The metabolic transition of a planned economy: Material flows in the USSR and the Russian Federation 1900 to 2010

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Abstract:

The study of long-term historical trends in material flows has gained some prominence in Ecological Economics since the first studies for Austria and the United Kingdom were published as part of a special section in 2002. This research expands the existing knowledgebase by presenting material flows for the Russian Federation and its predecessor states employing a standard accounting framework. The study of material flows for the Russian Federation provides an interesting and unique case of a planned economy and its transition to a market based form of economic organization. We show that in spite of considerable differences in the physical economy, the USSR developed material use patterns similar to that of Western industrialized economies. Lower levels of consumption were more than outweighed by inefficient production. The transition towards a market economy drove rapid improvements in resource productivity but also growth in metabolic rates. The results indicate that the transition to an industrial metabolic profile proceeds largely irrespective of economic and political conditions. An improved understanding of the evolution of socio-economic systems and the material flows that fuel them is increasingly relevant for designing new systems of production and consumption and facilitating a transition towards a more sustainable industrial metabolism.

Keywords: MFA; material flows; resource use; industrialization; dematerialization; material productivity; social metabolism

1 Introduction

Over the last century global natural resource use has grown at a fast pace and there is no sign of slowing down. Between 1900 and 2010 freshwater extraction multiplied from 580 to 4400 km³/yr (Shiklomanov, 2000) and primary energy consumption from 40 to 550 EJ/yr (Krausmann et al., 2009). Crop harvest has grown from 1 to 7.5 Gt/yr, iron ore extraction from 0.09 to 2 Gt/yr (Krausmann et al., 2009). As everything that goes in must ultimately also leave the economy, the amount of wastes and emissions has also surged: global CO₂ emissions from burning fossil fuels and cement production have risen from 0.5 Gt to 10 Gt/yr (Boden et al., 2009) and municipal solid waste from 0.1 Gt to 1.2 Gt/yr (Hoornweg et al., 2013). Human use of resources and the corresponding wastes and emissions, denoted as socio-economic metabolism, is the direct or underlying cause of a wide array of humanity's most challenging sustainability problems. It has been argued that the scale of socio-economic metabolism cannot continue to grow as in the past, and humanity must find ways to return to a safe operating space for material use within planetary boundaries (Bringezu, 2015; Haberl et al., 2011).

Understanding the historic trajectories that led to the current industrial metabolism is an important precondition for developing strategies for a transition towards more sustainable metabolic patterns (Gonzales de Molina and Victor Toledo, 2014). In this paper we apply material and energy flow accounting, a method of capturing the biophysical basis of the economy and physical exchange processes between the socio-economic system and its environment (Fischer-Kowalski et al., 2011), to investigate the evolution of resource use in the Russian Federation and its predecessor states in the 20th century. While in recent years material flow accounts have been made available for most countries of the world and the evolution of material flows has been thoroughly studied at a decadal scale, quantitative assessments which shed light on long-term historical trends in material use are still rare. Only a handful of studies have investigated the development of material flows over a whole century, covering key periods of the emergence of modern industrial economies. The existing studies include several economies of global importance: the United Kingdom as the forerunner of the industrial revolution (Schandl and Schulz, 2002), the USA as the country that dominated the global economy through much of the 20th century (Gierlinger and Krausmann, 2012), and Japan, a late comer which very rapidly caught up with Western industrial countries after World War II (WWII) (Krausmann et al., 2011). Most recently Spain has been added to the list (Infante-Amate et al., 2015). The only planned economy for which a long-term MFA has been compiled is Czechoslovakia (Kovanda and Hak, 2011). These studies show how material flows evolve,

how material use relates to economic development in different phases of industrialization and under which conditions dematerialization occurs. The observed pattern of the transition from an agricultural economy with biomass as the main resource, towards an economy with a fossil fuel based energy system, has been termed the metabolic transition (Haberl et al., 2011; Krausmann et al., 2008). It can also be observed in current industrialization processes in emerging economies like China (Schaffartzik et al., 2014).

This study adds an important element to the existing series of historical case studies of long-term material flow and resource productivity analysis. It presents a century-long MFA series for the USSR and the Russian Federation, its legal successor. The USSR is an interesting case of high global relevance as industrialization proceeded under fundamentally different economic and political conditions than in the West until the USSR finally collapsed in 1991 and turned into a capitalist market economy. The evidence we provide for the USSR complements a recently published study on material flows in the countries of the former Soviet Union (FSU) which focused on the period 1992 to 2008 (West et al., 2014). It also adds a biophysical reading of economic development to the considerable body of literature on the economic history of the region focusing on Soviet industrialization and transformation and to the few studies on its environmental history, mostly addressing issues of conservation and pollution (e.g. Gregory and Stuart, 1994; Allen, 2003; Josephson et al., 2013).

In this paper we present material flow data for the period 1900 to 2010, covering the full period of industrial development and important economic and political transformations. In line with most MFA studies we focus on extraction, trade and consumption of materials but do not quantify outputs of wastes and emissions for which the database is insufficient. We use a methodology consistent with that of existing long-term MFA studies. This allows for comparison of the trends observed for the USSR with those of Western industrial economies (UK, Japan, USA) and of planned economies of the former European Eastern Bloc (Romania, Bulgaria, Poland and Czechoslovakia), although most of the latter studies cover a much shorter time period. We explore differences and similarities in the transformation of the physical economy between planned and market oriented economies, and the impact of collapse and the restructuring of the economy on material use.

