Sociedad Española de Historia Agraria - Documentos de Trabajo

DT-SEHA 1507

Noviembre de 2015

www.seha.info

EMBODIED ENERGY IN AGRICULTURAL INPUTS. INCORPORATING A HISTORICAL PERSPECTIVE*

Eduardo Aguilera**, Gloria I. Guzmán**, Juan Infante-Amate**, David Soto**, Roberto García-Ruiz***, Antonio Herrera**, Inmaculada Villa**, Eva Torremocha**, Guiomar Carranza**, Manuel González de Molina**

*This work was supported by the research project Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture (SSHRC 895-2011-1020) funded by the Social Sciences and Humanities Research Council of Canada; and the project "Transformaciones agrarias y cambios en el paisaje, 1752-2008. Una contribución al estudio de la transición socioecológica en Andalucía", Plan Nacional de I+D (HAR2009- 13748-C03-03).

** Agro-Ecosystem History Laboratory
Pablo de Olavide University (Seville-Spain)

***University of Jaén (Spain)

Contacts: emagufer@upo.es, mgonnav@upo.es

ISSN: 2386-7825

Resumen

Este documento de trabajo analiza la energía asociada a los inputs agrarios en perspectiva histórica. El estudio se basa en una amplia revisión bibliográfica, que se ha complementado con estimaciones propias para crear una base de datos coherente que incluye toda la energía directa e indirecta asociada a los principales insumos agrícolas con el máximo nivel de desagregación posible. Estos insumos incluyen mano de obra, vectores energéticos como combustibles y electricidad, materiales, maquinaria, fertilizantes y pesticidas de síntesis, insumos orgánicos, material de propagación, insumos asociados al regadío, edificaciones, invernaderos, transporte y servicios no materiales. Para cada insumo se describe su evolución histórica desde la perspectiva energética, las metodologías más comúnmente empleadas en la literatura para el cálculo de su energía asociada, y se proporcionan series temporales sobre la evolución de esta energía. Las series temporales incluyen todo el siglo XX y la primera década del siglo XXI, y están expresadas en cortes decenales. Los valores ofrecidos son promedios globales o referidos a las principales regiones productoras. Los resultados muestran los grandes cambios que han ocurrido en la eficiencia energética de la producción de insumos agrícolas, subrayando la necesidad de emplear coeficientes dinámicos en el análisis energético de la evolución histórica de los sistemas agrícolas.

Palabras clave: Balances de Energía, Insumos Agrícolas, TRE, Análisis de Ciclo de Vida, Historia Industrial, Eficiencia Energética

Abstract

This working paper analyzes the energy embodied in agricultural inputs from a historical perspective. The study is based on a wide literature review, which has been complemented with own estimations in order to create a coherent database including all direct and indirect energy associated to the main agricultural inputs with the maximum possible level of disaggregation. The inputs studied include human labour, energy carriers such as fuels and electricity, materials, machinery, synthetic fertilizers and pesticides, organic inputs, propagation material, irrigation inputs, buildings, greenhouses, transport and non-material services. For each input we describe its historical evolution from an energetic perspective, the most common methods used for the calculation of its embodied energy published in the literature and temporal data series on the historical evolution of this energy. The temporal data series are expressed in 10-year time-steps and, in the majority of cases, they cover the whole 20th century and the first decade of the 21st century. The values provided are global averages or covering the main producing regions. The results show the large changes that have occurred in the energy efficiency of the production of agricultural inputs, underlining the need for the use of dynamic coefficients in historical energy analyses of agricultural systems.

Keywords: Embodied Energy, Energy Balances, Agricultural Inputs, EROI, Life Cycle Assessment, Industrial History, Energy Efficiency

JEL CODES: N54, Q01, Q18, Q57

EMBODIED ENERGY IN AGRICULTURAL INPUTS. INCORPORATING A HISTORICAL PERSPECTIVE

1. Introduction

During socio-metabolic transitions from traditional to industrial societies, the role of agriculture as the major source of energy and materials in pre-industrial societies gave place to fossil fuels and minerals in industrial societies (Krausmann and Haberl, 2002, Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2008, Kuskova et al. 2008, Infante-Amate et al. 2015). In the specific case of agriculture, metabolic transitions are characterized by large quantitative and qualitative changes in agrarian inputs, that usually were linked to increases in outputs (increased land productivity) and decreases in human labour (increased labour productivity) (Boserup, 1981, Giampietro et al. 1999, Fischer-Kowalski et al. 2014). Typically, solar-based local, organic inputs produced on farm such as manure and animal draft power were substituted by high amounts of fossil fuel-based external inorganic inputs such as synthetic fertilizers and pesticides, machinery, fuel and electricity (e.g. Guzmán Casado and González de Molina, 2009).

Energy assessments of agricultural systems started with the pioneer works of Sergei Podolinski in 1880 (Martinez-Alier, 2011), but they were practically abandoned for many decades. In the late 20th century, starting with the work of Odum (1971) and Rappaport (1971), and triggered by the new interest on energy issues that arose with the energy crises of the nineteen 70s and 80s, a series of works were published applying energy analyses to agriculture from the farm or crop scales (e.g. Pimentel et al. 1973, Berardi, 1978, Campos and Naredo, 1980, Pimentel and Burgess, 1980, Fluck, 1992a, see many examples in Smith et al. 2015) to the country scale, including USA (Steinhart and Steinhart, 1974, Hirst, 1974), UK (Leach, 1976), Australia (Watt, 1984) or Spain (Naredo and Campos, 1980). In the 1990s and 2000s, some studies developed methodological aspects of agricultural energy analyses (e.g. Giampietro et al. 1994, Audsley et al. 2003). More recent works have documented the situation in the last decades and explored possibilities for reducing food related energy consumption at the farm scale (e.g. Kaltsas et al. 2007, Guzmán and Alonso, 2008, Aguilera, 2009, Mikkola and Ahokas, 2009, Alonso ad Guzmán, 2010) and at the country scale (e.g. Dutilh and Kramer, 2000, Heller and Keoleian, 2003, Ozkan et al. 2004, Pimentel et al. 2008, Canning et al. 2010, Tabar et al. 2010, Woods et al. 2010, Cao et al. 2010, Markussen and Ostergaard, 2013, Infante-Amate and González de Molina, 2013). Many of these works, along with others, are reviewed by Pelletier et al. (2011).

In parallel, other works have focused on the historical perspective, assessing pre-industrial agricultural systems and metabolic transitions in agriculture (e.g. Bayliss-Smith, 1984, Cleveland, 1995, Krausmann, 2004, Cussó et al. 2006, Carpintero and Naredo, 2006, Guzmán and González de Molina, 2009, Infante-Amate et al. 2014). Recent works have also harmonized and updated energy contents of agricultural outputs and coefficients for estimating the net primary productivity of agroecosystems from a historical perspective (Guzmán et al. 2014).

To our knowledge, however, the changes in the energy efficiency of the production of inputs have scarcely been taken into account in the historical analyses of agricultural and agri-food systems. Only studies based on monetary data instead of on a process analysis systematically consider these changes because their calculations are based on year specific energy efficiencies (e.g. Cleveland, 1995, Cao et al. 2010, see Sections 2.7 and 14 of this document). Another interesting study (Pelletier et al. 2014) on eggs production in the US in 1960 and 2010 accounts for temporal changes in the energy efficiency of agricultural inputs from a LCA perspective.

Today there is a still scarce, although growing, body of information on the changes that have occurred in the production of most agricultural inputs. In terms of energy, the changes in inputs have not only been driven by the changes in their quantities and qualities, but also in the energy required to produce them. Technology improvements are responsible for a general trend in the 20th century towards increased energy efficiency in the production of most agricultural inputs, such as nitrogen and phosphate fertilizers or steel for machinery production (Smil, 1999, 2013, Jenssen and Kongshaug, 2003, Ramirez and Worrell, 2006, Dahmus, 2014). In some periods, such as the energy crisis of the 1980s, this trend has been intensified due to increased energy prices and concerns about the security of energy supply (Bhat et al. 1994).

There are some agricultural inputs, however, which required relatively low energy use in the early stages of their industrial developments, because their production energy is mainly used in mining activities, and easy to extract, high-grade ores were exploited first. The progressive depletion of these resources means increasing energy consumption to extract and refine the materials (Meadows et al. 1972), as lower-grade ores typically demand more energy to extract the resource (Gutowski et al. 2013). Therefore, despite technological improvements, the energy efficiency of the production of raw materials may ultimately decline. For example, this is the case of oil and gas production in the US (Hall et al. 2009, 2014), and also in other countries and in the world as a whole (Gagnon et al. 2009, Hall et al. 2014), whose energy return on investment (EROI) is already declining. As another example, the energy efficiency of potash fertilizer production in the US did not increase in the 1979-1987 period, despite high energy prices that boosted energy efficiency improvements in N and P fertilizers (Bhat et al. 1994).

In this work, we aim to provide a comprehensive compilation of embodied energy coefficients for the major agricultural inputs with a historical perspective. Our aim is not establish a methodology for the quantification of the embodied energy of agricultural inputs, but to provide a framework where researchers can situate their own choices. We have done this by reviewing the history of the agricultural use and production processes of agricultural inputs, and by constructing reasonable estimates, as disaggregated as possible, of the energy employed in the different phases of these production processes. Our main focus is on industrial inputs at the world level, for which we have aimed to construct a coherent, self-referenced database starting from the production of fuels and other energy carriers, raw materials and finally manufactured goods delivered to the farm. In the case of non-industrial inputs such as different types of biomass, animal work, human labour or non-material services we have just aimed to describe the most usual approaches for the estimation of their embodied energy.

2. Theoretical and methodological considerations

2.1 Definition of key concepts

In this work, the **embodied energy** of a given input refers to the sum of the higher heating value (gross energy) of the input plus the energy requirements for the production and delivery of the input. Thus, in most cases this metrics would be equivalent to the "cumulative energy demand" concept used in life cycle assessments, and also to the "energy intensity" concept used in some energy studies. All components of the embodied energy are expressed in terms of **higher heating value** or **gross energy**.

Energy requirements refer to the energy employed in the production of a given input. They are divided in direct and indirect energy requirements. **Direct energy requirements** refer to the gross energy of the fuels directly used in the production process. **Indirect energy requirements** include all remaining processes needed for the production of the input and its use at the farm, including **fuel** production and transport, **raw materials** production and transport, energy embedded in **buildings and equipment**, and **transport** of finished products up to the farm. It has to be clarified that only physical processes are included.

We follow the definition of **energy carriers** stated by Murphy and Hall (2011): "a primary energy source is an energy source that exists in nature and can be used to generate energy carriers (e.g., solar radiation, fossil fuels, or waterfalls). An energy carrier is a vector derived from a **primary energy source** (e.g., electricity, gasoline, or steam)". In this sense, an EROI should be based on an exergy point of view, which indicates that only useful energy should be taken as an input. This is, the EROI would represent the relationship between the energy carriers produced in an energy production process and the energy carriers employed in the process.

In this paper, **non-renewable energy (NRE)** includes fossil fuels, nuclear and, when the data is available (primarily when the data is gathered from ecoinvent), non-renewable biomass, which always represent a very small portion. **Renewable energy** is represented by hydro, renewable biomass, geothermal, wind and solar. The distinction between renewable and non-renewable energy sources is essential for the assessment of agroecosystem sustainability. Therefore, we provide data on NRE use for all items considered, as described in Section 2.4

The energy content of fuels and biomass products can be measured as the **lower heating value (LHV)** or the **higher heating value (HHV)**, also called net (NE) and gross (GE) energy values, respectively. As fuels usually have trace amounts of water, the LHV or NE considers only the energy that can be obtained from fuel combustion without recovering the energy in the evaporated water, while the HHV or GE considers all fuel energy (enthalpy) without correcting for water evaporation. The NE typically represents about 95% of the GE of liquid fossil fuels, and about 90% in the case of natural gas (IEA, 2004). We have employed the HHV or GE, as in many other energy analyses of cropping systems (e.g. Patzek, 2004, Pimentel, 2003) and in LCIA methods implemented in ecoinvent such as cumulative energy demand (Frischknecht et al. 2007a). However, the LHV or NE is also widely used in agricultural energy balances, and a consensus is far from being reached (see a review in Kim et al. 2014). For the analysis of the energy inputs of agricultural systems, we consider more appropriate to use the GE, as it reflects total energy contained in the input. In addition, agricultural energy outputs are almost always expressed as gross energy values, as we did in our review of the energy content of biomass products and residues (Guzmán et al. 2014). Hence, we have also employed gross energy (GE) values in our analysis of the embodied energy of agricultural inputs. On the other hand, we have not applied any quality correction factor to the heat value of the different fuels.

2.2 The energy embodied in agricultural inputs

Gutowski et al. (2013) made this definition of the embodied energy of materials: "The energy intensity (or embodied energy) is defined as the energy required to produce a material from its raw form, per unit mass of material produced. The energy is usually measured as the lower heating value of the primary fuels used plus any other primary energy contributions. These energy requirements are dominated by two main steps: (i) harvesting and (ii) refining."

In this work, we have broadly followed this definition, but utilizing higher heating values (gross energy) instead of lower heating values (see Section 2.3) and extending system boundaries up to the farm gate, in the case of manufactured inputs. This means that the steps considered in agricultural inputs production are, like in Gutowski definition, (i) harvesting (or extracting) and (ii) refining, but we also include (iii) manufacturing (in the case of manufactured products such as fertilizers or machinery), (iv) transport to the farm and (v) maintenance (in the case of capital goods).

Some considerations have been made about the use of the embodied energy concept in energy analyses. The EROI concept is a metrics of the net energy analysis (NEA) that refers to the energy return on investment. As was made clear by a debate in the journal Energy between Raugei (2013) and Raugei et al. (2015) and Weissbach et al. (2013, 2014), the definition of the “energy invested” in an EROI refers exclusively to societal uses of energy, and therefore excludes the energy of the feedstocks employed within an energy production process (for example, the energy in coal itself in coal-based electricity production). Therefore, this “energy invested” can differ from the “cumulative energy demand” (CED), or “embodied energy” (also termed “physical energy content method” or “primary energy method” (Harmsen et al. 2011) and “gross energy requirements”, GER (Harmsen et al. 2013)), which is employed in life cycle assessments (LCA) to “describe the total primary energy that must be extracted from the environment in order to deliver a given product or support a given process” (Raugei et al. 2015).

In agricultural energy analyses this question is more clarified by the distinction between external and internal energy inputs. Recent harmonization efforts have helped to develop a robust methodological framework with defined boundaries between components (Tello et al. 2015). Different indexes have been proposed based on the relationship between those components, including the final EROI, external final EROI and internal final EROI (Tello et al. 2015). This proposal has been complemented in another work by more indicators based on an agroecological perspective (NPPact EROI, Agro-ecological Final EROI and others) (Guzmán and González de Molina, 2015). To our knowledge, energy analyses of agriculture compute the energy in external inputs roughly following our definition of embodied energy, even though the processes included within its boundaries are variable depending on study objectives and data availability.

2.3 System boundaries and data representativity

Which specific agricultural inputs are to be studied and what amount of energy is estimated to be embodied in these inputs depends on system boundaries, which in turn depend on study objective. As Murphy et al. (2011) put it, “Once the objectives have been outlined, choosing the appropriate boundaries for an EROI analysis depends largely on two factors: (1) what level of energy inputs are going to be considered in the analysis, and (2) the methods chosen to aggregate energy units”. Following this reasoning, in this work we do not aim to make recommendations about the system boundaries of the studies using this information, because these boundaries would depend on the unit of analysis and the study objectives. Therefore, the main aim of this working paper is to provide energy values for the production of agricultural inputs with historical criteria, and to disaggregate these values into their different components.

Sun energy is obviously the ultimate energy source of all agricultural systems, both directly in the form of solar radiation used by plants for photosynthesis, and indirectly embedded in fossil or renewable energy inputs. This input is included in *emergy* analyses, which actually measure the value of a flow or storage by calculating the solar energy (although other types of energy could also be used) required to replace them, through the concept of *transformity* (Odum, 1988). Other agricultural energy studies, such as Bulatkin (2012), also take into account solar energy. These studies are conducted from an ecological perspective and aim to make comparable the qualitatively different types of energies. However, solar energy, either in the form of direct solar radiation or in natural transformed forms such as wind or moving water, is excluded from most agricultural energy analyses, as it is not considered a societal type of energy. Instead, it is considered as a given energy flux which is present whether used or not (although this assumption might be questionable, see De Castro et al. 2011), and does not have an opportunity cost in the economic sense. Only when it is harnessed and transformed into forms of energy used by society (such as biomass, electricity, mechanical power or heat) solar energy would enter into system boundaries in most studies.

Some inputs and processes are included within system boundaries in practically all energy assessments of cropping systems. For example, the energy directly consumed in the production of mineral NPK fertilizers, or the energy content of farm fuels. In other cases, such as the energy used for producing fuels, machinery and infrastructure, the variability is significant, and the choice of the system boundaries would depend on the objectives and the analytic rigor of the assessment.

The inclusion of human labour as an input in energy analyses of agricultural systems remains an issue of debate (see Section 3). Here we do not provide specific recommendations on which method to apply, as we consider that this is a choice of the researcher performing the agricultural energy balance. Nonetheless, we have to specify that we have not included human labour in the assessment of the embodied energy of the other agricultural inputs. This choice is mainly justified by the inherent complexity and lack of background data for these calculations as compared to the relatively low contribution of human labour to the energy requirements of industrial products. It must be noted, however, that the application of some methodologies for human labour energy assessment suggests that this input might be of considerable importance even in modern industrial processes (Prieto and Hall, 2013).

A particular issue in the determination of system boundaries is transport of inputs to the farm. Some methods for its estimation have been developed (e.g. Pimentel, 1980, Audsley et al. 2003, ecoinvent Centre, 2007). This energy is systematically included in life cycle assessments (e.g. Audsley et al. 2003, Grönroos et al. 2006) and in some energy analyses (e.g. Pimentel and Burgess, 1980, Pimentel, 1992), but most studies only acknowledge the transport of part of the inputs, such as fuels, machinery or manure (e.g. Kaltsas et al. 2007, Dalgaard et al. 2001) or do not mention whether it is included or not. On the other hand, transport might be excluded from agricultural energy analyses when the unit of analysis has been the agroecosystem or the crop and the objective to calculate the energy return of different technological packages (e.g. Campos and Naredo, 1980, Guzmán and Alonso, 2008, Alonso and Guzmán, 2010). We have reviewed information on energy use in transport and included this process in the embodied energy of all inputs following the procedure described in Section 13.

Buildings, equipment and other infrastructure used in the farm and also those required to produce inputs are commonly neglected in the estimations of inputs energy requirements, although they are commonly included in LCA, as they are inventoried in LCI databases such as ecoinvent (Althaus and Classen, 2007). These factors may amount from nearly zero to about 10% of total energy requirements of industrial products (Althaus et al. 2005). In this work, we have reviewed the contribution of buildings to the embodied energy of farm inputs when this information was available. We have also reviewed the embodied energy of buildings used in agriculture in Section 11.1.

Non-material services such as advertising, insurance and financial services also have an energy cost (Crawford, 2009). These services, as well as other non-material services such as governance and security services, are required for the production of all industrial inputs. Including these services in the estimation of the embodied energy of agricultural inputs, however, is beyond the scope of this work, which is based on a process analysis and thus focuses only on material components of the production chain. Therefore, the total embodied energy values provided in this paper should be considered conservative, as they do not include a significant fraction of the energy required to produce non-material services and also human labour. In any case, we do provide a short discussion for the estimation of the energy in non-material inputs (either in the embodied energy of industrial inputs to agriculture, or as agricultural inputs themselves) using hybrid methodologies based on input-output databases (Section 14).

The geographical representativity of the data is a particularly important point given the significant differences in energy efficiency between world regions that can be observed for many processes. When possible, we provide dynamic, world averaged coefficients. This was not always possible, and in those cases the estimations are based on a single country or region accounting for a significant share of world production (usually USA or Europe). Likewise, the estimation of dynamic factors was neither possible in some cases, so that fixed factors had to be used instead. In some cases we provide information of differences in energy efficiency between world regions for a single recent time point or for various time points.

2.4 Estimation of Non-Renewable Energy

We have estimated the share represented by NRE for all items and time periods studied. Specific information on NRE use was not available in many occasions. In those cases, we just took into account the relative share of NRE in world primary energy consumption. The reconstruction of long-term series of world primary energy consumption by source has been attempted in few occasions, usually including very gross assumptions particularly for the estimation of biomass energy. We have taken the data from Koppelaar (2012), who compiled some of the available series (e.g. Fernandes et al. 2007, Krausmann et al., 2009, Smil, 2010, BP, 2011), and constructed a unique long-term series of world primary energy consumption by source. The resulting estimation of the relative share of NRE in global primary energy production is given in Table 2.1. We also estimated the relative share of NRE in world electricity production and applied this coefficient to electricity use (Table 2.1. See Section 4.3 for details).

Table 2.1 Relative share of non-renewable energy in world primary energy production and world electricity production, 1900-2010 (%). Own elaboration from various sources (see text in this section and Section 4.3)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Primary energy	47%	56%	61%	62%	64%	70%	77%	83%	85%	86%	86%	86%
Electricity				99%	98%	95%	91%	88%	89%	91%	92%	91%

3. Human labour

The assessment of the energy embodied in human labour is highly controversial and varies widely depending on system boundaries and researchers criteria. The methods for accounting for the energy in human labour have been subject to debate along the history of agricultural energy analysis, and we are still far from a consensus (Rugani et al., 2012). The debate reaches metaphysical levels (Jones, 1989) and has been regarded as the continuation of a theological controversy (Stanhill, 1984). Herein we describe, largely following and continuing the review in Fluck (1992b), some ways in which human labour is accounted for in agricultural energy analyses, from its simple exclusion from system boundaries to various ways of quantifying the metabolic and exosomatic energy requirements. Here we will review these methods in a hieralchical way, from narrower (being the narrowest exclusion of this input) to broader system limits.

Many studies **exclude human labour** of agricultural energy assessments, particularly in industrialized systems. Some authors suggest that this input would only be important in traditional or developing agricultures (Stanhill, 1984, Cleveland, 1995). Others say that in industrial societies people would consume energy regardless of being in employment (Casper et al. 1975). Other authors reject to allocate an energy expenditure to agriculture arguing a lack of methodological consensus in the literature (Leach, 1976). The assessment of cumulative energy demand and other environmental impact indicators in modern internationally harmonized LCA methodology also excludes human labour from production system boundaries, despite not a clear explanation is provided for this choice (Rugani, 2012). The exclusion of human labour energy has been criticized by Jones (1989), who argues that a zero energy cost for labour would not explain the substitution of labour inputs by other inputs that take place in the industrialization process.

Some authors employ the **muscular power output** of human labour (e.g. Rappaport, 1971, Bayliss-Smith, 1982), which would represent the "direct energy input" in our terminology, and has also been termed "applied power" (Giampietro and Pimentel, 1990). This energy was estimated to represent 0.3-1.3 MJ/h in a range of agricultural tasks in a tribe of New Guinea, and 0.8 MJ/h for the average agricultural worker in a variety of examples of agricultural systems around the world (Bayliss-Smith, 1982). An accepted average value is 0.27 MJ/h (75 W) (Pimentel and Pimentel, 1979, Giampietro and Pimentel, 1990). Power output is on average 30% less for women (Giampietro and Pimentel, 1990). These authors estimate of 0.32 and 0.22 MJ/h (90 and 60 W) for men and women, and an average of 1:1 Male:female ratio in the population.

Probably the majority of agricultural energy analyses estimate the energy in human labour as the **dietary energy consumption**, this is, the metabolic requirements or the energy content of the food consumed by the workers. Direct dietary energy consumption may range between 0.35 and 0.61 MJ/h, for diets of 2000 and 3500 kcal/day, respectively. Krausmann and Haberl (2002) estimated that this energy increased from 0.42 to 0.52 MJ/h in the Austrian population during the period 1830-1995. However, we still have to decide how much dietary energy we allocate to an agricultural working hour. Fluck (1992b) identifies 3 methods for assessing the dietary energy of a working hour: as the **partial energy consumed from metabolized food during work**, excluding basal energy consumption; as the total **food energy metabolized during work**; or as the **total dietary energy consumed** by workers (during working days or the whole week). The average values obtained converting Fluck's daily values to labour hours (assuming an 8-hour day) are 0.6, 0.8 and 1.6 MJ/h, respectively. Cussó et al. (2006) propose a value of 3.6 MJ/working day, which translates into 0.45 MJ/h with an 8-hour working day, and was estimated using the total metabolized energy during work. Pimentel and Pimentel (1979) provide a value of 91 MJ/week for the average total dietary energy intake of agricultural workers, which translates into 2.3 MJ/h for a 40-hours week. The lower value in Fluck (1992b) seems to be due to the fact that he only computes working days in this metric. A similar value of 2.2 MJ/h, based in the data offered by Fluck (1992b), has been widely used in the literature (e.g. Kaltsas et al. 2006, Guzmán and Alonso, 2008, Alonso and Guzmán, 2010).

A further step, which would still fit within our definition of "embodied energy" is to take into account the **energy required to produce the food consumed by the labour**. This indirect energy input of the human diet would depend on the energy efficiency of the food production system, from agriculture to the consumption stage. The food production energy efficiency has been estimated to be 7.3 energy units consumed per dietary unit energy in the modern US agri-food system (Heller and Keoleian, 2003). A similar value of 7.4:1 has been estimated by Infante-Amate and González de Molina (2013) for the Spanish agri-food system. This might raise the energy allocated to agricultural labour to about 16 MJ/h. This approach has been rejected because of the lack of justification of including only the embodied energy of food and not of the other inputs used by labour (Fluck, 1992b), but the same reasoning could be applied to the other methods reviewed above. On the other hand, a problem of circular reference or double counting may arise with this method, as the product (food) is used as an (important) input of the system.

The **marginal substitution ratio** (Fluck, 1992b), also called marginal energy requirement of employment (Jones, 1989), is not a measure of the energy embodied in the processes that support labour, and therefore it will only be mentioned here for reviewing purposes. According to de Wit (1975), it represents the additional energy produced by the agricultural system per each hour of added labour at a given yield and technological level, and is calculated using iso-yield functions. Stanhill (1984) described it as the ratio of increasing fuel used to decreased labour used over time. This approach has rarely been followed in the literature.

Finally, the widest system boundary would be to consider the **energy required for supporting the lifestyle pattern of the worker**, and in some cases also of his family or the people who depend upon him (male workers are usually assumed). This value would therefore be dependent of the energy consumption level of the society and of the worker. Different approaches have estimated this energy considering different boundaries. A restricted variation is the farm family support energy, which has been estimated in 89.3 MJ/h in the US, apparently only taking into account direct and indirect dietary energy (Fluck, 1992b). Emergy analyses are in line with the lifestyle pattern approach, by estimating the incorporated solar energy (transformity) of human labour differentiated by knowledge levels, for example according to the level of education (Odum, 1988). Others have proposed the energy intensity of the economy as a way to assess labour energy based on its monetary cost, a method that yielded an energy equivalent of 181.3 MJ/h in the US in 1983 (Odum, 1983, in Fluck, 1992b). In a similar approach, other works have extended labour energy to the whole per capita energy use in society (Giampietro and Pimentel, 1990), obtaining an energy cost of 151-250 MJ/h depending whether energy expenditures of dependent workers are taken into account.

The lifestyle support energy approach has been criticized for double counting energy production inputs. Constanza (1980) proposed an input-output based method to avoid double counting by changing system boundaries to include embodied energy of labour in inputs and exclude the support of labour in outputs, which is considered an internal transaction. Another approach based in a similar reasoning has been recently proposed to estimate labour energy based on household consumption (Rugani, 2012). This author proposes the use of input-output tables to account for human labour in LCA, which is done by combining information on households expenditures gathered from the abundant published statistics with the environmentally extended input-output databases implemented in modern LCA software.

Another approach that maintains the philosophy of the lifestyle support energy methods but also tries to avoid double counting is the **net energy analysis** (Fluck, 1981, 1992b). In this method, it is assumed that a proportion of the GNP and its associated energy is reinvested in the economy to support labour, and another proportion is employed in different final uses (Figure 3.1). Fluck (1981) provides a value of 74.3 MJ/h for agricultural labour in the USA in 1973, and estimates that this value might range between 12.5 and 125 MJ/h depending on the consumption level of the society.

The reviewed methods for the estimation of the embodied energy of human labour are visually compared in Figure 3.2.

