questionable. We believe that it is very good from the beginning of the 19th century for metallic ores and fossil energy carriers (because these data are of importance to the State and its emerging statistical apparatus), that it is improving for biomass[2], but that it remains crude until 1945 for non-metallic ores (probably because they often have a low monetary value). Like all other MFA work going back to the 19th century, we needed to extrapolate and estimate some missing data for DE[3]. The most difficult estimations concern non-metallic ores and timber for the 19th century. While the vast majority of data is in tonnes, we had to complete a number of unit conversions. All details of the estimates and conversion factors are presented in the supplementary material.

1.2. Sources

The statistics of domestic extraction before 1945 were collected in these specific Ministry yearbooks for one year per decade (according to the implicit MFA convention, the year which closes the decade). After the Second World War, the *Institut National de la Statistique et des Études Économiques* (INSEE) produces a statistical directory which contains the necessary data for the DE database (INSEE, 2007). We obtained yearly DE data for the 1990–2015 period from the *Service de la Donnée et des Études Statistiques* of the Ministry of Ecological and Solidarity Transition. Several remarks are to be made (yet they go beyond the focus of our simple case study): self-consumption (production intended for home consumption) does not appear; flows related to smuggling (potentially high at the beginning of the 19th century) are not taken into account; there is a huge uncertainty about the extent of undeclared data (especially agricultural and fishing statistics); the way of producing agricultural statistics in the 19th century has been strongly contested (see additional material). Indirect flows of resource extraction are not included, mainly due to the lack of reliable data and methods for estimating these flows (Lutter et al., 2016). On this point, as on others, this opens the way for further research.

1.2.1. PTB

The main source for the PTB is the *Administration des douanes sur le commerce de la France* (1861–1923). For the period (1924–1996), the data come from the *Statistiques mensuelles du commerce extérieur de la France*. Finally, we obtained digitized statistics from the "National Directorate of Foreign Trade Statistics" for the period 1993–2015.

1.2.2. DE: Biomass

While statistics go back to the 19th century for certain materials (wheat for instance), others are absent until the 1950s (most fruits and vegetables). We used the *Enquêtes décennales* (1840, 1852, 1862, 1882, 1892, 1929), the *Bulletin de la statistique agricole* for the period (1881–1902), the *Statistiques agricoles annuelles* between 1886 and 1960 and we have completed these reports by the INSEE tables after 1946. Moreover, some estimates from studies like Toutain (1971) allowed us to fill in the sometimes incomplete statistical series. In the case of marine fisheries: the first summary of the quantities fished dates from 1874. The *Statistiques des pêches maritimes* include the period 1866–1987. Timber statistics required a twofold fix: they are very rarely available in tonnes and they are mostly scattered and missing before 1945. In some cases, they are found (particularly for 1840 and 1892) in agricultural statistics.

[1] In the sense that the variations concern only a few groups of materials and are relatively small compared to the total – well below the breaks observed for the countries mentioned above. The only exception is the exports of iron ore that suddenly increase by 50% between 1958 and 1959. For more information on statistical territory, data collected, methods and estimates used, refer to supplementary material.

[2] Despite the existence of national agricultural statistics since 1836, they remain for half a century based on the gross indications of local bigwigs, neglecting fruits and vegetables, underestimating self-consumption until the middle of the 20th century.

[3] For biomass, we have applied patches informed by the work of quantitative history since the 1970s (Toutain, 1971). See supplementary material.

1.2.3. DE: Nonmetallic Minerals

This category, the heaviest since 1945, is known to be the least documented (Miatto et al., 2016). For France, the data on quarries are not included in the statistics of the Mining administration before 1890[4]. All data come from *Annuaire Statistique de l'industrie minérale* and from the reports of *Union nationale des industries de carrières et matériaux de construction* (UNICEM, 1937-1974; UNICEM, 1975-1986; UNICEM, 1986-2003). We have produced an estimate for the older periods.

1.2.4. DE: Metallic Minerals and Fossil Energy Carriers

These data also come from *Statistique de l'industrie minérale*. National statistics exist for coal since at least 1787 and for most metals since 1830–1860.

2. Results: Long Trend Features of the French Physical Economy

This section presents the general trends of the French physical economy and justifies the time periods used in the following sections. Unlike many MFA articles, we do not provide any detailed graph regarding Material Intensity (defined as the DMC/GDP ratio), nor do we enter the debates on the "dematerialization" of the economy – this indicator has well known defects, in particular it makes invisible the resources incorporated in foreign trade goods. As it stands, our work cannot be used to examine these questions[5] Fig. 1 shows the per capita developments for France of its DE, DMC, and physical imports and exports from 1830 to 2015 through four main material groups.

A first major fact is the massive increase (apart from short periods of crises and wars) of the DMC (times 9 between 1830 and 2014), of the DE (times 7). This is a general conclusion valid for industrial countries and for the rest of the world. By comparison: for Spain the DMC has been multiplied by 10 between 1860 and 2010; DE multiplied by 17 for the United States; and by 36 for Japan between 1878 and 2005. One can find several other similarities with the countries already studied over the long term. France is moving from an organic to a mineral economy: the DMC is very strongly linked to biomass in the beginning of the period, and far less towards the end of the period. We also observe that fossil fuels have significantly increased since 1945 (with a slowdown after the 1970s). Moreover, there is a strong and continuous increase in non-metallic ores over the same period, and an increase in DE much higher than the rise of the population (which rules out the Malthusian explanations). Finally, there is a structural break around 1970 (as exemplified by Wiedenhofer et al. (2013) who found a stabilization of the use of per capita resources in developed countries in the early 1970s). A French peculiarity: the country almost only extracts biomass and non-metallic ores at the end of the period.

Fig. 2 shows a small difference between our data and those of Schaffartzik et al. (2014) for the PTB. Nevertheless, it seems that these authors underestimate the magnitude of material flows for DE[6].

