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Title: Energy use in the global food system

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Abstract:

The global food system is a major energy user and a relevant contributor to climate change. To date, the literature on the energy profile of food systems addresses individual countries and/or food products, and therefore a comparable assessment across regions is still missing. This paper uses a global multi-regional environmentally-extended input-output database in combination with newly constructed net energy use accounts to provide a production and consumption-based stock-take of energy use in the food system across different world regions for the period 2000-2015.

Overall, the ratio between energy use in the food system and the economy is slowly decreasing. Likewise, the absolute values point towards a relative decoupling between energy use and food production, as well as to relevant differences in energy types, users and consumption patterns across world regions. The use of (inefficient) traditional biomass for cooking substantially reduces the expected gap between per capita figures in high- and low-income countries.

The variety of energy profiles and the higher exposure to energy security issues compared to the total economy in some regions suggests that interventions in the system should consider the geographical context. Reducing energy use and decarbonizing the supply chains of food products will require a combination of technological measures and behavioral changes in consumption

patterns. Interventions should consider the effects beyond the direct effects on energy use, since changing production and consumption patterns in the food system can lead to positive spillovers in the social and environmental dimensions outlined in the Sustainable Development Goals.

1. INTRODUCTION

The global food system is a major energy user, responsible for between 15 and 20% of total energy use (Beckman et al. 2013). Energy is used in different forms throughout all the life cycle stages of food. Diesel serves as fuel in agricultural machinery and transportation activities, natural gas is a key input in the production of fertilizers, electricity is used to store and prepare food, etc. As a result, food systems are connected to several environmental impacts through the use of energy, most notably climate change.

The overall use of energy in the food system is shaped by several global factors. Growing populations and increasing affluence has resulted in large increases in food consumption and significant changes in dietary compositions, both of which impact heavily on energy inputs in the food system (Behrens et al. 2017). Increasing consumption volumes often require either the development of new arable land (requiring further energy input), or increasing yields (often resulting in increased fertilizers and energy inputs) (Woods et al. 2010). Changes in dietary composition, on the other hand, are driven by rising affluence, a process commonly termed the nutrition transition whereby diets move from vegetal staples to increasing amounts of animal products and processed foods (Popkin 2006). This increased emphasis on animal products increases the dependence on energy inputs as they are generally less efficient than vegetal alternatives (Pelletier et al. 2008). These trends have driven large developments in food system energy use (Canning et al. 2010) and will continue to do so for the foreseeable future (Woods et al. 2010).

The global food system is also characterized for being very inefficient with regard to waste. Currently, a third of all edible food is discarded globally along the life cycle stages of food (Gustavsson et al. 2011). Acting on it, as foreseen under the Sustainable Development Goal 12.3 ("By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses") (UN 2015b), could result in important environmental savings, including energy resources (Usubiaga et al. 2018). A further trend in food systems has been towards greater volumes of trade between nations, with increasing percentages of environmental impacts embodied in traded agricultural goods. For example, a quarter of all agricultural emissions are traded (Kander et al. 2015), along with 22% of all freshwater withdrawal (Dalin et al. 2012).

The combined pressures of increasing population and wealth will continue and intensify during a period in which society is under increasing pressure to transition to renewable and low-carbon technologies. The food system will need to transition but will face specific technological and social challenges distinct from those seen in other sectors. Compounding this is the need for heavy mobile machinery for production and pre-processing steps (ploughing, reaping, threshing, winnowing etc.), which require large mobile sources of energy to operate using high energy density fuels such as diesel. For example, while 15% of the overall electricity mix in the European Union was from renewable sources in 2015, this drops to only 7% in food systems (Monforti-Ferrario et al. 2015). Socio-economic challenges to transitioning to more efficient food production systems in some producer nations include the lack of financial and human resources, and inertia due to conservative approaches of producers. This comes on top of the existing barriers to changing food consumption patterns (Mozaffarian et al. 2018).

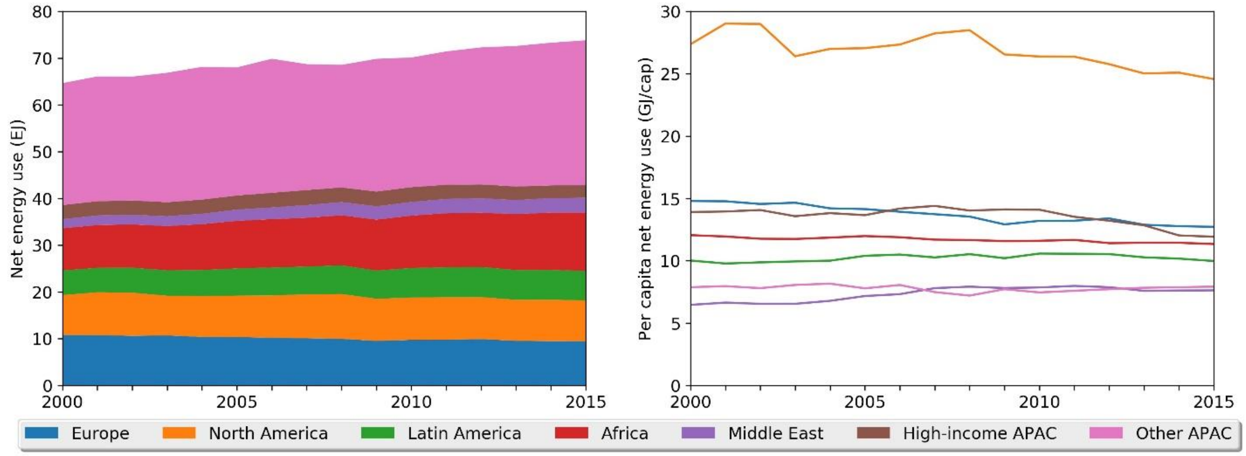
Against this background, the paper intends to provide a stock-take of energy used in the global food system and shed light on the energy profile of regional food systems. It is structured as follows. Section 2 provides an overview of previous assessments of the energy requirements of food systems and identifies the research gaps addressed in this paper. Section 3 describes the methodology. Section 4 and 5 present and discuss the results, while section 6 concludes.

