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The Social Metabolism of European Industrialization: Changes in the Relation of Energy and Land Use from the Eighteenth to the Twentieth Century

In recent years, social (or, more narrowly, industrial) metabolism has become a prominent concept in sustainability science because many global sustainability problems are directly associated with humanity's growing demand for raw materials and their transformation into wastes and emissions after processing and use. Industrialization involves a fundamental transformation of society's metabolism and in particular of the energy system. In this essay, I will offer an historical sociometabolic perspective on the changing relationship between energy and land use during industrialization. This perspective will highlight the difficulties in substituting biomass for fossil fuels, a strategy that is currently being pursued and that is central to sustainable development.

Agrarian societies are fuelled by a solar-based energy system. They tap into available flows of solar energy to sustain their energy needs, rather than exploiting stocks of energy carriers. In contrast to hunter-gatherer societies, agrarian societies actively manage terrestrial ecosystems in order to increase the output of useful biomass. The land-use-based energy system they establish—a system where most of the primary energy comes from agricultural sources—can be termed a *controlled solar energy system*. In this energy regime, biomass is quantitatively the most important source of energy and amounts to more than 95 percent of primary energy supply. Although water and wind power had some socioeconomic importance, quantitatively they were only of regional significance. In general, wind and water accounted for at most a few percent of the primary energy supply.

In the agrarian sociometabolic regime, the availability of land, the productivity of the land, and the efficiency of biomass conversion methods determine the amount of available primary energy. The land use system, with its limited potential to supply certain types and amounts of primary energy, therefore constitutes a major limitation on the growth of population and physical wealth.

There are distinct energy limits in agrarian societies. Pre-industrial land use systems are low input systems and external energy or nutrient subsidies are practically absent.

Agriculture relies more or less exclusively on natural cycles and local socioeconomic resources for energy and plant nutrients. Typically, this entails a complex optimization of locally available resources. Soil fertility is managed using a combination of strategies such as the rotation of land use, nutrient transfers between different land cover types, reuse and recycling of materials and plant nutrients, and minimization of losses. Farm animals provide the muscle power needed for farming the land as well as being a source of fertilizer, additional food, and raw material; they make it possible to utilize non-edible crop by-products, food waste, and land that is unsuitable for crops. A land-use system optimized in such a way allows for the maintenance of soil fertility and yields, and also allows for the production of a certain amount of agricultural surplus. It further satisfies the condition that land use achieve a positive energy return—that is, that the amount of energy produced in the form of food and fuel exceed the energy invested in cultivation. This positive energy return is an essential feature of agriculture in any agrarian sociometabolic regime.

Energy production per unit of cultivated land is variable and can be enhanced by agricultural modernization strategies. Ultimately, however, it cannot exceed a certain figure. Assuming a mix of land use types, including a certain share of low productivity land and land not available for biomass production, it has been estimated that agricultural land use systems under temperate climatic conditions yield up to 20–40 Gigajoules/hectare on average in the long run.

The inherent limitations of the biomass-based energy system, namely low power density, lack of conversion technologies, reliance on animate power, and high energy costs of transport also shape patterns of material use. Biomass is the most important raw material and is not only used as food for humans, feed for animals, and heating, but also for construction purposes, clothes, tools, and furniture. Except for biomass, all materials are used in rather low quantities, both in terms of volumes per capita and per area. Reconstructions of the historical metabolism of agrarian Austria and the United Kingdom show that the yearly consumption of all materials ranged from five to six tons per person, of which biomass constituted 80–90 percent.

The impact of the agrarian sociometabolic regime on demographic and spatial patterns is evident. Agricultural surplus is limited and the large majority of people live on and from the land. Spatial differentiation and urban concentration is limited by the high energy cost of land transport, which permits the transport of energy carriers and bulk materials only across comparatively short distances.

Agrarian regimes significantly alter the natural environment, changing the composition of vegetation and animal species as well as the properties of soils and water cycles. They also create a great variety of new ecosystems. Because agrarian regimes are based primarily on the use of renewable resources, maintaining ecological sustainability is essential. However, there is no guarantee against severe fluctuations and sustainability crises, or even collapse. Growth can be achieved only within certain limits; it is based on increasing efficiency and optimizing land use. Usually, such efficiency gains bring the whole system closer to a threshold: There tends to be positive feedback between biophysical growth and population growth, and agrarian societies show an overall tendency to increase area productivity (biomass production per unit of land) at the expense of labor productivity (biomass production per unit of labor input).

Under these conditions, material and energy output per capita reach a limit or even start to decline. Thus, in general, agrarian societies face sustainability problems as a result of the limited availability of resources, the difficulty of maintaining soil fertility over the long term, and a tendency for population growth to outstrip food supply. Pollution problems occur only locally at mining sites or in urban agglomerations.