A second fact, which emerges from Fig. 3, is that France is constantly in material deficit from 1830. Its economic prosperity has therefore rested on an unequal exchange of materials with the rest of the world (Hornborg, 2012). Unlike the United States, the United Kingdom, and Spain which were net exporters of materials for long periods, France has always had a positive PTB: from 1 Mt[7] in 1832 (imports represent then barely 1% of the DE) to 17 Mt in 1900 (I/DE then exceeds 10%), 24 Mt in 1930, 131 Mt in 1974 and 174 Mt in 2008 (I/DE reaches almost 50%). This contrasts with countries at the center of world-systems (United Kingdom, 1870; United States, 1940) that are net exporters of materials at their peak. As detailed in Section 3.1, during the 19th century France is the only major economic power experiencing physical deficit for all major commodities: coal, timber, grains, with the exception of metals. Import flows skyrocket after 1945, which emphasizes that strong economic growth also coincides with a very profitable integration in the world system dominated by the US (see Section 3.3). Another point of comparison: with more than 3 tonnes per capita per year (early 1970s and 2000s), France per capita imports are higher than those of the United States at its peak in the 2000s. Since the 1970s, France has been only a net exporter for the biomass category.

Another major characteristic in the long run: France is an importer of fossil energy carriers. Its shift to an industrial metabolism was not mainly built from national resources (such as coal in the British case, coal and oil in the US case until 1957, or China and India in recent decades). From this point of view, France is more alike Japan and Austria than the United States and the United Kingdom: it is a central country in the world-system resting upon energy imports.

Fig. 4 shows the PTB/DMC and IMP/DE ratios that provide a proxy for the commercial dependence from the material point of view. The higher these ratios, the more dependent the country of its imports, the more the indirect flows have a significant weight and the less the DMC can be used as a "dematerialization" metric. Regarding trade dependency, France is at some intermediate position between the United States (low dependency) and Japan (very high dependency[8]). The figure on the left gives details on this dependency by category: unsurprisingly, the strongest dependency is upon fossil fuels and the largest variations concern the smallest category, metals.

Fig. 5 shows the transition – well documented for all countries, from an agrarian (organic) economy to an industrial-mineral economy (Haberl et al., 2011). The abiotic DMC becomes greater than the biotic DMC only in 1930 (much later than the United States or the United Kingdom). In 1830, the consumption of biotic materials is about 14 times higher than that of abiotic materials, and 2 times less important in the 2000s. Rather than a shift, there is a very important addition of abiotic materials to biomass consumption per capita which remains very stable over the entire period (see Fig. 1A).

3. Socio-Metabolic Transitions and Additions

To study the socio-metabolic transitions and additions of France, four time periods are distinguished: 1830–1860, 1860–1930, 1948–1973, and 1980–2015. This periodization is based on annual indicators presented in Table 1.

3.1. 1830–1860: Slow Industrialization Within a Globalizing Economy

The material flow analysis confirms the historical thesis of a French path to industrialization seen as a slow and protracted process – which relied heavily on timber, hydraulic, and muscular energies – and which took place mainly in the countryside according to the putting-out production system.

From a metabolic point of view, France remained a "biotic economy" based on an "agrarian metabolism" (Fischer-Kowalski et al., 2014). In 1860, 75% of the DMC was still biotic. Domestic extraction (almost exclusively biomass) grew relatively slowly from 92 Mt to

[4] One comment points out that "the mining engineers are generally concerned with quarries only from the point of view of accidents and compliance with regulations. However, by way of exception, the Administration asked them, last year, for information on the production of these holdings in 1887." (Ministère des travaux publics, France, 1888, p. 49).

[5] It would be necessary to switch to a "consumption approach" (Material Footprint or Raw Material Consumption) in order to address this issue (Muñoz et al., 2009; Wiedmann et al., 2013; Lutter et al., 2016). Another approach may be to take into account accumulated material stocks (Krausmann et al., 2017).

[6] They recognize (p. 89) that their method underestimates the amount of non-metallic ores by 20 to 40%.

[7] 1Mt = 10^6 tonnes.

[8] In 2005, imports accounted for 80% and exports for 15% of DE for this country which was almost self-sufficient before the Second World War (Krausmann et al., 2011).