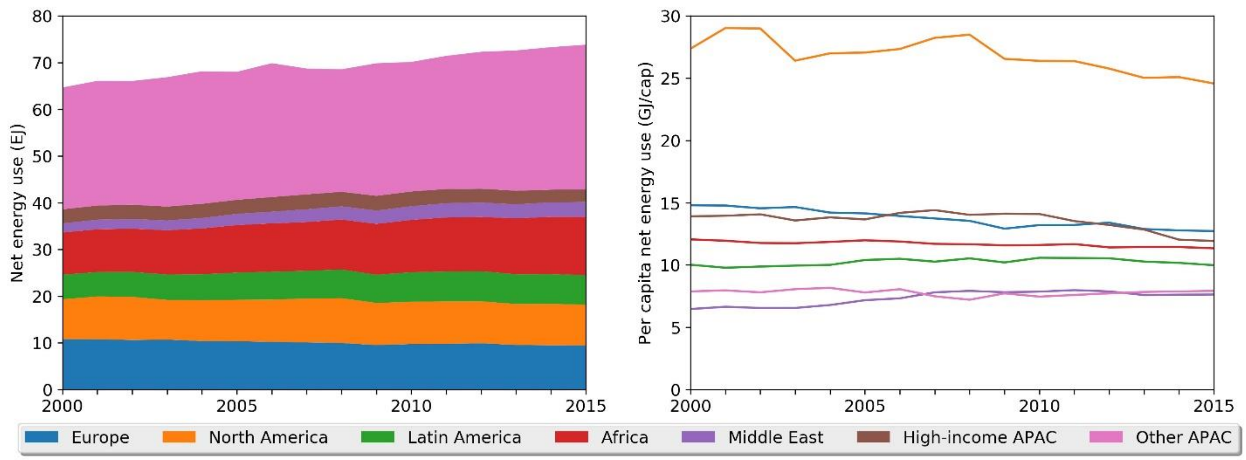
2. PREVIOUS ASSESSMENTS OF THE ENERGY PROFILE OF THE FOOD SYSTEM

Given these developments, research on the energy use in food systems has become increasingly relevant from a policy perspective. Although different methodological approaches have been used (Coley et al. 1998; Eshel and Martin 2006), the dominant approach has been Life-Cycle Assessments (LCA) (Pelletier et al. 2011). There have been several investigations of the large differences between food products (Foster et al. 2006; Pimentel et al. 2008; Laso et al. 2018). LCA assessments have been combined to form a basket of goods which may represent a typical diet (Monforti-Ferrario et al. 2015). They have also been used to investigate the energy requirements of different nutrients (González et al. 2011). Assessments of energy use in specific parts of the supply chain have been prominent, particularly on food miles and the regionality of production (Pretty et al. 2005; Hauwermeiren et al. 2007). Assessments of other areas of the supply chain have been less numerous due to methodological difficulties, for instance in packaging (Sanjuán et al. 2014; Molina-besch et al. 2019). Indirectly, many LCA studies have some consideration of energy consumption by focusing on greenhouse gas emissions, but the underlying composition of energy inputs into food is obscured (Tilman and Clark 2014).

However, there are several weaknesses of LCA for how energy is used across food systems (as opposed to individual product analysis). Firstly, being a bottom-up analysis, decisions on boundary settings, allocation choices, and background data makes results difficult to standardize and compare across studies (Ayres 1995). Secondly, there are estimation challenges when it comes to truncation errors, that is, where the boundaries of the system are drawn (Ward et al. 2017). Third, while there is increasing attention on the regionalization of data within LCAs, many use averages in nations rather than including different production factors across nations in the food supply chain (Yang and Heijungs 2016).

At a higher level of aggregation, encompassing broader sectors or product groups, environmentally extended Input-Output Analysis (EEIOA) has been used to estimate direct and indirect energy consumption across an entire economy. However, these analyses until now have been based on national investigations (Ozkan et al. 2004b; Bekhet and Abdullah 2010; Canning et al. 2010; Cao et al. 2010; Reynolds et al. 2015; Sherwood et al. 2017; Song et al. 2019) or highly aggregated food sectors (Alcántara and Duarte 2004). For national analyses, EEIOA studies have had to be complemented with exogenous data for supply chains outside the nation of investigation, leading to a number of simplifications and assumptions (Monforti-Ferrario et al. 2015).





There is also a ‘geographical-gap’ in studies as both LCA and EEIOA studies have focused predominantly on high-income nations (de Haes 2004; Aleksandrowicz et al. 2016). An exception is Turkey, for which several studies of different food types have been made (Ozkan et al. 2004b; Ozkan et al. 2004a; Hatirli et al. 2005; Kizilaslan 2009). A key challenge is to expand these analyses for other nations in a comparable manner which will incorporate heterogeneities in the amount and types of energy used in the food system (Pelletier et al. 2011).

Using environmentally-extended input-output methods generally trades product specificity in LCAs for a broader, global scope. Here we present, to our knowledge, the first comprehensive analysis of energy in food systems using a global environmentally-extended multi-regional input-output (EEMRIO) database. We analyze the use of energy in food supply chains using EXIOBASE, an environmentally-extended database with a high resolution in both food products, energy types, and also in related activities (Stadler et al. 2018). The level of product disaggregation available allows us to isolate the energy demands (in amount and type) of different food groups, while following this energy use through the supply chain. The database gives information on pre-production (i.e. energy for fertilizer inputs), production, processing, transport, consumption, and disposal. The database represents 10 middle-income nations as well as 34 high-income nations (with the remaining nations represented as five aggregated regions).