Figure 3.1. Net energy analysis of labour energy. Source: Fluck (1992b)

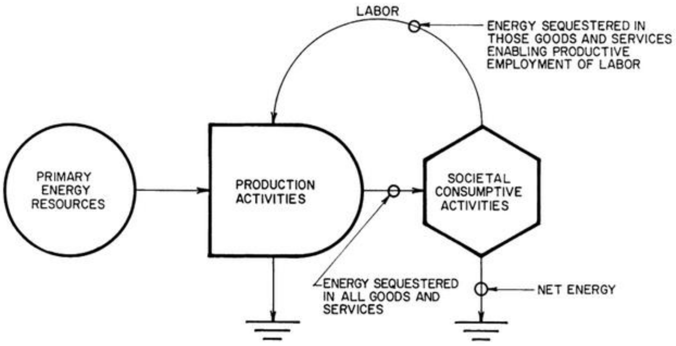
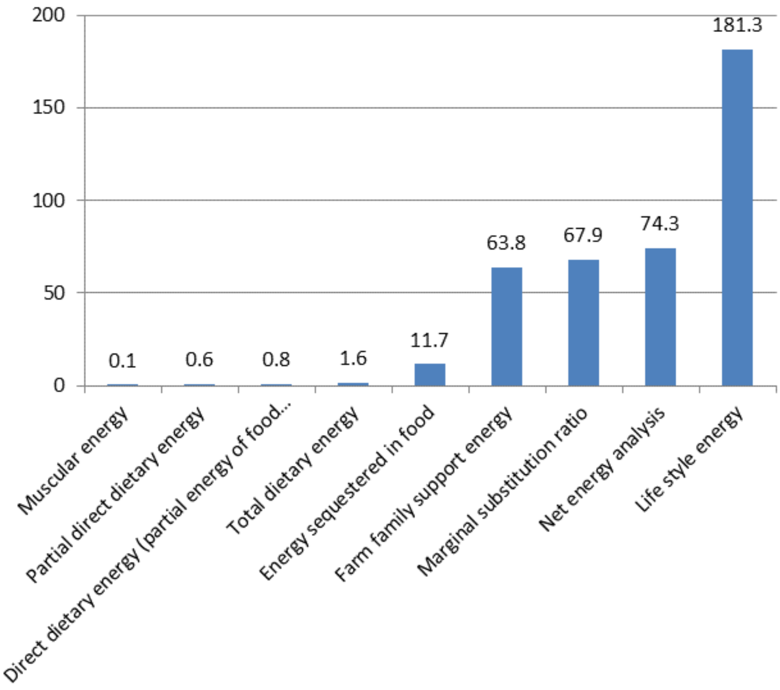
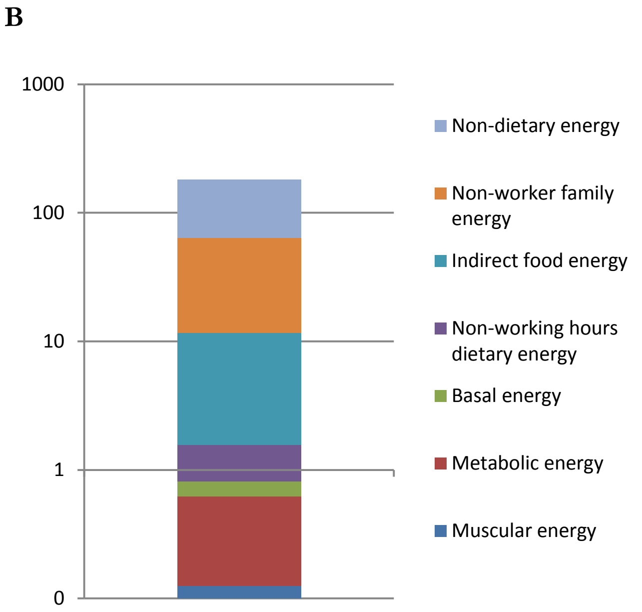


Figure 3.2. Typical values obtained by each method of human labour energy assessment as reported by Fluck (1992b) (A). An ideal composition of the energy expenditure of a working hour, depending on where the boundaries are set, is shown in panel B. All data is expressed in MJ/h. Note the log scale.

A





In conclusion, there is a wide disparity of criteria to account for human labour, which yield values that might differ in two orders of magnitude. In spite of this, it seems clear that this input has to be included in the energy analysis of traditional agricultures, where it usually represents a large share of total inputs, even if only the metabolic requirements of human labour are accounted for. In industrial agricultures, the metabolic requirements are usually insignificant compared with other inputs, but the energy in human labour could be relevant if all the energy required to support it is accounted for. This task, however, has proved to be challenging. The total energy content of all consumed food is a generally accepted criterion, although it fails to account for the energy sequestered in labour support in industrial societies. The consideration human being as an end in itself (Kant), which is not "produced" as a commodity for economic purposes, could be an acceptable criterion for differentiating human labour from other inputs, even if, as pointed out by Jones (1989), neglecting the energy needed to support human labour makes us to fail to explain many historical processes such as the search for increases in labour productivity. Thus, human labour represents the clear example of the importance of the definition of system boundaries in line with the study objective.

4. Fuels and electricity

Fossil fuels are widely used as the main direct energy source in mechanized agriculture. But they are also employed in the production of all other industrial inputs, including fertilizers and pesticides, and also electricity. Therefore, knowing their energy content and the energy required for their production is essential to model the energy balance of an industrialized agricultural system. From a historical perspective, there have been large changes in the EROIs of fossil fuels (and therefore in their energy requirements) and in the efficiency of electricity power generation.

4.1 Direct energy of fuels

Direct energy use in fuel and electricity consumption refers to the fairly constant and well-defined gross energy (GE) content of fuels and to the consumption of electricity, which is always expressed in energy units. Therefore, this factor does not need to be subject to a very wide review. The most significant source of variability between the values found in the literature is the choice of the lower (NE) or higher heating value (GE) of fuels. As explained in section 2.3, we have chosen the GE of fuels. In the case of coal and natural gas, the quality of fuels can significantly influence their GE and also their density.

Some widely used energy values for fuels are those provided by Cervinka (1980) and those provided by Audsley et al. (2003). Instead, we have preferentially taken most values from the energy statistics manual of the IEA (2004), as they represent the current international standard (Table 4.1). In the case of natural gas and coal, we have used ecoinvent (Frischknecht et al. 2007b) and Audsley et al. (2003) because IEA only provides ranges, and the values in those widely used references are within those ranges.

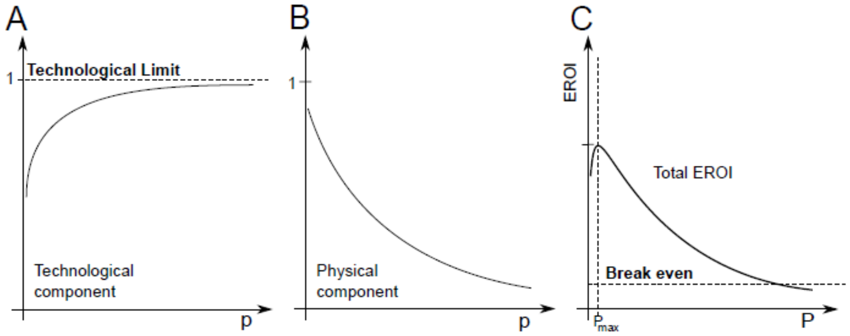
Table 4.1. Density and gross energy (higher heating value) of fossil fuels selected in this work. Sources: IEA (2004) for all data except coal (Audsley et al. 2003) and natural gas (Frischknecht et al., 2007b). Distillates are estimated as the average of fuel oil and diesel.

	Density	**Higher heating value**	
	g/l	**MJ gross energy/kg**	**MJ gross energy/l**
Fuel oil, kerosene	802.6	46.2	37.1
Gasoline	740.7	47.1	34.9
Diesel	843.9	45.7	38.5
Naphta	690.6	47.7	33.0
Distillates	823.3	45.9	37.8
LPG	522.2	50.1	26.2
Natural gas (m^3)	799.6	50.4	40.0
Average liquids	795.7	46.3	36.9
Coal		22.4	

4.2 Indirect energy of fuels

Indirect energy use in fuel production refers to the energy invested in extracting the resource, transporting and transforming the resource into a commercial fuel (refining) and distributing the fuel. These components of the energy budget vary widely around the world and along history, depending on the type of fuel, the type of reserves exploited, the technology for extraction and refining or the geographical situation of the final consumer in relation to the production site. Typically, the EROIs of energy resources tend to increase in the early phases of their historical extraction developments due to technological improvements (learning curves). In a latter phase, the EROI peaks and start to decline due to the depletion of the most accessible resources (Dale et al. 2011, Fig 4.1).

Figure 4.1. Theoretical evolution of the EROI of an energy resource as a function of cumulative production. Source: Dale et al. 2011

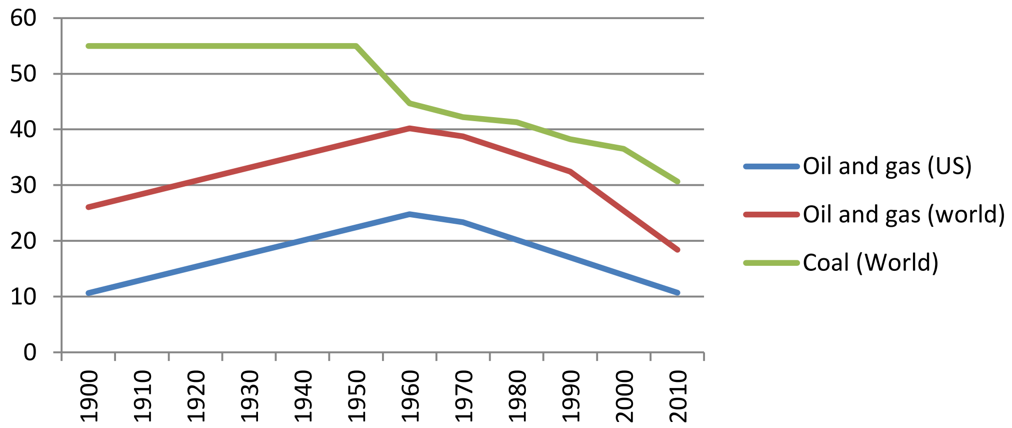


We have estimated the evolution of the EROI of world oil and gas production based on the data by Hall et al. (2014). Long-term evolution of EROI data is only available for the US (Guilford et al. 2011). World data is only available for the 1990-2010 period. In order to estimate a long-term world series, we have used the world trend from Hall et al. (2014) for the 1990-2010 period and assumed that the relationship between world EROI and US EROI is maintained for previous periods (Figure 4.2A). The corresponding energy requirements of gas and oil extraction are shown in Figure 4.2B.

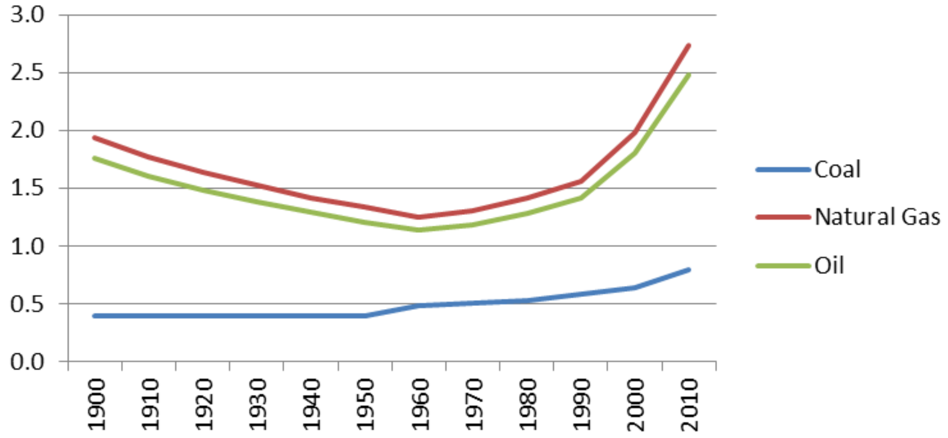
Historical information on coal production energy is scarce in the literature. Hall et al. (2014) provide some data for the US and China, which are highly variable in the case of US and very limited in time in the case of China. Average values are 55:1 and 23:1, respectively. Both countries are the largest coal producers in the studied period, the US up to 1980 and China afterwards. We have simulated the evolution of the EROI and energy requirements (Figure 4.2) of world coal production based on the relative share of US and China in total production, assuming that the mentioned values are maintained constant during all the period.

Figure 4.2. Historical evolution of (A) the EROI of fossil fuels (MJ/MJ) and (B) the energy requirements to produce (extraction) the main raw fossil fuels (MJ/kg), 1900-2010. Source: Own estimation based on Hall et al. (2014) (see text).

A



B



After extraction, oil has to be refined and distributed before being used in farm machinery. Refining oil to commercial fuels such as gasoline and diesel has an energy efficiency of 83-94% in the US, depending on the product and if the less desirable products are excluded or included (Wang, 2008). There exist opposite historical trends in refining energy requirements: on one side, efficiency gains due to technological improvements; on the other, the fact that much of the new oil production is heavy oil with a higher sulfur content and therefore requires more energy to refine (Bredeson et al. 2010, Karras, 2010). In fact, about 70% of the remaining oil reserves are heavy oil, tar sands or bitumens (Alboudwarej et al. 2006). CO_2 emissions from refining heavy oil and bitumen could be as much as 2-3 times the current refining average, a difference mainly driven by higher energy requirements (Karras, 2010). In addition, environmental and health regulations such as low sulfur content in diesel and gasoline are imposing higher refining costs (Guseo, 2011). Therefore, the refining energy cost is probably increasing in the last years, and will probably increase more as the share of heavy oil in world production grows (Hirshfeld and Kolb, 2012). Refining energy consumption data for oil-derived fuels in year 2006 have been taken from Wang (2008). These values have been modulated to take into account the increase in the share of unconventional oils from 1990 to 2010. We assumed that unconventional oil requires 2.5 more energy to refine than conventional oil, based on Karras (2010). The relative shares of the two types of oil were taken from IEA's World Energy Outlook (IEA, 2012, 2014).

For coal processing energy, we have assumed a fixed consumption of 6.5 kWh electricity/Mg coal during the whole study period based on data around year 2000 from ecoinvent (ecoinvent Centre, 2007), assuming that 90% of coal is hard coal and 10% is lignite. The results of these calculations indicate that 0.1, 4.1, 8.3 and 6.5 MJ/kg are consumed for processing or refining coal, fuel oil, gasoline and diesel, respectively.

For the estimation of transport emissions we have assumed a conservative average distance of 5000 km water transport and 500 km pipeline transport for oil, and 1000 km water and 200 km rail for coal around year 2000, based on the average of the country-specific values in ecoinvent (ecoinvent Centre, 2007). In the case of coal, we assumed a constant transport distance during the whole period (Table 4.2), which is in line with the constant and relatively low share of coal transported internationally along the whole period (Podobnik, 2006, Figure 4.3). In the case of oil, we have modified these values using as a proxy the share of crude oil traded internationally (Table 4.2). We have constructed the series shown in Figure 4.3 using UN (1952) data from 1929 to 1950 and BP (2014) data from 1970 to 2010. We estimated 1940 and 1960 data as the average of the values of the previous and former time steps. Furthermore, we assumed that the share of oil traded internationally in the period 1900-1920 was constant and similar to the value in 1930 (UN, 1952) (8%), which is in line with the average for that period in the USA (EIA, 2015a), which was the major oil producer and consumer at that time. For the construction of the long-term time series of natural gas distribution energy we have used European data (ecoinvent Centre, 2007) for around year 2000 as a reference value, modifying it with the share of internationally traded natural gas (BP, 2014, Figure 4.3) as an indicator of the changes in distribution energy requirements.

Figure 4.3. Share of world fossil fuel consumption traded internationally, 1900-2010 (%). Sources: Coal: Podobnik (2006); Oil: own elaboration from UN (1952) and BP (2014) (see text); Natural gas: BP (2014) since 1965, own estimation for previous dates.

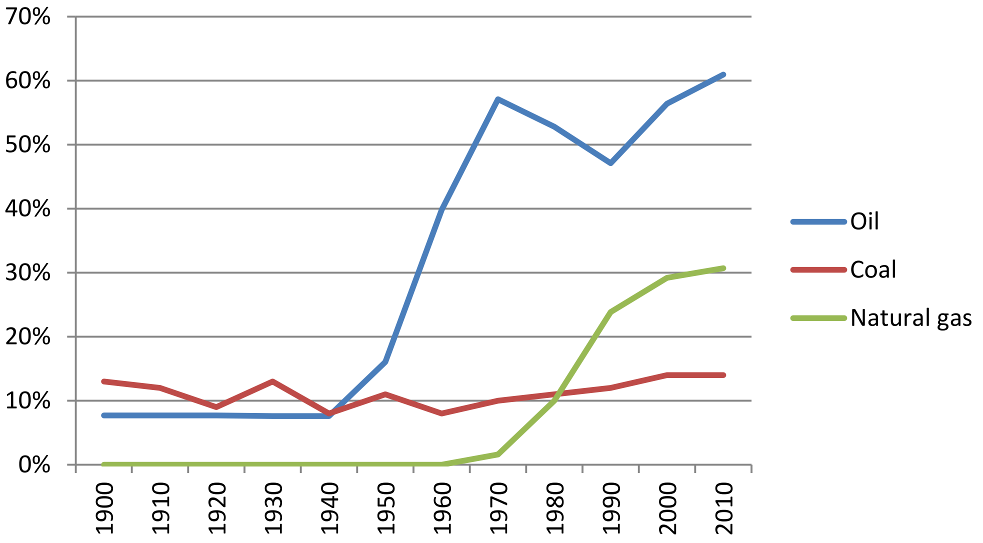


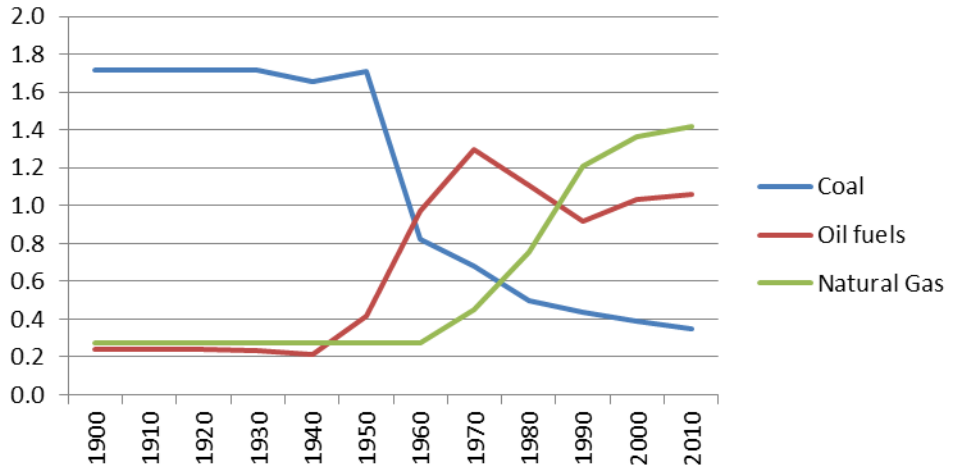
Table 4.2. Historical evolution of crude oil and coal transport distances assumed in this work (km), 1900-2010

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Crude oil												

Pipe	68	68	68	67	67	142	353	506	468	418	500	540
Sea (Tanker)	681	681	681	672	672	1,420	3,529	5,061	4,679	4,175	5,000	5,403
Coal												
Sea (container)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Rail	200	200	200	200	200	200	200	200	200	200	200	200

We have multiplied the values shown in Table 4.2 by our estimates of the embodied energy of transport modes calculated in Section 13, resulting in the values shown in Figure 4.4. It is worth noting that our world average values may substantially differ from specific values of each country and for each given period, but fine tuning these values would require a more detailed study.

Figure 4.4. Long-term evolution of the transport energy of the major raw fossil fuels, 1900-2010 (MJ/kg fuel). Source: own estimation (see text). Note that the transport energy of fuel oil, gasoline and diesel are the same.



The resulting total energy requirements values, including resource extraction, raw resource transport, refinery or processing energy and distribution of oil products to the farm (Section 13), are shown in Table 4.3.

Table 4.3. Historical evolution of total energy requirements for the production of the major fossil fuels (MJ/kg fuel), 1900-2010. The values include resource extraction, raw resource transport, refining or processing and distribution of refined oil products up to the farm. Source: own elaboration (see text)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Coal	2.2	2.2	2.2	2.2	2.1	2.2	1.4	1.3	1.1	1.1	1.1	1.2
Fuel oil	7.2	7.1	6.9	6.8	6.7	6.8	7.3	7.7	7.3	7.3	7.8	8.7
Gasoline	11.3	11.2	11.1	10.9	10.8	11.0	11.4	11.8	11.5	11.4	12.1	13.1
Diesel	9.5	9.4	9.3	9.1	9.0	9.2	9.7	10.0	9.7	9.6	10.2	11.1
Natural Gas	2.2	2.0	1.9	1.8	1.7	1.6	1.5	1.8	2.2	2.8	3.3	4.2

It was assumed that the share of non-renewable energy (NRE) in the production of fossil fuels was similar to ecoinvent (ecoinvent Centre, 2007) averaged values in years 2000 and 2010. For previous years, we took into account the changes in the relative share of non-renewable energy in total world primary energy production (Section 2.3). Total NRE use for the production of major fossil fuels is given in Table 4.4.

Table 4.4. Historical evolution of the total NRE requirements of the major fossil fuels (MJ/kg fuel). The values include resource extraction, refining or processing and distribution. Source: own elaboration (see text)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Coal	2.0	2.0	2.1	2.1	2.0	1.9	1.2	1.1	1.0	1.0	1.0	1.1
Fuel oil	5.4	5.5	5.5	5.4	5.3	5.7	6.7	7.3	7.1	6.9	7.6	8.4
Gasoline	9.5	9.6	9.6	9.5	9.4	9.8	10.8	11.4	11.2	11.1	11.8	12.8
Diesel	7.7	7.8	7.8	7.7	7.7	8.0	9.0	9.6	9.4	9.3	9.9	10.9
Natural Gas	2.2	2.0	1.9	1.8	1.7	1.6	1.5	1.6	1.7	1.8	3.3	3.0

We also present the results expressed per MJ of gross energy in the fuel (Table 4.5). In this case, we also include other energy carriers such as biomass and energy sources used in electricity production (nuclear, hydro, renewables including solar and wind). In the case of biomass, we have assumed a constant EROI of 10 for the whole period. In the cases of the energy sources used in electricity production, the calculations of their production energy are explained in the Electricity section (Section 4.3). In Table 4.5 we also include the weighted average of all fuels considered. To calculate this average, it is necessary to know the relative contribution of each energy source to world primary energy demand. In this case, again, we have used the data in Koppelaar (2012).

Table 4.5. Historical evolution of the total energy requirements for the production, refining and transport of the major fossil fuels and energy sources (MJ/MJ direct), 1900-2010. The values include resource extraction, refining or processing and distribution. Source: own elaboration (see text in this section and Section 4.3)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Fuel oil	0.16	0.15	0.15	0.15	0.15	0.15	0.16	0.17	0.16	0.16	0.17	0.19
Gasoline	0.24	0.24	0.23	0.23	0.23	0.23	0.24	0.25	0.24	0.24	0.26	0.28
Diesel	0.21	0.21	0.20	0.20	0.20	0.20	0.21	0.22	0.21	0.21	0.22	0.24
Oil fuels	0.20	0.20	0.20	0.19	0.19	0.19	0.20	0.21	0.20	0.20	0.22	0.24
Coal	0.10	0.10	0.10	0.10	0.10	0.10	0.06	0.06	0.05	0.05	0.05	0.05
Natural Gas	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.05	0.07	0.08
Nuclear							0.20	0.20	0.20	0.20	0.20	0.20
Hydro	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Biomass	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Renewable electricity								0.06	0.06	0.06	0.06	0.06
Weighted average	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13

Last, we have calculated total embodied energy in fossil fuels as the sum of their inherent energy (gross energy content) and their total energy requirements (Tables 4.6 and 4.7).

Table 4.6. Historical evolution of total embodied energy in fossil fuels (MJ/kg), 1900-2010. Source: own estimation (see text).

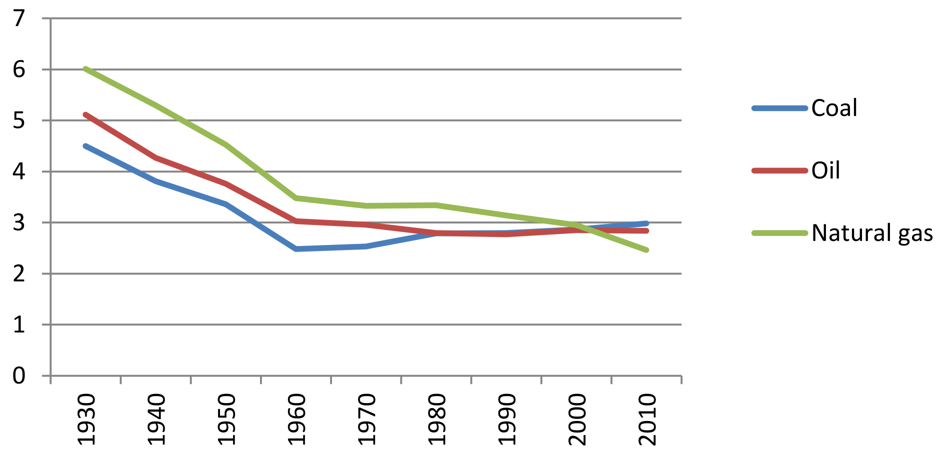
	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Coal	24.6	24.6	24.6	24.6	24.5	24.6	23.8	23.7	23.5	23.5	23.5	23.6
Fuel oil	53.4	53.3	53.1	53.0	52.9	53.0	53.5	53.9	53.5	53.5	54.0	54.9
Gasoline	58.4	58.3	58.2	58.0	57.9	58.1	58.5	58.9	58.6	58.5	59.2	60.2
Diesel	55.2	55.1	55.0	54.8	54.7	54.9	55.4	55.7	55.4	55.3	55.9	56.8
Natural Gas	52.6	52.4	52.3	52.2	52.1	52.0	51.9	52.2	52.6	53.2	53.7	54.6

4.3 Electricity

Electricity is a high-quality energy carrier with versatile applications, from the production of heat to the provision of power for electronic appliances. The efficiency of electricity usage varies widely depending on the type of use and its technological status (Ayres et al. 2005). However, we will not review here the factors involved in the efficiency of electricity use because the consumption of electricity is usually already provided in primary information sources as energy units (1 Kwh=3.6 MJ), and therefore we have the direct energy consumption of electricity without further calculations.

The energy intensity or energy embodied in electricity refers to the amount of energy consumed to produce and deliver electricity, including fuel energy and the energy required to produce the fuels and the facilities employed in electricity production, as well as the grid losses and the maintenance of the grid infrastructure until the electricity reaches the final consumer. The energy embodied in electricity generation depends on the power generation efficiency and on the energy embodied in the fuel employed. The first parameter varies depending on the fuel and the technology employed. It has improved during the 20th century (Dahmus, 2014) and is still improving in many parts of the world (IEA, 2013). Dahmus (2014) estimated the changes in the efficiency of US electricity production with the three major fossil fuels. These data are shown in Figure 4.5 converted to energy units using the coefficients of energy content of fuels from Section 4.1.

Figure 4.5. Historical evolution of the direct energy requirements for electricity production with fossil fuels, 1930-2010 (MJ/MJ). Source: own elaboration using data from Dahmus (2014) (see text)



The figure shows a clear downward trend in the energy required to produce electricity with the three fossil fuels in the period 1930-1960. For the rest of the period, efficiency gains only continue in electricity production from natural gas. In the case of coal there is even an increase in fuel consumption, probably related to higher air quality standards, which require removal of pollutants such as sulfur.

We have estimated total energy requirements of electricity production for each energy source. We have used the data shown in Figure 4.5 for direct energy requirements of electricity production with fossil fuels and EIA (2014) values for direct energy requirements of nuclear-based electricity. Indirect energy consumption was calculated using the fuel production energy values estimated in Section 4.2 in the case of oil, coal and natural gas, and data from different sources in the case of hydro, nuclear, solar and wind. Indirect energy use in nuclear energy production was assumed to represent 0.2 MJ/MJ electricity during the whole study period. This value is based on a meta-analysis of worldwide studies (Lenzen, 2008) and includes uranium mining, enrichment, fuel fabrication, reactor construction, reactor operation, decommissioning, fuel re-processing, nuclear waste storage, nuclear waste disposal and transport. Wind+Solar category was estimated assuming a mix of 90% wind and 10% solar. The embodied energy values of renewable energy sources (hydro, wind and solar) were taken from Asdrubali et al. (2015), who performed a meta-analysis and harmonization of published LCA data. Selected hydroelectricity embodied energy value, of 0.05 MJ/MJ electricity, is lower than the data reported by Ecoinvent (ecoinvent Centre, 2007) but higher than those reported by Rule et al. (2009). The value for wind energy, of 0.05 MJ/MJ electricity (Asdrubali et al. 2015), is lower than European data in ecoinvent (ecoinvent Centre, 2007), but higher than values in studies performed in China (Yang and Chen, 2013) and New Zealand (Rule et al. 2009), and similar to the value in a more comprehensive Australian study (Crawford, 2009). The energy embodied in solar energy production was assumed to be 0.17 MJ/MJ electricity, which is the harmonized average value for photovoltaics in Asdrubali et al. (2015). This value is similar or higher than those published in other reviews (e.g. Raugei et al. 2012, Peng et al. 2013, Bhandari et al. 2015), but much lower than other estimations, such as Ecoinvent European average (ecoinvent Centre, 2007) or a comprehensive study in well-irradiated Spain by Prieto and Hall (2013). The selected values are shown in Table 4.7, while Table 4.8 shows non-renewable energy requirements. We have assumed that all cumulative energy demand of fossil fuels is non-renewable.

Table 4.7. Historical evolution of total embodied energy of electricity production with different energy sources, at power plant gate (MJ/MJ electricity), 1930-2010. The values include the energy of electricity. Own elaboration from various sources (see text).