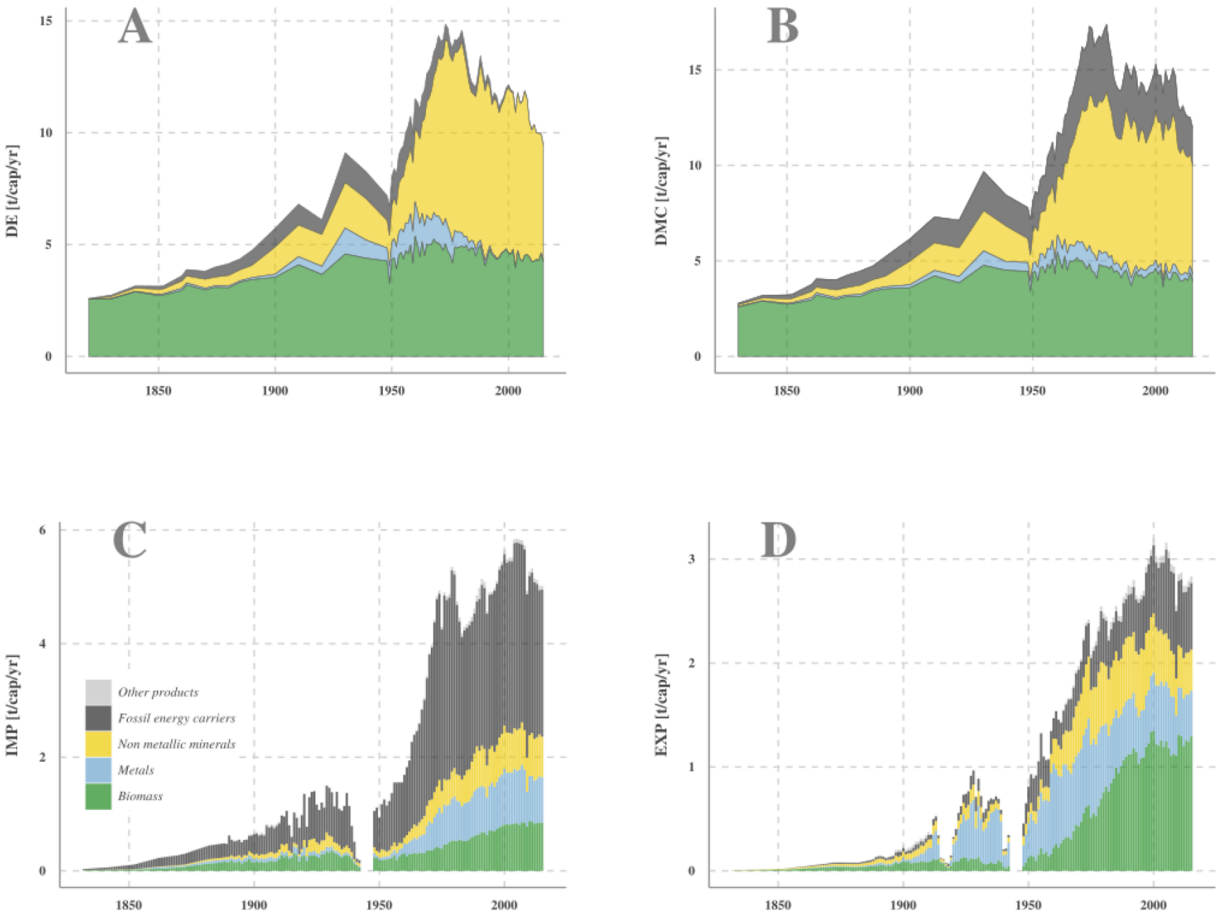

Fig. 1. Material flows in France in tonnes per capita per year (t/cap/yr), 1830–2015: (A) Domestic extraction of raw materials, (B) domestic material consumption, (C) imports, and (D) exports of raw materials and semi-manufactured products.

132 Mt between 1830 and 1860. Given the (moderate) population growth in France, this period has seen a relative stagnation of the domestic extraction per capita. According to the figures compiled by Gales (Kander et al., 2014), coal overpassed timber as the prevailing source of energy around 1860. The per capita available energy seems to have stagnated during the first half of the 19th century (0.94% of average annual growth for TPES/cap). Industrialization did not affect or enrich most of the population: first it was a slow and protracted process, and second the French rural population grew and enjoyed a relative prosperity (which increased the demand for goods), all this without a real metabolic shift.

On the other hand, the evolution of the PTB was much more dynamic. France has rapidly increased its physical trade balance from net imports of 834,000 tonnes per year for the 1827–1836 decade to nearly 6 Mt in the 1860s. France had a specificity in the 19th century: to be the world's greatest importer of coal, but also the second largest importer of biomass behind the United Kingdom. In short, it was the only major economic power of the 19th century having a deficit for the main raw materials: coal and timber, but also grains (more than 4 Mt a year at the end of the 19th century), textiles fibers, and building materials. This situation of a massively positive PTB which will become the norm for European countries after the Second World War was an exception in the 19th century.

For example, the United Kingdom compensated its imports of biomass and minerals with huge exports of coal (in great part to France after 1870). As a result, its PTB has been negative and became even more negative at the end of the 19th century until it reached minus 40 Mt (Schandl and Schulz, 2002). As the United Kingdom run a large trade deficit at this time, it exported increasing quantities of coal and metallurgical products embedding a lot of energy (Kander et al., 2017) – thereby reducing its "natural capital" – so as to compensate for a growing trade deficit. In the last third of the 19th century, the United States' PTB was in a similar situation with smaller exports of coal but very large exports of biomass (Gierlinger and Krausmann, 2011). Other countries had a metabolic relationship to the world-system that was closer to that of France, but quantities were of much less importance: Austria for example imported more coal than it produced in 1874 (Krausmann et al., 2008); the same for Japan under the Meiji era (Krausmann et al., 2011); in 1900, Spain and Italy imported respectively 40% and 93% of their coal from the United Kingdom (Thomas, 1903).

During the 1830–1860 period, coal accounted for almost all of the French PTB surplus. In 1860, France imported nearly 40% of its coal. The French transition to a fossil economy has mostly been achieved with the help of Belgium, which supplied 60% of coal imports. It is noteworthy that the young Belgian state was then a quasi-economic protectorate of France. France represented its main commercial outlet, its main source of funding, and above all French capital controlled most mines around Mons (Veraghtert, 1975), the very ones that supplied energy to the French economy.

In addition to coal, textile fibers – in the first place wool, cotton, and silk – were essential materials connecting France to the world-ecology. "Agricultural raw materials" (i.e., non-food biomass, cotton, wool) are, by value, the items whose imports share increased the most: from 27% in 1789 to 48% in 1860 (Toutain, 1977, p. 65). In terms of tonnage, the evolution is even more spectacular. Crude cotton imports increased from around 30,000 tonnes in the early 1830s to 123,700 tonnes in 1860. The origin of imported cotton changed: the United States eclipsed