This work addresses three key research gaps: firstly, the inclusion of several middle-income nations broadens our knowledge of food systems outside high-income nations; secondly, the coverage of different food and energy types allows for increased insight into how energy is used at an international level; finally, the inclusion of a time-series and GRMIO allows for the investigation of the evolution of energy use in international food supply chains in a way that previously has not been possible.

3. METHODS

In this paper, we characterize the energy profile of regional food systems both from the production and consumption perspectives for the period 2000-2015. To this end, we use a global

EEMRIO database with high sectoral detail, which in this context can provide policy-relevant insights on energy mixes, drivers, energy self-sufficiency, etc. The following subsections define the system under study, and describe the methodology and main data sources used in the analysis.

3.1. Food system

Here we assimilate the food system to the part of the economy that is activated to produce the food (including beverages) purchased directly or in restaurants and hotels by final consumers such as households, governments, NGOs and similar organizations, as well as to produce the energy products these final consumers use in food-related activities such as cooking and refrigeration.

The activities involved in the production of food are not restricted to the agricultural sector, food processing, packaging and distribution. They also cover the life-cycle stages of the inputs required to support each of these activities (e.g. fertilizer and pesticide production, extraction of raw materials, manufacturing industries, energy production and distribution, service industries, etc.). This approach ensures that all the elements involved directly or indirectly in food production for and consumption of final consumers are accounted for. Purchases made in other food-related industries (e.g. hospitals, universities, schools, prisons, stadiums, cinemas, etc.) are not included in this analysis.

3.2. Data sources

The energy profile of the food system can be assessed from two sides: production and consumption. The production side shows the domestic energy supply or use associated with the food system. The consumption side, on the other hand, depicts the upstream energy demand related to food consumption activities, independent from where energy is used. The upstream energy demand of consumption is commonly referred to as energy footprint. We use the term ‘energy foodprint’ to refer to the energy footprint of food systems.

EEMRIO databases provide the means necessary to assess both the production and consumption perspectives. Here we use EXIOBASE 3.6 (Stadler et al. 2018) as the core data source. The monetary structure of EXIOBASE represents 200 product groups for 44 countries that account for more than 90% of the world’s GDP. The remaining countries are grouped in five ‘rest of world’ regions. For ease of reporting, we aggregate countries, food products, energy users and energy products as shown in Table 1. Details on the mapping of the EXIOBASE countries and products classification to the groups represented in this paper are available in the supporting material.

Table 1: Regions, food product, user and energy product groups used in this paper

Regions	**Food products**	**Energy user**	**Energy products**
Europe	Meat	Agriculture	Coal electricity
North America	Fish	Fishing	Gas electricity

Latin America	Dairy and other animal products	Other Primary	Oil electricity
Africa	Grains	Food Processing	Nuclear electricity
Middle East	Vegetables, fruits and nuts	Chemicals	Renewable electricity
High-income Asia and Pacific	Other	Other manufacturing	Biomass/waste electricity
Other Asia and Pacific		Electricity/heat	Heat
		Transport	Coal
		Services	Gas
		Households	Oil products
			Nuclear fuels
			Biomass/waste

In its current publicly available version (v3.4), EXIOBASE contains detailed industry- and product-specific energy accounts. The database includes primary energy accounts (supply) and gross energy accounts (supply and use) for around 60 energy products. In contrast to primary energy accounts, gross energy accounts represent certain energy flows twice (e.g. coal for electricity production and the electricity itself), which makes them inadequate for footprint calculations (Arto et al. 2016). The use of primary accounts as environmental extension avoids this double accounting problem.

Primary energy accounts can contain primary energy supply (PES) – domestic extraction of energy – and net energy use (NEU) – end use of energy products (excluding exports) plus all losses of energy – data. Each type of account is intended to address a different set of research questions (Owen et al. 2017). For instance, energy footprints based on PES data are best suited to shed light into the origin of the energy associated with final consumption activities, while footprints based on NEU data are more appropriate to attribute the actual energy use to industry sectors.

Because EXIOBASE only contains data on PES, we have generated NEU accounts to be used as environmental extension following the guidance provided in the official energy accounting manuals (Eurostat 2014; UN 2015a). This required the conversion of IEA extended energy balances (IEA 2017b, 2017a), from the territory to the residence principle (see Usubiaga and Acosta-Fernández (2015) for more details), filtering the net energy use data and allocating the resulting energy use to the EXIOBASE product and industries following the allocation procedure in Stadler et al. (2018). A more detailed explanation is available in the supporting information.

Given that our definition of the food system covers food-related activities that take place within the household, we have also estimated the direct energy use required for cooking and refrigeration within the household. To this end, we have extracted the product-specific percentages of residential energy devoted to such activities from the TIMER model (Daioglou et al. 2012) and incorporated it in the NEU extension as described in the supporting information.

3.3. Energy profile of the food system

We have computed production- and consumption-based accounts (footprints) for the whole economy and for the food system using both PES and NEU as environmental extensions. In the figures we use net energy use to refer to the production-based energy use, and energy foodprint for the consumption perspective. The mathematical formulation is the same irrespective of the extension used. In the equations below, bold lower case refers to vectors, bold upper case to matrices and italics to scalars. The dimensions of all the variables are given in the supporting information).

