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Reducing energy consumption without compromising food security: the imperative that could transform agriculture

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1. Introduction

The imperative of carbon neutrality requires a drastic, rapid, and sustained reduction in fossil energy consumption and greenhouse gas emissions. The Russia-Ukraine war has led to a major energy crisis, whose end does not seem imminent. The sudden and major increase in energy prices resulting from this crisis has major impacts on many sectors of the societies. This is especially true for agriculture, a direct consumer of energy that also has considerable indirect consumption through the manufacture, transport, and distribution of chemical inputs such as fertilizers and pesticides. Taking the example of France, from July 2021 to July 2022, farmers were challenged with price increases as high as 48% and 111% for energy and fertilizers, respectively (Agreste 2022). At the global scale, in 2018, greenhouse gas emissions from fossil energy consumption in agriculture represented 0.9 Pg CO_2 eq. (against 9.3 Pg CO_2 eq. due to agriculture, excluding emissions due to this energy consumption) and those emissions have increased by 23% since 2000 (FAO 2020).

This context calls for in-depth transformation of agriculture, which is currently overly dependent on non-renewable energy in high-income economies. While research on the subject continues to grow (figure 1, box 1), this large body of work focuses more on assessing the energy consumption of current agricultural systems using multiple metrics (box 2) than on developing supply- or demand-side alternatives that use less energy. In response to these trends, Ramankutty and Dowlatabadi (2021) suggested pathways to sustainable food systems. However, while their recommendations included energy reduction options on the food consumption side, their focus on farming practices was restricted to improving the energy efficiency of current agricultural systems and missed the necessary redesign of farming and food systems.

Box 1. Growth of the literature on energy in agriculture

From 1959 to 2021, 576 articles on energy in agriculture were published, with 5–15 articles per year on average until 2010, followed by a rapid increase (figure 1). Most articles focused on direct and indirect energy consumption of current (in most cases) and alternative (in a few cases) agricultural systems using a variety of metrics and indicators, such as energy consumption, energy balance, and energy efficiency (box 2). These indicators were sometimes combined with other environmental (e.g. greenhouse gas emissions) and economic (e.g. economic efficiency) indicators. Leading countries on the topic included China, India, Iran, the USA, Turkey, and Italy, each with more than 15 articles published from 2017 to 2021.

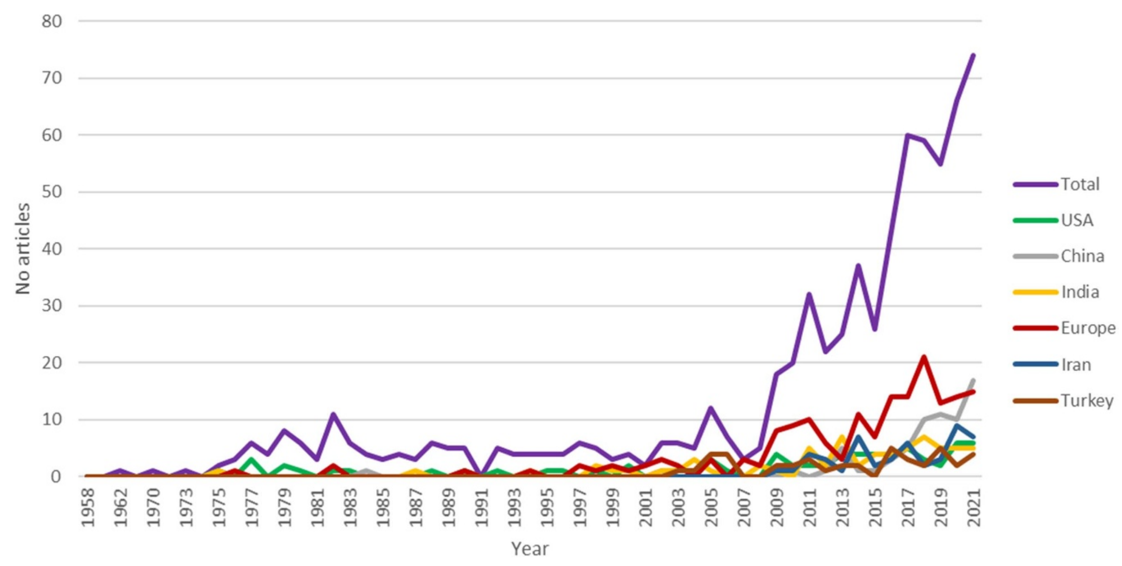

Figure 1. Number of articles published per year and indexed in the Web of Science that match the query TI = (farm* OR crop* OR agro* OR agri* OR livestock OR animal* OR horticultur* OR vine* OR orchard) AND TI = ((‘consumption’ OR ‘use’ OR ‘utilization’ OR ‘utilisation’ OR ‘autonomy’ OR ‘sufficiency’ OR ‘efficiency’ OR intensi* OR requir* OR input*) NEAR/1 (gas OR fuel OR energ*)) NOT TS = (‘essential oil*’ OR ‘biogas’ OR ‘wind farm*’ OR ‘fuel cell*’) AND DOCUMENT TYPES: (Article OR Review). The query was performed on 21 April 2022.