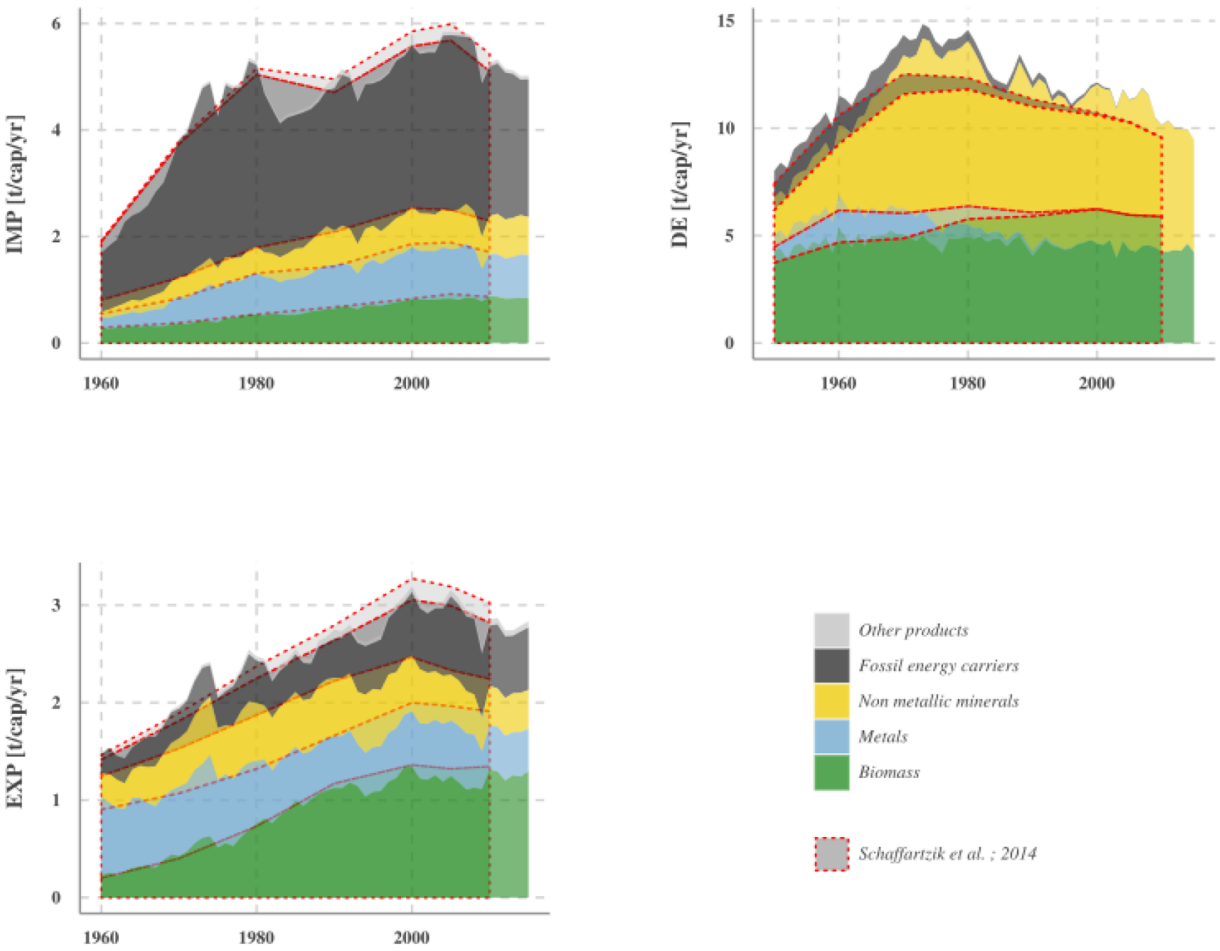

Fig. 2. Comparison for the period 1950–2010 between Schaffartzik et al. (2014) (shaded areas) and our data. t/cap/yr = tonnes per capita per year.

former producers like Turkey and the Levant, and its imports share increased from 55% in 1820 to 93% in 1860. At that time, it would have taken about 6 million hectares of French countryside – that is 20% of the agricultural area – to produce the 123,000 tonnes of imported cotton (Pomeranz, 2001). The period 1830–1860 was also marked by a steep growth in imports of raw wool. While in 1830 only 10% of the wool processed in France was imported, mainly from neighboring countries, in 1862 the share of foreign imports had already increased to 45% (nearly 100,000 tonnes) corresponding to more than 5 million of "ghost hectares."[9]

As early as the 1860s, the French economic activity depended on a material base located largely outside its national territory. For example, the 5 Mt of imported coal in the 1860s represent a quantity of energy comparable to the 18 Mt of domestic timber[10]. Similarly, the development of the French textile industry, a leading sector of industrialization according to economic historians, depended very closely on environmental assistance from the United States, Australia, New Zealand, and Argentina. By the end of the 1860s, producing 100,000 t of imported wool would have required about 5 million hectares, or 17% of the country's agricultural area (on the methodology for calculating these estimates, see Riello (2013, p. 240–241) and Riello, 2004). In the 1860s, France benefited from the world-system dominated by the United Kingdom and shaped by the export of coal and humans to America and Oceania. France benefited directly from the demographic growth of the Anglo-world, which was one of the most fundamental factors of the world-economy of the 19th century (Belich, 2009).

3.2. 1860–1930: Coal, Empire and Industrial Metabolism

Compared to the previous period, years 1860–1930 were characterized by a faster growth of domestic extraction and a slowdown of the physical trade balance. Domestic extraction went from 135 Mt per year to 379 Mt, despite a sluggish population growth. The most striking fact is the rise of coal's domestic production from 8.7 Mt in 1860 to 55 Mt in 1930. More generally, there was a shift towards abiotic resources: in 1860, the French economy consumed four times more biomass than minerals and coal, and in 1930, the biotic and abiotic DMC became equivalent. This period corresponds to the peak of the dependence of the French economy on coal. Its proportion of the total energy consumed rose from less than 50% in the early 1860s to more than 70% at the eve of the Second World War, peaking at nearly 82% in 1924. Correlatively during this period, miners' unions gained as much power as necessary to interrupt most of the energy flow supplying the French economy. Following the arguments of Mitchell (2011), one can wonder on the relationship between coal, the strengthening of the working class illustrated during the great waves of strikes (1891, 1906, 1919, 1920, 1936), and the major social reforms that made France a mass democracy.

Nevertheless, the French metabolism's globalization followed a bumpier trajectory, based on wars and economic crises that marked out the period. This globalization first stagnated from 1870 to the early 1900s. The economic crisis that Western Europe went through between 1873 and 1897 led to protectionist policies. The Meline tariff (1892)

[9] A term introduced by Pomeranz (2001) to designate extra-territorial hectares that serve the development of a country's economy.

[10] Usually, calorific values for a kilo are respectively of 3000 kcal for timber and 7000 kcal for coal (Kander et al., 2014, p. 60).