Production-based accounts for the economy as a whole are given by the environmental extension. In the case of food systems (^{FS} superscript), these are a function of the demand of food by final consumers such as households, government, etc., and energy products used by households in food-related activities such as cooking and refrigeration, which is shown in equation 1, where $\mathbf{x}$ represents output, $\mathbf{L}$ is the Leontief inverse, $\mathbf{y^{F}}$ the final demand of food, $\mathbf{z^{F\text{-}R}}$ the direct input of food products associated with final consumers´ purchases in restaurants and hotels, and $\mathbf{y^{E\text{-}F}}$ the final demand of energy products for cooking and refrigeration purposes. The last two elements are calculated as shown in equations 2 and 3. In equation 2, $\mathbf{A^{F}}$ describes the input coefficient matrix where the non-food input coefficients are converted to zero and $\mathbf{y^{R}}$ the final demand of hotels and restaurants. Equation 3 shows the element-wise multiplication of the final demand of energy products ($\mathbf{y^{E}}$) and the share of each product that is used for cooking and refrigeration ($\mathbf{w^{E\text{-}F}}$).

$$\mathbf{x^{FS}} = \mathbf{L}\,(\mathbf{y^{F}} + \mathbf{z^{F-R}} + \mathbf{y^{E-F}}) \qquad (1)$$

$$\mathbf{z}^{\mathbf{F-R}} = \mathbf{A}^{\mathbf{F}}\,\mathbf{y}^{\mathbf{R}} \qquad (2)$$

$$\mathbf{y}^{\mathbf{E-F}} = \mathbf{y}^{\mathbf{E}} \circ \mathbf{w}^{\mathbf{E-F}} \qquad (3)$$

In equation 4, **D_prod** and **S** represent production-based accounts and the stressor (primary energy supply or net energy use) intensity respectively. The element $\mathbf{fh}^{\mathbf{FS}}$ refers to the direct food-related energy use of households in physical terms. This is a positive value when using net energy use as extension and equals 0 when using primary energy supply, for the extraction of primary energy products is not undertaken by final consumers.

$$\mathbf{D\_prod}^{\mathbf{FS}} = \mathbf{S}\,\mathrm{diag}(\mathbf{x}^{\mathbf{FS}}) + \mathbf{fh}^{\mathbf{FS}} \qquad (4)$$

The calculation of the energy footprint of country *i* (equation 5) and of its food consumption (equation 6) is carried out using the standard formula for EEIOA, where **D_cons** denotes the energy foodprint and $\mathbf{fh}^{\mathbf{FS}}$ the direct food-related energy use of households. This last item is 0 when using PES as extension.

$$\mathbf{D\_cons}_{\mathbf{i}} = \mathbf{S}\,\mathbf{L}\,\mathrm{diag}(\mathbf{y}_{\mathbf{i}}) + \mathbf{fh}_{\mathbf{i}} \qquad (5)$$

$$\mathbf{D\_cons}_{\mathbf{i}}^{\mathbf{FS}} = \mathbf{S}\,\mathbf{L}\,\mathrm{diag}\left(\mathbf{y}_{\mathbf{i}}^{\mathbf{F}} + \mathbf{z}_{\mathbf{i}}^{\mathbf{F-R}} + \mathbf{y}_{\mathbf{i}}^{\mathbf{E-F}}\right) + \mathbf{fh}_{\mathbf{i}}^{\mathbf{FS}} \qquad (6)$$

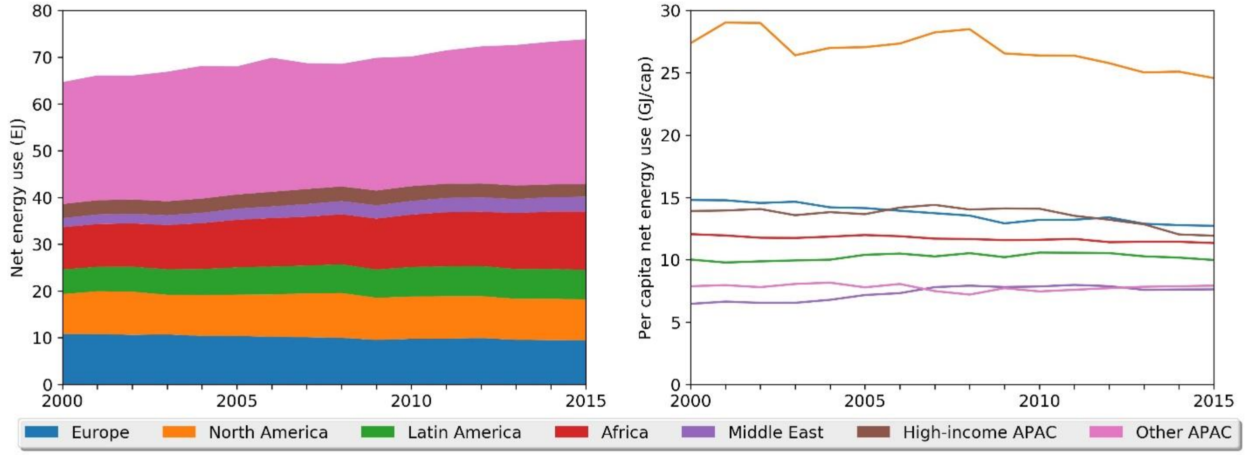
We have also compared the import dependency (i_dep) of different energy products for the food system and the whole economy. The equation below shows the dependency for the economy where *j* and *k* refer to energy products and industries respectively. The import dependency of the food system is calculated the same way using the $\mathbf{D\_prod^{FS}}$ and $\mathbf{D\_cons^{FS}}$ matrices instead. In this case, the production- and consumption-based indicators use PES as extension.

$$\mathrm{i\_dep}_i = 100 * \frac{\sum_{j,k} \mathbf{D\_cons_i} - \sum_{j,k} \mathbf{D\_prod_i}}{\sum_{j,k} \mathbf{D\_prod_i}} \qquad (7)$$

4. RESULTS

Overall, the food system accounts for approximately 13% of the global net energy use (dropping from over 15% in the early 2000s, see Figure S1). Between 2000 and 2015, absolute net energy use in food systems has increased by 14% approximately (Figure 1). Small absolute reductions are seen in high-income regions (Europe, high-income Asian and Pacific countries (APAC)) with the exception of North America. Larger absolute increases are seen across predominantly middle- and lower-income regions. The trends in middle- and lower-income regions are partially explained by population growth, as absolute increases are much higher than those in per capita terms. Some middle- and lower-income regions actually show reductions in per capita terms (e.g. Africa).