Industrialization is a transition process during which the growth-related sustainability problems of the agrarian sociometabolic regime can be overcome. Social and technological change based on the use of a new type of energy carrier, namely fossil fuels, extends the inherent growth limits by removing the negative feedback loops—that is, loops that reverse whatever change is imposed upon the system—operative in the agrarian regime. This triggers a transition that ultimately transforms most features of society. Gradually the problems of energy scarcity and the concomitant environmental burdens are resolved, to a certain extent at least. The industrial sociometabolic regime, however, creates new types of sustainability problems.

Such a transition process was experienced for the first time in England under a unique combination of institutional change, population growth, improvements in land use practices, and the increasing use of coal. Coal-based industrialization, while allowing for the introduction of the new industrial sociometabolic regime, was characterized by population growth, as increased industrial production led to a growing demand for human and animal labor. The rapidly growing population had to rely on the delivery of food from a largely pre-industrial low-input agricultural regime. The United Kingdom, as well as most of the rest of Europe, did not achieve a mature energy system based on fossil fuels until after the 1950s, when oil and electricity and the internal combustion engine replaced the older coal-based technologies, leading to the industrialization of agriculture as well as a gradual decoupling of industrial production and human labor.

The agricultural limitation on physical growth was not removed until the twentieth century. The transformation of agriculture based on fossil-fuel driven technologies began in the New World and took off in European countries only after World War II. Among the key processes that drove the industrialization of agriculture were the substitution of fossil-fuel driven machinery for human and animal labor, the removal of the nutrient limitation through the availability of inexpensive fertilizers and other agrochemicals, and road-based transport, which allowed inexpensive transfers of large quantities of inputs and agricultural products, facilitating large-scale specialization. In European countries, draft animals disappeared within just two decades, the agricultural labor force was reduced by more than 80 percent, and nitrogen availability increased by a factor of 10. Agriculture underwent a fundamental alteration. The traditional local combination of intensive (e.g. cropland) and extensive (e.g. pastures, woodland) land-use types and crop cultivation with livestock husbandry became obsolete. External inputs and energy subsidies abolished the strong dependence on natural regeneration rates and scarce internal resources. Large-scale differentiation and specialization of land use became possible and triggered transfers of large quantities of food, feed, and plant nutrients across increasing distances.

In the two decades after World War II, yields per unit of area tripled and the overall output of food products doubled. However, the increases in output were achieved through fossil-fuel-based inputs, and the surge in agricultural area and labor productivity came at the expense of energy efficiency. While Austrian agriculture produced 5–10 units of output per joule of invested energy in the nineteenth century, this ratio declined to less than one unit per joule in the 1970s. Agriculture changed from a low-input system to a throughput system with high inputs and high outputs.

The availability of an area-independent source of energy and the fossil-fuel-powered transformation of agriculture from an energy-providing activity to a drain on useful energy were the two main factors that allowed for a far-reaching decoupling of energy provision from land use and the control of territory. At the same time, the exploitation of large stocks of fossil fuels of high energy density by new technologies, such as the internal combustion engine and the electric motor, allowing conversion of primary energy into useful work, led to novel biophysical patterns of production and consumption, far-reaching structural change, a certain worldwide uniformity in social forms and institutions, and a surge in material and energy use per capita.

Even if "mature" industrial economies have left behind the strong momentum of biophysical growth, a high level of energy and material use is maintained. Material and energy use per capita exceeds the values typical for advanced agrarian regimes by a factor of three to five. At the same time, a surge in agricultural output permitted population densities 10 times higher than in most agricultural societies. As a result, the material and energy use per unit of area has multiplied by a factor of 10–30. The contribution of biomass to total primary energy and materials supply dropped to 10–30 percent yet the overall use of biomass increased: The substitution of fossil energy carriers for biomass allowed for new uses of biomass instead of reducing biomass consumption (e.g. reductions in the use of wood fuel were outweighed by the demand for paper and timber). In the industrial regime, the absolute amount of biomass used is thus higher than ever before. Due to tremendous increases in agricultural labor productivity, industrial regimes are characterized by a very low level of agricultural population, often lower than 5 percent. Urban population levels are high. Low transport costs support large scale spatial differentiation and concentration; they also support transfers of huge amounts of all kinds of bulk materials and energy carriers over long distances.

In agrarian regimes, scarcity, poverty, and an overexploitation of natural resources are always an imminent threat. In contrast, the dominant impression within mature industrial regimes is one of abundance, however unevenly distributed. Because of its enormous material and energy turnover, the industrial regime currently faces sustainability problems related to output. These problems stem from pressure on the regional and global absorptive capacity of natural ecosystems for wastes and emissions. Some of these problems, like acid rain, have been solved through technological advances, but other local and global environmental problems of the industrial socioecological regime develop or worsen. The list of severe sustainability problems experienced by the industrial socioecological regime includes climate change and global warming, biodiversity loss, and desertification. The relative freedom from scarcity, however, is likely to change. The industrial socioecological regime is based on the use of exhaustible key resources. The industrial metabolic regime, therefore, is a transitory rather than a stable regime.

Further reading

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