The main goal of the paper is to analyze the development of material extraction, trade and consumption of the USSR and the Russian Federation in the context of its economic and political development and in international comparison. This contributes to a better understanding of the global metabolic transition. All data are made available publicly for further

use.¹ The next section provides a concise overview of data sources and methods. Based on the results of the material flow analysis we then discuss the evolution of the physical economy of the USSR and its successors during different periods of economic and political development. In section 4 we investigate differences and similarities in the pattern of the metabolic transition with other Western and centrally planned economies. Finally we explore the coupling of material use and economic growth, the factors underlying the low level of material productivity (section 5) and how the USSR missed chances to develop a less material intensive metabolic profile (section 6). We end with some conclusions on how the USSR fits into the general pattern of the metabolic transition.

2 Methods and data

Territorial system boundaries: We compiled data for the extraction and trade of materials for the period 1900 to 2008/2010. This entailed several changes in territorial system boundaries. The USSR as such existed between 1922 and 1991. For the period 1900 to 1921 data refer to the Russian Empire²; for 1922 to 1991 they refer to the USSR. The USSR expanded its territory in several steps³ between 1922 and the end of World War II. It reached its largest expansion in 1946 and remained constant until its dissolution in 1991. For the time period after the disintegration of the USSR we show data for both the Russian Federation, the largest successor state, and an aggregate of all other successor states. Data for the other successor states are based on West et al. (2014). For years around the two world wars data are too fragmented to compile reasonable aggregates; thus no results are shown for the periods 1914 to 1919 and 1941 to 1945. While territorial changes may appear in absolute numbers as minor statistical breaks, this is of less significance for values expressed per capita or per unit of GDP.

Reliability of Soviet statistics: We used national and international statistical sources to compile data on extraction, imports and exports. The reliability of statistical data published by the USSR has been an issue of debate among economic historians (Davies et al., 1994; Jasny, 1959, Allen, 2003). Despite the fact that the USSR developed a very extensive statistical reporting system and invested significant resources into recording and reporting statistical data as a basis for

¹ Data will be made available at: <http://www.uni-klu.ac.at/socec/inhalt/1088.htm>

² The territory of the Russian Empire was not stable in the observed period. During and after WWI the territory of the Russian Empire contracted as parts of today's Finland and Poland and the Baltic States were lost.

³ The Turkmen and Uzbek S.S.R.s were established in 1924, the Tadzhik S.S.R. was established in 1929, and the Kazakh and Kirgiz S.S.R.s were established in 1936. In 1940 the Karelo-Finnish, Moldavian, Estonian, Latvian, and Lithuanian S.S.R.s were established. These additions increased the population of the original USSR by approximately 10 to 13%.

centralized planning (Grossman, 1960), concerns have been raised that statistics have been manipulated to produce the impression of achievements greater than those actually attained. There is little doubt that some of the official figures published by Soviet authorities are flawed. However, it has been shown that this mostly concerns important general aggregate indices like national income, industrial output or labor productivity. In contrast, the detailed, more technical underlying statistical information from, for example, industry statistics on the output of individual commodities has indeed been judged as reliable by economic historians (with some exceptions, see Allen, 2003). This involved archival research which compared unpublished records with published data and tested for internal consistency in the statistics (Allen, 2003). Data quality also varies over time but the quality of Soviet statistical records generally improved over time. Overestimations in individual materials don't seriously distort the overall picture presented for the four main material groups in this paper.

Data sources and estimation procedures: We apply the methodology of economy wide material flow accounting (MFA, see Fischer-Kowalski et al., 2011) and follow the system boundaries and accounting guidelines proposed by the European Statistical Office (Eurostat, 2009) and the adaptations of estimation procedures for global and long-term historical application suggested by Krausmann et al. (2015). This methodology is largely consistent with the methods applied in other long-term MFA studies and produces comparable results. We quantify three types of direct material flows: Domestic Extraction (DE), Imports, and Exports, and calculate the material flow indicators Domestic Material Consumption (DMC; DE plus Imports minus Exports), Physical Trade Balance (PTB; Imports minus Exports), Material Productivity (MP; GDP/DMC) and Material Intensity of fossil and mineral materials ($MI_{\text{min\&foss}}$; $DMC_{\text{min\&foss}}/\text{GDP}$). The MFA database comprises 60 to 70 different material groups. We present material flow data in aggregation by four main material groups: biomass, fossil energy carriers, ores and metals and non-metallic minerals.

The material flow account is based on data available from international and national statistical sources and data compilations and for some material groups estimates are used. All estimates are based on physical data, no monetary information was used to estimate physical flows.

DE biomass: Extraction of crops was sourced from the statistical yearbooks of the Food and Agricultural Organization of the United Nations for 1947 to 1961 (FAO, 1947–1961), its precursor from 1909 to 1941 (IIA, 1912–1947) and FAOSTAT (FAO, 2013a) for 1961 to 2010. Additionally we used revised data on grain production for 1920 to 1956 reported in Nove (1969) and Davies et al. (1994) and data on vegetable and fruit production from Pockney (1991). The

amount of used crop residues was extrapolated from crop production by using time specific harvest factors reflecting changes in the Harvest Index based on Krausmann et al. (2013). Biomass harvest from grassland and grazed by livestock was estimated on the basis of livestock numbers from IIA, FAO, FAOSTAT and Pockney (1991) and species and time specific coefficients for daily roughage demand were based on Krausmann et al. (2013). Data on wood extraction are fragmentary and have been sourced from FAOSTAT and from Clarke (1972). Fish-catch was sourced from FAO yearbooks, FAO's fishery statistics (FAO, 2013b) and Clarke (1972).