Figure 1: Overview of the absolute (a) and per capita (b) net energy use in the global food system, 2000-2015 (D_prod^{FS}).

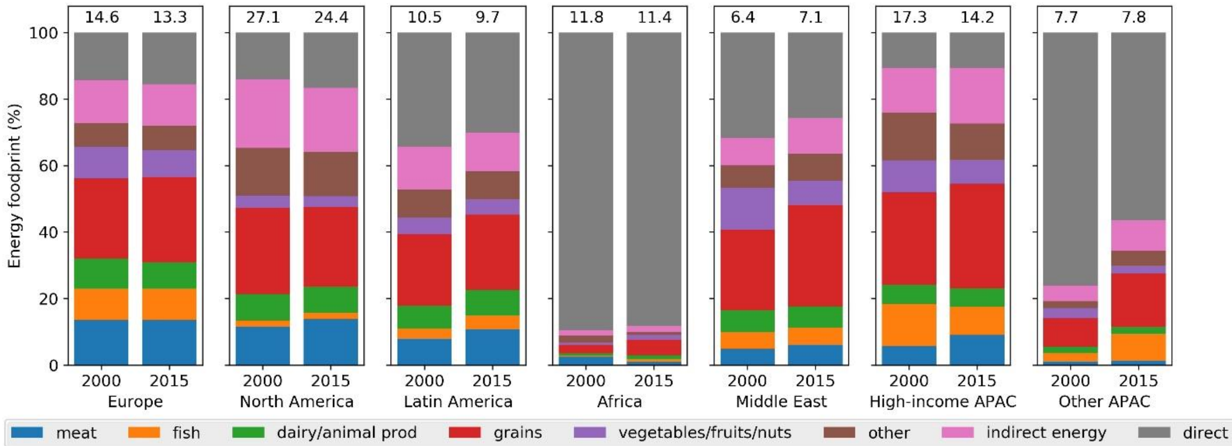


The large per capita energy intensity gap between North America (mainly the United States) and the rest of the world has narrowed slightly over the period. While this fell for many countries from 2000 to 2015, it fell more rapidly in North America (see Figure 1). However, North American energy inputs into the food system are almost double than the next closest high-income region, in this case Europe.

From a footprint perspective, the demand of grains for human consumption drives the largest energy inputs in all regions (see Figure 2). This statement should be interpreted carefully though, for although the ‘grains’ category includes grains and grain-based processed products, the latter often covers processed products with many ingredients such as meat, vegetables, vegetable oils and sugars that belong to other categories, but could be allocated to them (see related limitations in and full product correspondence in the supporting information). This estimate does not include the as much as 36% of all grains in some regions that are directed to livestock rearing

(Cassidy et al. 2013). The energy inputs required to produce the grains fed to livestock are embodied in the corresponding category of animal products. The energy inputs for all animal products (meat, fish, dairy and other products) is roughly equivalent to the energy inputs for grains produced for human consumption in some regions such as Europe. In total, between 23% and 31% of all net energy use from European, North American and high-income Asian and Pacific countries' foodprint is linked to animal products. Although, the per capita figures of related to animal products are far from those in high-income countries, their relevance is increasing over time in Latin America, the Middle East and other APAC countries. In this line, most of the foodprint associated with food purchases is driven by consumption within the household, although purchases in restaurants and hotels are not negligible in most high-income regions (Figure S2). Direct energy use for refrigeration and cooking varies widely from region to region, comprising as little as 11% in high-income Asia Pacific nations, to 88% in Africa. As might be expected, higher income nations generally have a more efficient use of direct energy in food supply, as driven by developed electricity grids and improvements in refrigeration and cooking technologies. Because higher income countries tend to use electricity and natural gas within the household, the indirect energy required to produce – especially the former – is higher than in low- and middle-income countries and can represent an important share of its foodprint.

Figure 2: Breakdown of per capita energy footprint driven by the purchase of different food types across regions (%), 2000 and 2015 (D_cons^{FS}). The total per-capita figures on the top are given in GJ/cap.

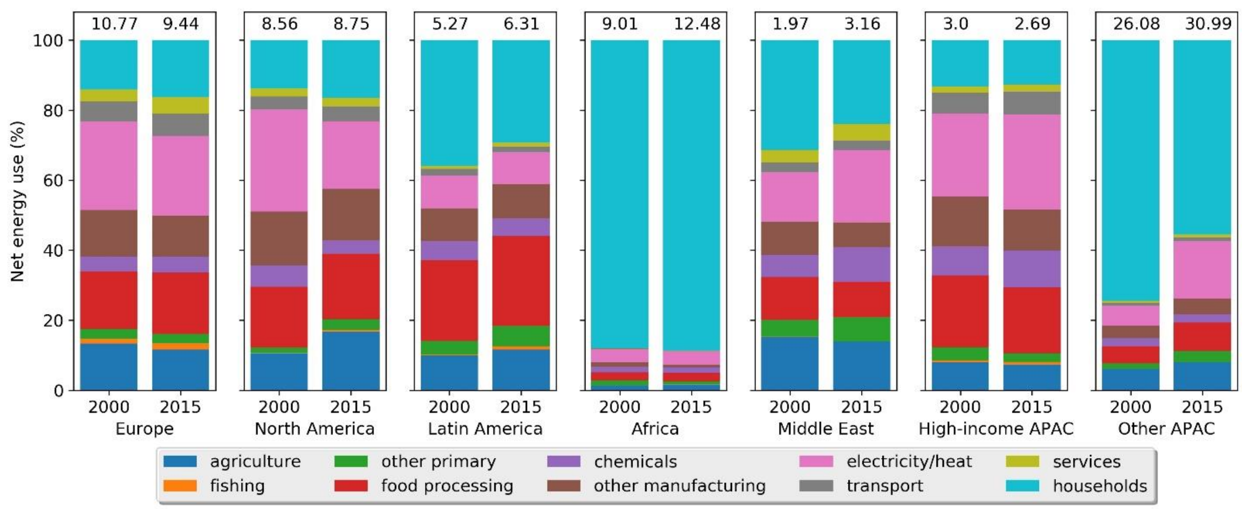


Note: The direct energy represents energy required in cooking and refrigeration. Indirect energy use refers to the energy used in the production of the food-related energy products consumed within the household. ‘Grains’ include, among others, grains and grain-based products such as bread and pasta whether or not cooked or stuffed, as well as other products such as biscuits, pastries and cakes. ‘Other’ includes sugar products, beverages, oil seeds and other vegetable fats (all plant-based products).