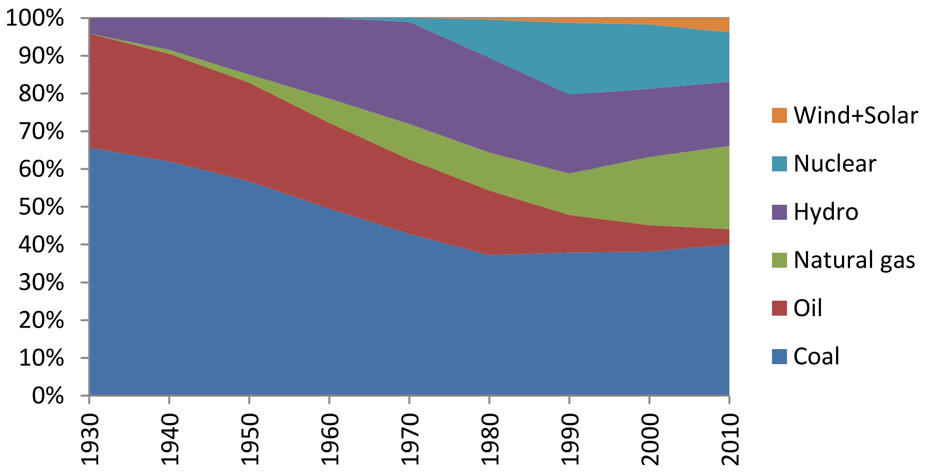
	1930	1940	1950	1960	1970	1980	1990	2000	2010
Coal	4.95	4.18	3.68	2.63	2.67	2.92	2.93	3.00	3.14
Oil	5.74	4.78	4.23	3.43	3.38	3.19	3.16	3.28	3.32
Natural gas	6.22	5.47	4.67	3.58	3.45	3.49	3.31	3.15	2.66
Nuclear				3.26	3.26	3.26	3.26	3.26	3.26
Hydro	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Solar					1.17	1.17	1.17	1.17	1.17
Wind					1.05	1.05	1.05	1.05	1.05
Wind+Solar					1.06	1.06	1.06	1.06	1.06

Table 4.8. Historical evolution of non-renewable energy use in electricity production with different energy sources, at power plant gate (MJ NRE/MJ electricity), 1930-2010. Own elaboration from various sources (see text).

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Coal	4.92	4.15	3.65	2.61	2.66	2.91	2.92	2.99	3.13
Oil	5.61	4.67	4.15	3.40	3.36	3.18	3.14	3.27	3.31
Natural gas	6.22	5.47	4.67	3.58	3.43	3.45	3.26	3.15	2.61
Nuclear				3.24	3.25	3.26	3.26	3.26	3.26
Hydro	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Solar					0.12	0.12	0.12	0.12	0.12
Wind					0.02	0.02	0.02	0.02	0.02
Wind+Solar					0.03	0.03	0.03	0.03	0.03

Figure 4.6 shows the relative contribution of the major energy sources to world electricity production. The data from 1980 onwards is taken from IEA (2015). We did not find world electricity production data by sources previous to 1980. Therefore, we estimated the contribution of the different energy sources assuming that all hydro, renewables (wind and solar) and nuclear are electricity, and that the share of the other energy sources is similar to their relative share of primary energy demand, as reported by Koppelaar (2012). The relative contribution of oil and coal in electricity production was assumed to be constant.

Figure 4.6. Relative contribution of primary energy sources to global electricity production, 1930-2010. Sources: Own estimation based on final energy data from World Bank from 1980 onwards; own estimation for previous years (see text).



Using the information from Table 4.7 and the energy mix shown in Figure 4.6 we have reconstructed the world average embodied energy of electricity production from 1930 to 2010, expressed as MJ primary/MJ electricity. This data is shown in Figure 4.7 and Table 4.9. The uncertainty of the estimate is relatively high until 1980, given the uncertainty in the electricity energy mix.

Figure 4.7. Historical evolution of the total embodied energy in world average production of electricity by energy source, at power plant, 1930-2010 (MJ Primary/MJ electricity). Source: Own estimation (see text).

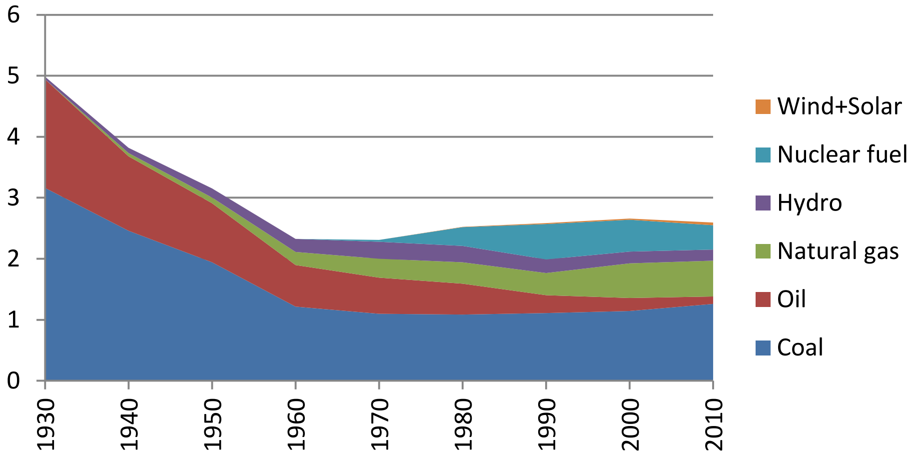


Table 4.9. Historical evolution of renewable and non-renewable energy (NRE) embodied in electricity, at power plant gate, 1930-2010 (MJ/MJ electricity). Sources: Own estimation (see text)

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Total NRE	4.8	3.8	3.1	2.2	2.1	2.3	2.4	2.5	2.4
Total Renewables	0.1	0.1	0.1	0.2	0.3	0.3	0.2	0.2	0.2
Total	4.9	3.9	3.2	2.4	2.4	2.6	2.6	2.7	2.6

Grid construction, maintenance and losses consume significant amounts of energy, particularly electricity. The electricity output has to be modulated to meet the demand, and this implies losses in storage or generation overcapacity. In addition, the voltage also has to be scaled to the demand, which implies that the high voltage output of large power generation facilities and long transmission lines has to be reduced to medium or low voltages depending on the final users. Each transformation requires high quantities of materials and implies energy losses. Grid electricity losses in the world averaged 8.3% in the 1960-2010 period, and they remained within a range of +-1% of that value during the period (IEA, 2015).

On the other hand, grid construction is heavily dependent of copper, which embodied energy is projected to increase in the coming years, as the richest ores are gradually depleted (Harmsen et al. 2013). These authors also point out that the intermittency of renewable energies will also impose an expanded grid network. Both trends, the increasing embodied energy of copper and the increased grid network, would ultimately increase gross energy requirements of world electricity use in the coming decades. Therefore, there is a need to take into account the characteristics of the electricity grid and its temporal changes in the estimation of the embodied energy of electricity. However, the reconstruction of the evolution of the energy embodied in grid construction and use in the different world regions is completely beyond the scope of this working paper on agricultural energy inputs. Instead, we provide a corrected series of electricity embodied energy at the point of use, based on the data in Table 4.9 and the value of 8.3% average losses provided by IEA (2015) (Table 4.10).

Table 4.10. Historical evolution of world average renewable and non-renewable energy embodied in electricity at the point of use (including production and grid losses), 1930-2010 (MJ/MJ electricity). Source: own estimation (see text).

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Total NRE	5.2	4.1	3.3	2.3	2.2	2.5	2.6	2.7	2.6
Total Renewables	0.1	0.1	0.2	0.2	0.3	0.3	0.2	0.2	0.2
Total	5.3	4.2	3.5	2.6	2.6	2.8	2.8	2.9	2.8

4.4 Heat

Heat is used in various applications in agriculture. Probably the most common ones are grain drying and heating of greenhouses and livestock buildings. Energy requirements of heat production include direct and indirect energy of the energy carriers used (fuels or electricity) and embodied energy of furnaces. The latter process could be considered negligible in energy analyses of agriculture.

Crop drying is usually necessary in cold and humid areas to achieve a proper humidity content for grain storage (approximately 14% wet basis). Direct energy use in grain drying depends mainly on initial water content of the grain and on the drying method. These methods usually include heating air to a given temperature and making this air circulate through the grain with fans. Therefore, electricity energy consumption in fan operation also has to be accounted for. Peart et al. (1980) calculated the energy requirements of drying corn from various initial water contents using high-temperature and low-temperature methods. We recommend using direct information to estimate energy consumption in crop drying in agricultural energy assessments. Otherwise, Peart et al. (1980) tables could be used for estimating this energy input.

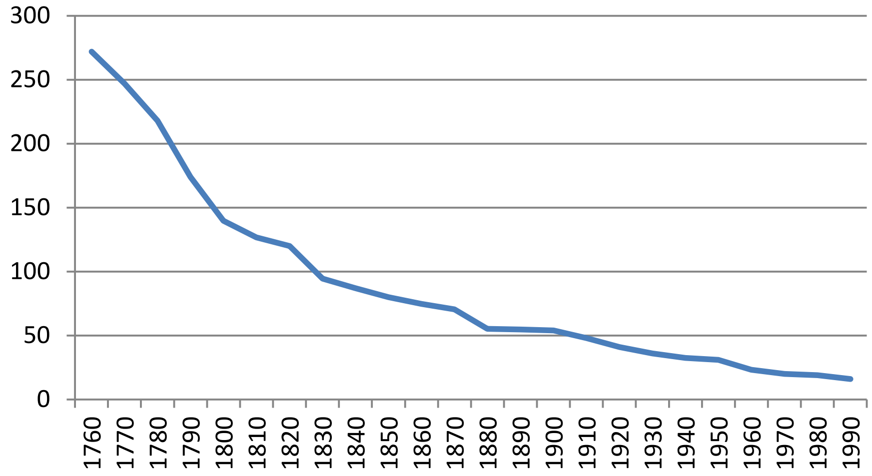
Heating of greenhouses and livestock buildings can consume very significant amounts of energy. For example, heating represented 97% and more than 60% of the total warming potential of glass greenhouse tomato cultivation in Britain and Austria, respectively (Williams et al. 2006, Theurl et al. 2013).

5. Raw materials

5.1 Metallic materials

Steel and other iron-based materials are the basic component of machinery, and their production is responsible for the majority of machinery production energy requirements. This material is also a major component of irrigation systems, greenhouse infrastructures and buildings. The energy efficiency of iron smelting has drastically increased in the last 250 years (Smil, 1999, IEA, 2007, Dahmus, 2014, Figure 5.1).

Figure 5.1. Historical evolution of the direct energy requirements of pig iron smelting, 1760-1990 (MJ/kg). Source: Smil, 1999

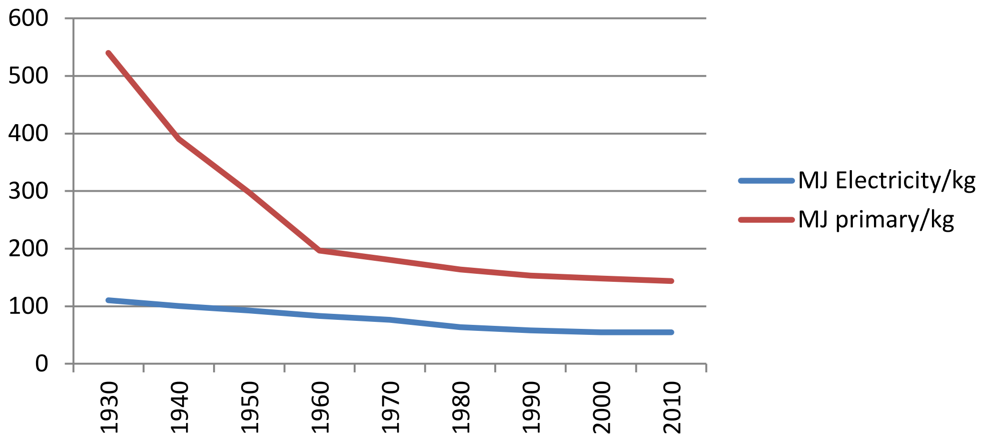


Since 1760 to 1990, the direct energy required to smelt pig iron decreased from 270 MJ/kg to 16 MJ/kg (Smil, 1999). In the period after 1990, despite energy efficiency of steel production was still improving in most countries, the world average efficiency did not improve much because the production shifted to more energy intensive countries such as China (31% of global steel production and 42% of global pig iron production in 2005). In addition, the growth in efficiency has slowed down in countries like Japan, where energy efficient technologies had deployed prior to 1990 (IEA, 2007).

Our estimations of the evolution of energy use in the production of ferrous metals are based on Smil (1999) data on direct energy use in pig iron production up to 1990 and IEA (2007) data on global trends from 1990 to 2010. This series is complemented with an estimation of indirect energy use based ecoinvent (ecoinvent Centre, 2007) data on additional energy requirements of ferrous metals production (excluding chromium steel), as compared to direct energy use in pig iron smelting. This additional energy also includes mineral extraction and beneficiation, fuel production and transport, buildings and other infrastructure, transport of intermediate materials and disposal of residues (Althaus and Classen, 2005). The change in the energy requirements of chromium steel production has been equaled to the change in those of pig iron.

A similar approach has been used for aluminium, using Dahmus (2014) and IEA (2007). The data in both sources is shown KWh/kg aluminium. We have converted them to primary energy consumption requirements (Figure 5.1) using our own estimate of electricity energy (Section 4.3). The results for the years 2000-2010 are similar to the value provided by ecoinvent (ecoinvent Centre, 2007).

Figure 5.2. Historical evolution of the direct and total energy requirements for aluminium production, 1930-2010. Sources: Direct electricity energy use from Dahmus (2014) and IEA (2007). Indirect energy based on own calculations (see text).



The energy requirements of the other metals, based in the data reported by ecoinvent (ecoinvent Centre, 2007) are presented in two categories: lead and an aggregated category calculated as the weighted average of the remaining metals, copper, zinc and brass. The decadal change in the energy efficiency of these categories is modeled as the mean of the change of pig iron and aluminium in each period (Table 5.1).

The energy required for the production of iron-based irrigation and greenhouse infrastructure components ("Steel (irrig.)" category in Table 5.1) was modeled assuming that these materials are made by 15% chromium steel and 85% regular steel. For the estimation of NRE, we assumed that all direct energy is from coal in all cases except aluminium. Wood was still used for iron smelting during the beginning of the 20th century, but it had already been almost completely substituted by coal during the 19th century (Madureira, 2012). In any case, the contribution of wood to metal production has to be taken into account in assessments of periods previous to 1900. The estimation of the contribution of NRE to indirect energy consumption was made based on the NRE share of world primary energy production and the share of NRE in each metal production in year 2000 (ecoinvent Centre, 2007) as a reference value. In the case of aluminium, we assumed that the direct energy is electricity, and its indirect energy requirements and NRE correspond to the world average values calculated in Section 4.3. The estimated total and non-renewable energy requirements of all metallic materials studied are shown in Tables 5.1 and 5.2, respectively.

Table 5.1. Historical evolution of total embodied energy for the production of metallic materials used in agricultural systems, 1910-2010 (MJ/kg). Own estimation from various sources (see text)

	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Pig iron	69.3	59.2	51.7	46.9	44.8	33.4	28.9	27.4	23.1	23.1	23.1
Steel (machin.)	70.9	60.5	52.9	48.0	45.8	34.1	29.5	28.1	23.6	23.6	23.6
Steel (irrig.)			73.3	65.6	61.4	50.1	42.4	39.4	33.9	32.2	32.2
Chromium steel			189.5	165.4	150.2	140.7	115.6	103.5	92.1	80.7	80.7
Lead		42.3	36.1	31.5	28.6	26.8	22.0	19.7	17.5	15.4	15.4
Aluminium			540.0	390.1	297.2	196.9	180.4	162.7	150.8	146.2	142.2
Other metals		102.2	87.3	76.2	69.2	64.9	53.3	47.7	42.4	37.2	37.2

Table 5.2. Historical evolution of NRE use in the production of metallic materials used in agricultural systems, 1910-2010 (MJ NRE/kg). Own estimation from various sources (see text)

	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Pig iron	61.6	53.9	47.2	43.0	42.1	32.2	28.5	27.2	23.0	23.0	23.0
Steel (machin.)	62.4	54.5	47.8	43.6	42.6	32.5	28.8	27.5	23.2	23.3	23.3
Steel (irrig.)			66.3	59.6	57.2	47.8	41.3	38.6	33.3	31.7	31.7
Chromium steel			171.2	150.2	139.7	134.2	112.6	101.4	90.5	79.5	79.5
Lead		38.2	32.7	28.7	26.7	25.6	21.5	19.4	17.3	15.2	15.2
Aluminium			528.7	381.7	283.7	179.6	159.8	147.0	139.6	136.8	131.7
Other metals		92.1	78.9	69.2	64.4	61.9	51.9	46.7	41.7	36.6	36.6

5.2 Non-metallic materials

A wide range of non-metallic materials are used in agricultural systems. Plastic are probably the most important ones from an energy point of view. We have not found information on the evolution of energy efficiency of plastic production. However, an examination of sources used in the literature reveals important differences between estimated energy requirements in the early 1970s and those in the early 2000s (Table 5.3).

Table 5.3. Embodied energy of irrigation systems materials in the early 1970s (Batty and Keller, 1980) and in the early 2000s (various sources, see note) (MJ/unit).

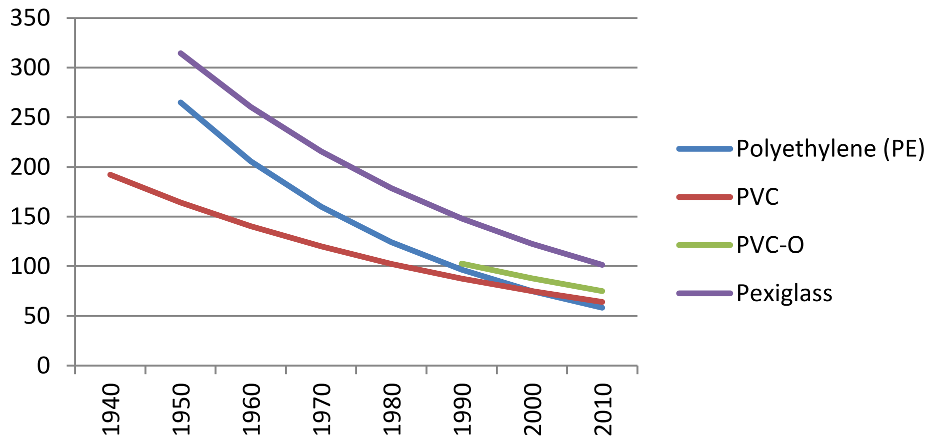
	Unit	Batty and Keller (1980)[a]	Recent sources
Pumping unit, electric	kg	81.2	

Pumping unit, diesel	kg	71.0	
PE	kg	160.0	75.2[b]
PVC	kg	120.0	74.9[c]
PVC-O	kg		87.9[b]
Aluminium	kg	195.9	143.2[d]
Steel	kg	47.5	23.6[d]
Ductile iron	kg		38.0[b]
Concrete	kg	2.0	1.34[e]
Reinforced concrete	kg		3.5[e]
Other	kg	48.0	
Grading	m3	14.9	
Ditching	m	15.9	

Notes: (a) Data originally compiled by Batty et al. (1975); (b) Data from Ambrose et al. 2002; (c) Data calculated by Piratla et al. (2012) using original data from various PVC types from Ambrose et al. (2002); (d) Own estimation for year 2010, see Section 5.1; (e) Data from various sources in Du et al. (2013)

The plastic materials energy coefficients from the 1970s are still widely used in the literature. For example, Lal (2004) estimated the carbon footprint of irrigation systems based on Batty and Keller (1980), and Lal's values have been used many times afterwards in carbon footprint assessments of cropping systems (e.g. Aguilera et al. 2015). As another example, Diotto et al. (2014) used the values from Boustead and Hancock (1979), which are very similar to those of Batty and Keller (1980) (110.7 MJ/kg PVC). However, Ambrose et al. (2002) values, which have been used in studies of water distribution systems (e.g. Piratla et al. 2012, Du et al. 2013) are very close to ecoinvent values (Hischier, 2007), so probably they represent the present situation more accurately. Therefore, the published information shows consistent differences between the energy requirements of plastics production in the 1970s and the 2000s. In order to take into account these changes, we have estimated the evolution of the energy required for plastic pipes production (Figure 5.3) assuming a constant rate of efficiency gain between the values of Batty et al. (1975) and those recent values compiled in Table 5.3. We have estimated NRE content of plastics assuming that its share over total plastic embodied energy is equivalent to the average share of NRE over cumulative energy demand in plastic production as modeled in ecoinvent (ecoinvent Centre, 2007).

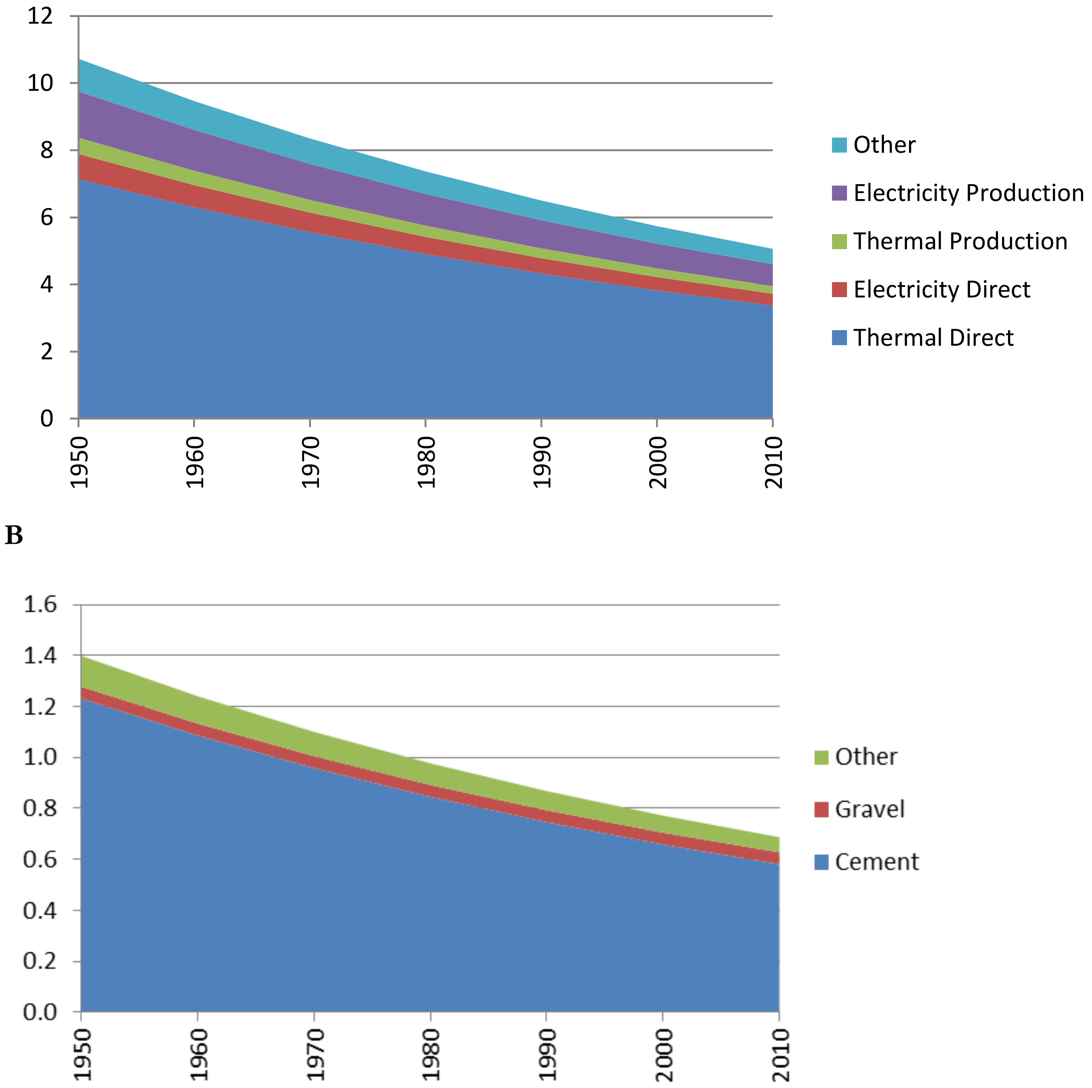
Figure 5.3. Historical evolution of the embodied energy of major plastics used in irrigation and greenhouses, 1940-2010 (GJ/kg). Own estimation from various sources (see text)



Concrete is commonly used for the foundations of greenhouses and in the construction of ditches and other irrigation infrastructure. In the case of concrete, we assumed 300 kg cement, 1890 kg gravel, 186 kg water and 226 GJ direct energy consumption per m^3 of concrete, with a density of 2.38 Mg/m^3. In the case of reinforced concrete, we assumed 4.7% steel content. The energy embodied in water has not been accounted for. Additional energy for concrete manufacturing has also been included, using data from ecoinvent (Kellenberger et al. 2007). Gravel energy requirements have been considered to be fixed along the studied period and have been taken from ecoinvent (Kellenberger et al. 2007). Cement energy requirements have been calculated based on the examination of various sources. Worrell and Galitsky (2008) reviewed the evolution energy requirements in cement production in the US during the period 1970-2005. They observed an initial improvement in energy efficiency followed by a slight increase and then a slight decrease in energy use. Hu et al. (2014) observed a significant decrease (25%) in energy consumption in cement production in China during the period 1990-2008. Madlool et al. (2011) reviewed energy efficiency status of cement industry around the world. They provide data of average thermal and electric energy consumption in cement production for the major producing countries. We have used the average value of all country-specific data in Madlool (2011) as the reference value for thermal and electricity energy consumption in 2000. To this value, we have added the energy required to produce the fuels used in thermal energy production (average of coal, oil and natural gas, Section 4.2) and the electricity, using our own estimation of world electricity energy efficiency (Section 4.3). We have also added the extra energy (transport, buildings, raw materials) needed for producing cement as a percentage of direct energy use-related energy requirements, using data from ecoinvent (Kellenberger et al. 2007). Over this basis in year 2000, we have modeled the changes during the studied period (1950-2010) assuming that the average rate of efficiency gain is constant and equal to the average of efficiency gains in the US (Worrell and Galitsky, 2008) and China (Hu et al. 2014). Total estimated energy requirements of cement and concrete production are shown in Figure 5.4 and Table 5.5. Direct and indirect energy requirements are shown in Appendix A3. Note that direct energy requirements include direct energy use in cement and steel production.

Figure 5.4. Historical evolution of the embodied energy of cement (A) and concrete (B) production, 1950-2010 (MJ/kg). Source: own estimation from various sources (see text)

A



In the case of glass, we have taken European glass production (Flat glass, uncoated) data (Kellenberger et al. 2007) as the reference for partitioning direct energy use between electricity and other fuels and for including energy consumption not related to direct energy use (mainly transport and buildings). Changes in direct energy use have been modeled based on Van Der Woude (2013), who provides energy efficiency data for the Netherlands glass industry from 1950 to 2005. We have estimated indirect energy related to the production of energy based on our own estimations of the energy requirements of electricity (Section 4.3) and fossil fuels (Section 4.2) (average of oil, gas and coal). The results are shown in Table 5.4. Table 5.5 shows the estimated energy requirements of all non-metallic materials studied.

Table 5.4. Historical evolution of the embodied energy of glass production, 1950-2010 (MJ/kg). Source: own estimation (see text).

	1950	1960	1970	1980	1990	2000	2010
Electricity (direct)	1.5	1.2	1.0	0.9	0.7	0.6	0.5
Fossil fuels (direct)	18.3	15.4	13.0	10.9	9.2	7.7	6.5
Electricity production	3.6	1.9	1.6	1.5	1.3	1.2	0.9

Fossil fuels production	0.6	0.5	0.4	0.4	0.4	0.4	0.4
Other	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Total Glass production	25.9	20.9	17.9	15.6	13.5	11.8	10.3

Table 5.5. Energy requirements of non-metallic materials, 1950-2010 (MJ/kg). Own elaboration from various sources.

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Plastics									
Polyethylene (PE)			264.7	205.8	160.0	124.4	96.7	75.2	58.5
PVC		192.2	164.2	140.4	120.0	102.5	87.6	74.9	64.0
PVC-O							102.8	87.9	75.1
Pexiglass			314.6	260.5	215.8	178.7	148.0	122.6	101.5
Construction									
Cement	13.8	12.2	10.7	9.5	8.3	7.4	6.5	5.7	5.0
Concrete	1.8	1.6	1.4	1.2	1.1	1.0	0.9	0.8	0.7
Reinforced concrete	5.0	4.3	3.8	3.4	3.1	2.5	2.2	2.0	1.7
Other									
Glass			26.0	21.0	17.9	15.6	13.5	11.8	10.3

6. Traction power

Agricultural operations in traditional systems were made with renewable local materials and powered by animal and human power sustained mainly on on-farm production. In the US, the presence of tractors was almost negligible by 1900. Steam power engines provided motive power for some particular tasks, but most of the power was provided by horses in the majority of the farms. The invention of internal combustion engines was followed by their application to farm machinery, first to stationary machines and in 1902 to mobile traction machines, which were known as "tractors". Tractors and implements grew rapidly in the US especially after 1935, until levelling off in the 1960s. At the same time the number of draft horses and mules dropped drastically from 26 million heads in 1917 to about 3 million heads in 1960 (Gross, 2014). The mechanization process took place in different periods during the 20th century in other parts of the world. For example, the number of tractors and harvesters in Spain was still 64,000 in 1960, compared to 1.39 million in 2010 (Infante-Amate et al. 2014).