DE fossils: For the period 1950 to 2010 we used data on the production of fossil energy carriers available from UN energy statistics (UN, 1976; UNSD, 2011) and the International Energy Agency (IEA, 2012). Data for earlier years were sourced from statistical compilations (Pockney, 1991; Etemad et al., 1991; SZM, 1956).

DE metal ores: The main source for metal ore extraction was data collected from the British Geological Survey which provides information on the production of most metals back to the 1920s (BGS, 2012). Additionally we used data from the United States Geological Survey (USGS, 2012), from UN Industrial Commodities Production Statistics (UN, 2010) and from Mitchell (2003). Data gaps were closed by using a variety of additional sources, e.g. Davies et al. (1994), Segal (1936), Stanlov and Segal (1929) and SUIB (1929). For the most important ores production was reported as gross ore. In cases where no information on gross ore extraction was available we used average ore grades to extrapolate gross ore from metal content. In these cases coupled production was taken into account (see Eurostat, 2009).

DE non-metallic minerals: We used the same main sources as for ores (BGS, USGS and UN, 2010). However, large mass flows of non-metallic minerals are not reported in statistical sources. We estimated the extraction of limestone required for cement production and the extraction of sand and gravel based on requirements for concrete and asphalt production using estimation procedures and coefficients provided in Krausmann et al. (2015), cement data from Cembureau (1998 and 2013) and bitumen use from IEA (2012) and UNSD (2011). The extraction of clay for brick production was estimated from information on brick output from UN (2010) and extrapolated for earlier years. Estimates for construction minerals must be considered conservative and most likely underestimate actual use of construction minerals by 20 to 40%. This may contribute to an underestimation of total DMC by 1-5 % in the first and by 4-14% in the second half of the 20th century.

Trade flows: Data on imports and exports are fragmentary for the period 1900 to 1950. Based on international compilations and national publications we compiled trade data for the major bulk commodities which dominate physical trade flows: cereals, wood, iron ore, coal and oil. Sources used for this period were IIA and FAO yearbooks, Spectator (1921), Segal (1936) and Mitchell (2003). For the period after 1950 data are largely complete. For trade in agriculture and forestry products we used FAOSTAT from 1961 onwards; for fossil energy carriers UN energy statistics from 1950 onwards. For trade with mineral and metal commodities for the period 1955 to 1990 we used data from Soviet trade statistics (MVT, 1959–1991). This source reports data for approximately 900 different commodities which we allocated to material groups. Unfortunately, data for trade with ores and raw metals are missing for the period 1991 to 1994; the impact of data gaps on DMC can be considered low, as net exports of these material groups amount to only 1 to 3% per year compared to total DMC in the 1980s and 1990s. From 1994 onwards data from the UN's international trade database (UNSD, 2012) could be used.

Overall, data coverage is fragmentary for the early period, in particular for the Russian Empire. But for the main mass flows data series are generally complete and of good quality. We therefore assume that in terms of the main indicators (DE, PTB, DMC) and the main material groups the overall trend and composition of flows is quite robust.

GDP and population: We used Maddison's long-term estimates (Maddison, 2013), which are considered reliable for the USSR, although it has been argued that they may understate rather than overestimate Soviet GDP (Allen, 2003). All GDP data are in constant international \$ of 1990.

3 The metabolic transition in the USSR and the Russian Federation

The USSR: During the seven decades of its existence, the USSR emerged as a major global political and economic power, in particular during the period of post-World War II industrialization and the Cold War. With a territory of roughly 22.4 million km² in 1991 the USSR was the world's largest country occupying 16% of the global (ice free) land area. Since its foundation in 1922 its population roughly doubled to 290 million by 1991 but population density remained low reaching only 13.1 persons per km² (compared to 33 cap/km² in the USA and 3.4 cap/km² in Canada). Its peak economic performance in the late 1980s measured in terms of GDP was similar to that of Japan and about one third of that of the USA. The USSR, however, did not reach a similar level of wealth as Western industrial economies: peak income

(GDP/cap/yr) was, according to Maddison's estimates, around \$7000 or about one third to half that of other industrial economies at that time. The USSR with its huge territory and low population density was rich in natural resources; its successor states also have large reserves of important metals, fossil energy carriers and timber and have agricultural potential. The Russian Federation has emerged as one of the larger providers of natural resources for the world market.

Figure 1: Aggregate material flow indicators for the USSR and the FSU for the period 1900–2008. Domestic Extraction (Fig. 1a), Physical Trade Balance (Fig. 1b), Domestic Material Consumption (DMC) and GDP (splitting the period 1992 to 2010 into the Russian Federation and other successor states) (Fig. 1c) and Domestic Material Consumption per capita (metabolic rate) (Fig. 1d).