Splitting further between where the energy is used in the food chain, direct energy used by the household for food preparation and storage is significant as also shown in Figure 3, even in higher-income nations, varying from 13 to 16% of the total energy used in the food system across North America, Europe and high-income Asia Pacific nations to as much as 55% and 89% in other APAC nations and Africa respectively. In both cases, the domination of in-house energy use is due to inefficient cooking methods and lack of electrification in rural areas (see Figure 3).

Other Asia Pacific nations, and the Middle East have seen significant reductions in the energy use by households since 2000. The proportion of energy use used in food processing and in primary cultivation or livestock rearing is similar in most regions, with slightly more energy use in processing within high-income APAC and Latin American nations. Chemical use in the food chain, including those for plastics and fertilizers are larger in the Middle East and high-income APAC nations and has grown larger over time.

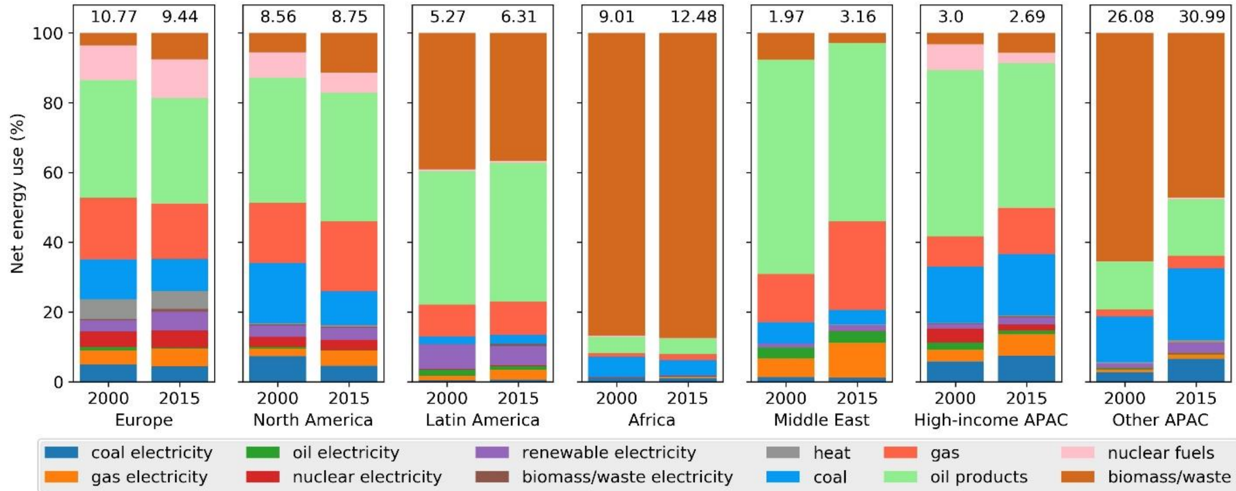
Figure 3: Net energy use for the food system within different sectors across regions (%), 2000 and 2015 (D_prod^{FS}). The total per-capita figures on the top are given in EJ.



Note: The chemicals sector includes energy use for both fertilizers and plastics. Households refers to direct use of energy for food use in the home. Services includes construction and non-transport services such as financial services, education, waste management and real state.

Fuel use in the global food system is dominated by the use of fossil fuels and biomass (see Figure 4). Fossil fuels include their end use (e.g. combustion of diesel in machinery, but not as input of oil in a refinery) and the losses incurred in transformation, transport, etc. A maximum of 21% of energy in the food system comes from electricity. Higher-income nations tend to have a lower biomass to fossil fuel ratio, with middle- and lower-income nations the reverse. Between 65% to 87% of net energy use is derived from fossil fuels across higher-income nations, with the Middle East reaching 95%. The relative lack of electricity in the food system as compared to other systems highlights the decarbonization challenge for energy in the food sector. There is some growth of renewable energy as a proportion in some regions, with the largest proportional increase in Europe. There are also large proportional increases in biomass for Europe and North America, likely driven by increasing interest in, and expansion of biofuels. Across high-income nations, oil makes up between 31% (Europe) and 43% (high-income APAC nations) of total energy use in the food system. The large amount of direct oil use (i.e. not converted into electricity) in the food sector highlights the challenge for the renewable transition within the food sector.

Figure 4: Different types of net energy use in the food system across regions, 2000 and 2015 (D_prod^{FS}).