The type of traction power (animal or mechanical) has a deep influence on the energy balance of agroecosystems, although the net effect on energy consumption per hectare may depend on the specific system. Typically, mechanical power employs fossil fuels and complex steel-based machinery, thus being associated to a higher use of non-renewable energy. On the other hand, animal power requires a high energy input for feed production due to the low conversion efficiency of animals. A competition with the commercial output of grain occurs specially for grain-based diets of equids (horses, mules and donkeys), and presumably not as much if they are ruminants (e.g. hoxes or water buffaloes) and use residues as feed. An additional burden may arise if agricultural tasks are concentrated during the year, which would mean that a larger working herd has to be maintained despite being idle much of the time. This may result in a feed-to-traction conversion efficiency as low as 3.8%, but external energy efficiency could be maintained high due to the reliance on on-farm produced residues for animal feed (Campos and Naredo, 1980).

The results of the study by Baum et al. (2009) suggest that animal horse traction power is much more inefficient than tractor power, mainly due to the high feed input that must be used for animal maintenance. On the contrary, Cerutti et al. (2014), in a farm-scale study, found that animal traction reduced greenhouse gas emissions by 74-94% when compared to mechanical power, although they did not assess energy use.

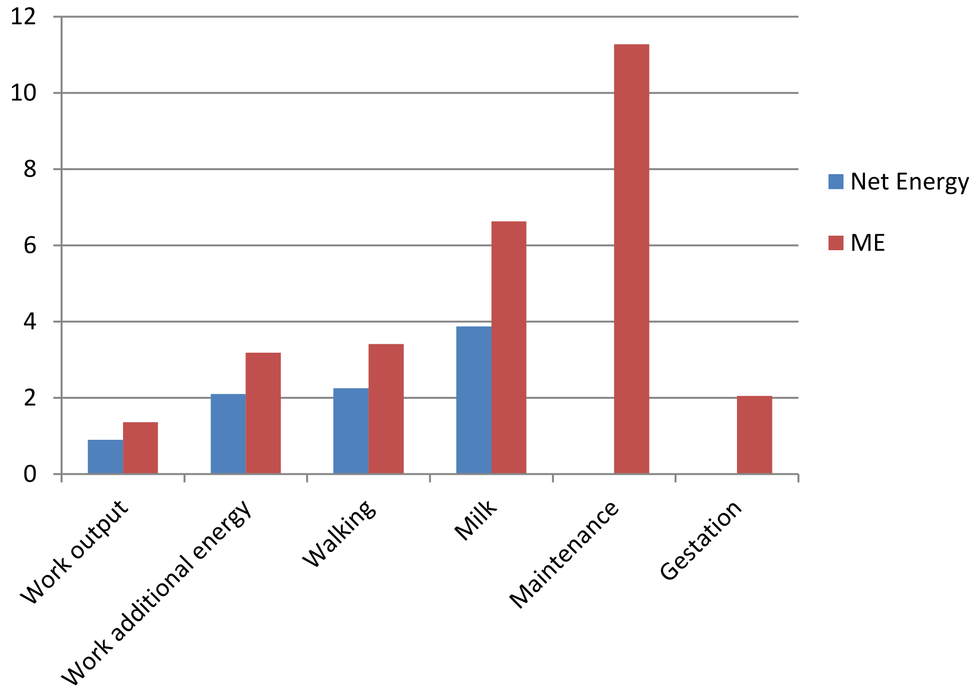
6.1 Animal power

Animals were the main source of traction power in traditional agricultures (Krausmann, 2004). The power that can be developed by draft animals depends on their species/breeds and the working speed (Smil, 1999). As in the case of human labour, muscular energy ("applied power") and energy embodied in feed have been two indicators used in the assessment of draught animals energy. Other authors reject the inclusion of draught animals' energy in their energy balances (e.g. Bayliss-Smith, 1982), arguing that, as long as the animals are fed with the production of the agricultural system, their energy is an internal loop that is already taken into account by the decreased output. Obviously, the choice again depends on the objective of the assessment and its corresponding system boundaries.

In the cases of oxen and equines, a common approach is to allocate all gross energy of feed to animal work, as these draught animals do not have any other significant purpose in the agroecosystem. Therefore, their replacement and maintenance costs can be attributed solely to work. Campos and Naredo (1980) offer values of 979 MJ/working day for a team of 2 equids (mules or horses) (489 MJ/working day per animal head) and 837 MJ/working day for a team of 2 oxen (418 MJ/working day per ox). These values already include the proportional feeding and maintenance energy consumed during non-working days. In order to obtain an annual consumption figure, these values should be multiplied by the number of days worked by the animals, which in this case were 64.5 days for the mules and 106.5 days for the oxen. In another work, González de Molina and Guzmán Casado (2006) offer values of 938 MJ/working day for a team of 2 equids (mules or horses) (469 MJ/working day per animal head) and 1060 MJ/working day for a team of 2 oxen (530 MJ/working day per ox). In this case the number of days worked by the animals was 188 days. The relatively small differences observed between the energy requirements in the two studies are due to the differences in the number of working days (in which feed consumption is higher) and to the composition of the diet.

In the case of double-purpose animals (production of meat and/or milk and work) it is necessary to segregate the gross energy employed by the animal in food production from that employed in work (Zerbini and Shapiro, 1997). The net working energy developed by a milk-draught cow reported by Zerbini and Gebre Wold (1999) was 3.6 MJ per 4-hours working day or 0.9 MJ per hour. This work required the metabolization of 4.5 MJ feed during working time. On the other hand, the cow also invests 6.6 MJ to produce 3.6 MJ milk during the reference working hour. In addition, a total of 21.3 MJ/h is consumed for walking, maintenance and gestation taking into account proportional non-working hours during a working day (Figure 6.1). Thus, even knowing the energy partitioning of multifunctional animals, we still have to allocate maintenance and reproduction energy between the different functions. It is necessary to take into account that feed energy is usually presented as net or metabolizable energy, so it has to be converted to gross energy. However, we can still use the fractions of metabolizable energy employed for the different tasks performed by the double-purpose livestock to allocate the gross energy between these tasks.

Figure 6.1. Net energy and metabolizable energy (ME) partitioning of draught –milk cows (MJ/h). Own elaboration from Zerbini and Gebre Wold (1999). Data for a 4-hours working day have been converted to 1 hour dividing by 4.



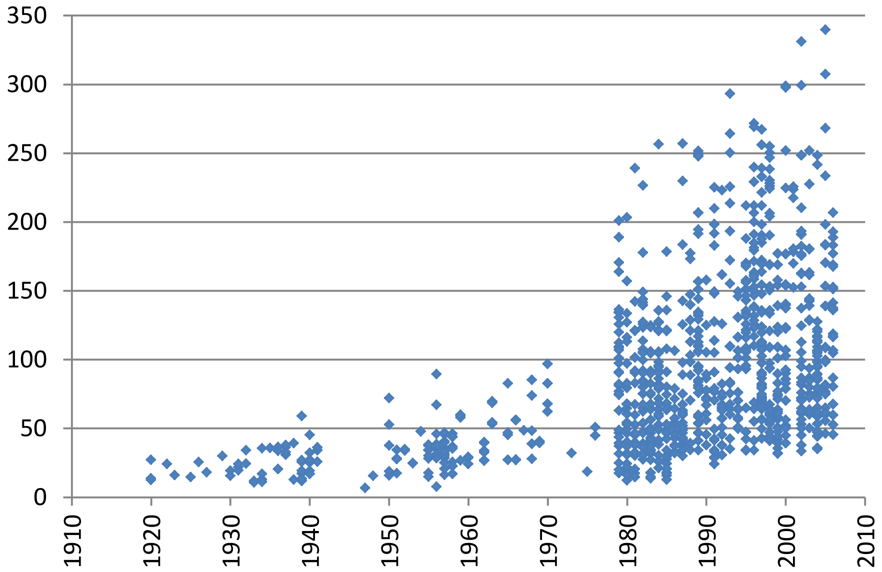
6.2 Machinery use

The energy consumption of machinery and implements is attributable to four factors: production of raw materials, manufacture, repair and maintenance, and fuel consumption. In this section, we will study the first three factors, related to the embodied energy of the machinery itself. We largely follow the approach developed by Doering (1980), based on raw materials embodied energy, fabrication energy, and the energy employed in repairs and maintenance expressed as a proportion of original equipment energy costs. Different works have estimated the energy consumption in the production of farm machinery, and Stout and McKiernan (1992) have outlined some changes in the energy requirements that have taken place during the technological development of farm machinery.

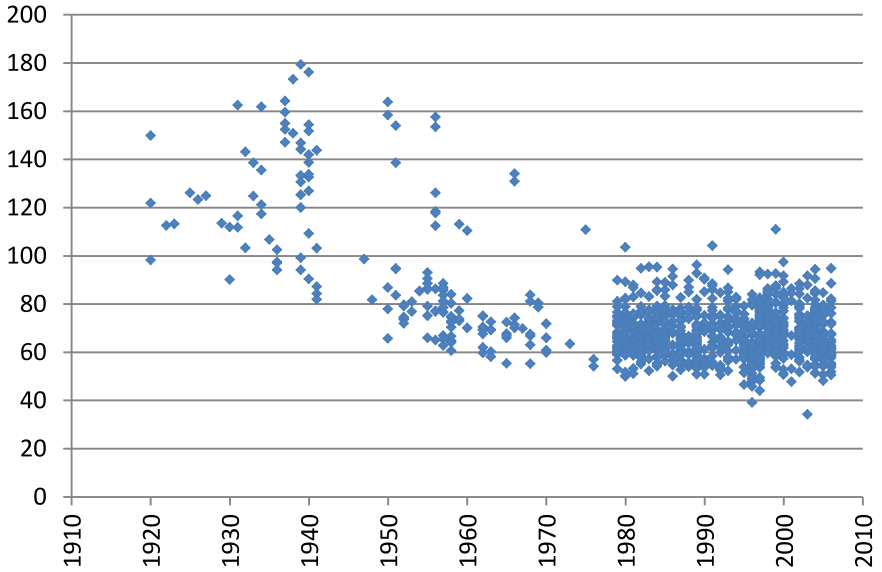
Machinery design has greatly changed during the history of mechanized agriculture. The first step was the use of metals in farm implements. Wooden tillage implements were the rule until the 19th century. The first decades of the 19th century witnessed the invention of cast iron and steel ploughs and other tillage and farm implements. Threshing machines, powered first by animals and later by steam and tractors, were invented in the first half and expanded in the second half of the 19th century. Steam traction engines were already available in the last decades of the 19th century, but they were heavy, dangerous machines and their yearly installed capacity never grew above that of horses. The invention of the tractor in the turn of the century was followed by important improvements in tractor design, with the introduction of technologies such as the power take-off, rubber wheels, diesel engines and the power lift. By the mid-1930s, the "dominant design" of tractors over the three next decades was already established (White, 2008).From the heavy steam engines of the early 20th century to modern electronically controlled tractors of the 21th century, engineers have accomplished great improvements in the fuel efficiency and overall operating performance of farm machinery (White, 2008, Stout and McKiernan, 1992). As can be observed in Figure 6.2, the average power of tractors has increased and their weight has decreased significantly during their history.

Figure 6.2. Historical evolution in the tractor rated power (kW) (A) and specific weight (kg/kW rated power) (B) as reported by the Nebraska Tractor Tests, 1920-2010. Data collected from various sources (see text)

A



B



5.2.1 Specific weight of tractors

Figure 6.2.B suggests that the average specific weight of tractors decreased steadily in the period 1920-1980. However, from that year to 2006 no clear trend can be observed. Therefore, we have constructed a historical series of materials requirements of tractors distinguishing those two periods. An exponential trend was fitted to the data in the first period (Fig. 6.3), and the average of all data points was assumed for the second period. The result is shown in Table 6.1.

Figure 6.3. Estimated trend in the evolution of tractor specific weight, 1920-1980 (kg/kW rated power), based on the Nebraska Tractor Tests (see text for details)

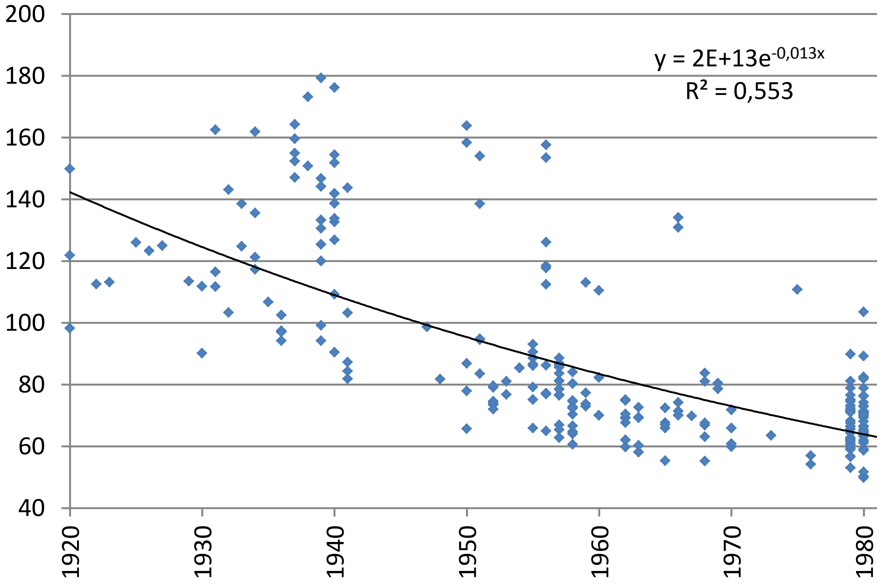


Table 6.1. Historical evolution of the specific weight of tractors, 1920-2010 (kg/kW rated power). Sources: own estimation using data from Nebraska Tractor Tests, collected from various sources (see text)

	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Specific weight	142	125	109	95	83	73	64	64	64	64

6.2.2 Raw materials production

Steel is the major component of machinery both in term of weight and raw materials energy requirements. Despite the importance of this material in modern machinery production, the raw materials employed for machinery construction have changed over time to meet the performance demands of new engines (Stout and McKiernan, 1992). New designs of ever more powerful, efficient and lighter engines (see Fig. 6.2) require more resistant materials to bear higher temperatures and pressures and to reduce the thickness of the walls of the components. Other material capabilities such as insulation are also required in some components to improve engine performance. Thus, lighter and more efficient engines imply lower material consumption in machinery production (this section) and lower fuel consumption in machinery use (Section 6.2.4), but more energy is demanded for the use of scarce metals in alloys or more complex production processes. The main material in the 1950s was gray iron, but it was substituted by cast iron and aluminium in the 60s. In the following decades, new alloys of cast iron were developed, as well as other variants such as compacted graphite iron (Stout ad McKiernan, 1992).

The use of more energy-intensive materials in machinery construction has increased in the last two decades with the increasing use of electronics. These technologies, such as the electronic diesel control, have become widespread in farm machinery, as already predicted by Stout and McKiernan (1992). They have helped to improve engine performance reducing fuel consumption, but they also require high amounts of energy for their manufacture. For example, the energy requirements of the manufacture of a laptop computer range between 504 and 945 GJ/kg (Andrae and Andersen, 2010), compared to 5-40 MJ/kg used in modern steel production around the world (IEA, 2007). Hence, these electronics may significantly contribute to the energy requirements of machinery production, together with the energy cost of communications technologies infrastructure. Park and Malakon (2013) found that the implementation of infrastructures for fuel-saving communications technologies in vehicles was associated to an energy use equivalent to 36% of vehicle production energy.

We have attempted to reconstruct the energy requirements of machinery production taking into account the changes in the efficiency of the production of the raw materials and the changes in the raw material composition of the machinery. The historical evolution of metallic and non-metallic materials was analyzed in Section 5. Here we also include rubber used in wheels and an additional category named "Other materials". This category includes alkyd paint, flat glass, polypropylene and paper, that jointly represent roughly 5% of tractor weight in ecoinvent inventory (ecoinvent Centre, 2007), being polypropylene the main contributor to total energy. The embodied energy of these two categories (rubber and other materials) is assumed to be constant during the studied period, given the lack of specific historical information. We have taken the energy requirements of rubber from

Lawson and Rudder (1996). In the case of Other materials, we have calculated the weighted average of the cumulative energy demand of these materials in ecoinvent database (ecoinvent Centre, 2007). For the estimation of NRE, we have assumed the same share of NRE in rubber as in plastics, and for Other materials we have assumed the same share as in world primary energy use. The estimated energy coefficients for all materials used in machinery are shown in Table 6.2, and the NRE coefficients are shown in Appendix A4.

Table 6.2. Historical evolution of the total embodied energy of machinery raw materials (MJ/kg), 1920-2010. Own estimation from various sources (see Section 5.1 and text in this section)

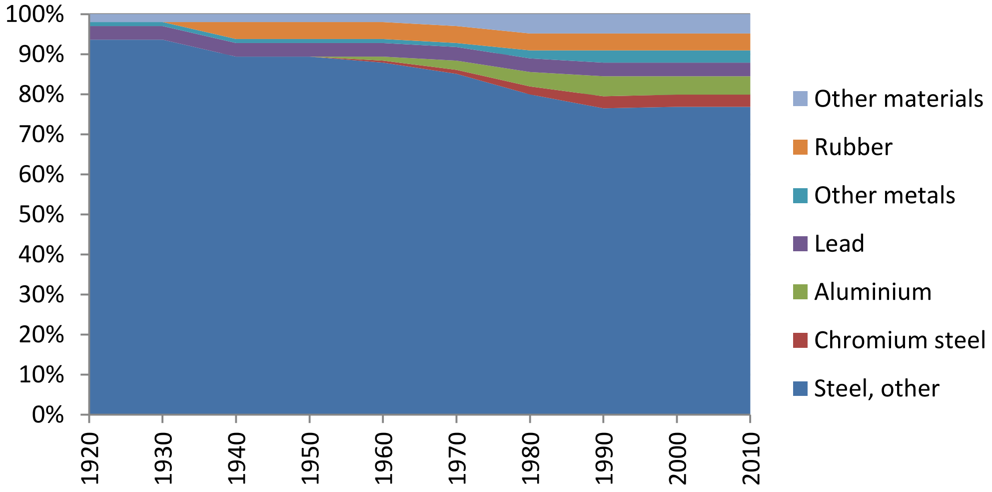
	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Steel (machin.)	61	53	48	46	34	30	28	24	24	24
Chromium steel				150	141	116	103	92	81	81
Aluminium					197	181	164	153	148	144
Lead	42	36	32	29	27	22	20	18	15	15
Other metals	102	87	76	69	65	53	48	42	37	37
Rubber			110	110	110	110	110	110	110	110
Other materials	64	64	64	64	64	64	64	64	64	64

The next step to calculate machinery energy requirements is to know the relative share of each material in machinery compostion. The composition of the actual machinery has been modeled based in ecoinvent (ecoinvent Centre, 2007). In the case of rubber, the material requirements that can be attributed to maintenance are classified in that category. The same is done for lubricating oil.

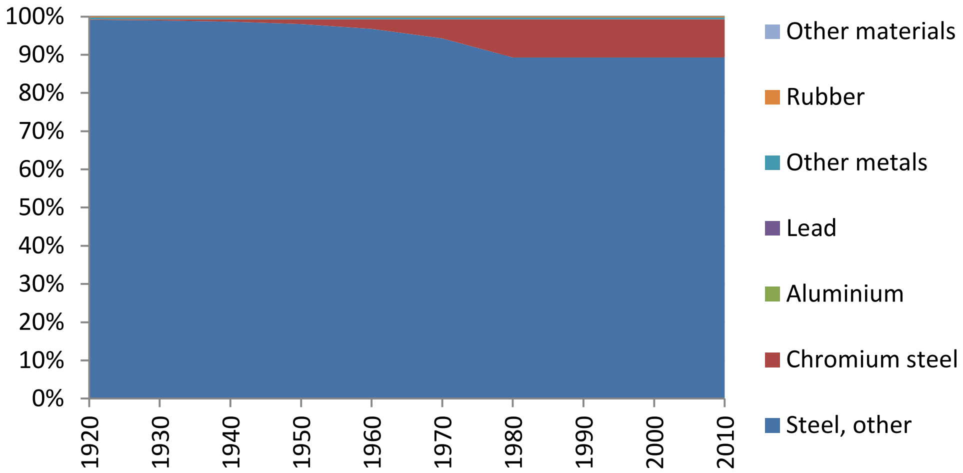
As described in previous paragraphs, the composition of machinery has changed over time. Given the lack of quantitative data, we have estimated these changes based on the qualitative information reviewed. The estimated changes in the composition of the machinery are shown in Figure 6.4.

Figure 6.4. Composition of machinery, 1920-2010. Tractors and other self-propelled machinery (A), tillage machinery (B), other machinery (C)

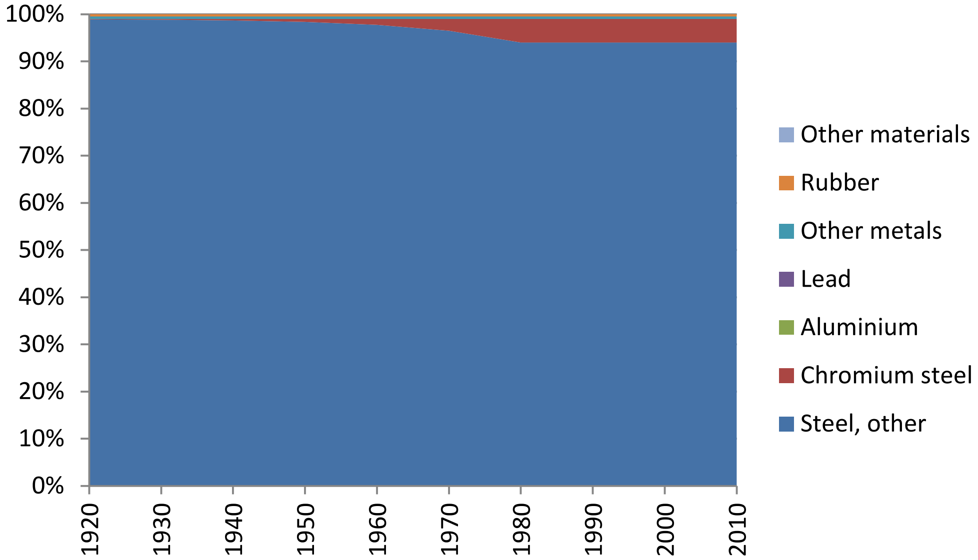
A



B



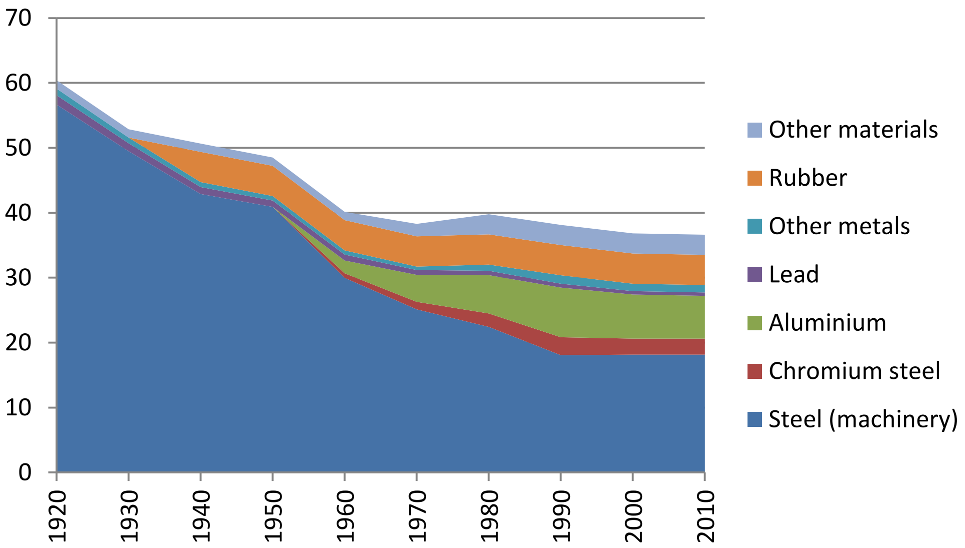
C



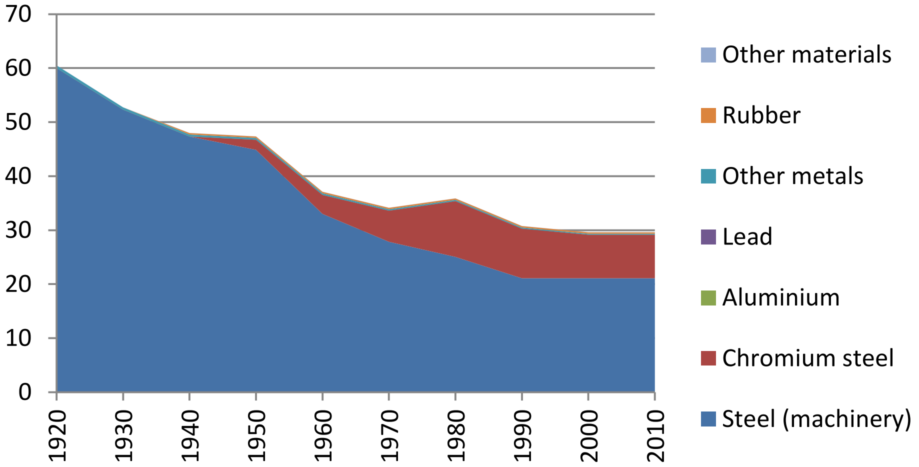
Using the information about raw materials embodied energy (Table 6.2) and of the composition of the machinery (Figure 6.4), we have estimated the evolution of the energy embodied in raw materials for each kg of machinery (Figure 6.5).

Figure 6.5. Historical evolution of the energy embodied in machinery raw materials production, 1920-2010 (MJ/kg machinery). Tractors and other self-propelled machinery (A), tillage machinery (B), other machinery (C). Own estimation (see text).

A



B



C

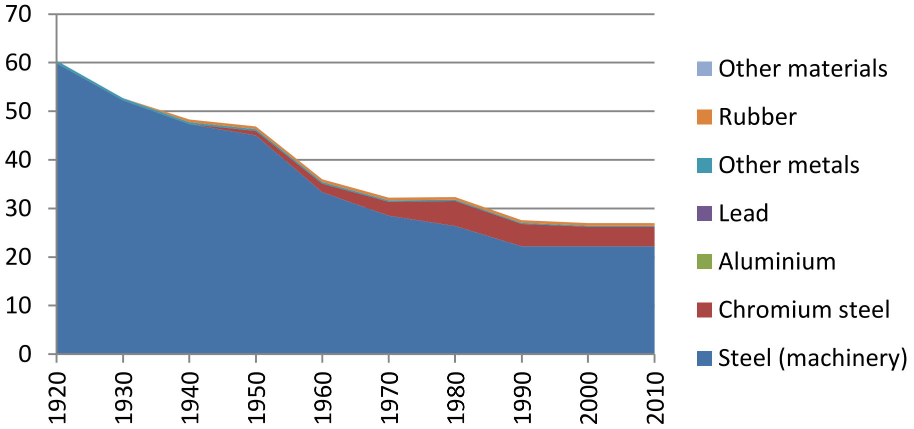


Figure 6.5.A suggests that the energy requirements per kg of self-propelled machinery are today about half of those in 1920, mainly due to the increase in the energy efficiency of iron smelting. However, the trend is almost flat since about 1970, due to the introduction of new, more energy-

intensive materials and to the stagnation of efficiency increases in raw materials production. We have to indicate that the effect of materials substitution must be underestimated in our calculations because we have not taken into account the changes in the types of ferrous metals in farm machinery, other than the introduction of chromium steel. We neither took into account the introduction of electronic components, as we found not enough information to include them. The estimated values for self-propelled machinery for the mid-1970s are somewhat lower than the values taken by Doering (1980), of 49.5 and 50.3 MJ/kg, respectively.

The change in energy efficiency has been more pronounced in the case of tillage implements and other non-motorized machinery, because chromium steel is the only energy intensive material that has been assumed to have been introduced in recent decades.

In the case of tractors and other self-propelled machinery, we have also estimated the machinery production energy requirements related to the power output (Figure 6.6), by multiplying the energy intensity of each kg of machinery (Figure 6.5) by the specific weight of the machinery (Table 6.1).