In the observed period the region experienced major economic and political change. A series of revolutionary events in 1917 ended the Tsarist autocracy of the Russian Empire and led to the foundation of the Soviet Union in 1922. In stark contrast to Western industrial economies the USSR adopted a centrally planned economy, where the production and distribution of goods were centralized and directed by the government in state owned industry and collectivized agriculture following development goals set in formal five year plans based, among others, on material balances (Gregory and Stuart, 1994). Attempts to reform the USSR into a social democracy in the late 1980s by the last Soviet leader Mikhail Gorbachev failed and in 1991 the USSR dissolved into 15 constituent republics, with the Russian Federation as the legal successor of the USSR. It is the largest of the new states, occupying 77% of the territory of the former USSR, but comprising only 51% of the population. The collapse of the USSR was followed by massive economic turbulence, a 40% decline in economic output in the region, and restructuring towards a capitalist market economy.

As the results of the material flow analysis (Figure 1) show, over the observed period the USSR developed from an economy with an agrarian metabolic profile based on biomass as the key resource and a per capita DMC of around 4 t/cap/y to a country with a typical industrial metabolic profile, with mineral and fossil materials as resource base and a multiple per capita use of materials (Krausmann et al., 2008). We can observe different phases in this transition process (see Table 1):

Agrarian Russia 1900 to 1914 and early Soviet industrialization 1920 to 1938: The largely agrarian economy of Russia considerably lagged behind Central European countries, which at the beginning of the 20th century already used large quantities of ores and minerals. Coal consumption per capita, for example, was only 250 to 300 kg in the first decade of the 20th century as compared to 1500 kg in France or the Habsburg Empire and 5000 kg in Germany (Mitchell, 2003). DMC was low at 4 tons per capita per year, while the share of biomass in DMC was high at 80 to 85% (Figure 1d). Material extraction and use changed only slowly during the final decades of the Russian Empire, with DMC/capita growing at 0.3% per year in the period before World War I (WWI) (Table 1). Physical growth gained some momentum after WWI when Lenin's New Economic Policy aimed at modernizing farming and industrialization as a basis for recovery from the war and increased further with the introduction of the first five year plan under Stalin, which has been denoted as the beginning of the Soviet Industrial Revolution (Allen, 2003). With the expansion of heavy industry and large scale infrastructure

projects under Stalin, the transition from biomass to fossil/mineral materials took off: by 1940 the share of biomass in DMC was down to 62% and per capita consumption of fossil energy carriers had reached 1200 kg per year, well above the global average (1000 kg/cap/yr), but still below European industrialized economies. In this period the Soviet Union developed a powerful industrial sector and began to catch up with Western industrializing economies (Nove, 1969). Steel production went up and the pre-war level was reached in 1927, having increased from 20 to roughly 100 kg/cap/yr (compared to 95 kg in Japan or 270 kg in the UK). Electrification was a particular prestige project, and moved forward rapidly. A large number of power stations were built throughout the USSR and a grid was established. Electricity use quickly increased with the pre-WWI level of 20 kWh per capita and year regained by 1925, increasing to 250 kWh per capita and year by 1940. The expansion of material intensive industries and large scale infrastructure projects drove up material use, in particular of mineral and fossil materials, which grew at annual rates of 10% and above, faster than GDP (Table 1). Both extraction and use of materials almost doubled between 1900 and 1938 from 2.9 to 5.4 t/cap/yr (Figures 1a and d) but remained low compared to the UK or the USA (Fig.2a). The world economic crisis of 1930 hit the self-sufficient USSR less than Western economies and is hardly visible in aggregate economic and biophysical indicators (Figure 1c). By 1940 the USSR consumed 9% of all materials extracted globally. The USSR was more or less self-sufficient and participated little in international trade (Gregory and Stuart, 1994). Physical imports and exports were low and amounted to less than 0.5% of DE, the largest net export flows being wood and fossil energy carriers (Figure 1b).

	Agrarian Russia 1900–1914	Early Soviet industrialization 1920–1938	Rapid growth & industrialization 1946–1978	Stagnation 1978–1991	Collapse 1992–1998	Restructuring 1998–2008
Population	2.0%	1.2%	1.3%	0.8%	–0.0%	–0.2%
GDP	3.1%	8.1%	5.3%	0.7%	–6.8%	7.1%
DMC _{biomass}	1.8%	2.5%	3.6%	–0.1%	–7.2%	4.6%
DMC _{foss/min}	3.0%	10.3%	7.1%	–0.3%	–9.6%	4.3%
DMC/cap	0.3%	3.2%	4.4%	–1.0%	–8.9%	4.6%
PTB	–2.9%	25.0%	14.5%	–6.3%	13.8%	7.0%
MP _{biomass}	1.2%	5.3%	1.4%	0.8%	0.4%	2.4%
MP _{foss/min}	0.1%	–2.0%	–1.7%	1.0%	3.1%	2.7%
Steel	6.3%	25.5%	7.9%	0.7%	–7.1%	4.6%
Electricity		25.7%	10.5%	3.4%	–10.0%	2.3%

Table 1: Average annual growth rates of socio-economic and metabolic indicators during different periods of development. Rates for the periods of collapse and restructuring refer to the whole former Soviet Union.