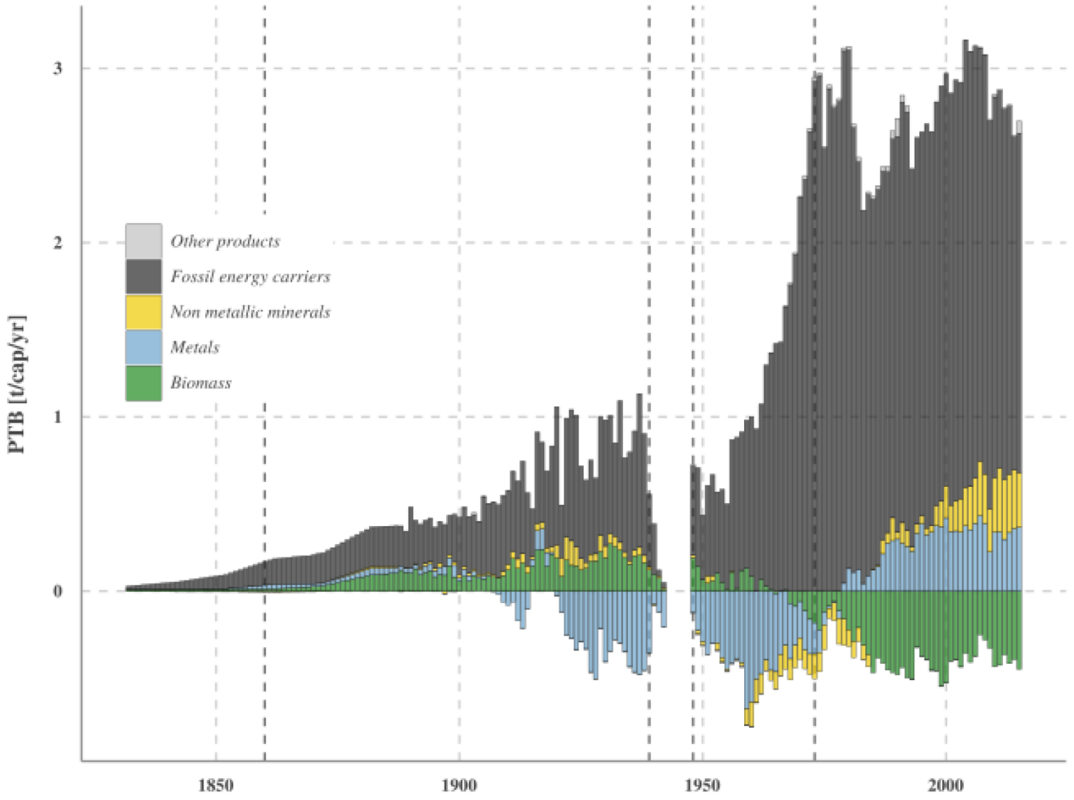

Fig. 3. Physical trade balance (PTB) per capita per year.

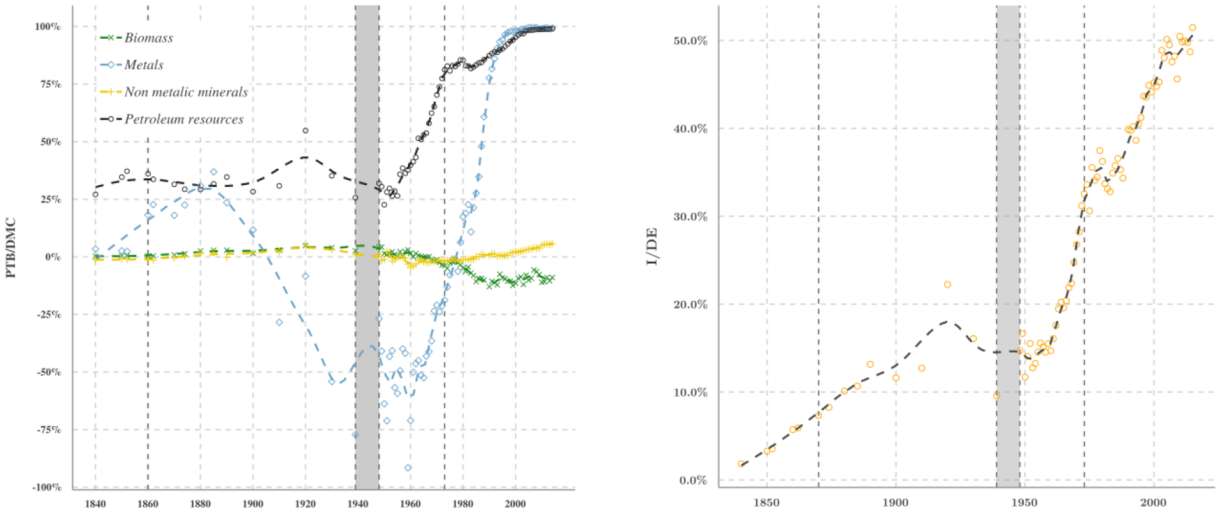

Fig. 4. Trade dependency of France: ratio PTB/DMC by main material group (left), ratio I/DE (right).

which tripled agricultural duties aimed to protect French farmers from international competition and to rally rural population to the Republican regime. In value, agricultural raw materials in imports dropped from 48% in 1860 to 24% in 1939 (Toutain, 1977, p. 66). In volume, the imported biomass remained stable around 6 Mt from 1890 to 1910. After the First World War, the PTB has showed a more dynamic growth.

There have been several exceptions to this partial shelving of the French economy from the globalization of years 1870–1914. First, imports of coal and textile remained strong. Those of coal went from 10 Mt in the 1890s to 20–30 Mt in the 1930s (with significant fluctuations). Secondly, biomass imports for industrial production also remained dynamic: the government looked after the interests of the textile industry by promoting wool imports from Argentina, Australia, and Cape Town for example. In 1896, 250,000 tonnes (nearly 80% of the wool consumed) were now imported representing the equivalent of 130,000 km^2 of ghost pastures (about 40% of the French agricultural area). Third, during the 1930s economic crisis, trade with the colonial Empire (mainly Algeria) was also dynamic, as the French economy was retreating to its empire (Marseille, 1984). Imports from the empire rose in value from 300 million to nearly 2 billion francs between the 1880s and the 1930s (Marseille, 1984, p. 47–48), even while imports from abroad fell sharply during the 1870–1890 crises and the 1930s. Trade with the Empire began to weigh in the PTB mainly through the import to mainland France of Algerian iron ore and livestock in the 1880s, then mostly with the exploitation of the very rich phosphate deposits in