Figure 6.6. Historical evolution of the energy requirements raw materials production of tractors and other self-propelled machinery, 1920-2010 (GJ/kW rated power)

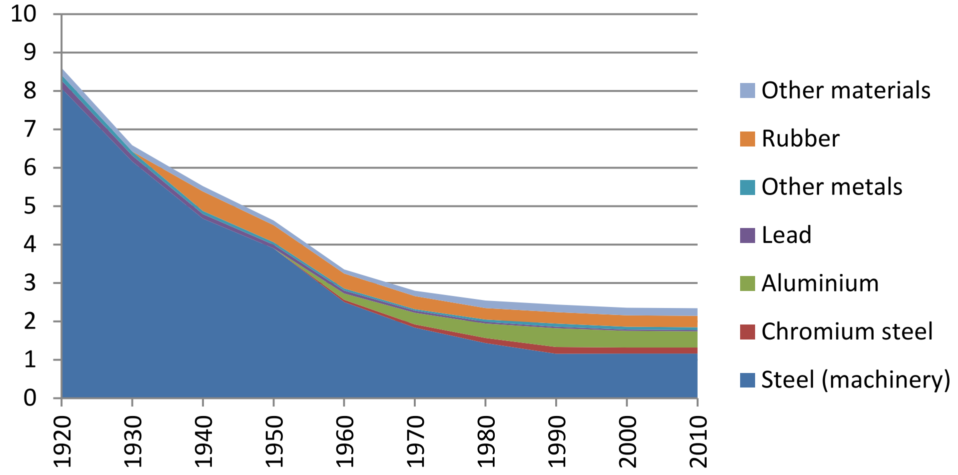
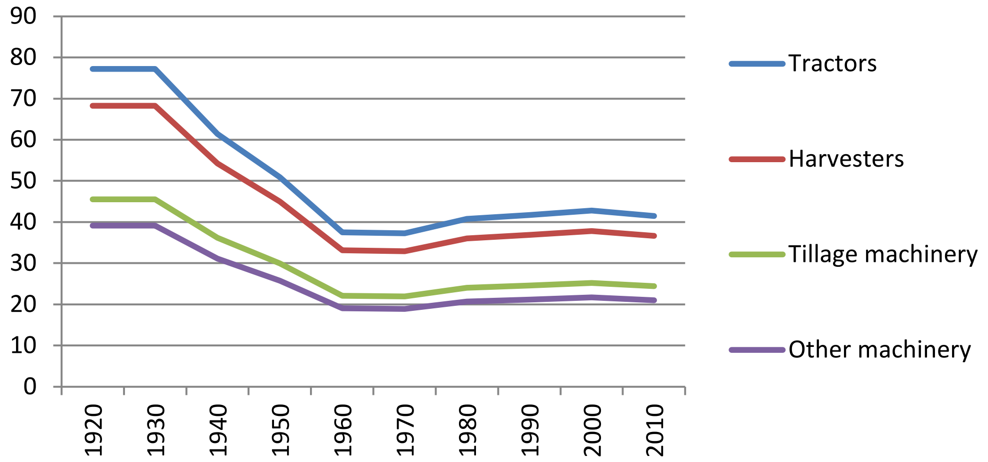


Figure 6.6 shows that the energy requirements of machinery raw materials per kW of rated tractor power now represent about 20% of those of 1920. This higher efficiency increase is due to the combination of decreased specific weight with decreased energy intensity of raw materials. In this case, the stagnation in efficiency only occurs in the last decade.

6.2.3 Machinery manufacture and maintenance

Machinery manufacture direct energy use has been taken from Doering (1980), who provides a value of electricity consumption that has been used in many other works (e.g. Audsley et al. 2003, Guzmán and Alonso, 2008). This value has been assumed constant, but the energy requirements of electricity production and delivery have been modeled using our own world average estimations described in Section 4.3. The changes in the efficiency of electricity production explain the changes in the total energy requirements of the manufacture of the four types of machinery shown in Figure 6.7.

Figure 6.7. Historical evolution of the total energy requirements of machinery manufacture, by type of machinery, 1920-2010 (MJ/kg machinery). Own estimation based on Audsley et al. (2003) (see text)



The energy in repairs and maintenance is usually expressed in the literature as percentage in total machinery production energy requirements. In the case of tractors, this value may range between 45% used by Audsley et al. (2003, from Mughal, 1994), 49% in Doering (1980), 50% in FAO (1994) and 72% in ecoinvent database (ecoinvent Centre, 2007). For harvesters, the range is even larger: 23% in Audsley et al. (2003, from Mughal, 1994) to 55% in ecoinvent database (ecoinvent Centre, 2007) and 100% in FAO (1994).

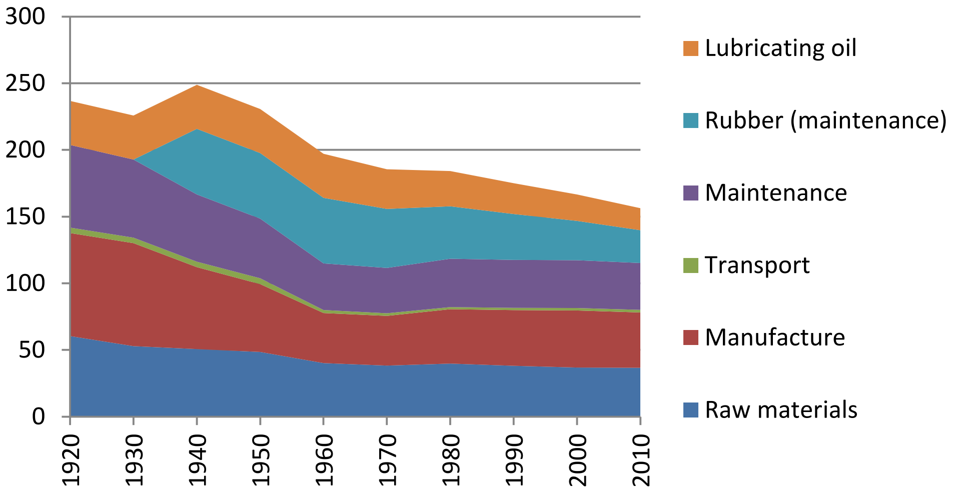
We have taken the values in Audsley et al. (2003) (Table 6.3) but have added the extra rubber and lubricating oil required for machinery use in the case of self-propelled machinery. The evolution of total energy requirements of machinery production and maintenance are shown in Figure 6.7.

Table 6.3. Repair and maintenance energy requirements of different types of machinery (% of production energy). Source: Mughal, 1994, in Audsley et al. 2003

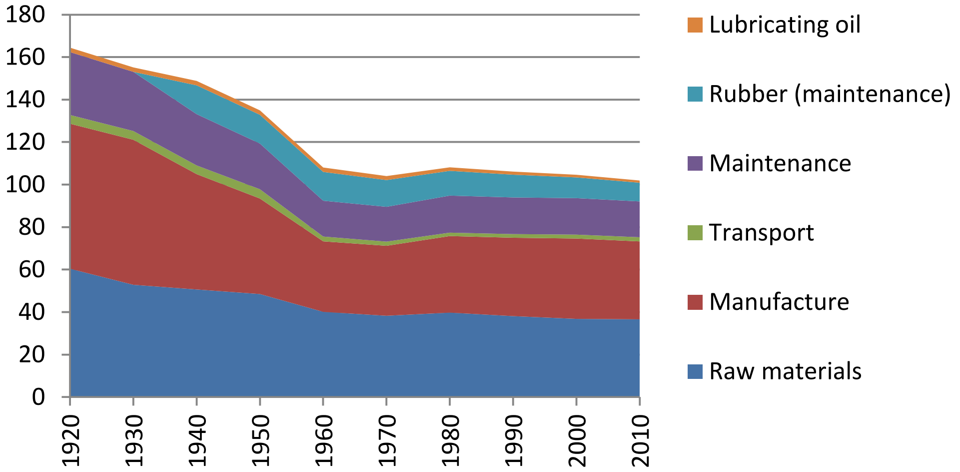
	Repair factor
Tractors	45%
Combine harvesters	23%
Tillage machinery	30%
Other machinery	26%

Figure 6.8. Historical evolution of total embodied energy in the production and maintenance of machinery, 1920-2010 (MJ/kg), per type of machinery, including self-propelled machinery (A), combine harvesters (B), tillage machinery (C) and other machinery (D). Own estimations based on various sources (see text).

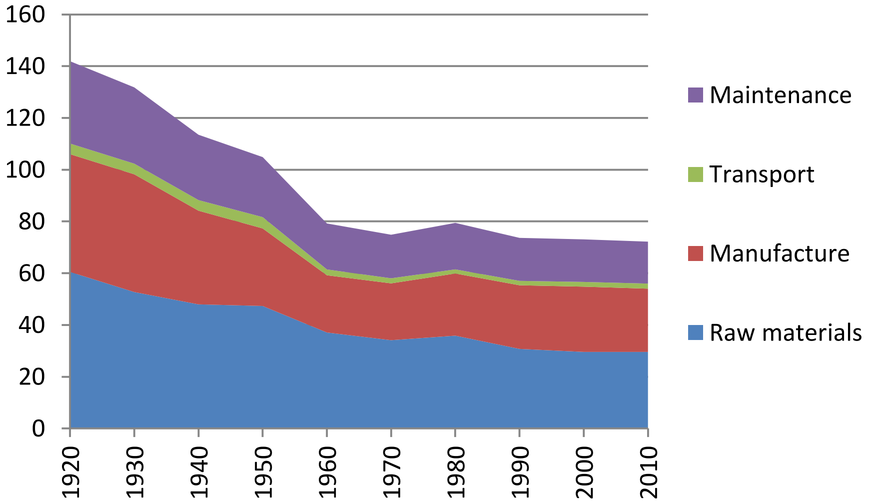
A


300
250
200
150
100
50
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Lubricating oil
Rubber (maintenance)
Maintenance
Transport
Manufacture
Raw materials

B


180
160
140
120
100
80
60
40
20
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Lubricating oil
Rubber (maintenance)
Maintenance
Transport
Manufacture
Raw materials

C


160
140
120
100
80
60
40
20
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Maintenance
Transport
Manufacture
Raw materials

D

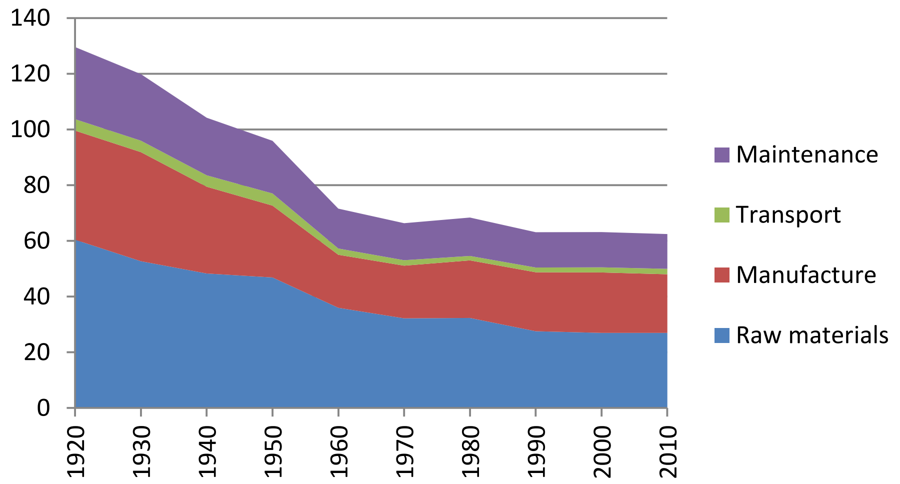


Figure 6.8.A suggests that the introduction of rubber wheels, despite being responsible for significant improvements in fuel efficiency, was also related to an increase in maintenance energy requirements

Once we have all energy inputs related to machinery production and maintenance, we have to know the average useful life in order to estimate an hourly machinery energy use. This parameter has a great influence on the estimation of machinery embodied energy, while it also has variability, depending on the tractor model, the working conditions and the user choice. This uncertainty makes it difficult to allocate the embodied energy to the whole lifetime (Mikkola and Ahokas, 2010). The published estimations suggest that the average useful life of farm machinery has changed over time. The values published from the early 1960s to the early 2000s range between 10000 and 16000 hours for tractors and 2000 hours for combine harvesters (Rotz, 1987, ASAE, 2000), while in Audsley et al. (2003) they range between 2500 and 7200 hours for tractors and 1400 ha for combine harvesters, and Ecoinvent (2007) assumes 7000 hours for tractors and 1300 hours for combine harvesters. Therefore, we have assumed that the average useful life of self-propelled machinery decreased from 1960 to 2010. Based on the information reviewed above, we have assumed the useful life values shown in Table 6.4

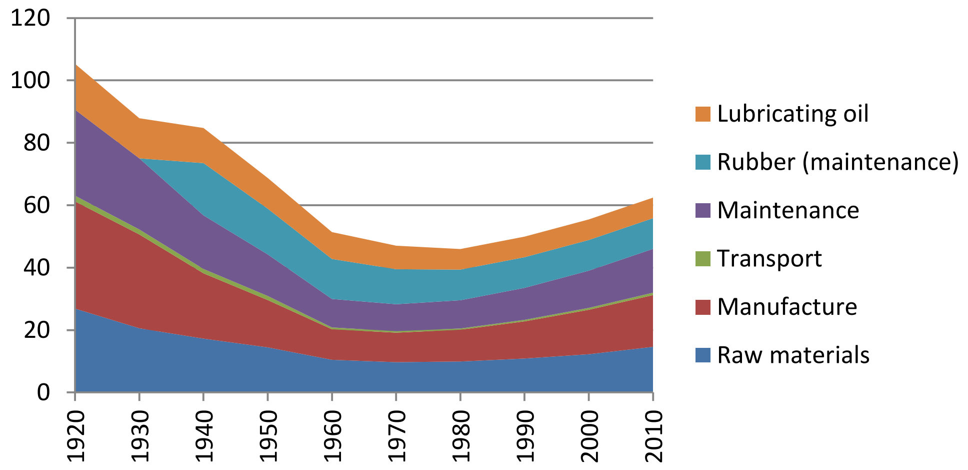
Table 6.4. Historical evolution of useful life of self-propelled machinery (hours). Own estimation from various sources (see text)

	1920	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**
Tractors	16,000	16,000	16,000	16,000	16,000	14,400	12,800	11,200	9,600	8,000
Harvesters	2,000	2,000	2,000	2,000	2,000	1,860	1,720	1,580	1,440	1,300

We have multiplied the embodied energy per kg of machinery (Figure 6.8) by the specific weight (Table 6.1) and by the rated power (50 kW) and divided by the useful life (Table 6.4) to obtain hourly embodied energy values for self-propelled machinery use along the studied period (Figure 6.9).

Figure 6.9 Historical evolution of the embodied energy of the hourly use of self-propelled machinery, 1920-2010 (MJ/h), including a 50-kW tractor (A) and a 100-kW harvester (B). Own elaboration from various sources (see text)

A



B

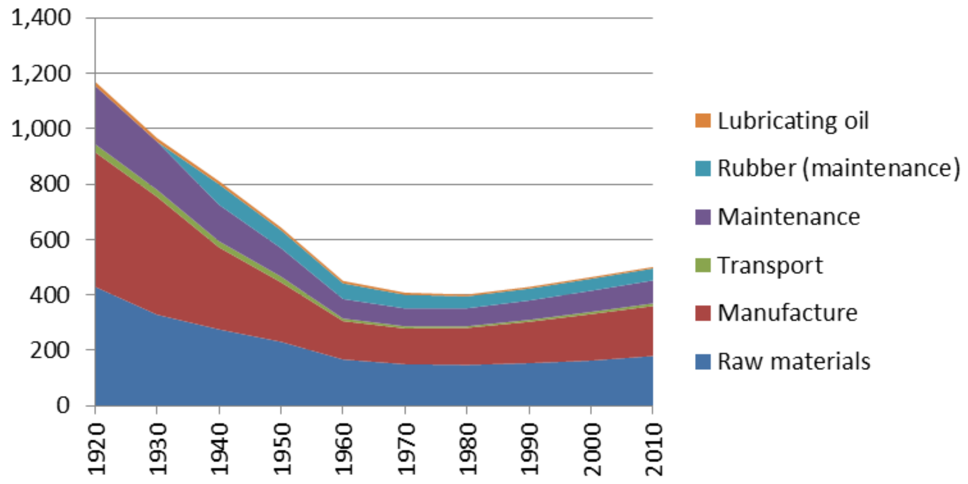


Figure 6.9 suggests that, despite the embodied energy of the hourly use of machinery has decreased by about one half in the studied period, the decreasing trend only lasted until the mid-20th century, while in the last decades this coefficient actually increased due to various factors, including the stagnation of efficiency gains in machinery materials production and in specific weight reductions, and the decrease in the useful life of machinery. This last parameter might be highly dependent on the specific situation of the farm or area of study, so we recommend using site-specific sources when possible.

In the case of tillage machinery and other implements, the data in Audsley et al. (2003) is sometimes referred to hectares, other to hours and other to other units such as loads. Therefore, we have rather chosen ASAE values (ASAE, 2000), which express useful life in hours. When a particular farm implement was missing in ASAE database, we took the value of a similar item. ASAE useful life values are usually higher than those reported by Audsley et al. (2003) and ecoinvent Centre (2007). Table 6.5 shows the selected weight and useful life values of relevant types of machinery implements. The weights of tractors and harvesters are not shown because they are better expressed in kg/kW, which has already been estimated in section 6.2.1, while their useful life is shown in Table 6.4.

Table 6.5. Weight and useful life of relevant types of machinery. Sources: weight data from Audsley et al. (2003) and useful life data from ASAE (2000)

	Type	Weight (kg)	Useful life (h)
Tillage machinery			
Plough: two-furrow plough	B	600	2,000
Plough: four-furrow plough	B	1,300	2,000
Rotary cultivator (3m)	B	1,000	1,500
Rotary cultivator (4m)	B	1,300	1,500
Cultivator (2.2m)	B	700	2,000
Spring tine cultivator (6m)	B	500	2,000
Harrow with spring teeth (3m)	B	650	2,000
Clod-breaking rollers (3m)	B	700	2,000
Other machinery			
Drill: 3m	C	550	1,500
Drill: 6m	C	1,200	1,500
Disc broadcaster: under 450R (12m)	C	130	1,200
Disc broadcaster: over 450R (12m)	C	280	1,200
Mounted crop sprayer: 600R (12m)	C	400	1,750
Mounted crop sprayer: 1000R (12m)	C	800	1,750
Twin wheels	C	160	1,500
Four wheel trailer (8t)	C	2,500	3,000
Round baler	C	1,700	2,000
Frontloader	C	400	2,000
Straw chopper	C	500	1,200
Manure spreader (4.5t - 5.5t)	C	1,400	1,500
Hydraulic loader	C	1,600	1,500
Slurry pump	C	380	1,500
Three-point reel (300m)	C	450	1,500
PVC hoses (100m)	C	200	1,500
Three-point spreader	C	110	1,500
Round bale press	C	1,700	1,500

We have multiplied the embodied energy per kg of machinery (Figure 6.8) by the specific weight of each implement (Table 6.5), and divided by the useful life (Table 6.5) to estimate the evolution of the energy intensity of one hour of use of each implement (Table 6.6).

Table 6.6. Historical evolution of the energy requirements of the hourly use of farm implements, 1920-2010 (MJ/h). Own elaboration from various sources (see text)

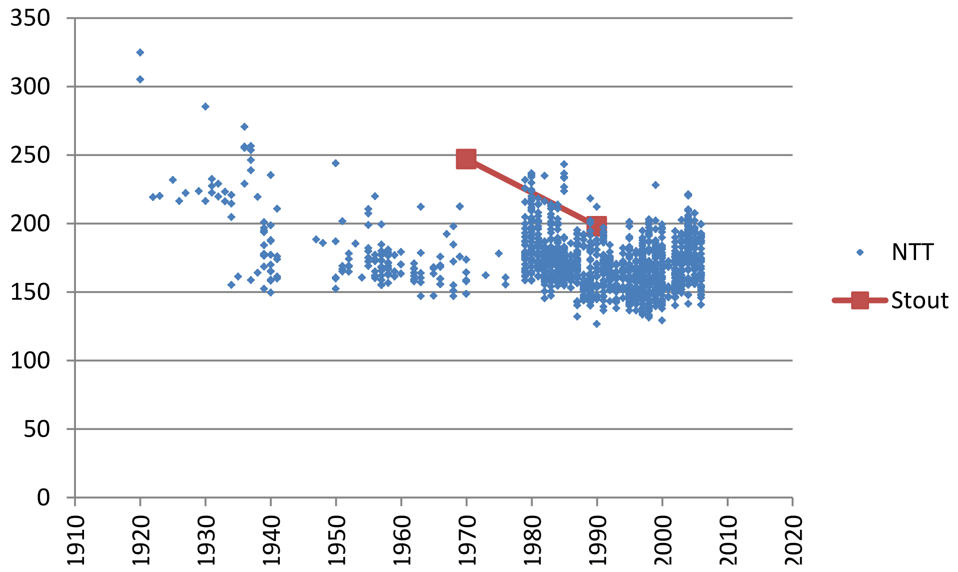
	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Tillage machinery										
Plough: two-furrow plough	43	40	34	31	24	22	24	22	22	22
Plough: four-furrow plough	92	86	74	68	52	49	52	48	48	47
Rotary cultivator (3m)	95	88	76	70	53	50	53	49	49	48
Rotary cultivator (4m)	123	114	98	91	69	65	69	64	63	63
Cultivator (2.2m)	50	46	40	37	28	26	28	26	26	25
Spring tine cultivator (6m)	35	33	28	26	20	19	20	18	18	18
Harrow with spring teeth (3m)	46	43	37	34	26	24	26	24	24	23
Clod-breaking rollers (3m)	50	46	40	37	28	26	28	26	26	25

Other machinery										
Drill: 3m	48	44	38	35	26	24	25	23	23	23
Drill: 6m	104	96	83	77	57	53	55	50	51	50
Disc broadcaster: under 450R (12m)	14	13	11	10	8	7	7	7	7	7
Disc broadcaster: over 450R (12m)	30	28	24	22	17	15	16	15	15	15
Mounted crop sprayer: 600R (12m)	30	27	24	22	16	15	16	14	14	14
Mounted crop sprayer: 1000R (12m)	59	55	48	44	33	30	31	29	29	29
Twin wheels C	14	13	11	10	8	7	7	7	7	7
Four wheel trailer (8t)	108	100	87	80	60	55	57	53	53	52
Round baler	110	102	89	82	61	56	58	54	54	53
Frontloader	26	24	21	19	14	13	14	13	13	12
Straw chopper	54	50	43	40	30	28	28	26	26	26
Manure spreader (4.5t - 5.5t)	121	112	97	90	67	62	64	59	59	58
Hydraulic loader	138	128	111	102	76	71	73	67	67	67
Slurry pump	33	30	26	24	18	17	17	16	16	16
Three-point reel (300m)	39	36	31	29	21	20	21	19	19	19
PVC hoses (100m)	17	16	14	13	10	9	9	8	8	8
Three-point spreader	10	9	8	7	5	5	5	5	5	5
Round bale press	147	136	118	109	81	75	77	72	72	71

6.2.4 Fuel consumption

The calculation of energy use in agricultural systems is sometimes hindered by the lack of data on fuel consumption. In these cases, it is necessary to estimate fuel consumption based on the available management information. Typical values of hourly fuel consumption by types of machinery could be used if we have information on the time that the machinery is used in each task. However, these values would depend on the efficiency of the engine, which has changed over time. Figure 6.9 shows some published values of tractor fuel consumption (brake specific fuel consumption, BSFC).

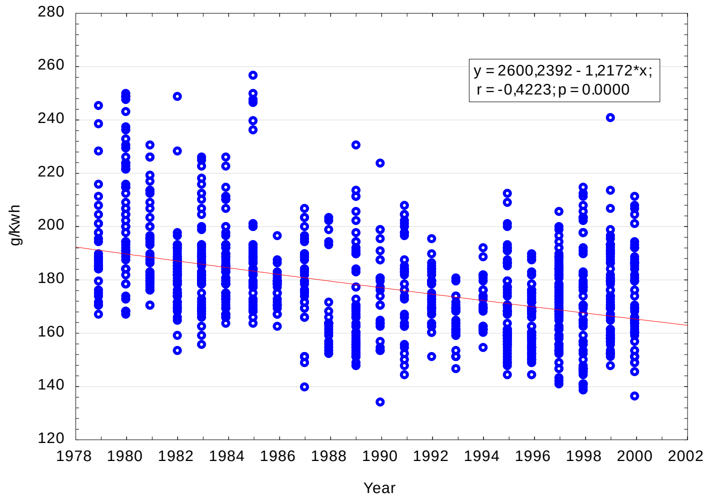
Figure 6.10. Comparison of the tractor brake specific fuel consumption data from the Nebraska tractor tests with tractor fuel efficiency data published by Stout and McKiernan (1992) (g fuel/kWh). Sources: see text.



The data shown in Figure 6.10 suggest that the decreasing trend in Stout and McKiernan (1992) might be overestimated. In fact, the Nebraska tractor tests show that very low fuel consumption was achieved by some tractor models as early as 1940.

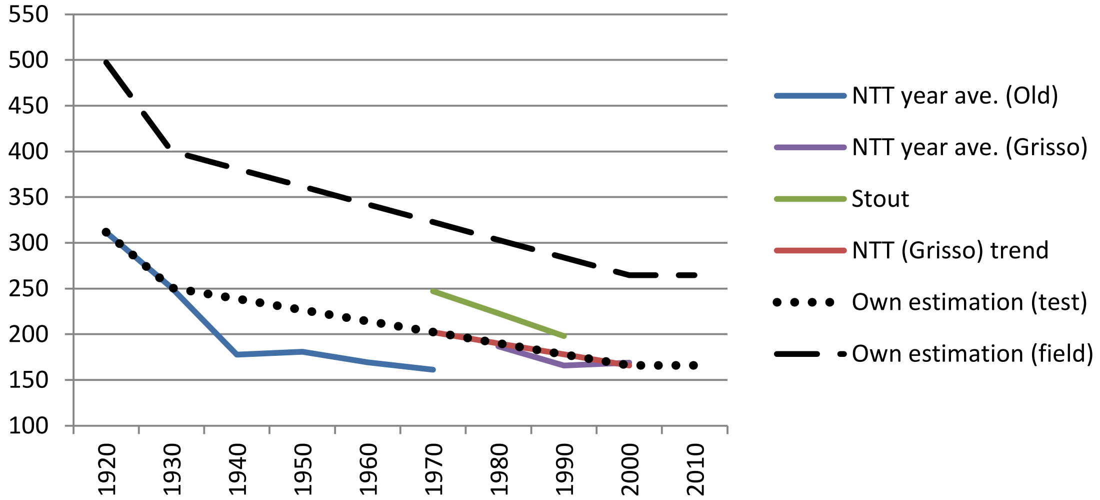
We estimated the evolution in tractor fuel consumption using the reviewed Nebraska Tractor Test series. We divided the data in two periods. The period between 1920 and 1970 is based mainly on the data compiled by Evans (2004), using different sources, mainly the extensive review of Nebraska tractor tests by Wendel (1985). This dataset is not representative of the average trend, as it only covers a few companies. Hence, this data was complemented with some Ford models data from Wendel (2005). For the period between 1980 and 2010, the dataset of Nebraska tractor tests data from Grisso (2007) was used. This is a very comprehensive dataset covering about 1500 Nebraska tractor tests from 1972 to 2006. In this dataset we can observe a trend towards decreased fuel consumption from 1976 to about year 2000 (Figure 6.11).

Figure 6.11. Brake-specific fuel consumption of tractors tested in the Nebraska Tractor Tests, 1979-1998 (g fuel/kWh). Best fit showed. Source: own elaboration with data from Grisso (2007).



From 2000 to 2006, an increasing trend is observed (Figure 6.10). We do not have comparable data for the years after 2006, so we cannot confirm if this trend continues. Therefore we have assumed that fuel efficiency in the 2000-2010 period remains constant. We have extrapolated backwards the 1980-2000 trend shown in Figure 6.11 to estimate specific diesel consumption up to 1940. Our estimated data points for 1920 and 1930 correspond to the average of our reviewed Nebraska tractor tests for these years. Last, we have used a multiplier for correcting NTT-based values for field operating conditions. Following ASAE standards, we have added 15% to NTT fuel consumption data to simulate engine inefficiency under field conditions. We have also added 39% to the vale obtained to take into account higher relative fuel consumption under lower than rated power output. This percentage is the average of 5 data points representing a range between 20% and 100% of the rated power output of the tractors in Grisso, 2004. Our test-based and field-based estimations of the average tractor fuel consumption in the studied period, and the series in which it is based, are shown in Figure 6.12.

Figure 6.12. Different estimations of tractor fuel consumption, 1920-2010 (g fuel/kWh). Own elaboration from various sources (see text)



The "Field estimation" was converted to volume units to provide a series of tractor fuel consumption over the 1920-2010 period (Table 6.7).

Table 6.7. Specific fuel consumption of tractors under field conditions (l/kWh). Source: own estimation (see text)

	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Specific fuel consumption	0.62	0.49	0.47	0.45	0.38	0.36	0.34	0.32	0.30	0.30

Our estimated value of average specific fuel consumption in 1980-1990, of 0.0.34-32 l/kWh, is similar to the 0.35 value estimated by Alonso (2008) using Gil (1992) data for that period.

The values in Table 6.7 represent parameter *c* in the equation below, which can be used to estimate fuel consumption of a tractor of a given rated power

$$FC = c * P * R$$

Where FC is fuel consumption (l/h), c is the specific fuel consumption under field conditions (l/kWh), P is the rated power of the machinery (kW) and R is the ratio of the equivalent power to the rated power (the percentage of the full load that is being used). We show reference values of R for typical tasks in Table 6.8.