Rapid growth and industrialization 1946–1978: The first year for which data of reasonable quality and completeness are available after WWII is 1946. During the war, the Soviet economy and infrastructure suffered massive devastation and required extensive reconstruction (Hanson, 2003). During the immediate post-war period, the Soviet Union rebuilt and expanded its economy, while maintaining strict centralized control. From 1946 to the late 1970s all material flows grew steadily and at very high rates as shown in Table 1. In particular the use of fossil and mineral materials grew faster than GDP. This period of Soviet industrialization saw a multiplication of the size of the physical economy and a rapid transition towards an industrial metabolic regime. During this 32 year period of rapid industrialization DE grew sixfold from 0.8 Gt/yr to 5.1 Gt/yr, with particular growth in mineral and fossil materials, but biomass extraction also rose (Figure 1a and Table 1). With the foundation of the Council for Mutual Economic Assistance (Comecon) in 1949 and the Warsaw Pact in 1955 international trade began to surge and the USSR became a major exporter of raw materials, mainly providing to its allies. Net exports rose sharply in parallel with DE, from near zero after WWII to 0.38 Gt/yr (7% of DE) in 1978 (Figure 1b). Major export commodities in terms of mass flows were coal and petroleum, iron ore and timber. The share of DE that was exported grew from only a few percent before World War II to 26% for fossil energy carriers and 17% for metal ores. In the 1960s imports also began to increase, in particular of food. In spite of continuous efforts to industrialize the collectivized agriculture and increase production, food output did not keep pace with population growth and in particular the rising demand for meat. Imports of cereals increased to one quarter of domestic consumption in the late 1970s. In the period of growth after WWII material consumption increased in parallel with GDP by a factor of six and material use per capita grew from below 5 t/cap/yr shortly after the war to an all-time peak of 18.3 t/cap/yr in 1978 (Figures 1c and 1d), a high level even in comparison with Western economies, as discussed in section 4. The consumption of mineral and fossil materials grew at an average rate of 7% per year (Table 1), with the share of biomass in DMC declining to 28% (Figure 2b). While the significance of biomass declines, the numbers also show, that biomass remains a key resource also in the industrial regime; the per capita use of biomass even increases. The period saw massive development of heavy industry and manufacturing, expansion of agriculture to the East as a result of the Virgin Lands Campaign (Josephson et al., 2013), expansion of infrastructure (rail and air transport, energy networks) and of urban development and housing projects (Andrusz, 1986; Nove, 1969). In the 1980s the production and consumption of major industrial commodities such as steel (580 kg/cap/yr), cement (480 kg/cap/yr) and electricity (5000 kWh/cap/yr) reached levels typical of Western industrial

countries, while per capita income remained much lower. At peak DMC the USSR consumed roughly 16% of all globally extracted mineral and fossil materials, while inhabited by only 6% of the global population. The rising metabolic rates reflect that physical wealth and standards of living (food availability, urban housing, and household appliances) improved considerably over this period (Allen, 2003). A consumer society emerged – although at a much more moderate level than in the West.

Stagnation 1978–1991: While the Western economies were severely affected by the oil price shocks of the 1970s which caused recession and short term decline in material use, they had little immediate negative impact on the Soviet economy (Cooper and Schipper, 1992). Kotkin (2008) argues that, as a major oil producer, the USSR was isolated from the price shocks and rather benefitted from the high oil price. In contrast to Western economies there was little incentive to invest in the modernization of energy and resource intensive industries (Cooper and Schipper, 1991), a situation which produced a legacy in later years when the USSR fell further behind Western economies in terms of resource productivity, as discussed in section 5. The economic literature refers to the period of the 1970s and 1980s as a period of economic, political, and social stagnation in the USSR (Hanson, 2003), with GDP growth slowing down markedly. Also the physical economy shows this stagnation, but it only sets in in the late 1970s. DMC first declined and then stabilized at a high level around 18 t/cap/yr in the later years of the 1980s (Figure 1d). The only material group whose consumption keeps growing in those years are fossil energy carriers, although at a slightly slower pace than in the decades before. Economic stagnation was caused by largely internal rather than external problems. Arguments brought forward include a lack of economic reforms and the failure of important sectors like agriculture to deliver, as well as the increasing economic burden caused by military expenditures during the cold war (see e.g. Hanson, 2003). Allen (2003) points out that the resource base in European Russia, where most of the industry was located, was increasingly exhausted and that the expansion of resource exploitation into Siberia was costly and hampered productivity growth. While Western economies experienced a shift from heavy industries towards service sectors from the 1970s onward, in the USSR heavy industries continued to prevail, in particular steel (Cooper and Schipper, 1991). Soviet industry also increasingly lagged behind technological standards, as investments were low and tended to go into retrofitting existing facilities rather than establishing new ones (Allen, 2003). The quality of products deteriorated and Soviet industries increasingly produced negative economic value, that is their products had a lower value than their raw material inputs at world market prices (Senik-Leygonie and Hughes, 1992; Thornton, 1996). While the USSR had acquired an industrial

metabolic profile and a level of material use similar to other European economies, economic output and living standards increasingly fell behind Western standards in the 1980s on many metrics, for example, in square meters of living space per capita, the number of cars per 1000 inhabitants, and the diffusion of household appliances and household electricity use (Cooper and Schipper, 1992).