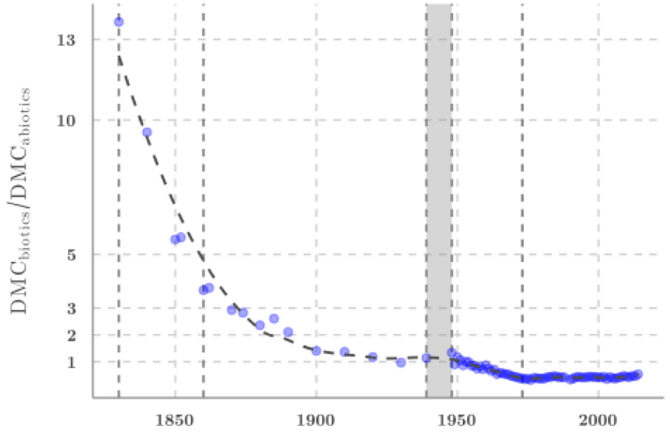

Fig. 5. Ratio biotic DMC/abiotic DMC.

Table 1
Average annual growth (ag) rates of population, gross domestic product (GDP), total primary energy supply (TPES), and other material use during different periods of the metabolic transition. The last four rows are average ratios.

	1830–1860	1860–1939	1948–1973	1980–2015
Population ag	0.44	0.16	0.94	0.51
GDP ag	1.74	1.41	5.47	1.52
TPES ag	1.39	1.77	3.75	0.20 (2008)
TPES/cap ag	0.94	1.61	2.79	− 0.31 (2008)
DMC ag	1.51	1.52	4.21	− 0.56
DE ag	1.38	1.49	3.91	− 0.63
DMC biotics/cap ag	0.51	0.69	0.35	− 0.53
DMC abiotics/cap ag	5.35	2.61	5.41	− 1.29
DMC fossil/cap ag	5.81	2.49	3.23	− 1.63
DMC biotics/DMC abiotics	7.61	2.29	0.74	0.43
I fossil/DMC fossil	0.33	0.37	0.58	1.15
(E+I)/DE	0.04	0.15	0.31	0.66
I/DMC	0.03	0.1	0.17	0.36

Northern Africa.

3.3. 1945–1973: The Great Acceleration: Oil, Decolonization, Pax Americana, and the European Construction

The decades following World War II showed a specific form of the integration of the French economy in the new world-economy. As shown in Table 1, the DMC experienced an unprecedented growth from 320 Mt in 1948 (7.8 t/cap) to 897 Mt in 1973 (17.3 t/cap). The fossilization of the French metabolism accelerated together with the rise of oil and gas. The fossil DMC/cap went from +2.49% per year between 1860 and 1930 to +3.23% per year between 1948 and 1973. This growth constituted a significant drive for the GDP growth (+5.47%/year).

Among the fossil fuels, coal regressed for the benefit of oil and gas – in absolute mass, coal DMC only decreased by one third (1948: 59 Mt; 1973: 43 Mt). More specifically, two phases can be distinguished: a first phase, which spanned from 1948 to 1960 and showed a moderate growth of the fossil DMC from 1.6 t/cap in 1948 to 2.3 t/cap in 1960; and a second phase post-1960 where the consumption of fossil fuels jumped to 3.6 t/cap in 1973. Imports of fossil fuels remained moderate until the mid-1950s (less than 50 Mt, 26.4 Mt in 1948). It then increased until 1973 to 171.2 Mt. The structure of imports drastically changed: in 1930, coal represented 95% of the fossil DMC, then 88% in 1948, and only 23% in 1973. As oil is energetically denser than coal, one can speak of energy addition rather than energy substitution.

This evolution can be explained by a transformation of the French policies towards energy. If the petrolization began with the Marshall Plan's support which subsidized imports of oil from the Middle East (Painter, 2009), the successive governments of the 4th Republic also strongly supported the revitalization of the domestic coal production (45.1 Mt in 1948, 58.3 Mt in 1960). They promoted exploration and exploitation of gas and oil on mainland France as well, for which the domestic extraction has jumped from 0.19 Mt to 4.5 Mt between 1948 and 1960. The exploitation of 1951-discovered Lacq's deposit started at that time. In 1959, the Parisian basin produced about half a million tonnes of oil and the companies flourished. Even though it represented only a small share of the domestic consumption, the basin exemplifies policies directed towards a general mobilization of the territory's resources in order to minimize the trade deficit, thanks to investments in oil production – controlled by a state-owned monopoly.

In contrast, the first fifteen years of the 5th Republic (1958–1973) met with a boom of fossil fuels imports. This was a choice of the Gaullist power to "petrolize" the economy in order to ensure an energy base as cheap as possible for the industrial and agricultural competitiveness in the context of European markets: the Jeanneney Plan in 1960 for a setback in coal production and an elimination of 2400 mining jobs, the creation of the UGP – General Union of Oils – in 1960, investments in refineries such as the Feyzin refinery that was opened in 1964. This oil push during the decades following World War II happened under the dominance of the United States. US firms provided a large share of the imports and managed several refineries. However, French oil imperialism also organized itself. The first oil cargo from French black Africa arrived in Port-Gentil in 1957. In the 1960, more than a third of oil imports came from Algeria[11]. Then after 1962 continuity agreements maintained the presence of French firms until their nationalization in 1971.

Beyond tensions with the other oil-colonial powers – such as the United States, the United Kingdom and Italy – for the control of resources (Cantoni, 2017), the French petrolized economy benefited *de facto* from the *Pax Americana* and from the low oil prices it ensured. As well as it had profited from the British coal and textiles from Anglo-Saxon countries during the 19th century, France partook in the Great Acceleration as part of a specific world-ecology, where high quality energy was low-priced. The productivity gains that oil allowed stabilized the "Fordist wage relation" (Boyer, 2015), which granted wage increases to workers – thus guaranteeing a demand that met mass production – in exchange of implementing Taylorism. Some economists estimate that 2/3 of the French economic growth during the *Trente Glorieuses* is the mechanical result of the expansion of fossil fuel consumption (Giraud and Kahraman, 2014).