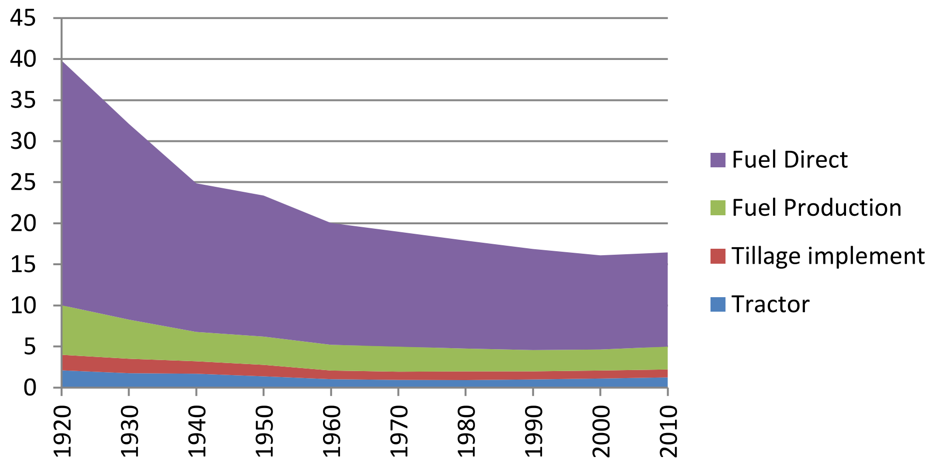
Table 6.8. Ratio of used power to rated tractor power for different tasks. Source: Leach (1976)

	Load (R)
Cultivating	66%
Ploughing	75%
Rolling	25%
Seeding	50%
Fertilizing	25%
Spraying	25%
Harvest	85%

Not only the amount of fuel used, but also the type of fuel has changed during the history of farm mechanization. A first period of relative high diversity of fuels used was followed by the dieselization of the machinery. The first internal combustion engine tractors in the early 20th century used gasoline, and kerosene and distillates became common in the 1920s. Diesel engines were first released in 1931 (Economic Research Service, 1993) and in the 1960s diesel became the major fuel, until today. On average, a diesel tractor use approximately 73% as much fuel in volume as a gasoline tractor, and liquefied petroleum gas (LPG) tractors use approximately 120% as much (Grisso, 2004). These values correspond to 88% and 90%, respectively, when fuel is expressed in mass units, and to 87% and 96%, respectively, when it is expressed in energy units. For the period 1940-2010, these data can be used to correct our estimations if fuels other than diesel are used. For the previous period, our data represents an average of liquid fuels (diesel, gasoline, kerosene and distillates).

Now we know the energy use by farm machinery and fuel per hour, we can estimate total energy requirements per hour of work for a given power level. In Figure 6.13 we show our estimation of direct and indirect fuel energy and machinery production and maintenance energy use per hour of tillage work and kW of rated tractor power. Direct fuel energy has been estimated as described previously in this section. Indirect fuel energy has been estimated using our own data of diesel production energy (Section 4.2), tractor energy and implements energy using data in Section 6.2.3 and assuming that the task is performed with a 50 kW tractor (i.e. dividing hourly implement energy by 50).

Figure 6.13. Historical evolution of total embodied energy per hour and per kW rated power during a tillage operation performed with a 50 kW tractor at full load, 1920-2010 (MJ/kW h)



6.2.5 Machinery and fuel consumption per hectare

If data on hourly tractor use is not available, fuel consumption and total energy requirements can be estimated using average values of consumption per hectare for each agricultural task. These values are also sensitive to the changes in energy efficiency, indicating the need to account for temporal changes. In fact, field performance of the machine does not only depend on engine efficiency. In 1932, rubber wheels were found to reduce fuel consumption by 25% (Economic Research Service, 1993), and they had largely substituted steel wheels by 1938 (White, 2008).

In order to know fuel consumption per hectare, and knowing the hourly fuel consumption of the machinery, it is necessary to know the time employed in the task for a given machine power. Leach (1976) provides working time data for different agricultural tasks, which are comparable to those published by Aguilera (2009). We have taken the machinery working time data from Leach (1976) and converted them to 3 different levels of tractor power (Table 6.9).

Table 6.9. Machinery working time (hours/ha) and engine load (%) for typical agricultural tasks and three levels of tractor power. Source: own elaboration, based on Leach (1976)

	Rated tractor power		
	20 kW	**50 kW**	**100 kW**
Cultivating	3.02	1.10	0.60
Ploughing	7.03	1.83	1.41
Rolling	0.84	0.36	0.17
Seeding	3.86	0.55	0.77
Fertilizing	1.24	0.68	0.25
Spraying	1.75	0.28	0.35
Harvest	6.16	1.40	1.23

With this information and our estimations of the evolution of machinery energy requirements through the studied period, we have calculated total fuel consumption (Table 6.10) and total energy consumption (Table 6.11) for these tasks. As an example, we show a figure of a tillage operation energy requirements (Figure 6.13). The values apply to all tractor powers, except machinery implements which are calculated for the working times employed by a 50 kWh tractor at the load specified in Table 6.8. Moreover, 25% extra fuel consumption has been added in 1920 and 1930 to account for the extra fuel consumed in the field by tractors with metallic wheels. All data, together with the corresponding NRE values, is shown in Appendix A4.

Table 6.10. Historical evolution of total fuel consumption per hectare for some agricultural tasks, 1920-2010 (l/ha). Source: own estimation (see text)

	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Cultivating	28.0	22.4	17.0	16.2	14.0	13.2	12.4	11.6	10.8	10.8
Ploughing	52.9	42.3	32.1	30.5	26.3	24.8	23.3	21.8	20.3	20.3
Rolling	3.5	2.8	2.1	2.0	1.7	1.6	1.5	1.4	1.3	1.3
Seeding	10.6	8.5	6.4	6.1	5.3	5.0	4.7	4.4	4.1	4.1
Fertilizing	6.6	5.3	4.0	3.8	3.3	3.1	2.9	2.7	2.5	2.5
Spraying	2.7	2.1	1.6	1.5	1.3	1.2	1.2	1.1	1.0	1.0
Harvest	45.9	36.8	27.9	26.5	22.9	21.6	20.3	19.0	17.7	17.7

The estimated fuel consumption values can be compared to those published in the literature. For example, Lal (2004) reviewed a number of sources, obtaining ranges of 15-49 l/ha for moldboard plow and 7-25 l/ha for chisel plow. The average published values for the different tasks reviewed by Mikkola and Ahokas (2009) were also very similar to our 1980-2010 values. The variability is due to numerous factors besides tractor engine efficiency and implement used. The fuel requirement increases with deeper plowing, higher tractor speed, heavier textured soils and higher cone index (Lal, 2004, ASAE, 2000). Moreover, a higher content of soil organic matter might decrease traction energy requirements up to 25% (Peltre et al. 2015).

Figure 6.14. Historical evolution of total embodied energy per hectare for a tillage (cultivator) operation with a 50 kWh tractor, 1920-2010 (MJ/ha). Source: own estimation (see text)

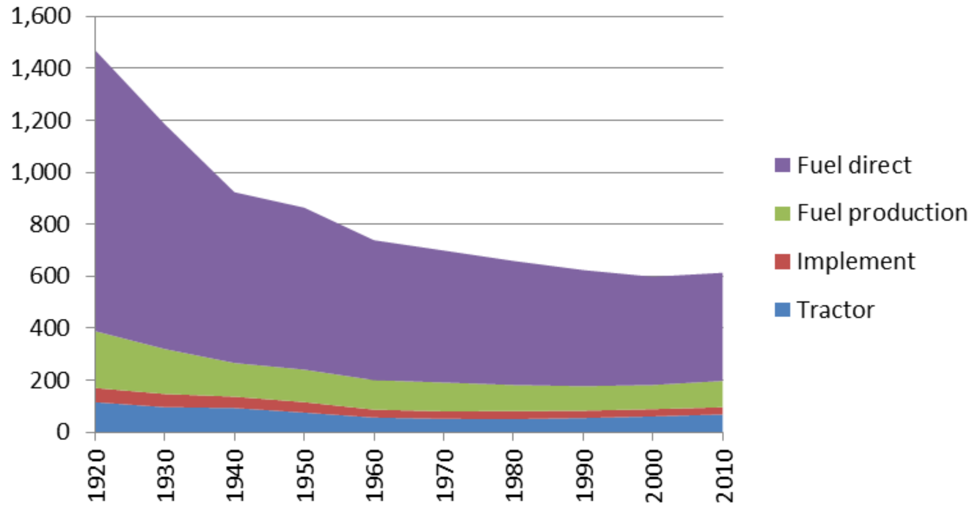


Table 6.11. Historical evolution of total embodied energy per hectare for some agricultural tasks, 1920-2010 (MJ/ha). Source: own estimation (see text)

	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Cultivating										
Tractor	116	97	93	76	57	52	51	55	61	69
Implement	55	51	44	40	31	29	31	28	28	28
Fuel production	219	173	130	125	114	111	101	94	93	101
Fuel direct	1,081	865	657	623	538	508	477	447	416	416
Total	1,470	1,185	923	864	739	699	659	624	598	614
Ploughing										
Tractor	192	160	155	126	94	86	84	91	101	114
Implement	78	72	62	57	43	41	44	40	40	40
Fuel production	413	326	245	236	214	209	190	178	175	191
Fuel direct	2,039	1,631	1,239	1,175	1,015	958	900	842	785	785
Total	2,722	2,190	1,700	1,594	1,367	1,294	1,218	1,151	1,101	1,129
Rolling										
Tractor	38	32	31	25	19	17	17	18	20	23
Implement	18	17	14	13	10	10	10	9	9	9
Fuel production	27	22	16	16	14	14	13	12	12	13
Fuel direct	135	108	82	78	67	63	60	56	52	52
Total	219	178	143	132	110	104	99	95	93	96
Seeding										
Tractor	58	48	47	38	28	26	25	27	30	34
Implement	42	38	33	31	23	21	22	20	20	20
Fuel production	83	66	49	47	43	42	38	36	35	38
Fuel direct	410	328	249	236	204	192	181	169	158	158
Total	592	480	378	352	298	281	266	253	244	250
Fertilizing										
Tractor	72	60	58	47	35	32	31	34	38	43
Implement	15	14	12	11	8	8	8	7	7	7
Fuel production	51	41	30	29	27	26	24	22	22	24
Fuel direct	254	203	154	146	126	119	112	105	98	98
Total	392	318	255	234	196	185	175	168	165	171
Spraying										
Tractor	29	24	23	19	14	13	13	14	15	17
Implement	4	4	3	3	2	2	2	2	2	2
Fuel production	21	16	12	12	11	10	10	9	9	10
Fuel direct	102	82	62	59	51	48	45	42	39	39
Total	156	126	101	93	78	73	69	67	65	68
Harvest										
Machinery	147	123	119	96	72	66	64	70	78	87
Fuel production	359	284	213	205	186	182	165	154	152	166
Fuel direct	1,772	1,417	1,076	1,021	882	832	782	732	682	682
Total	2,278	1,824	1,407	1,322	1,140	1,080	1,012	956	912	935

7. Synthetic fertilizers and pesticides

The industrial production of mineral fertilizers started in the mid-to-late 19th Century, after the diffusion of Liebig's mineral theory, triggered by the increasing need of yields improvement (Cordell, 2009) due to various factors including population pressure, soil fertility loss due to de-localization of crop production and new residue management systems in cities. The fertilizer industry grew rapidly during the 20th century, while the use of synthetic fertilizers in combination with new crop varieties was associated to major yield increases (Isherwood, 2003). Fertilizers became a major commodity in world trade and a major component of the globalization process (Park, 2001).

Table 7.1 shows nutrient content of some common mineral fertilizers. Nutrients are expressed following the standard conventions: elemental nitrogen (N), phosphate equivalents (P_2O_5) and potash equivalents (K_2O). Taking into account their molecular composition and atomic mass, the percentage of elemental P in P_2O_5 is 43.7%, while K represents 83% of K_2O molecular mass.

Table 7.1. Nutrient content of the most common mineral fertilizers. Sources: Jenssen and Kongshaug (2003), Ramirez and Worrell (2006)

		Percentage of final product mass			
Name	**Abbreviation**	**N**	**P_2O_5**	**K_2O**	**SO_3**
Ammonia		82			
Ammonium Nitrate	AN	35			
Ammonium Sulfate	AS	21			59
Calcium-Ammonium Nitrate	CAN	25			
Calcium Nitrate	CN	16			
Urea	U	46			
Potassium Nitrate	NK	13-25		15-46	
Complex NPK fertilizers	NPK	5-25	5-25	5-25	
Mono Ammonium Phosphate	MAP	11	52		
Di Ammonium Phosphate	DAP	18	46		
Ammonium phosphate*	AP	14.5	49		
Phosphate rock	P rock		32		
Triple Superphosphate	TSP		48		
Single Superphosphate	SSP		21		25
Slag	Slag		5-15		
Complex PK fertiizers	PK		22	22	
Muriate of potash (potassium chloride)	MOP (KCl)			60	
Sulfate of potash	SOP (KS)			50	46

***Average of MAP and DAP**

7.1 Phosphorus

Agricultural phosphorus sources were of organic origin up to the mid-19th Century, being recycled from crop residues, animal manure and, to a lesser extent, human excreta. In the early 19th Century, guano production started as a new phosphorus source, but the reserves were limited and this source never represented a large share of global phosphorus use. In 1842, John Bewnes Lawes patented a method for supherphosphate production by acidifying mineral phosphates (bones, lime, phosphate rock) with sulfuric acid. This acidulation process allowed phosphates to be easily released to the soil and absorbed by plants (water-soluble phosphorus, WSP). Thus began industrial superphosphate fertilizer production from phosphate rock (usually fluoroapatite, $Ca_5(PO_4)_3F$), that became the main external source of phosphorus to agricultural systems before the end of the 19th century, although it was still far from manure P applications. In 1870s began the production of another phosphorus source, slag from P-rich iron ores, but the abundance was limited and the P concentration was only 2-6.5%, versus 7-10% of single superphosphate (SSP). By 1955, phosphate rock-derived fertilizers represented more than half of total agricultural phosphorus inputs, and since 1975 they represent about 85% of P inputs (Cordell, 2009).

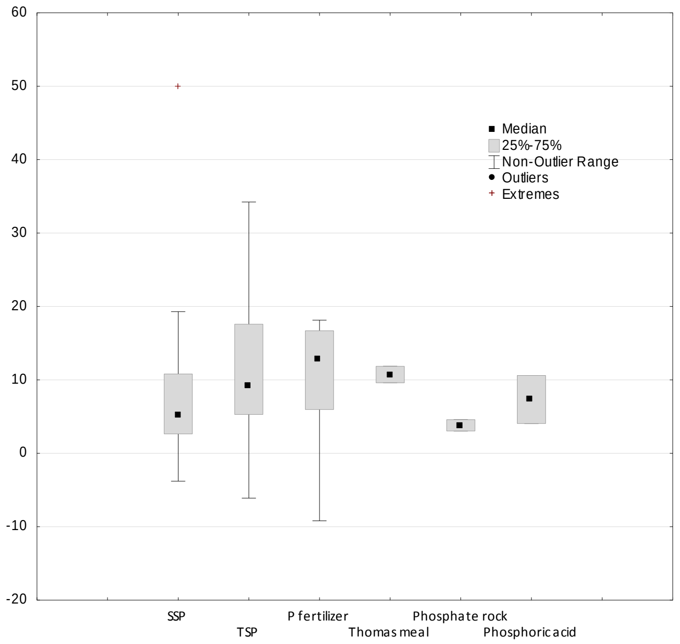
Phosphoric acid production employs fine ground phosphate rock and sulphuric acid. This process generates phospho-gypsum as a by-product. The disposal of phospho-gypsum is related to important environmental problems (Park, 2001). The acidulation reaction is usually a first step to make compound chemical fertilizers. Common forms of P fertilizers are single superphosphate (SSP), triple superphosphate (TSP), di-ammonium phosphate (DAP), monoammonium phosphate (MAP), and compound NPK fertilizers.

Energy requirements involve mining and beneficiation of phosphate ore, sulfur production at crude oil refinery, phosphate rock and sulfur transport, sulfuric acid production, superphosphate manufacturing and granulation of the final product. Phosphate rock mining requires between 0.3 and 2.8 MJ/kg P_2O_5 depending on accessibility (Jenssen and Kongshaug, 2003). LCA approaches using data from ecoinvent (Nemecek et al. 2007) give about 4.6 MJ/kg.

Useful energy can be obtained from the exothermic reaction of rock phosphate and sulfuric acid. This process generates useful energy (steam) in modern plants and consumes it in old ones (Jenssen and Kongshaug, 2003).

The literature shows a relatively high variability in the energy requirements of phosphate fertilizers (Figure 7.1). This variability is driven by the aforementioned technological changes in the energy efficiency of superphosphate production, by regional differences in mining and beneficiation of phosphate rock and elemental sulfur, and by differences in the boundaries of the studies, for example in the inclusion of processes such as buildings, transport or packaging, or in the allocation of the energy output of sulfuric acid production. In fact, very variable values are provided by different studies that ultimately refer to the same primary data. For example, Linderholm et al. (2012) found that the energy intensity of average TSP production in Europe ranged from 12 to 80 MJ/kg P in a selection of studies, in spite of they being all interlinked and ultimately referred to Kongshaug (1998), later amended by Jenssen (Jenssen and Kongshaug, 2003)

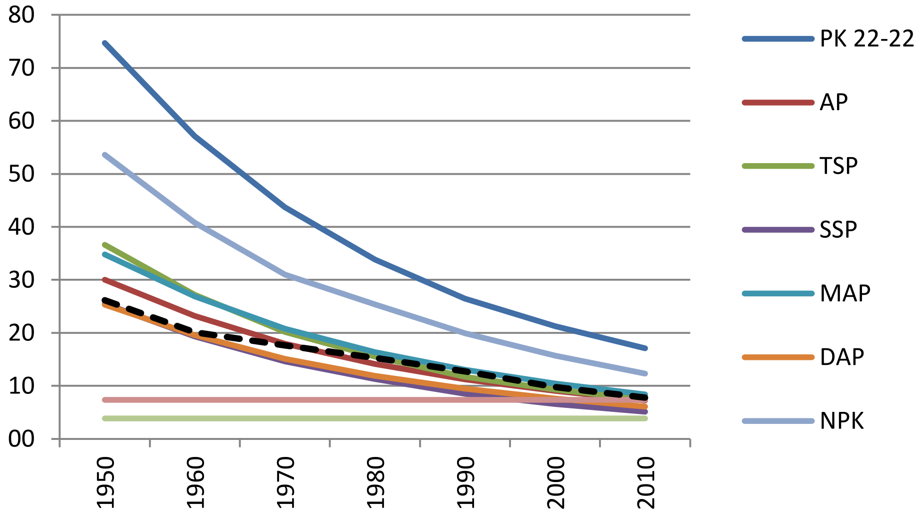
Figure 7.1. Dispersion of published values of the energy requirements for the production of phosphate fertilizers (MJ/kg). Sources: Nemecek et al. (2007), Ledgard et al. (2011), Jenssen and Kongshaug (2003), Shapouri et al. (2002), Silva and Kulay (2003), Wang et al. (1997), Lockeretz (1980), Dovring and McDowell (1980), Pimentel (2003), Patzek (2004), Nielsen et al. (2003), NREL (2010), Audsley et al. (2003), Leach (1976), Helsel (1992), Bhat et al. (1994), Ramirez and Worrell (2006)



Ramirez and Worrell (2006) estimated the evolution of the gross energy requirements of phosphate fertilizers building blocks from 1960 to 2001. The averages they provide for year 2000 are in line with the median values of our review of published values shown in Figure 7.1. In addition, they clearly limit the boundaries of their study to the gross fuel requirements of fertilizers production, which includes direct fuel consumption and fuels used in electricity production, but not the energy used to produce the fuels and other aspects such as transport, buildings and packaging.

Therefore, we used the information in Ramirez and Worrell as the basis to estimate the evolution of the embodied energy of the most common phosphate fertilizers from 1950 to 2010. We extrapolated their 1990-2000 and 1960-1970 trends up to 2010 and 1950, respectively. We did not estimate the energy intensity in previous years due to the lack of information. We also allocated the energy in compound fertilizers to N, P and K based on their respective energy requirements. The data is shown in Figure 7.2.

Figure 7.2. Historical evolution of the direct energy requirements of phosphate fertilizers production, 1950-2010 (MJ/kg P_2O_5). Source: own elaboration based on Ramirez and Worrell (2006) (see text).



We added the energy required to produce the fuels using our own estimations of fuel energy intensity (Section 4.2), and assuming that the relative use of each fuel type in phosphate fertilizers production is similar to that of world primary energy production. The result is shown in Figure 7.3, together with the estimation of the weighted global average of phosphate fertilizers production. The latter has been calculated using the relative shares of each fertilizer in total phosphate fertilizer production (Figure 7.4).

Figure 7.3. Energy requirements in phosphate fertilizers production, including production energy of fuels, 1950-2010 (MJ/kg P_2O_5). Source: own elaboration with data from Ramirez and Worrell (2006) and FAOSTAT (FAO, 2015)

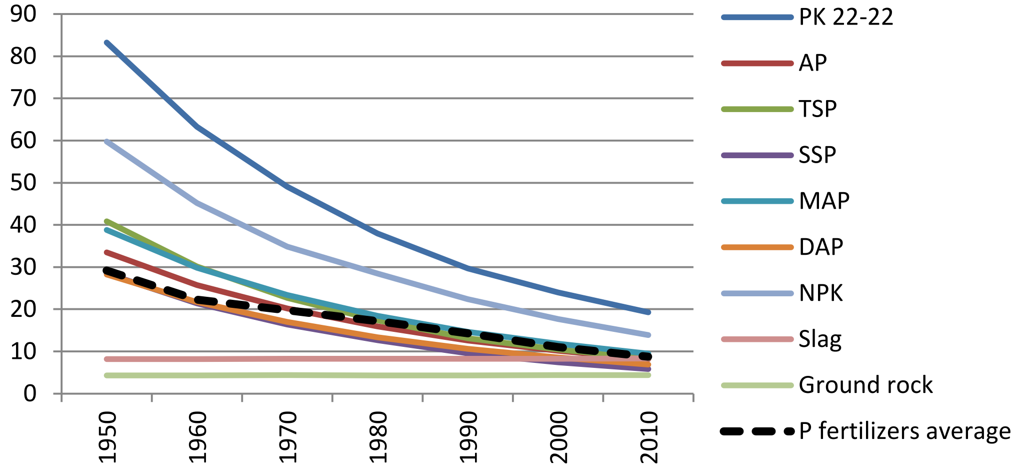
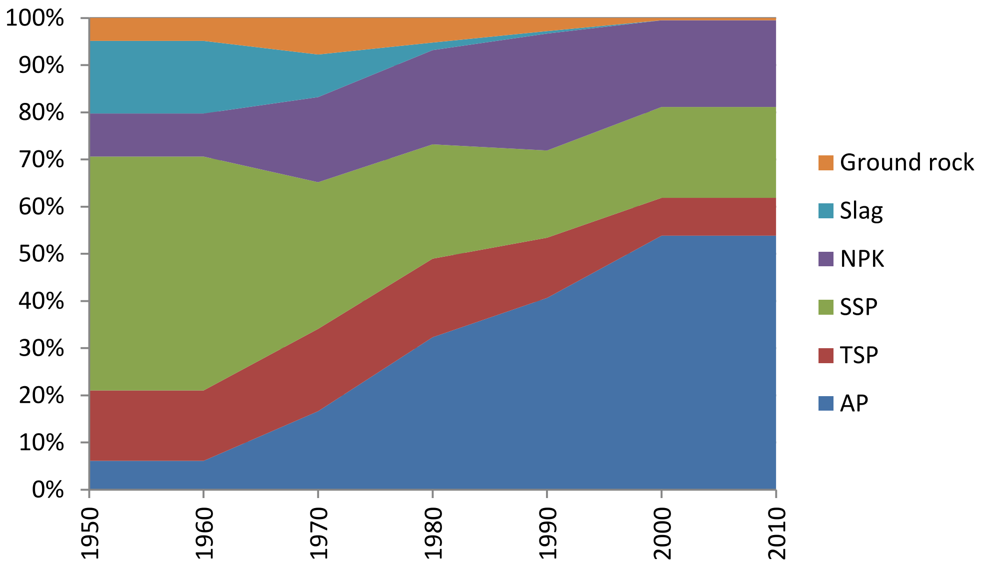


Figure 7.4. Historical evolution of the relative shares of phosphate fertilizer types in world phosphate fertilizer production, 1900-2010. Sources: own elaboration from FAOSTAT (FAO, 2015) data from 1960 to 2000. Assumed constant during the rest of the period.



We can observe in Figure 7.3 that the rate of decrease in the energy requirements of average phosphate fertilizer production is not as fast as the individual rates of each fertilizer. As was already acknowledged by Ramirez and Worrell (2006), this is due to the shift to more energy-intensive fertilizers, such as NPK.

In order to calculate total energy requirements of phosphate fertilizers production we added the energy embodied in buildings and equipment (based on ecoinvent Centre, 2007), as well as the energy required to package the fertilizers (2.7 MJ/kg P_2O_5), taken from Helsel (1992). In the case of compound fertilizers, we allocated transport and packaging energy based on a mass criterion. All these factors are assumed to be constant during the studied period. In the case of transport, we used our own general assumptions of agricultural inputs transport distances and modes described in Section 13. We corrected the energy values to take into the weight of P_2O_5 in relation to total fertilizer weight (Figure 7.5).

Figure 7.5. Embodied energy in buildings, equipment and packaging for the production of phosphate fertilizers (MJ/kg P_2O_5). Sources: buildings and equipment adapted from ecoinvent Centre (2007, see text). Packaging from Helsel (1992)

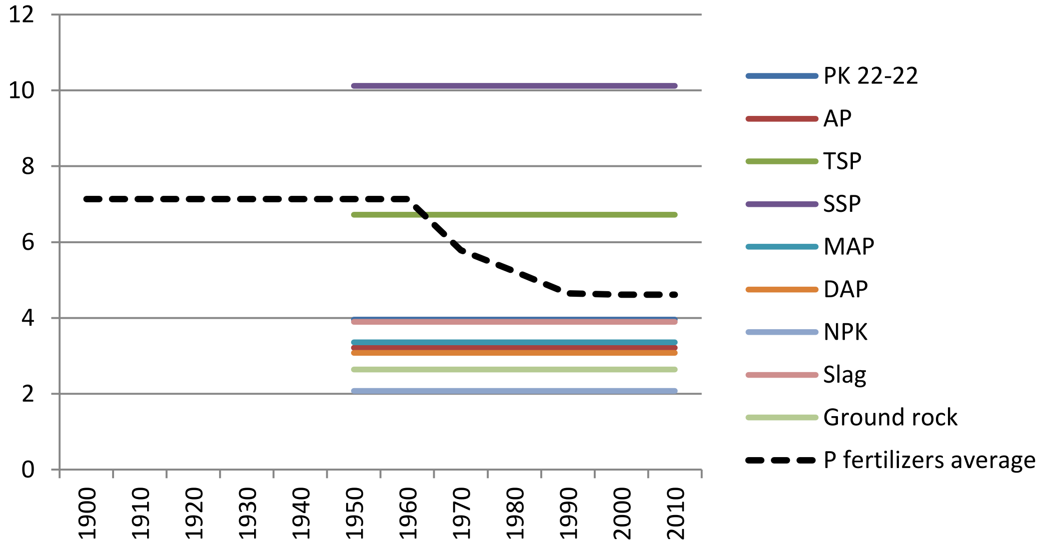


Figure 7.6 shows the relative share of different energy inputs to total energy requirements of average P fertilizers production in year 2000. Table 7.1 shows the historical evolution total energy requirements of all types of phosphate fertilizers considered. Further data, including NRE use, is provided in Appendix A6.

Figure 7.6. Energy inputs in all phosphate fertilizers considered, around year 2010 (MJ/kg P_2O_5). Own elaboration from various sources (see text).