Box 2. Metrics and indicators used to assess energy consumption and related performances of agricultural systems

A theoretical framework called agrarian metabolism (Guzman *et al* 2018) stemming from the social metabolism framework (Giampietro *et al* 2009) has been developed to study the exchange of energy and materials between a given society and its agrarian environment. Following this agrarian metabolism approach, a farm can be depicted as having physical boundaries, receiving inputs from suppliers, and providing outputs to clients. Within the farm, internal biomass flows can occur between production activities (e.g. manure transfers from livestock to crop production). Those exchanges create energetic inflows, outflows and internal flows. Inputs can lead to both direct energy consumption (on-site, foreground system) and indirect energy consumption for the production of inputs (off-site, background system) (figure 2). Among the multiple internal flows, self-fueling is of utmost importance. It corresponds to the biomass used as food for farmers and feed for draft animals, which lies at the base of the energy that is reinvested in the system.

The energy performance of agricultural systems is assessed mainly through their energy consumption and their energy input/output ratio. The former assesses impacts on energy resource availability, while the latter reflects energy use efficiency also called energy return on investment (EROI), that is the amount of energy required to provide a given product or service. Consumption metrics often differ in their system boundaries, making their comparison difficult (Hercher-Pasteur *et al* 2020). For instance, the life cycle assessment framework includes both direct and indirect energy consumption. Other approaches focus only on a few sources of energy consumption (e.g. fertilizers, pesticides, irrigation, and machinery use in crop production) and sometimes on only one of them. Self-fueling is rarely considered as an energy input in agricultural production.

A common approach for assessing the energy consumption of farms is to multiply physical amounts of inputs by their energy density (e.g. in $MJ \cdot kg^{-1}$) retrieved from the literature. However, such an approach is often highly aggregated and does not help identify the farm components that consume the most energy. In contrast, model-based predictive approaches enable *ex-ante* assessment of ‘what if’ scenarios to explore effects of changes in management practices (Lampridi *et al* 2020).

In this article, we look back to understand how agricultural systems came to progressively depend on non-renewable energy. We then briefly review agricultural practices and systems reducing energy consumption without compromising energy efficiency. Finally, we propose future research avenues to explore pathways for reducing energy consumption without compromising food security and sustainability challenges.

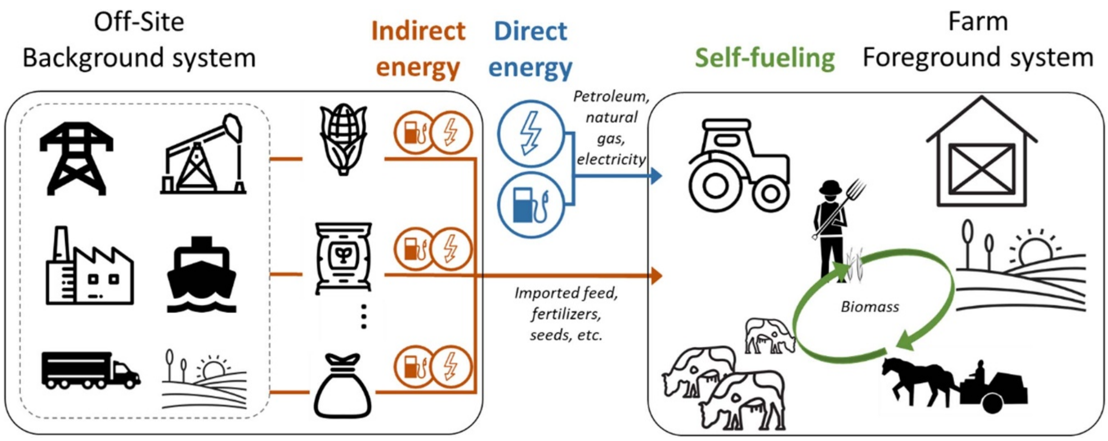

Figure 2. Direct and indirect energy consumption on a farm. Self-fueling includes the energy of the farmer and draft animals that is reinvested in the system.