Collapse 1992–1998 and Restructuring 1998–2008: The collapse of the communist system and the disintegration of the USSR and the Comecon in December 1991 deeply affected the economy of the Russian Federation and the other successor states, causing a massive decline in economic output (GDP/cap/yr declined by 35 to 45%) and a recession that lasted for almost a decade (Figure 1c). This is mirrored by the physical economy: between 1991 and 1998 the extraction and consumption of materials slumped by 41% in whole the former Soviet Union (FSU) (by 33% in the Russian Federation). DE declined most for biomass (–39%) and non-metallic construction minerals (–65%), materials which are predominantly used for domestic purposes. In contrast, fossil energy carriers and metal ores were much less affected (–16%). The mining sector quickly recovered, as ores, oil and gas could be sold on international markets irrespective of low domestic demand. Consequently, DMC declined even more than DE. Industrial output slumped and the decline in metabolic rates reflects considerable reductions in physical wealth. According to Golubev and Dronin (2004) caloric intake declined by 22% and meat consumption by 36%. A dearth of capital investments left the FSU with decrepit infrastructure, industrial facilities and housing. A number of processes contributed to this “dematerialization” of the economy after 1991: the massive decline in economic output necessitated a process of structural change which included abandonment of many obsolete heavy industries, collapse of the collectivized farming industry (in particular livestock production), and modernization of the remaining primary and heavy industries to use more efficient technologies and reduce waste. These all contributed to the decline in material use, a process which has been described in detail for the CSSR by Kovanda and Hak (2011) (see also West et al., 2014).

2a

2b

Figure 2: International comparison of socio-metabolic indicators. Metabolic rates (DMC per capita and year) (2a) and share of mineral and fossil materials in DMC (2b) for UK, USA, Japan and USSR in the period 1900–2008. Sources: Schandl and Schulz (2002) and Weisz et al. (2007) (UK); Gierlinger and Krausmann (2011) (USA), Krausmann et al. (2011) (Japan).

The economies of the Russian Federation and most successor states only began their recovery in the mid to late 1990s. With growing GDP extraction and consumption of materials increased from around 1998, accelerating significantly after 2000 (Figure 1c, Table 1). Between 2000 and 2008 the use of materials grew at average annual rates of 1.7% for fossil materials and 8.3% for non-metallic minerals. By 2008, DMC had reached 75% of 1991 levels for fossil and mineral materials, and 92% for biomass. The extraction of materials increased even faster, as export rates grew rapidly. Exports of raw materials were least affected by the collapse of the Soviet economy and surpassed the 1989 level in the late 1990s, in spite of a considerable reduction in domestic extraction of these material groups (Figure 1a). As a consequence, the share of exports in DE increased to 38% for fossils by 1999 and 38% for ores by 2007 in the FSU; in the Russian Federation the export share was even higher. Quite interestingly, the Russian Federation (and the FSU as a whole) turned into a net exporter of biomass in 1995, even though biomass extraction was much lower than in the biomass importing USSR. While raw material extraction and export boomed, most other sectors suffered from outdated technology and inefficient production. They were largely neglected and could not compete on global markets. In 2008 metabolic rates in the Russian Federation and the FSU had reached 15

t/cap/yr or 85% of the peak the USSR had reached in 1989. The global financial crisis then hit the region and caused material flows to decline considerably. Between 2008 and 2010 DMC in the Russian Federation declined by 15% (for the FSU no data are available).

4 Soviet resource use in international comparison

From the foundation of the USSR to its dissolution the size of its metabolism grew. Material use increased by a factor of 10, from 0.5 to 5 Gt/yr, and metabolic rates multiplied sixfold peaking at 18t/cap/yr in the 1980s (Figure 1). The trends in metabolic rates (Fig. 2a) and the share of mineral and fossil materials in DMC (Fig. 2b) show that the USSR did indeed follow a pattern of metabolic transition which was in many ways similar to that of Western market economies. The trajectory bears a particular resemblance to that observed for Japan. Both Japan and the USSR were late comers to industrialization, which only took off in the first half of the 20th century, at a time when the USA and UK were already advanced industrial economies characterized by mineral intensive industrial production, a high share of urban population and elaborate infrastructure. This is reflected in their higher metabolic rates and the high relative share of fossil and mineral materials in DMC (Figures 2a and 2b) at the beginning of the 20th century. Figure 2a shows how growth in metabolic rates began to accelerate in all four countries after World War II. This acceleration was particularly strong in the USSR and Japan. Both countries had suffered massive devastation during WWII, so intensive post-war efforts to reconstruct and expand infrastructure, re-establish resource intensive heavy industries and press ahead with urban development all drove rapid increase in materials extraction and use. Metabolic rates also increased significantly in the UK and the USA in the decades following WWII as a new pattern of mass production and consumerism emerged. By the 1970s, both the USSR and Japan had acquired metabolic profiles similar to that of the two advanced economies: material use had reached 17t/cap/yr, with mineral and fossil materials, the material basis for industrial development, accounting for more than two thirds of DMC and large stocks of materials accumulating in buildings and infrastructure. The USSR even surpassed the metabolic rates of Japan and the UK, both very densely populated net importers, two factors which have been shown to contribute to relatively lower per capita DMC (Steinberger et al., 2010; Weisz et al., 2006). In biogeographic terms the USSR is more similar to the USA, as both are large, sparsely populated countries and comparatively rich in natural resources, factors that are linked to higher per capita DMC – although the USSR lagged behind in industrial output, infrastructure development (e.g. length of road networks) and physical wealth.