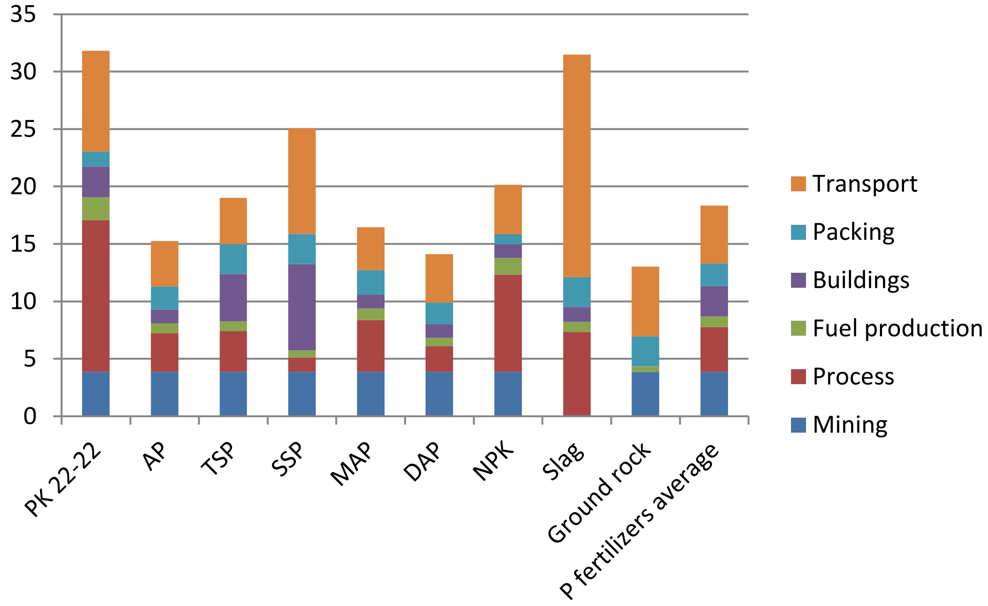


Table 7.1. Historical evolution of total embodied energy of phosphate fertilizers production, 1950-2010 (MJ/kg P_2O_5). Own elaboration from various sources (see text)

	1950	1960	1970	1980	1990	2000	2010
PK 22-22	107.1	77.5	61.9	49.2	41.3	36.2	32.1

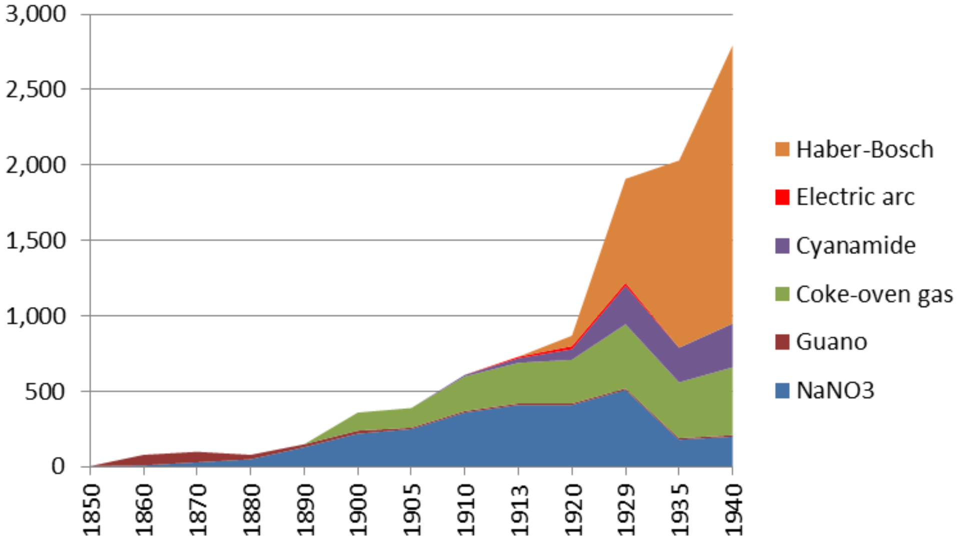
AP	45.6	33.6	27.4	22.4	19.3	17.1	15.4
TSP	56.6	41.6	33.5	27.4	23.4	21.0	19.1
SSP	59.4	42.3	35.9	30.4	27.8	26.3	25.2
MAP	50.5	37.5	30.5	24.8	21.2	18.7	16.6
DAP	40.8	29.7	24.3	19.9	17.4	15.6	14.2
NPK	71.5	52.3	41.3	34.1	28.2	23.8	20.3
Slag	55.8	34.6	31.8	28.1	29.2	30.5	31.7
Ground rock	20.6	14.0	13.1	12.0	12.3	12.7	13.1
P fertilizers average	56.8	40.0	32.9	27.0	23.5	20.4	18.5

7.2 Nitrogen

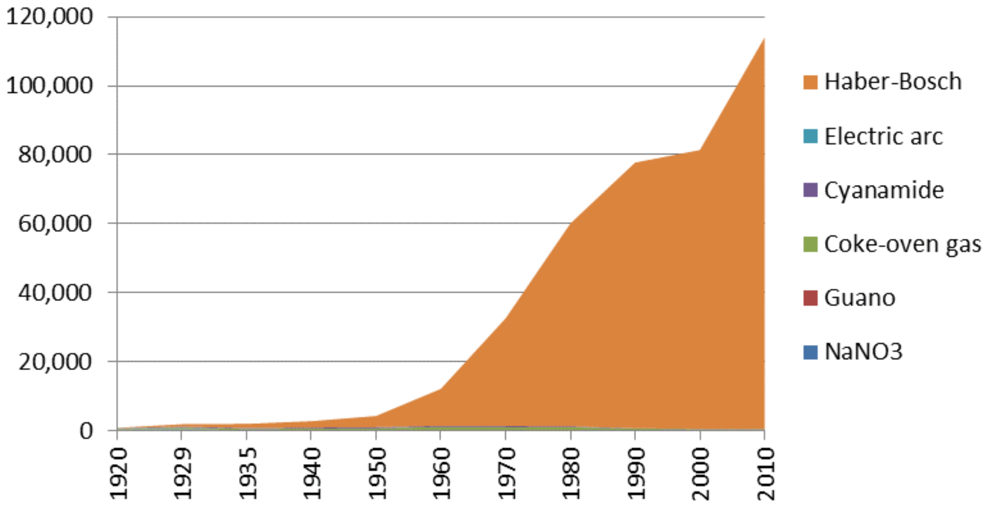
The artificial fixation of nitrogen and its industrial development has probably been one of the major events in agricultural history. As described by Smil (2004), the artificial fixation of nitrogen was being actively sought during the 19th Century, as the importance of this element for crop growth had being sufficiently proved by the research of Liebig and other chemists and by the field experience of many farmers that were applying high-nitrogen sources such as guano and Chilean Nitrate ($NaNO_3^-$). These commodities, however, were physically and geographically limited, which promoted the research in long-term-cultivated European countries to obtain alternative sources of reactive nitrogen. One method was the recovery of by-product ammonia from coking. Gas recovery coke ovens expanded in Europe since their first developments in 1860s, and represented significant fractions of total world supply of mineral nitrogen in the beginning of the 20th Century, although they never surpassed Chilean Nitrates (Figure 7.7). Ammonia production from coke ovens was limited by the low quantity of nitrogen contained in coal (1-1.6%) and by the inefficiency of the process, which only released 12-17% of the fuel nitrogen as ammonia.

Figure 7.7. Historical evolution of external nitrogen fertilizer production (Gg) between 1850 and 1940 (A) and between 1900 and 2000 (B). Source: Smil, 2004 for all data except 2010, which is from FAOSTAT (FAO, 2015)

A



B



We have not found any data to model the embodied energy of the early nitrogen fertilizers such as guano, saltpeter or ammonium sulphate obtained from coke production. Therefore, we have equated it to other processes reviewed. In the case of ammonium sulphate from coke production, we have used the same energy consumption than in the processing of Haber-Bosch N fertilizers, excluding ammonia synthesis. This assumption involves a relatively high energy consumption (despite much less than for ammonia synthesis at the time), which is in line with the fact that heat is needed to recover ammonia from coke oven gas. In the case of guano and saltpeter production, which are obtained by mining, we have used phosphate rock mining as the reference. To these figures we have added indirect energy consumption, buildings and packaging energy, and transport energy. Unlike the rest of agricultural inputs studied in this working paper, guano and sodium nitrate were assumed to be transported by water to Europe or North America, which meant a distance of ca. 16,000 km in the beginning of the century, which dropped to ca. 10.000 km after the opening of the Panama Canal in 1914. In order to simplify, we have allocated all guano embodied energy to nitrogen, despite it also contains phosphorus and potassium (see results in Appendix).

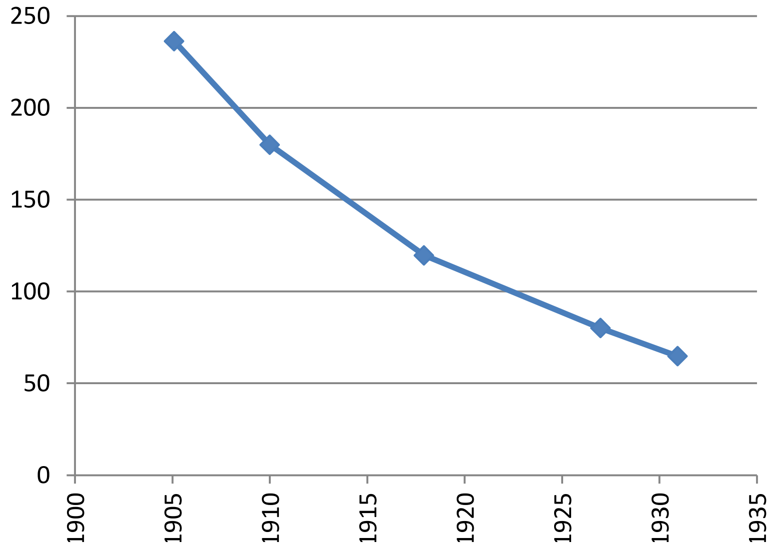
An obvious alternative to these limited nitrogen sources was to exploit the enormous stock of this element contained in the atmosphere. However, the task of breaking the triple bound of the N_2 molecule in order to make reactive nitrogen proved to be technically challenging; the first attempts, such as cyanamide and electric arc, which were developed in the first decades of the 20th Century, never surpassed 15% of global mineral nitrogen supply (Figure 7.7). We have modelled the evolution of cyanamide energy consumption based on the data in Jenssen and Kongshaug (2003) and Smil (2002), assuming a linear efficiency gain from 1900 to 1960 (see Appendix). We have assumed that 75% of the energy used in cyanamide production was thermal energy from coal and 25% was electricity.

The breakthrough discovery for ammonia synthesis was known as the Haber-Bosch process, which drastically reduced the energy need for ammonia production (Figure 7.8). Fritz Haber discovered a method to produce ammonia from its elements, nitrogen and hydrogen, using a catalyst under pressurized conditions. Then, Carl Bosch developed the process at the industrial and commercial scales at BASF facilities. With impressive technical accomplishments, the production was rapidly scaled up from the laboratory in 1909 to become the first global source of mineral N in the early 1930s (Figure 7.7). This rapid expansion was not only triggered by the demand of agricultural fertilizers, but also by the use of reactive N in explosives production. Thus, Haber-Bosch process had a major influence on both World Wars and subsequent conflicts (Erisman et al. 2008). It has been estimated that Haber-Bosch fixed N inputs to world croplands in 2010 were three times larger than biologically fixed N and four times larger than manure N inputs (Lassaletta et al. 2014). This nitrogen has been estimated to have feed 27% of the world population in the 20th Century, and 44% of the population in year 2000 (Erisman et al. 2008).

After first developments with coal, natural gas soon became the main source of H and energy for the process, and now 80% of ammonia production is based on natural gas. In 2006, gas represented more than 90% of ammonia feedstock in all world regions except China and India, where it represented 20% and 50%, respectively (IEA, 2007). The energy efficiency of NH_3 production increased rapidly (Figure 7.8) from more than 100 GJ/Mg N-NH_3 after the invention of the Haber-Bosch process to nearly 30 GJ/Mg N-NH_3 in modern plants (2006, Smil, 2004, Jenssen and Kongshaug, 2003), and there is still some potential for improvements (Rafiqul et al. 2005). Similar drops in energy requirements were reported by Ayres et al. (2003) for NH_3 production in the US.

Figure 7.8. Historical evolution of the energy efficiency of nitrogen fixation (GJ/Mg N) in 1905-1935 (A) and 1920-2000 (B). Dots in 1905 and 1910 represent nitric acid production by electric arc and calcium cyanide production, respectively; dots from 1917 onwards represent N fixation by Haber-Bosch process. Sources: (A) Jenssen and Kongshaug (2003); (B) Jenssen and Kongshaug (2003), Smil (2004), Dahmus (2014).

A



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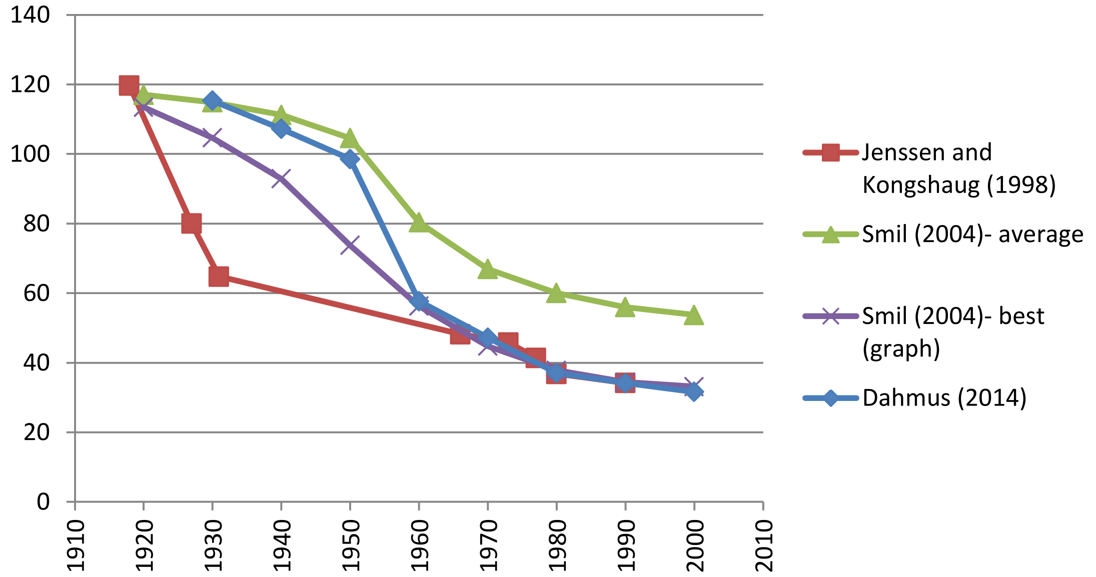
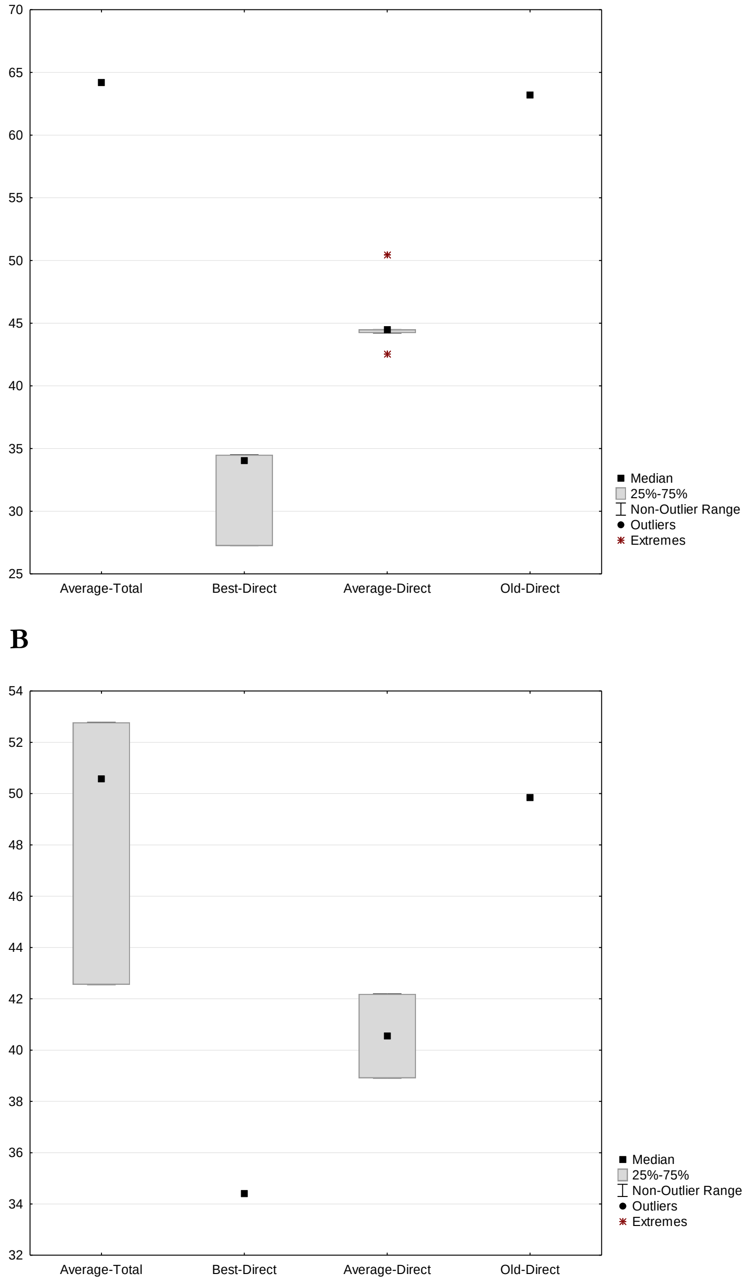


As can be observed in Figure 7.8.B, most estimations show a similar energy requirement of 110-120 GJ/Mg N-NH_3 around year 1920. The estimations differ up to about 1970, when both estimations on best available technologies show a similar value around 42 GJ/Mg N, while estimations on average technology are 10-20 MJ higher.

Around year 2000, energy efficiency of ammonia synthesis in best plants was reported to be 30+-3 GJ/Mg N-NH_3, while the world average direct energy consumption was about 44 GJ/Mg N-NH_3 (Figure 7.9.A). This value rises to about 63 GJ/Mg N when upstream energy consumption is also accounted for (Kool et al. 2012). In Europe, similar trends and lower absolute values can be observed (Figure 7.9.B).

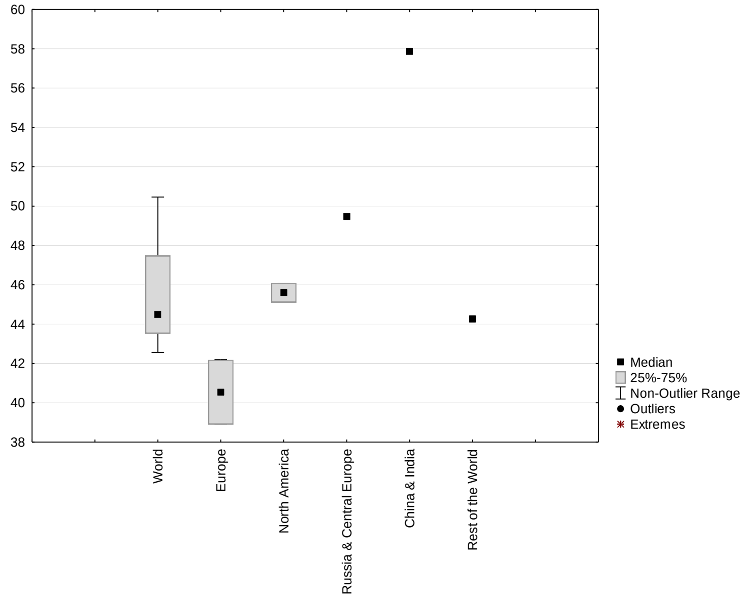
Figure 7.9. World (A) and Europe (B) direct and total energy use in ammonia production around year 2000 (GJ GE/Mg N-NH_3). "Old" represents average technology around 1970. Sources: Kool et al. (2012), Smil (2004), Nemecek et al. (2007), Jenssen and Kongshaug (2003), IEA (2007), Haas and van Dijk (2010), IFA (2009), Williams and Al-Ansari, 2007, Worrell et al. (2000), Bhat et al. (1994), Ramirez and Worrell (2006)

A



IEA (2007) conducted an extensive survey of ammonia plants around the world and provide average energy intensity values of ammonia production in different world regions. These values are plotted in Figure 7.10, together with other published values for the world, Europe and North America.

Figure 7.10. Direct energy use in ammonia production (GJ/Mg N-NH_3) in selected world regions around year 2000. Sources: Smil (2004), Nemecek et al. (2007), Jenssen and Kongshaug (2003), IEA (2007), Haas and van Dijk (2010), IFA (2009), Worrell et al. (2000), Bhat et al. (1994), Ramirez and Worrell (2006)

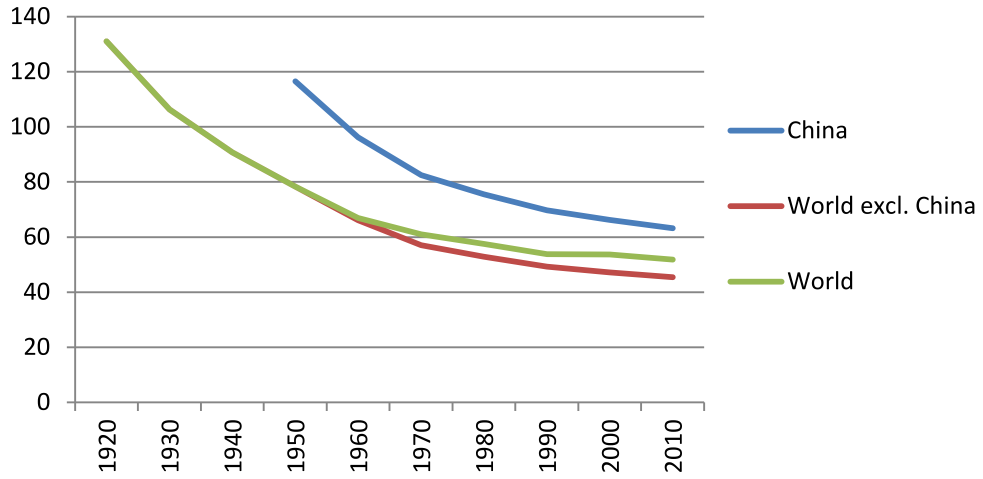


Steam reforming with natural gas as feedstock is the main technology employed in world ammonia production, although the partial oxidation process, which employs heavy fuel oil or coal as feedstock, are also common (Rafiqul et al. 2005). The latter process is more energy intensive, and this differences partially explain the variability between world regions shown in Figure 7.10, where coal-based ammonia production in China shows the highest energy intensity. The energy intensity can also be high in countries such as Algeria (Makhlouf et al. 2015).

Liquid ammonia is a dangerous and difficult to handle material. For this reason, and in order to improve its performance as fertilizer, ammonia undergoes further chemical and physical processes until obtaining commercial fertilizers. These processes involve energy consumption and, in some cases, also the consumption of other nutrients such as phosphoric acid and potassium for MAP, DAP and compound NPK fertilizer production. The energy required for these processes has also experienced significant reductions in the last decades, in some cases resulting in net energy exports (Ramirez and Worrell, 2006, Jenssen and Kongshaug, 2003). However, the composition of the mix of fertilizer types employed has also changed, and now more energy-intensive fertilizers like urea are more common (Ramirez and Worrell, 2006). The processing of ammonia may also involve significant greenhouse gas emissions as N_2O (in nitric acid production). Last, after being produced in commercial forms (usually granules), the resulting fertilizers have to be packed and distributed.

The energy consumed in NH_3 production was estimated based on different data sources. The work by Ramirez and Worrell (2006) probably represents the most comprehensive review of the evolution of energy consumption in world ammonia synthesis along the 20th century. Their estimated values are intermediate between other two long-term estimates available in the literature, Smil (2004) and Jenssen and Kongshaug (2003) (see Figure 7.8.B). However, the value offered for year 2000 is based on very few data points, and is much lower than the 2005 average world value provided in an extensive study conducted by IEA (2007) (42.6 and 50.5 GJ/Mg NH_3-N, respectively). China is the first global producer of NH_3 in the 21th century, with a share ranging from 33% to 39%, and the largest urea exporter. Energy use in ammonia production is very high in this country, where coal is the main ammonia feedstock. However, China was usually omitted in previous assessments of world ammonia energy consumption, and it significantly raises the world average in IEA study. Therefore, we corrected the series by Ramirez and Worrell (2006) taking into account the energy use of ammonia production in China. In order to simplify, we divided the world in two regions: China and the rest of the world. The latter was modeled as in Ramirez and Worrell (2006), extrapolating the 1990-2000 efficiency trend up to 2010. For China we took IEA (2007) data for 2005 and assumed the same efficiency changes as in the rest of the world.

Figure 7.12. Historical evolution of direct energy requirements of Haber-Bosch ammonia production, 1920-2010 (GJ/Mg NH_3-N). Source: Own estimation (see text)



The energy embodied in the raw materials used for ammonia production (Figure 7.13) was calculated based on our own estimations of the evolution of the energy intensities of fuels (see Section 4.2). We assumed that the fuel composition of ammonia production in China and the rest of the world were static along the studied period, with 70%, 20% and 10% of coal, natural gas and oil in China and 92% and 8% of natural gas and oil in the rest of the world. We also included the energy embodied in buildings (including equipment) and transport of raw materials to the ammonia plant. The energy in buildings and transport was assumed to be constant during the studied period.

Figure 7.13. Historical evolution of the energy embodied in the production and delivery of the raw materials/fuels required for ammonia production, in GJ/Mg NH_3-N. Source: Own estimation (see text)

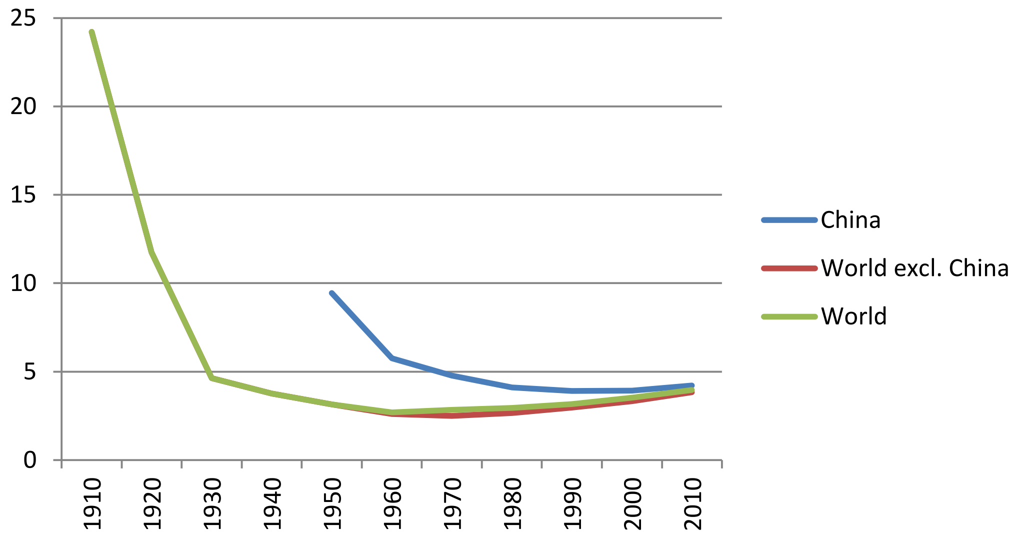
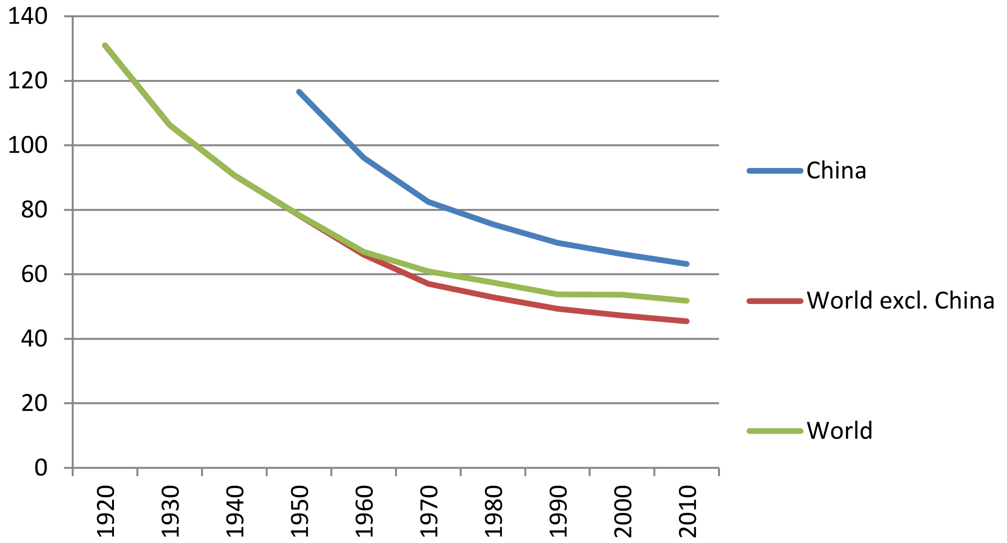


Fig. 7.14. Historical evolution of total energy use in ammonia production, per world region, in GJ/Mg NH_3-N (1920-2010). Source: Own estimation (see text)



Last, the changes in the energy employed in the manufacture of the commercial fertilizers was estimated based mainly in Ramirez and Worrell (2006), who reviewed the world trends in the energy efficiencies of the chemical reactions involved in the production of the final fertilizers. They derived average trends, to which we added the energy required for producing the primary fuels employed, assuming that all processes are based on natural gas. We also included the energy embedded in buildings (including equipment) using data from ecoinvent database (ecoinvent Centre, 2007), which represented 3-8 MJ/kg N. In the case of transport, we assumed our own standard distances and transport modes described in Section 4.2, scaling up the factors to take into account the other materials transported along with nitrogen. In the case of complex fertilizers, we allocated transport energy to each nutrient based on their relative weight. We also included packaging energy, estimated in 2.6 MJ/kg N (Helsel, 1992). The energy in buildings, transport and packaging was assumed to be constant during the studied period.

We extended the trends exponentially up to 2010. We did not estimate the trends in the individual fertilizers prior to 1960 because of the high uncertainty. We estimated AS energy intensity based on European data in Jenssen and Kongshaug (2002). In the case of MAP and DAP, we used Ramirez and Worrell (2006) data on ammonium phosphate (expressed as P_2O_5), and allocated to N and P_2O_5 based on the energy requirements, following ecoinvent (Nemecek et al. 2007). For NPK complex fertilizers, we assumed that the proportion of NPK1 (based on AN) and NPK2 (based on urea) depends on the proportion of AN and urea in world fertilizer production. We have also estimated a weighted average of energy use in fertilizer production taking into account the relative shares of each fertilizer in world production, as reported by FAOSTAT (FAO, 2015) (Figure 7.15). The results are shown in Figure 7.16.