2. Historical overview of energy sources and consumption in agriculture

Mechanization and industrialization of agricultural systems have deeply transformed agricultural energy flows. In preindustrial agriculture, cropping operations were inseparable from draft power provided by livestock and farmers, which were sustained completely by self-fueling (i.e. internal energy sources). In industrial agriculture, energy is consumed directly and indirectly by on-farm machinery and inputs (in particular in fertilizers), respectively, both of which depend on external energy sources, mainly fossil fuels (box 3). A recent analysis (Harchaoui and Chatzimpiros 2019) revealed that the agricultural transition from internal to external energy sources in France occurred within ∼25 years—the percentage of fossil fuels in total energy consumption increased from ∼10% in 1946 to ∼90% in 1970, along with a massive displacement of farming jobs—and that this transition drove unprecedented increases in agricultural surplus (i.e. the difference between the net production of farms and self-fueling), international trade (Dupas *et al* 2022), feed for livestock production, and the total energy consumption (figure 3).

In the current context, regaining agricultural energy self-sufficiency seems an imperative challenge. Self-fueling is one option, but it implies that most of the population return to agriculture, and goes with high risk of competition between self-fueling and farm surplus production. Farm surplus in France has increased six-fold from the early 20th century to the present (i.e. from 6.8 to 40 GJ ha^{-1} yr^{-1}, respectively), and the external energy consumption nearly equals this surplus (figure 3, box 3). Consequently, energy self-sufficiency is currently impossible without profound structural changes in energy consumption in agricultural and food systems.

Box 3. Changes in the energy mix in agricultural production

Agricultural mechanization and industrialization have replaced biomass (which contributes to self-fueling) with fossil energy (external energy) in the energy mix of agricultural production. The proportion of electricity in the current total energy consumption in agriculture is small and restricted to on-grid uses such as irrigation pumps, milking machines, lighting, and heating of livestock buildings and greenhouses. Since the mid-20th century, the total energy consumption in agriculture has been a variable mix of biomass, fossil fuels, and electricity, but due to differences in energy density among sources, it is challenging to quantify the contribution of each source in the mix. A given amount of energy can have multiple uses, with varying efficiency depending on its form. For example, one joule of biomass and of petroleum have the same calorie content but not the same capacity for mechanical work. One way to bridge differences in density among energy sources is to express all energy consumption in terms of a reference fuel, such as primary biomass by using equivalence coefficients depending on how the energy had been used.

3. Agricultural practices and systems that reduce energy consumption

Except for a few alternative agricultural systems, such as the most ambitious forms of permaculture, no systems are independent from fossil energy in advanced economies. Nonetheless, despite remaining uncertainties in estimates, some agricultural practices and systems reduce energy consumption. Interestingly, most of them do not compromise energy efficiency