As shown in Figure 2a the fast post-war growth in metabolic rates came to a halt after a few decades in all four countries. For the Western economies this coincided with the oil price shocks of the 1970s and has been termed 1970s syndrome (Wiedenhofer et al., 2013). The reasons for this phenomenon are not yet fully understood, but a range of different factors probably contribute, from the rising oil price and subsequent efforts to improve resource efficiency, to saturation in material intensive consumption and the diffusion of new ICT technologies, combined with a shift away from expanding material intensive infrastructure towards maintaining it (see also Kander et al., 2014). The growth in material use also came to a halt in the USSR, but roughly a decade later than in Western economies. The delay may relate to the fact that the USSR, as an oil exporter, actually benefitted from the oil price shocks that hit the Western economies hard (Hanson, 2003). Saturation effects, efficiency gains and structural economic change are less likely to have had an influence in the USSR, so the factors underlying the stabilization of metabolic rates there, and the comparative delay of this phenomenon, really require further research. The development path of the USSR and the Western physical economies only diverge strongly with the collapse of the USSR and the accompanying radical decline in material use. While metabolic rates in the successor states of the USSR have been recovering, rising rapidly in the early 21st century and again catching up to the level of Western economies, Japan and the UK show some signs of dematerialization in that period (Fig. 2a).

The development of material use observed in the USSR closely resembles that in other Central European planned economies. Figure 3a shows trends in metabolic rates for the period 1961 to the early 21st century in Romania, Bulgaria, Poland and Czechoslovakia to illustrate this. All of these Eastern Bloc countries exhibited steep growth in metabolic rates (average rates of 2 to 4.4% per year) during post-WWII industrialization which lasted until the late 1970s. Detailed data show that growth was strongest for fossil and mineral materials, but also biomass DMC grew faster than population due to the industrialization of agriculture and a shift towards intensive livestock production. In all countries metabolic rates stabilized around 1980 at a high level of per capita DMC until the collapse of the communist regime and the planned economy resulted in steep decline: in the first few years DMC went down by 30 to 40%. Rapid growth of material use only set in around the year 2000 – when DMC grew at rates of 5 to 6% per year, at a pace even faster than in the decades after WWII, yet by 2008 none of the four countries had reached the level of material use of the 1980s (Figure 3b). Quite interestingly, in all countries material use peaked in the late 1980s and was already in decline before the actual collapse of the communist regime.

Figure 3: Development of metabolic rates (DMC per capita and year) (3a) and material productivity (MP; GDP per DMC) (3b) in Eastern European planned economies from 1961–2009. Source: Böhm (2015) (Romania); Altaparkmanova (2015) (Bulgaria); Kovanda and Hak (2011) (Czechoslovakia (CZSK)); SEC (2015) (Poland).

5 Material productivity

The development of DMC and GDP shown in Figure 1c indicate that material use and economic development have been tightly coupled in the USSR and its successors. During most of the observed period, material consumption by and large followed the development of GDP. A comparative perspective on material productivity MP (GDP/DMC) and the fossil and mineral intensity of the economy ($DMC_{foss\&min}$ per GDP) sheds further light on this coupling. Figure 4a reveals that the USSR significantly lagged behind the other Western industrial economies in terms of material productivity, in particular in comparison with the UK and Japan. Interestingly, in the first half of the 20th century MP was similar to that of the USA but at much lower levels of both economic output and material use; only after WWII, during the period of rapid industrialization, did the USSR fall behind the USA, where MP significantly improved. During the period of immediate post-WWII growth, MP in the UK and Japan made little progress, indicating that in that crucial period of the metabolic transition, when metabolic rates multiply, fast economic growth requires high inputs of materials. The main turning point, when the gap between USSR on the one hand and Japan and the UK on the other, actually begins to widen,

is after the oil price shocks in the 1970s: in this period all Western economies show strong signs of what has been termed decoupling (UNEP, 2011). Resource productivity improves at a fast pace and DMC grows much slower than GDP. In the 1970s and 1980s MP increased by 2 to 3% per year in the Western economies but only by 0.8% in the USSR. As shown in Figure 3b this pattern also holds true for other centrally planned economies, where MP in the 1960s was much lower than in the West (0.3\$/kg vs 0.7\$/kg in the 1960s) and barely improving. MP finally began to improve rapidly only after the collapse of the USSR and with radical economic restructuring: in the FSU MP increased at a high rate of 3.4% per year between 1992 and 2008. Also in the other planned economies the fall of the communist regime and the transition towards a market economy resulted in significant gains in MP (Fig. 3b). But in spite of considerable improvements, MP in the former planned economies remained low: in Western economies two or three times as much value added (1 to 2 \$/kg) is created compared to the Russian Federation or the FSU in the first decade of the 21st century (0.6 \$/kg). The lower productivity of the USSR economy is particularly visible in the material intensity for mineral and fossil materials, which measures the amount of these materials required per unit of GDP (Fig. 4b). This value typically shows an inverted U shape over time: it increases during the early stages of industrial development, when the use of these materials for industrial development starts from a low level and increases at much higher rates than GDP and only later begins to improve when gains in technological efficiency and a shift from resource intensive sectors towards sectors with a higher value added per unit of material input slow down the demand of these materials relative to economic growth. In the UK this turning point was achieved in the 19th century, in the USA after WWI, in Japan in 1974 and in the USSR only in 1981 and at a much higher level than in the other economies. Also the FSU economies, in spite of massive economic restructuring and investments in new technologies after the turn towards capitalism, still use two to three times more fossil and mineral resources per unit of GDP than the three Western economies. This indicates the prevailing significance of resource intensive industries and the role of these countries in the global economy as providers of raw materials.

4a

4b

Figure 4: Material productivity (GDP/DMC) (4a) and Intensity of use of fossil and mineral materials (DMC_{foss&min} per unit of GDP) (4b) in the UK, USA, Japan and USSR. Sources: See Figure 2.