Only under the infusion of inexpensive oil could France become a net exporter of biomass in the 1960s. Indeed, while France had been a net importer of biomass for its industrial production and its food supply during the long 1830–1960 period, the biomass physical trade balance became negative in 1960. It went from +2.7 Mt in 1950 to −0.7 Mt in 1965 and −9.5 Mt in 1973. That year, biomass exports represented 26% of total exports and 13% of biomass domestic extraction in mass. Both oil shocks of the 1970s stalled French agricultural exports; the French biomass PTB clearly decreased then due to the oil counter-shock of the 1980s (−8.6 Mt in 1979 and −28.8 Mt in 2015). This agricultural exporting changeover of France followed the same path as the one of the United States, which was net importers of biomass after World War I until the 1950s, and then became massive exporters from 1960 (Gierlinger and Krausmann, 2011). This shows the inclusion of France in a new "agri-food regime", that Harriet Friedmann (2005) named "mercantile-industrial", in which France became exporter of grains not only to Europe but also to Africa and to Western Asia. In 1973, the biomass exported by France represented 12.1% of its

[11] The Algerian production represented 45% of the French consumption in 1960 (Demagny-Van Eyseren, 2009).

domestic extraction against 8.8% for the United States (Gierlinger and Krausmann, 2011). Since France is less vast and more densely populated than the United States, a country that had traditionally been an agricultural exporter, it illustrates a strong biomass extroversion for France. In 1974, France became the second world agricultural exporter after the United States (Gervais et al., 1992, p. 123) thanks to both the Common Agricultural Policy that has been promoting exports and a fast shift from a "low input, low output" agriculture towards a "high input, high output" agriculture. It also benefited from a "fossil-dependent food export regime" (Harchaoui and Chatzimpiros, 2018).

If the inexpensive oil led to an integration of France in the post World War II United States-led world-system as an agricultural exporter, this also fostered a "concretization" of France (major phenomenon in our data since 1945) that is visible in the significant domestic extraction of non-metallic minerals from 1.2 t/cap in 1948 to 8 t/cap in 1973 – the DE for the category "gravel and sand" alone went from 31 Mt in 1948 to 340 Mt in 1973. Indeed, the inexpensive oil allowed the state to multiply the infrastructure projects (highways, roads, dams) but also to foster urban sprawl, in particular through the modernism of *villes nouvelles* or new cities (Vadelorge, 2013). This process went together with the strong growth of the motor vehicle industry – a key sector of the Fordist accumulation regime in France (Boyer, 2015) and a symbolic object invading every aspect of French identity and culture (Ross, 1996) – that required ever-larger oil imports.

This environmentally problematical circle was a key to the strong economic growth of the so-called *Trente Glorieuses*. The 1945–1973 period has been tagged the "Great Acceleration", concomitant of oil imports and of sand and gravel extraction. We can also notice a strong rise of the domestic production of cement, which generates significant emissions of greenhouse gases (producing 1 t of cement generates about one tonne approximately 1 t of CO_2). This accelerated growth phenomenon of "technomass" and of concrete was also witnessed in various countries. Studies have underlined that those materials created a strong path dependency, because of the stocks accumulated that must be preserved or repaired (Krausmann et al., 2017).

3.4. 1980–2015: Post Oil Shock Post-Industrial Consolidation (Financialization and Neo-Imperial Way of Life)

The oil shocks of 1973 and 1979 opened a new period. For France, it halted the strong growth of energy carrier imports (from 171 Mt in 1973 to 183 Mt in 1980, 151 Mt in 1990, 178 Mt in 2000, 176 Mt in 2010), which however remained the main import item, both in terms of value and volume. It occurred despite the development of nuclear energy which emerged at the same time. After 1979, the DE and the DMC (about 764 Mt and 913 Mt that year) fluctuated downward for several decades (with some upward periods). Foreign trade increased little until 2000, before a new rise that culminated around 2007 (the country then imported almost half of the DE). In addition, biomass consumption fluctuates around 250 Mt from 1980 to 2015; non-metallic minerals declined and then stabilized at a high level (with a peak just before the 2008 financial crisis). All these trends led to a decline in the DMC from 17.4 t/cap in 1980 to 15.5 t/cap in 2000, and 12.5 t/cap in 2014. Unlike earlier episodes (the 1929–1933 crisis and the two World Wars), this decline of the DMC/cap is neither a temporary phenomenon, nor a drop of GDP and standard of living.

This decline of the DMC/cap as well as the fall of GDP's material intensity, that has been observed in many European and North-American countries[12], has sometimes been interpreted as a sign of a post-industrial transition (Bell, 1973) and in any case of a better energy and material efficiency of Western economies. This reading, which is consistent with the discourses of "sustainable development" and "ecological modernization", does not take into account, in our opinion, deeper and more global socio-ecological phenomena.

Firstly, consumption-based studies in France (only available for the recent period) show rather a stagnation of the material footprint per capita since 1990 of around 22 t per year (UNEP, 2016, p. 111), which reinforces the hypothesis of an industrialized economy close to the "material saturation" stated by some authors (Miatto et al., 2016; Krausmann et al., 2017).

Secondly, the decline of the DMC/cap testifies the integration of France in a new world-ecology, in which industrial activities with high level of energy, workforce, and sanitary and environmental impacts were relocated outside OECD countries, particularly to Asia. From 1973 onwards, the rise of oil prices gradually disrupted global capitalism. The rise of interest rates in the United States entailed increasing debts of peripheral countries[13] subject to a neoliberal path (Washington consensus) that pushed to the liberalization and globalization of their economies. In Western Europe, according to the *Régulation* approach, the deceleration of productivity gains put an end to the intensive "Fordist" accumulation regime in the 1970s (Boyer, 2015) while Keynesian policies have been slowly abandoned.