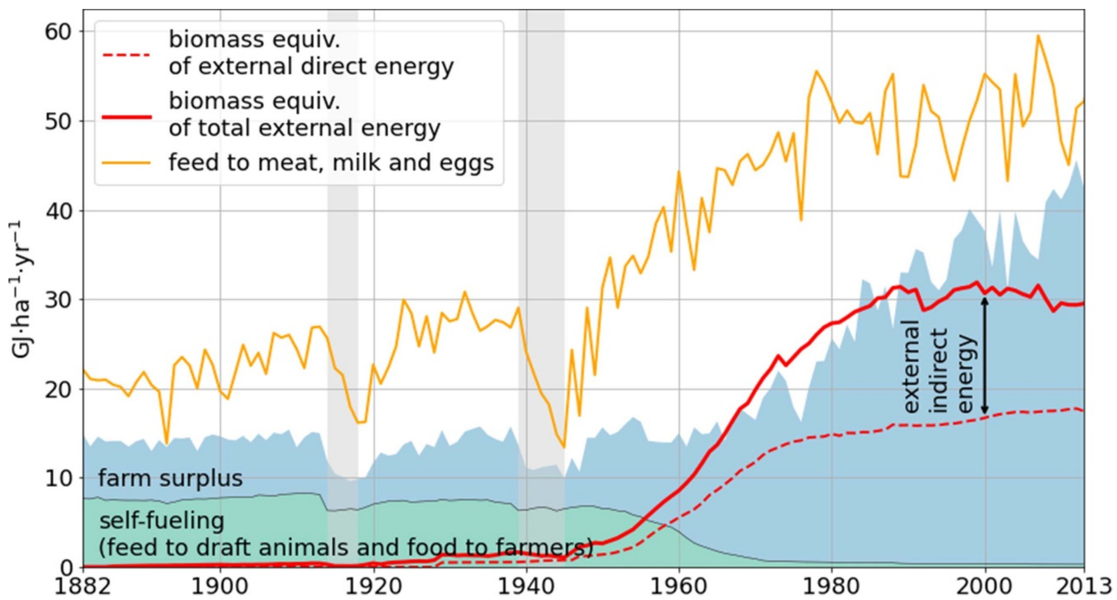

Figure 3. Major input, output, and internal energy flows in French agriculture (GJ·ha^{-1}·yr^{-1}) during its transition period (1882–2013) (Harchaoui and Chatzimpiros 2019). Input flows include energy consumption from internal (self-fueling, green area) and external sources (direct (dashed red line) and indirect (solid red line) energy consumption). Feed for livestock (orange line) includes domestic and imported feed. Farm surplus (blue area) includes livestock production and is the energy output from agriculture to the rest of society. Energy consumption from external sources (fossil fuels and electricity) is expressed as biomass-equivalent energy (box 3) to consider differences in the energy density of biomass and external energy sources.

of crop and livestock production systems and, unsurprisingly, all of them are based on increased circularity to decrease their dependence on inputs.

In the context of farm and herd expansion in ruminant livestock production, inputs, concentrate feed, and fuel for machinery have been used to simplify work and replace on-farm labor. In France, this increased reliance on inputs resulted in a 60% increase in work productivity from 1990 to 2012 (Veysset *et al* 2015) but also in an increase in the energy consumed per unit of meat or milk produced. Livestock feed cultivation, harvest, and distribution represent nearly 75% of the energy consumption (both direct and indirect) of livestock farms. This is due to feeding strategies that have increasingly focused on (i) ensuring high animal productivity using highly nutritious feed diets, (ii) producing standardized livestock products using calibrated diets regardless of the season, (iii) producing off-season using stored feedstuffs, and (iv) simplifying work by feeding animals using standardized feedstuffs whose distribution can be mechanized. In contrast, agricultural systems based on pasture feeding are more self-sufficient and rely less on non-renewable energy. Products from these systems provide nutritional advantages such as better micronutrient and lipid profiles. However, their production is often highly seasonal, being highly synchronized with pasture production, and poorly standardized (e.g. in terms of age and types of carcass at slaughter; Benoit *et al* (2019)). Thus, livestock farming practices and systems that use less energy exist, but their scale is contingent upon consensus with downstream actors.

For arable cropping, reducing tillage intensity and synthetic nitrogen fertilization are key to decrease direct and indirect energy consumption at the cropping system scale, respectively (Nemecek *et al* 2008), along with recycling crop residues, cover cropping, and crop-livestock integration. Reduced tillage can decrease direct energy consumption by up to 18% and improves soil fertility and erosion control (Terbrügge and During 1999). However, it often results in an increase in herbicide use (especially glyphosate), which remains a major environmental concern. Increasing the frequency of legume crops in crop rotations can help reducing further fertilizer applications and decreasing N_2O emissions, on top of reducing energy consumption. However, increasing legume frequency in crop rotations can lead to soil-borne diseases, nitrate leaching in certain situations (e.g. the absence of a catch crop), and decrease in cereal yields. Another step towards attenuating energy use entails drastic reduction in fertilizer use below crop nitrogen requirements. In addition to further decreasing grain yields and protein contents, these changes would require adjustments in downstream food industries to address changes in technological properties of grain and consumers' habits (Meynard *et al* 2018).

Vegetable production systems have the highest variability in production technologies, including outdoor production, greenhouse cultivation (heated or not), and plant factories (i.e. soilless, fully-closed controlled systems relying on artificial lights, also called 'vertical farms'). These systems have contrasting levels of energy consumption (from 29 to

Table 1. Product, energy input, yield, energy output, and energy return on investment (EROI) of contrasting vegetable production systems.