Overall, the strong improvements in aggregate material productivity (Fig. 4a) did not lead to absolute dematerialization in the FSU economies. Instead, DMC recovered in the late 1990s and per capita material use rose fast until the global financial crisis in 2008, which again caused a significant decline (Fig. 1). Several factors have contributed to the comparatively poor material productivity observed in the USSR and to the widening gap compared to Western industrial economies: next to the specific economic structure with a very high significance of large material intensive heavy industries (Cooper and Schipper, 1991), biogeographic disadvantages may also contribute to over-proportionally high metabolic rates. This includes the cold climate, low population density and the increasing distances between the resource deposits in the East and the centers of industry and population in the West (Cooper and Schipper, 1992). Above all, an increasingly inefficient use of energy and materials was an important factor. This was partly the result of more and more outdated technologies and infrastructure due to a lack of investment, but also to a lack of effort to improve resource productivity. Material losses in Soviet industries have been extremely high in key material intensive industries such as metallurgy: according to Sinyak (1991) metal losses in steel production were around 28% and in machinery production 20% due to obsolete machinery and inefficient processes. Similarly, transport and distribution losses of energy carriers such as oil and gas were far above Western levels (Dones, 1994 in Ayres, 2007; Cooper and Schipper,

1992). Martinot (1998) shows that residential space heating intensity was 2.5 times higher than in northern European economies as a result of high losses in centralized heating systems and poor insulation of buildings. These are all examples of the soaring inefficiency of material and energy use in the Soviet economy. They all contributed to metabolic rates at or above those of Western industrial economies while GDP was still much lower, as well as consumer amenities and standard of living, resulting in poor and deteriorating performance of MP. While MP had already begun to improve in Western economies in the 1970s, this process took off in the planned economies only after the collapse of the USSR. In spite of significant improvements since, there is still room for further resource savings (West et al., 2014).

6 Missed opportunities

The biophysical economy of the Soviet Union differed in several ways from that of Western industrial economies. Soviet economists originally had an inherently biophysical understanding of the economy and monitored a broad range of material flows and physical parameters to support economic planning based on material balances (e.g. Montias, 1959; Gregory and Stuart, 1994). In theory this provided excellent preconditions for efficient use of natural resources and to avoid externalities (Gregory and Stuart, 1994). Centrally planned industrial facilities also bore potential for industrial symbiosis, that is, to realize efficiency improvements, reduce waste and increase recycling (Chertow, 2000). But in spite of some rhetoric of resource conservation in planning circles, this never was an issue of high priority in the USSR (Allen, 2003). Instead, resource shortages were dealt with by using supply side solutions, for example by expanding production towards mineral deposits in Siberia; demand side solutions and in particular improving efficiency were not pursued (Cooper and Schipper, 1992; Allen, 2003). In terms of transport the USSR followed a significantly different path by focusing on rail transport for freight and opposing the idea of individual mass passenger car ownership. The proximity of housing projects and industrial facilities reduced commuting distances (Cooper and Schipper, 1992). As a consequence, the USSR did not develop an extensive (and material demanding) road network, had a much lower car ownership rate than Western economies and carried most of its high freight volume on rail (Ambler et al., 1985). Communal housing with district heating systems was given preference to detached housing, with high potential for efficient resource use. Ultimately, although the USSR did develop a consumer society, levels of consumer amenities and household consumption were considerably lower than in the West. So from a certain perspective, the USSR did follow a path of development of the biophysical economy

and biophysical wealth that differed from that pursued in Western industrial economies. But a somewhat lower level of final consumption was more than outweighed by inefficient production and distribution patterns. In Soviet practice none of the considerable potentials to reduce resource use were realized as Soviet planners were mainly concerned with increasing physical output regardless of cost (Hanson, 2003). As a consequence, resource use rose with industrialization in the USSR, as in other industrial economies, and with all the associated negative environmental consequences ranging from depletion and overexploitation, to large scale destruction of ecosystems, to high levels of pollution – even more severe and intense than in the West (Josephson et al., 2013).

7 Conclusion

The case of the USSR corroborates the hypothesis that industrialization drives a typical change in material use patterns quite irrespective of political and economic conditions. Our results provide more evidence for the tight linkage between material use and industrial development: material intensive industries, building up infrastructure for transport, energy and water supply and treatment, and rising levels of per capita consumption require growing material inputs. These physical realities have driven the metabolic transition in the past; the political and economic systems seem to have been of little significance for the overall outcome of the metabolic transition in terms of the overall pattern of resource use. Rather, these factors influence the speed and dynamic of the process. In the end, the pattern of growth in material use observed in the USSR and in other planned economies is remarkably similar to that of Western market economies.

The transition from planned to market economy led to adjustments in the physical economy, but did not fundamentally alter the trajectory. The restructuring of the economy and industrial production driven by the transition towards a market economy on the one hand greatly improved the efficiency with which economic value was added to the materials used, but on the other hand triggered rapid economic growth and an expansion of extractive industries which drove up material demand and per capita DMC. The case of the USSR does not indicate that the transition process with its very fundamental structural changes and the opportunity to change structures helps to leapfrog towards a more sustainable industrial metabolism. Rather it converges the former planned economies to the metabolic profile typical for Western market economies. But there is still considerable potential to improve material productivity, to allow for relative decoupling and increases in wealth with less growth in resource use.

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