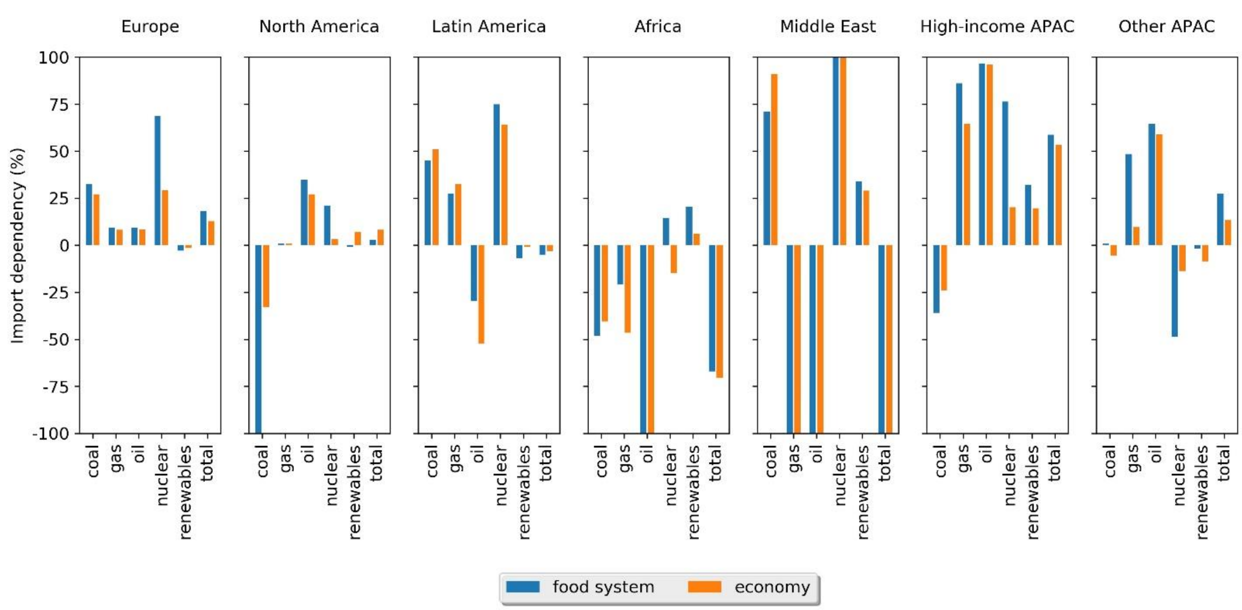


Note: The figures for electricity and heat refer to the actual generation. Losses in the transformation process, as well as in the storage and transportation of fuels are allocated to the fuel.

The large dependency on oil and gas also highlights potential issues of energy security within the food system. Given the high regional dependency on these resources, disruptions to energy supply may influence food systems. Figure 5 shows the difference in energy dependency (modelled through equation 7 above) between energy used in the food system compared to the whole of the economy. European countries see an increased import dependency on all fuels in the food sector (when compared to the rest of the economy) except for renewable energy. In total, Europe sees roughly a 50% higher dependency in the food system than the overall economy. North American dependencies are more mixed, with its large endowments of coal and shale oil/gas reducing dependency. Latin America shows a similar dependency for coal and gas as Europe, but with less reliance on overseas oil. In Africa, the largest difference between the food system and the whole economy is seen in renewables and nuclear. The middle east shows expected trends in domestic supply of oil and gas and import dependency on all others. High-income APAC countries show heavy energy dependency on imports for all fuels except for coal. Across all fuels except coal, the food system is more dependent than the rest of the economy.

It should be noted however that trade interdependency may be larger than this picture shows due to the different grades of fuels within energy types. For example, US imports and processes large amounts of heavy crude oil, but exports large amounts of light crude oil produced domestically. These two grades are not easily fungible in the energy system so grouping by energy type can sometimes underestimate the underlying trade in fuels.

Figure 5: The import dependency of different energy types as used in the food system and the economy by region, 2015 (i_dep).



Note: This figure does not include the category 'biomass and waste' (see limitations in supporting information). The reader should note that individual energy carriers may represent varying portions of absolute energy demand (see Figure 4).

5. DISCUSSION

With global population expected to be close to 10 billion people in 2050 (UN 2017), a zero hunger goal will inevitably require more food to be produced in the future. The key to ensuring that food production can be reconciled with the biophysical limits of the planet will be to decouple food production from the inputs of natural resources as much as possible. These natural resources include energy, and its associated environmental impacts, most notably climate change. Energy use patterns vary widely both across regions with different and similar income levels and there is variation in both the proportion of energy used in different food production and consumption stages and the types of energy used. Because of this, measures for improving efficiency and facilitating the low-carbon energy transition should be adapted to each geographical context.

Across all high-income nations there is the large opportunity to reduce food waste, particularly at the point of consumption (Gustavsson et al. 2011). Such efforts have large upstream benefits. For instance, halving consumer food waste could potentially reduce the environmental foodprint of Europe by 10-11% on average (Usubiaga et al. 2018). In less industrialized countries, most food is lost in the production, processing, storage and transportation stages before it reaches the consumer (Gustavsson et al. 2011), which also offers substantial possibilities to increase the efficiency of the system.

Across lower-income regions, the reduction of direct energy use while concurrently improving refrigeration and reducing food losses in the production chain are key options. Low efficiency cooking and heating using traditional biomass leads to large energy use in regions that rely on it, leading to the counterintuitive result that per-capita food-energy use in Europe and Africa are closer than expected (Figure 1). Latin America, the Middle East and other APAC nations also have some reliance on traditional biomass but all except Africa have seen significant progress from 2000 to 2015 in reducing those energy inputs. While the deployment of clean cookstove efforts has been partially successful (Rosenthal et al. 2017) a prominent lesson from these efforts is the need to ensure that solutions are location specific so that options address local differences in cookware (i.e. flat or curved pans), cooking habits (i.e. appropriate for local dishes and cultures), yet are still scalable at the same time (Diehl et al. 2019). A further important factor at the African household level may be the continuing reduction in solar energy costs and potential for electric refrigeration (N'Tsoukpoe et al. 2014). Improving the diffusion of clean refrigeration and cooking technologies is a key task in achieving numerous SDGs relating to poverty, health, gender equality, and maintenance of environmental services (Oparaocha and Dutta 2011; Rao and Pachauri 2017; Fuso Nerini et al. 2018).