System	Product	Energy input (E_{in}, GJ·ha^{-1}·yr^{-1})	Yield (t DM·ha^{-1}·yr^{-1})	Energy output (E_{out}, GJ·ha^{-1}·yr^{-1})	EROI (E_{out}/E_{in})	Source
Outdoor, organic, France	Mix of vegetables	29	1.3	22	0.75	Pépin *et al* (2022)
Outdoor, Greece	Industrial tomato	103	7.6	131	1.27	Ntinas *et al* (2017)
Outdoor, Greece	Fresh tomato	275	2.4	41	0.15	
Unheated greenhouse, organic, France	Mix of vegetables	387	3.4	58	0.15	Pépin *et al* (2022)
Heated greenhouse, Netherlands	Lettuce	12 100	21.0	361	0.03	Graamans *et al* (2018)
Plant factory, Netherlands	Lettuce	70 900	50.0	860	0.01	

70 900 GJ·ha^{-1} yr^{-1}) and annual dry matter yields (from 1.3 to 50 t DM·ha^{-1} yr^{-1}) (table 1). Yield increases as energy input increases (i.e. producing a given quantity of vegetables requires less land as energy input increases), which indicates that land and energy inputs are substitutable. However, energy use efficiency, expressed as EROI (i.e. energy in vegetables produced per unit of energy input), decreases as energy input increases, from ca. 1 for outdoor conventional and organic production to 0.01 for a plant factory (table 1), thereby contrasting the promises suggested by others (e.g. Ramankutty and Dowlatabadi 2021). Like for ruminant livestock and arable crop production, shifting to vegetable production systems that use less energy would have major impacts for downstream food industries, in particular in terms of range of vegetables available over seasons. Producing certain vegetables (e.g. tomatoes) would not be possible in the coldest areas, which would require changes in trade and possibly consumption patterns.

4. Research avenues to reduce energy consumption in agriculture

Additional research is needed to explore the necessary shift in agricultural systems to reduce energy consumption and increase energy efficiency without compromising food security and other sustainability challenges.

4.1. Improving the methods and scope of energy consumption and efficiency assessment

Although energy analysis can be used to assess energy consumption and efficiency in the framework of agricultural sustainability assessment, it may ignore trade-offs and synergies with other indicators (e.g. pesticide use). Thus, energy issues are best analyzed in the framework of multicriteria assessments. In addition, progress is needed to (i) make the farm or food system boundaries and assumptions used in each study more explicit to ensure comparability among cases (Hercher-Pasteur *et al* 2020) and (ii) go beyond a simple input-output approach by considering internal flows, especially for agroecological systems oriented toward circular economy. From this perspective, alternative agricultural systems such as permaculture require further study. This requires using up-to-date databases to represent technological progress in reducing energy consumption.

4.2. Clarifying the potential of technological innovation

Propelled by the hype for 'Agriculture 4.0', technological innovations (e.g. sensors, robots) are often promoted as promising options to reduce fossil energy consumption in agriculture. This is especially true for agricultural equipment used for field operations, which strongly influences overall energy consumption and efficiency. Technological innovations are being developed to propel tractors with renewable energy sources and to use inputs more efficiently (e.g. sensor-based intelligent spraying systems). However, most of these technologies contain batteries and/or digital components that require rare metals, and their actual benefits for reducing energy consumption have yet to be demonstrated from a life cycle perspective. Reducing energy consumption should start instead with designing agricultural systems that depend less on external inputs and manufactured equipment, and depend more on ecological processes. Low-tech equipment that maximizes the performance of operations while minimizing energy consumption need to be developed.

4.3. Embracing food-system transformations

Reducing energy consumption requires transformational changes in agricultural systems, such as the location, species, and animal body size in livestock systems (Benoit and Mottet 2023) or the mix of crops grown in arable systems. These transformational changes are likely to have profound consequences for downstream and food demand, as mentioned, thereby calling for a food-system perspective. Several scenario studies have shown the potential to transform agricultural and food systems using the principles of agroecology (especially increased diversity at field, farm, and landscape scales) and circularity (especially waste reduction and increased resource recycling), with promising benefits for energy consumption. However, these supply-side solutions should include demand-side innovations, including social changes in dietary habits towards more plant-based diets lower in fat and sugar, and reduced food waste and losses (e.g. Röös *et al* 2022). Indeed, moving away from e.g. energy intensive livestock production in the absence of major dietary shifts towards plant-based products would not result in improved farming sustainability (Clora *et al* 2021). These food-system scenarios require additional assessment based on an energy perspective, e.g. to confirm whether plant-based or organic-based diets are associated with lower energy consumption. Further investigation of the complex interplay between dietary shifts, land use changes and farming practices is also needed as e.g. replacing energy intensive livestock systems with pasture-based systems cannot be done in isolation of concurrent changes in crop production. Another challenge is to define the pathways required to achieve these transformations at scale. Many food chains are organized at the global scale. Global food-miles have shown an unprecedented increase in the past few decades, with transport accounting for ca. 19% of greenhouse gas emissions of the food system (Li *et al* 2022). Thus, food systems that reduce energy consumption and increase energy efficiency will require major reorganization towards more polycentric models.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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