Thirdly, the new "financialized accumulation regime" – where international integration is very strong even on the physical side– has been the first explanation for the decline of DMC/cap after 1980 in France, following the same path of several European countries and Japan (for the United States, there was a slight drop in the growth of the DMC compared to that before 1973[14]). Kovacic et al. (2018) show that financialization has played a crucial role in the decoupling of GDP growth and energy in most industrialized economies by making relocation and tertiarization possible (energy-intensive sectors have been metamorphosed and redistributed geographically).

In France, as in other OECD countries, the decline of both DMC/cap and energy intensity was not linked to the successful adoption of metabolic and energy transition policies. It was rather the consequences of new arrangements of uneven ecological exchange with the outsourcing of polluting and material-consuming and energy-consuming activities to the global South (Muradian et al., 2012). This has been the case of iron and steel industries: France has moved from an exporter country before 1973 to an importer country in 1980–2015. This was also the case with the adoption of renewable energy: solar panels and wind turbines require rare metals that involve a strong mobilization of material for their extraction outside Europe. Agriculture which consumes space, energy, and biodiversity was also affected by this movement: the French biomass PTB stagnated between 1973 and 1979, before falling again. But this growing export trade balance did not follow the 1960–1973 trend and masked the rise of biomass imports. These lasts, in a context of liberalization of agricultural markets and food globalization, increased from 29 Mt in 1980 to 55 Mt in 2015.

Finally, the specificity of nuclear energy in the French trajectory since 1973 is worth mentioning. A massive development plan for nuclear energy was adopted in 1974, leading to the construction of 58 nuclear reactors. In the 1990s and 2000s, 75 to 78% of electricity came from nuclear technology, which was the highest percentage in the world. Nuclear production culminated in 2005, at 452 terawatt hours (TWh), with averages just over 400 TWh, equivalent to 106.8 million tonnes of oil equivalent (Mtoe). It can therefore be estimated that nuclear energy reduced fossil fuel imports (and fossil DMC) by a hundred

[12] In France Schaffartzik et al. (2014) calculate that the ratio of DMC/GDP has halved between 1980 and 2010.

[13] On this tipping point of global capitalism and its effects in Latin America, see Ortiz (2016).

[14] In the United States, the DMC/cap increased by 0.4% from 1980 to 2005 (Gierlinger and Krausmann, 2011, p. 371). It happened as if it had achieved various strategies to consolidate its metabolic way of life. This is one of the reasons why this country has been much more extractive on its territory and less dependent than France on foreign trade (I/DE ratio much lower). The United States exit from the Paris Agreement (COP 21) in 2017 could be questioned anew, given this metabolic trajectory.

million tonnes, through importing 24,000 tonnes of uranium, mostly extracted from Africa (Hecht, 2012). Thanks to this importance of nuclear power – which also raises new risks and new challenges illustrated by the waste problem – electricity production has tripled in France between 1973 and 2009 (in energy used France passes from 3370 toe per capita to 4301 in 2004[15]).

The French economy no longer fits into a well-polarized world-economy, with China as a center for example[16], but ingeniously takes advantage of new global value chains. The "Fordist" regime has created, through new infrastructures and superstructures, new consumption norms which are deeply rooted in everyday practices and still present during the last period. This "mode of living" (Brand and Wissen, 2012) is imperial because it relies on a principally unlimited appropriation of resources, space, and workforce from other territories. This appropriation is either legally warranted (GATT, WTO, bilateral free trade treatises) or provided by the mean of violence. The ongoing financialized accumulation regime, far from being more green or efficient than the previous ones, increasingly makes invisible the damage and socio-environmental conflicts that it keeps provoking in ever more remote regions.

Conclusion

Since Braudel and Wallerstein's works, global economic history has sought to explain both the integration of growth in different regions of the globe and the strong asymmetries between them, using the key concepts of "unequal exchange" and "center-periphery" economic hegemonies (Arrighi, Jorgensen, Moore). In our opinion, quantification and material flow approaches allow to better discuss, explain, or nuance these "world-system" perspectives, by documenting the physical dimensions of the economy.

Let us take the issue of uneven ecological exchange as one of the engines of economic growth in the "central" countries (Hornborg, 2012). Concerning the United Kingdom and the United States, this thesis remains problematic: in the 19th century, the United Kingdom imported biomass, but emptied its coal stocks for the benefit of its European neighbors; in the 20th century, the United States is characterized by a much higher domestic extraction than most European countries and is a net exporter of many raw materials. France is clearly less central in the world-system than the two formers. It is not a resource-rich country: for two centuries, its main raw materials have been those with the lowest monetary value in terms of weight, namely biomass (grain) and building materials (sand and gravel). But in the end, the country has been remarkably successful in the global competition of material exchanges for two centuries. Even more than the United Kingdom or the United States, it is the archetype of a country enjoying unequal ecological exchange. France has been one of the greatest "parasites" of the world-ecology since the 19th century. Even today, despite a lower economic growth than that of emerging countries, despite a much less favorable trade balance than that of Germany, France derives an extraordinary material benefit from the world-ecology of financialized capitalism (outsourcing its ecological footprint).

By bringing together material flow analysis, economic history, global environmental history, and the world-system's eco-Marxist theories, we have established a "rematerialized" picture of the French economy in a framework that allows us to: i) go beyond the limits of the only-MFA approaches that are under-theorized and descriptive; ii) avoid the pitfalls of the *Régulation school*[17] (Zuindeau, 2007); iii) to overcome the shortcomings of standard economic history of France in the 19th century; iv) to deepen the reading of unequal ecological exchange in the different capitalist world-systems. We have contented ourselves in this work with a narrative from aggregated data. As we possess the detail for dozens of material flows, other finer studies for limited periods will be carried out in order to understand more precisely the variations of the metabolic trajectory of the French economy that we have just described.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.12.001.

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[15] https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE?locations=FR

[16] As for many African or South American countries for which researchers talk about the "Beijing Consensus" (Svampa and Slipak, 2015).

[17] In addition to its environmental and energy blindness, this approach keeps the national space as a scale of analysis. Our work highlights the need to consider an enlarged space to make industrialization and accumulation intelligible.

(*footnote continued*)

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