Significant embodied dependencies in the food system have been found for virtual water and other resources (Dalin et al. 2012), but to the best of our knowledge there has been no estimate of embodied energy in global food trade. Similar to water security issues driven through trade, energy security through trade has important implications. We find that the European food system has a higher exposure to imported energy embodied in food than the rest of the economy across all energy types except for renewables. This suggests there may be an underappreciated food supply risk benefit in further decarbonization of the European energy system. That is, further development of European renewables may improve food supply security as well as energy security (although there are concerns about the material requirements for renewable energy and their potential supply risks). The interplay between energy and food security is one that is relatively understudied, with nexus studies often focusing on water as the coordinating resource (Lawford et al. 2013).

There is an urgent need for a low-carbon energy transition across all regions and sectors. Progress to decarbonize the electricity system, although insufficient, has been much faster than other energy sectors (Davis et al. 2018). The food system commonly lags behind in the penetration of renewables compared to the rest of the economy (Monforti-Ferrario et al. 2015) because the use of energy tends to be more diffuse than in other sectors with a particular focus on transport and heating fuels. With new renewable energy installations in many countries at, or cheaper than, the price of existing fossil fuel generation (McKinsey 2019) we can assume that electricity in the food system (Figure 4) can be made renewable with relative ease at low cost. Much harder is the use of oil in food production and transportation. Despite the fact that transport currently makes up a small amount of the total energy used in food systems it may become a dominant proportion for food-system emissions as the rest of the energy services decarbonize. There is increasing innovation in electrifying farming equipment (Monforti-Ferrario et al. 2015), but the electrification of long-distance transport still poses a significant challenge, especially in shipping (Davis et al. 2018). Potential exists to reduce the energy use and emissions of long distance freight through modal shift and fuel switching in freight, but the required changes in logistics and infrastructure are not expected to be widespread in the short term (McCollum et al. 2009; Kaack et al. 2018).

Monforti-Ferrario et al. (2015) have also documented options to increase the amount of renewable energy in the production of ammonia and hydrogen for fertilizer production. The ban of single-use plastics – included in the chemical sector in Figure 3 –, which includes unnecessary packaging in the food industry also offers benefits. Irrigation practices also represent an interesting example, where switching from open channel flow delivery systems to pressurized networks can lead to significant water savings at the expense of higher energy use (Díaz et al. 2009). In these cases, important energy savings can be achieved by optimizing the operation of the pumping station (Díaz et al. 2009; Lamaddalena and Khila 2012).

Changes in dietary trends and consumer behavior – especially in high-income nations – and can also offer large benefits in several environmental aspects (Behrens et al. 2017) – including energy – and health systems (Willett et al. 2019). Benefits are not only linked to changes in the dietary mix, but also to reducing total food intake in some regions (Alexander et al. 2017). Changing consumption and a focus on local and seasonal food products are likely to significantly reduce the demand for freight transport, refrigeration, and fertilizers. Furthermore, diets with reduced meat consumption limit the demand of, and consequent emissions from, land-use and have been highlighted as a potentially important aspect of climate change mitigation pathways (van Vuuren et al. 2018).

Economic instruments such as removing environmentally harmful subsidies in the agricultural sector and putting in place taxes that help food products reflect their true environmental cost and nutritional value are options that could go a long way, but seem harder to implement.

6. CONCLUSIONS

So far, most analyses of the energy profile of the food systems have a national or product-level focus. This paper uses a global EEMRIO database to characterize the energy profiles of regional food systems around the globe and their evolution between the years 2000 and 2015. By using a single database, the analysis, which shows energy users, drivers and energy types across world regions, is carried out in a comparable manner, which is something missing in the literature to date.

Overall, the ratio between energy use in the food system and the economy is slowly decreasing. Current trends also point to a relative decoupling between net energy use (up 12% between 2000 and 2013) and food production (up 23% in the same period, (FAO 2017)). There is a myriad of factors affecting this effect, including changes in population, diets, yields, electrification, energy efficiency, food waste, access to food, etc., which make it very difficult to disentangle the main drivers behind this phenomenon. The magnitude of the decoupling effect can be influenced by the fact that our energy figures do not consider some of the food consumed outside the household (e.g. cinemas, hospitals, canteens, etc.).

The energy profiles of world regions vary widely in terms of the energy types used, the energy users, the food products driving consumption, or the dependency of imported energy in the food system. This diversity in profiles arises from the variety of energy services demanded in the food sector ranging across processes (production, processing, storage) and relevant actors (producers, distributors, consumers). The difference in how food is produced, prepared and consumed across the world suggests that interventions will need to prioritize different parts of the system depending on the location. This implies that the solutions for reducing energy use, increasing energy efficiency and decarbonizing energy supply in the food system will be substantially different across regions and has an intimate interaction with the rest of the economy.

As a general observation, in high income regions energy use in food production is spread over the supply chain, with production, processing, manufacturing and household energy use all contributing significant amounts of energy demand. This demand is satisfied mainly through the use of significant volumes of oil products (transport, packaging), as well as electricity and gas (processing, cooking). In lower income regions, the nature of food production and distribution, as well as the use of inefficient cooking fuels (i.e. traditional biomass) leads to energy use being concentrated at the 'end-use'. Thus, electrification and access to cookstoves is key in reducing biomass use for cooking in less industrialized countries. Thus, in higher income regions broader strategies are required concerning electricity production, freight transport and heating technologies.

Technological solutions will need to be complemented with changes in consumer behavior, especially in industrialized countries with carbon-intensive diets and high food waste figures.

Interventions should, in any case, consider the effects beyond the immediate effects on energy use, for changes in how food is produced and consumed can have spillovers and positive synergies with respect to the social and environmental dimensions outlined in the SDGs.

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SUPPORTING INFORMATION

The Word version of the supporting information provides an additional figure, an extended description of the net energy use accounts generated and a description of the limitations of the results. The Excel file contains the correspondence tables used and the data represented in each figure.