Figure 7.15. Historical evolution of the relative share of the main N fertilizers in world fertilizer consumption. U: Urea; NPK: Complex fertilizers; CAN: Calcium-Ammonium Nitrate; AS: Ammonium sulfate; DAP: Di-ammonium phosphate; MAP: Mono-ammonium phosphate; AN: Ammonium nitrate. Source: FAOSTAT (FAO, 2015)

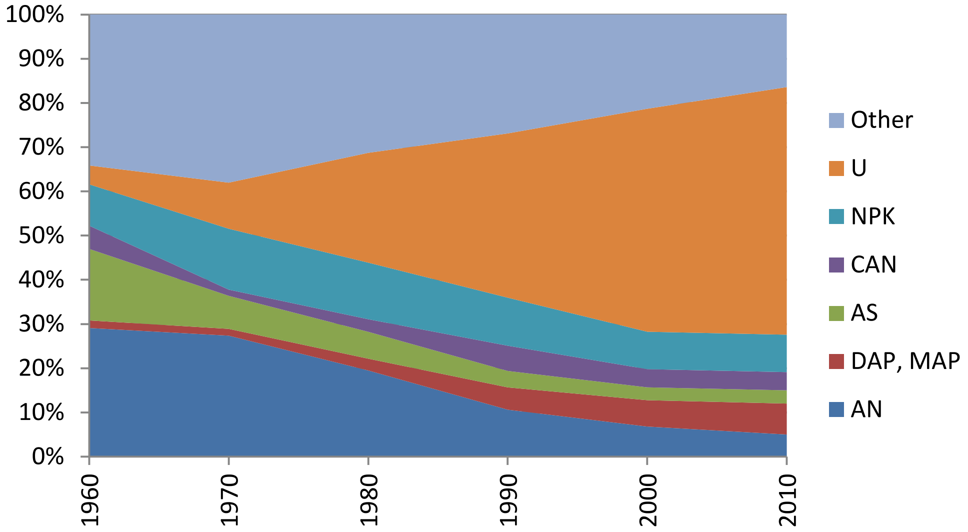
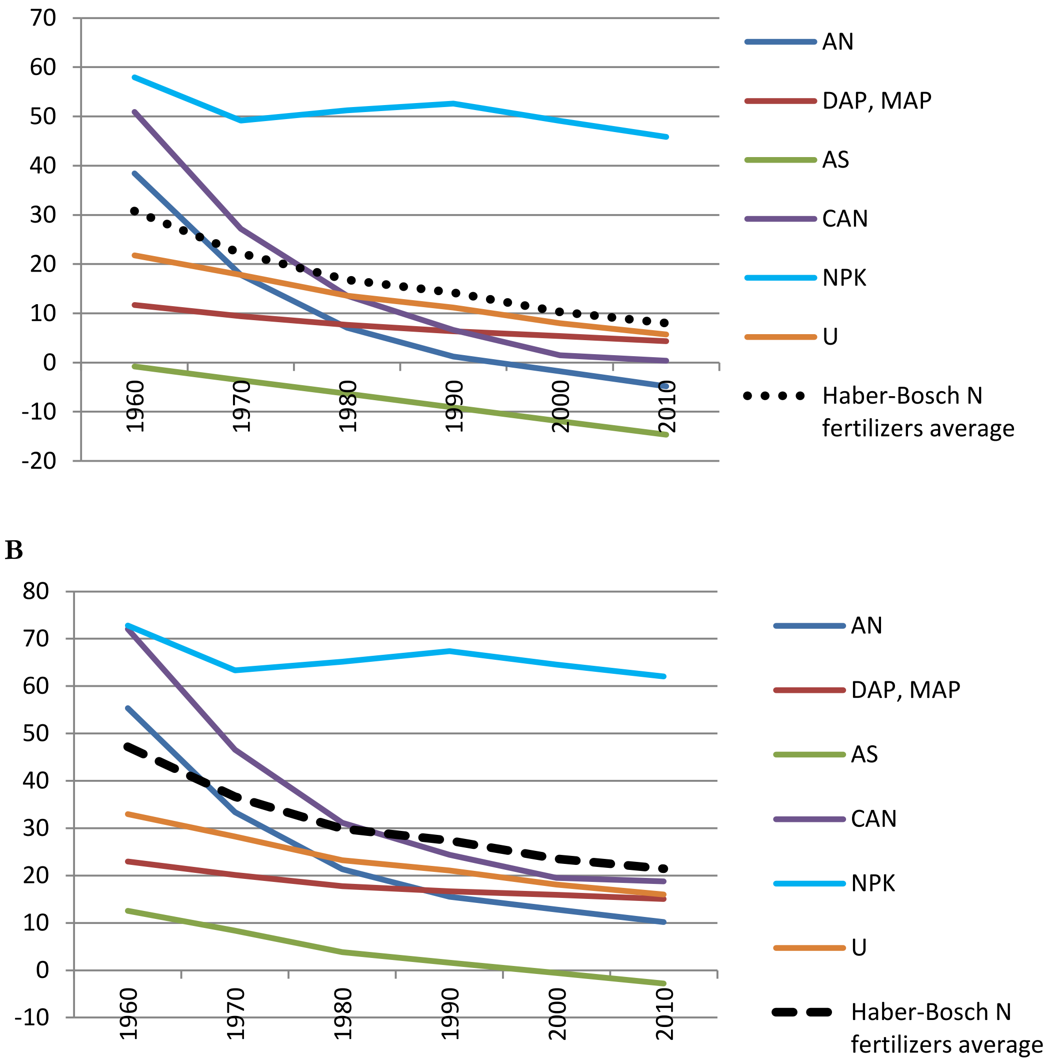


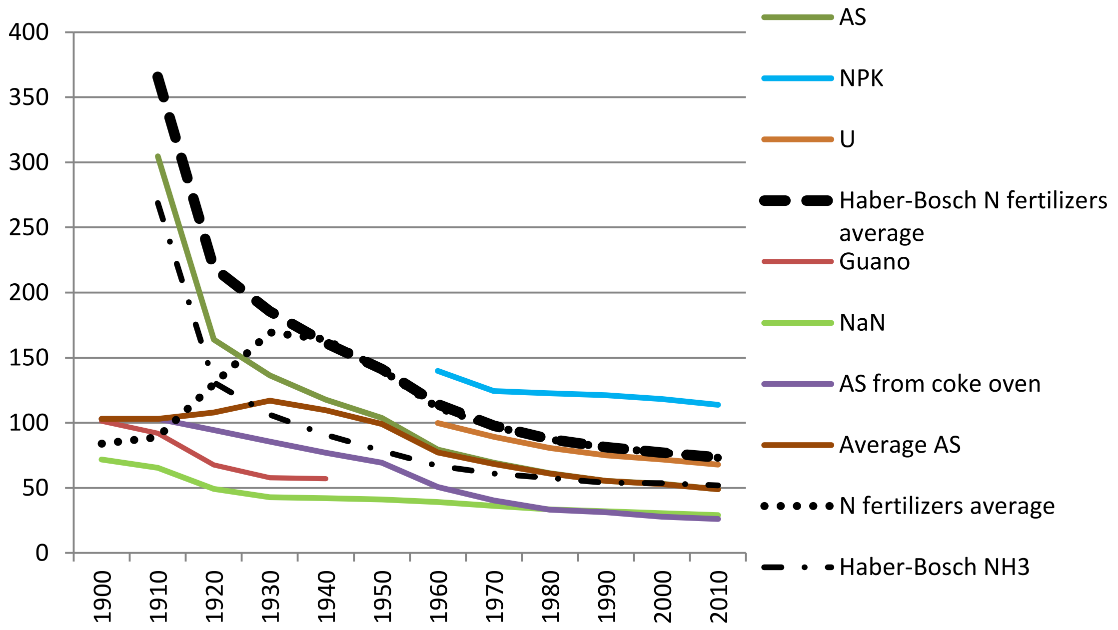
Figure 7.16. Historical evolution of the direct process energy requirements for the production of N fertilizers (A), and of total embodied energy in the production of N fertilizers (B), excluding NH_3 energy, 1950-2010 (GJ/Mg N). U: Urea; NPK: Complex fertilizers; CAN: Calcium-Ammonium Nitrate; AS: Ammonium sulfate; DAP: Di-ammonium phosphate; MAP: Mono-ammonium phosphate; AN: Ammonium nitrate. Source: Own estimation (see text)

A



Some fertilizers show negative values because they export energy from exothermic chemical reactions (Figure 7.16.A). Most of these energy credits are compensated by the energy consumed by buildings, transport and packaging (Fig. 7.16.B). The majority of fertilizer energy, however, is from ammonia production. Figure 7.17 shows total energy use in N fertilizers production.

Figure 7.17. Historical evolution of total embodied energy of selected N fertilizers and NH_3 (1900-2010), in GJ/Mg N. U: Urea; NPK: Complex fertilizers; CAN: Calcium-Ammonium Nitrate; AS: Ammonium sulfate; DAP: Di-ammonium phosphate; MAP: Mono-ammonium phosphate; AN: Ammonium nitrate. Source: Own estimation (see text)



We can identify a trend towards increased energy efficiency in most of the studied fertilizers. However, the weighted average trend during the first decades of the 20th century suggest an increasing energy consumption due to the transition from mining and sub-product sources of N to artificially fixed sources, which were still very inefficient at this time. We must acknowledge, however, the high uncertainty of our estimations during this early period, particularly regarding to transport distances and efficiency assumptions. On the other hand, the rate of efficiency gain of Haber-Bosch ammonia is very high during the first half of the studied period but is greatly reduced from around 1970, as some of the efficiency gains in ammonia production are offset by increases in feedstock production energy and the shift to more energy-intensive production countries (China). This stagnation indicates that a major part of efficiency gains were obtained in latter phases of fertilizers production process. In the period prior to 1960 the uncertainty is very high. The relative contribution of each stage is shown in Table 7.2.

Table 7.2. Historical evolution of energy use in Haber-Bosch NH_3 and N fertilizers production, 1900-2010 (GJ/Mg N). Own estimation from various sources (see text)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Direct energy NH_3		243	118	100	86	74	63	57	53	49	49	47
Total embodied energy NH_3		269	131	106	91	78	67	61	57	54	54	52
Total embodied energy Haber-Bosch N fertilizers		366	219	186	161	141	114	98	87	81	77	73
Total embodied energy N fertilizers	84	89	130	170	164	141	111	97	87	81	77	73

We have estimated the regional and world average energy consumption of the most common N fertilizers based on our estimated averages of ammonia energy consumption in Europe and the world, and in IEA (2007) data for the remaining regions. Indirect energy use in ammonia and commercial fertilizers production was added to these values, and was estimated as explained above.

These data are only estimated for around year 2000, as the uncertainty in previous periods is very high due to lack of specific data of the evolution of each type of N fertilizer in each region of the world (Table 7.3).

Table 7.3. Estimated embodied energy of different types of N fertilizers in world regions around year 2000, from cradle to store (MJ/kg N). Sources: own estimations based on IEA (2007) and own calculations.

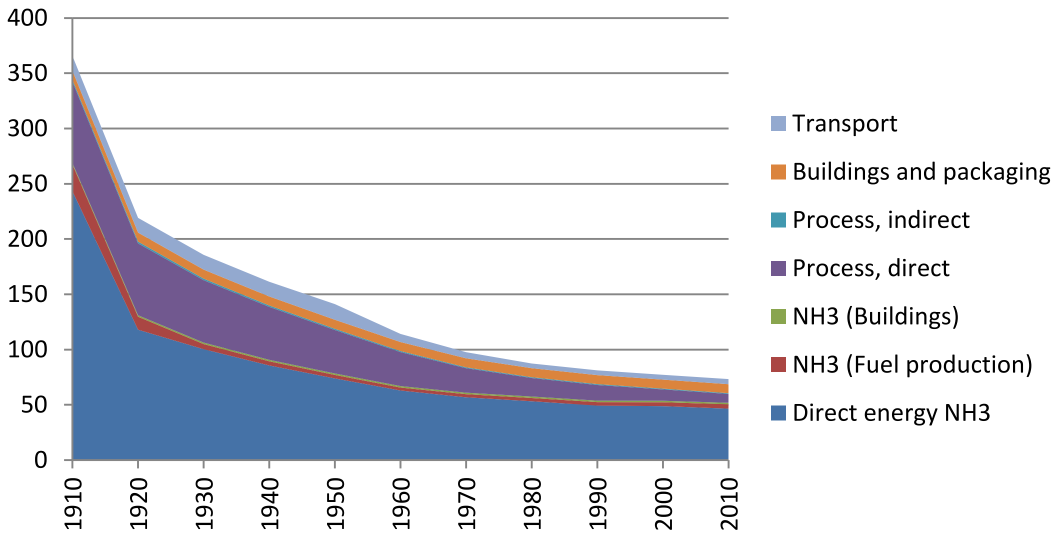
	World	**World Excl. China**	**Europe**	**North America**	**Russia + Central Europe**	**China + India**	**ROW**
NH_3 (direct)	49	43	41	46	49	61	44
NH_3 (total)	54	47	45	51	55	66	49
N fertilizers (average)	77	70	68	75	78	89	73
AN	66	60	50	57	74	79	54
DAP, MAP	69	63	61	67	71	82	65
AS	52	46	44	50	54	65	48
CAN	73	66	64	71	74	85	69
NPK	118	111	109	116	119	130	114
UAN	69	62	60	66	70	81	64
U	71	65	63	69	73	84	67

Last, we provide a series showing the evolution of world average energy consumption in N fertilizer production (Table 7.4). This series is general for all types of fertilizer prior to 1960, and neither distinguishes between world regions because, as already explained, we have not found information on the region-specific and fertilizer-specific evolution of energy efficiency. This series could be adapted to specific regions using data from Table 7.3 if the authors of case studies consider it necessary. We also show graphically the evolution of all components of synthetic N fertilizers embodied energy (Figure 7.18). All data can be found in Appendix A5.

Table 7.4. Historical evolution of world average embodied energy of the most common N fertilizers 1910-2010, from cradle to store (GJ/Mg N). Source: own estimation (see text).

	1910	**1920**	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**
AN						122	94	79	69	66	62
DAP, MAP						90	81	75	70	70	67
AS						80	69	61	55	53	49
CAN						139	108	89	78	73	71
NPK						140	124	123	121	118	114
U						100	89	81	75	72	68
N fertilizers average	366	219	186	161	141	114	98	87	81	77	73

Figure 7.18 Historical evolution of total embodied energy of world average Haber-Bosch N fertilizers production, 1910-2010 (MJ/kg N). Own estimation from various sources (see text)



7.3 Potassium and other fertilizers

Potassium is an essential nutrient of plants. Its main biological role is the regulation of the electrochemical and osmotic potentials across the cell membrane. This element is a chemically reactive metal, which is always found in combination with other elements. Soils are usually rich in potassium, but most of it is bound in insoluble mineral forms and not available to plants, even if the extent of this availability has recently been questioned (Khan et al. 2014).

Potash fertilizers include many K-bearing minerals, of which the most important is potassium chloride (KCl), also known as muriate of potash (MOP). Other potash fertilizers include potassium sulfate [K_2SO_4, or sulfate of potash (SOP)], potassium-magnesium sulfate (K_2SO_4•$MgSO_4$, or sulfate of potash magnesia), potassium nitrate (KNO_3, or saltpeter), and mixed sodium-potassium nitrate ($NaNO_3$+ KNO_3, or Chilean saltpeter).

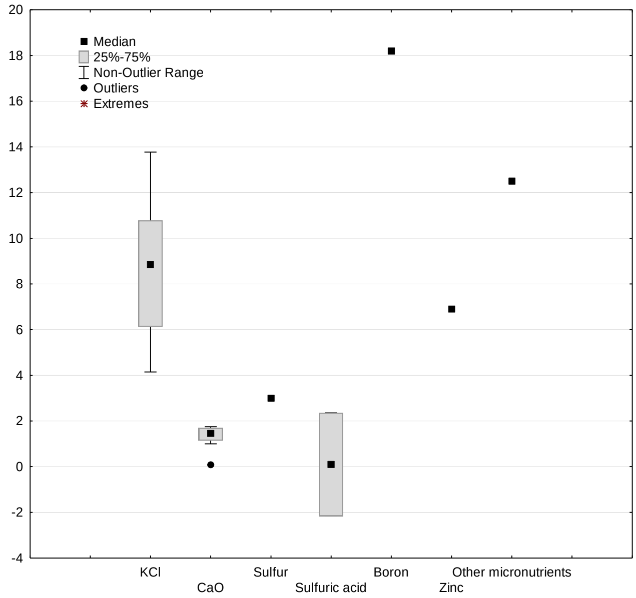
First sources of potash were organic. Potash was made boiling wood ash and used for making glass and soap. The first mines of potash were opened in Germany in 1861. Mine sources allowed a larger scale and a higher K content in the final product. This situation, combined with the spread of recent Liebig's theories on mineral crop nutrition, promoted the start of the use of potash as fertilizer, although it was slow to develop. The supply of potash was cut off in many countries during World War I, triggering an intensive search for potash in North America and Europe. In the following decades, the industry was developed in the US, Soviet Union, Canada and several other countries (Russell and Williams, 1977, Darst, 1991, Ciceri et al. 2015). However, industrial uses still prevailed, and the use of potassium as fertilizer really took off in the 1960s with the development of Canadian mines (Khan et al. 2014).

Most potash is found in sedimentary deposits and extracted from underground mines, usually several hundred meters belowground. Some potash is produced from evaporation of brines. Potash ores usually contain high amounts of NaCl, for example sylvinite ore, which is the main source of muriate of potash. NaCl can be removed with wet or dry methods, and then dumped to open-air piles. Potash fertilizers are more the product of physical rather than chemical processes (Russell and Williams, 1977).

Potash fertilizer consumption was about 8 Tg (expressed as K_2O-equivalent) in 1961 and reached about 34 Tg in 2011 (Park, 2001, IFA, 2014, FAO, 2015).

Energy use in potash production includes mining and processing of the ores, as well as packaging and transport of the final products. Figure 7.19 shows the range of published values of the energy intensity of potash production, as well as of the production of other fertilizers or building blocks such as lime, sulfur, sulfuric acid and micronutrients.

Figure 7.19. Dispersion of published values of energy intensity of the production of potash and other fertilizers. Sources: Nemecek et al. (2007), Ledgard et al. (2011), Jenssen and Kongshaug (2003), Shapouri et al. (2002), Wang et al. (1997), Lockeretz (1980), Dovring and McDowell (1980), Terhune (1980), Pimentel (2003), Patzek (2004), Nielsen et al. (2003), Audsley et al. (2003), Leach (1976), Helsel (1992), Bhat et al. (1994), Ramirez and Worrell (2006)



The variability is relatively high for potash fertilizers and lower for lime (CaO). Sulfuric acid production can consume or produce energy depending on the recovery of steam. All other reviewed nutrients are represented by only one value, taken from Helsel (1992).

The energy efficiency of potash fertilizer production in the US did not increase in the 1979-1987 period despite high energy prices (Bhat et al. 1994). However, Ramirez and Worrell (2006) report a decrease in the world average energy use in potash fertilizer production during the 1960-2001 period. We have estimated the evolution of the energy use in potash production based on the data in Ramirez and Worrell (2006) and extrapolating the trends up to 1900 and 2010. We have distinguished simple potash fertilizers (primarily KCl) from complex fertilizers using the 1960-2012 data on world total potash fertilizer consumption in FAOSTAT (FAO, 2015) (Figure 7.20) and our own estimation of complex potash fertilizer use, based on the average of complex N and P fertilizers (Figure 7.21).

Figure 7.20. Historical evolution of the global production of potash fertilizers, categorized in NPK compound fertilizers and KCl fertilizers and expressed a K_2O equivalents (Tg K_2O). Sources: own elaboration from FAOSTAT (FAO, 2015) data.

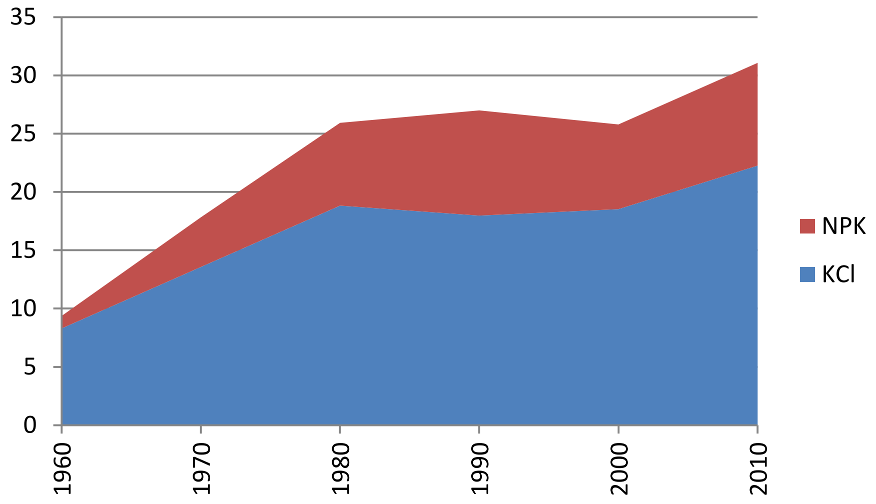
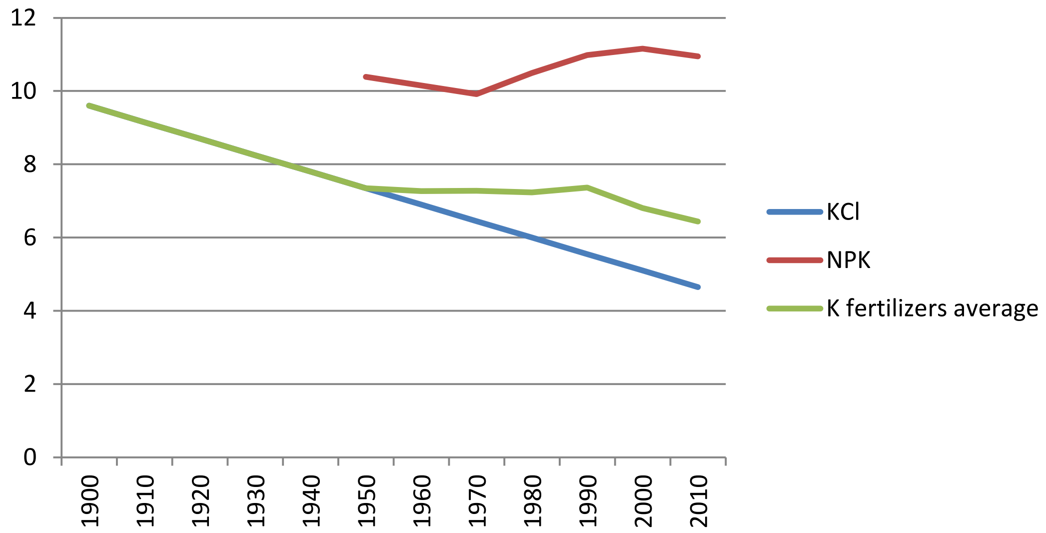


Figure 7.21. Historical evolution of mining and process direct energy requirements of potash fertilizers, 1950-2010 (MJ/kg K_2O). Source: own elaboration from the data in Ramirez and Worrell (2006)

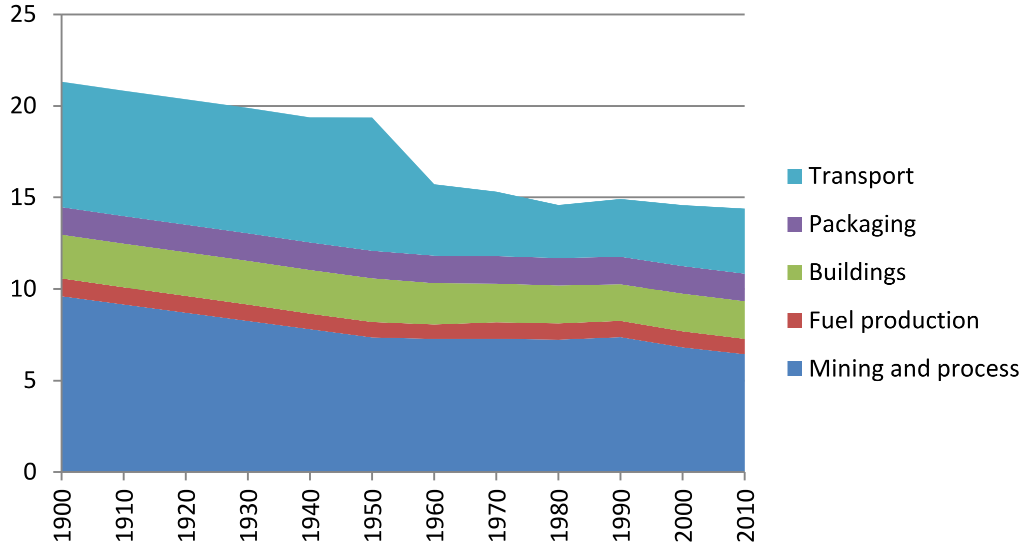


To the direct energy used in potash fertilizers production we have added the energy consumed in fuels production, buildings and equipment, packaging and transport. Fuel production energy has been estimated using our own coefficients (Section 4.2), and assuming that the energy mix of potash fertilizers production is similar to the world primary energy mix. Buildings and equipment energy has been obtained from ecoinvent database (Nemecek et al. 2007). Packaging energy has been obtained from Helsel (1992) and corrected for the relative mass represented by potash in complex fertilizers. Transport energy has been estimated using our own assumptions for agricultural inputs transport distances and modes (Section 13), taking into account the relative weight represented by potash. All data is shown in Appendix, and the total values are shown in Table 7.5. We also include a graph showing the evolution of the different components of total embodied energy of average K fertilizers (Figure 7.22).

Table 7.5. Historical evolution of total embodied energy of potash fertilizers, 1900-2010 (MJ/kg K_2O). Source: own elaboration from the data in Ramirez and Worrell (2006)

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
KCl	21.3	20.8	20.4	19.9	19.4	19.4	15.3	14.4	13.3	13.0	12.7	12.4
NPK						24.0	19.0	18.2	18.0	18.8	19.4	19.4
K fertilizers average	21.3	20.8	20.4	19.9	19.4	19.4	15.7	15.3	14.6	14.9	14.6	14.4

Figure 7.22 Historical evolution of total embodied energy of world average K fertilizers production, 1900-2010 (MJ/kg N). Own estimation from various sources (see text)

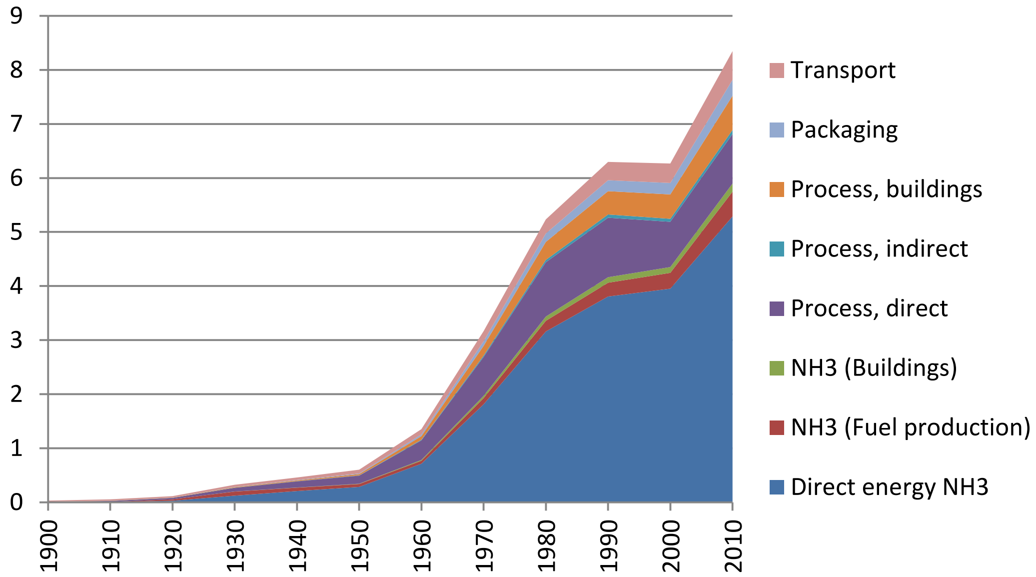


7.4 Energy use in world fertilizers production

Our reconstruction of the energy use in fertilizers production and total use of fertilizers allows us to estimate the historical evolution of the energy use in world fertilizers production. These data are shown in Figure 7.23, while Figure 7.24 shows the relative contribution of fertilizers production to total world energy use.

Figure 7.23. Historical evolution of total energy use in nitrogen (A), phosphorus (B), potassium (C) and total (D) fertilizers production in the world, 1910-2010 (EJ). Own elaboration (see text)

A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Process, direct
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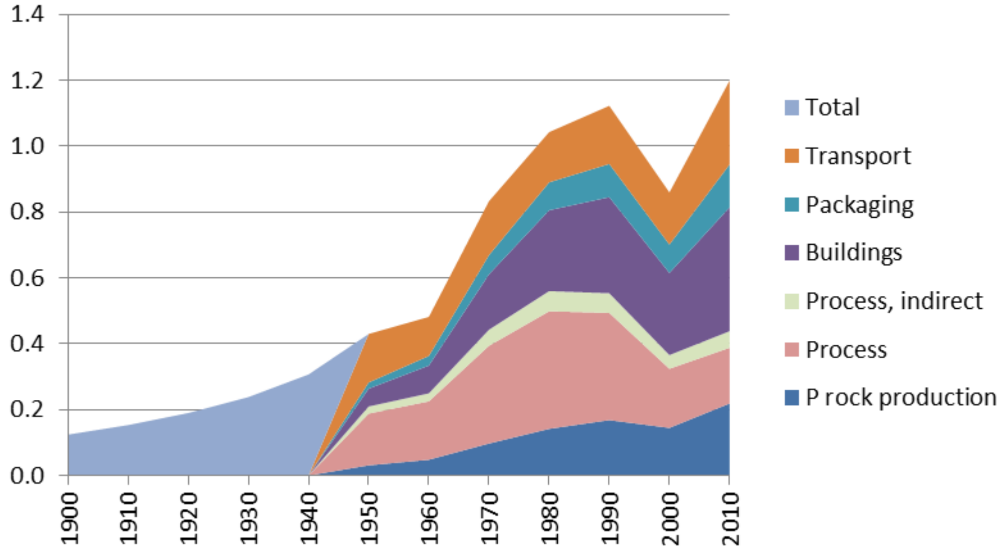
NH3 (Fuel production)
Direct energy NH3

B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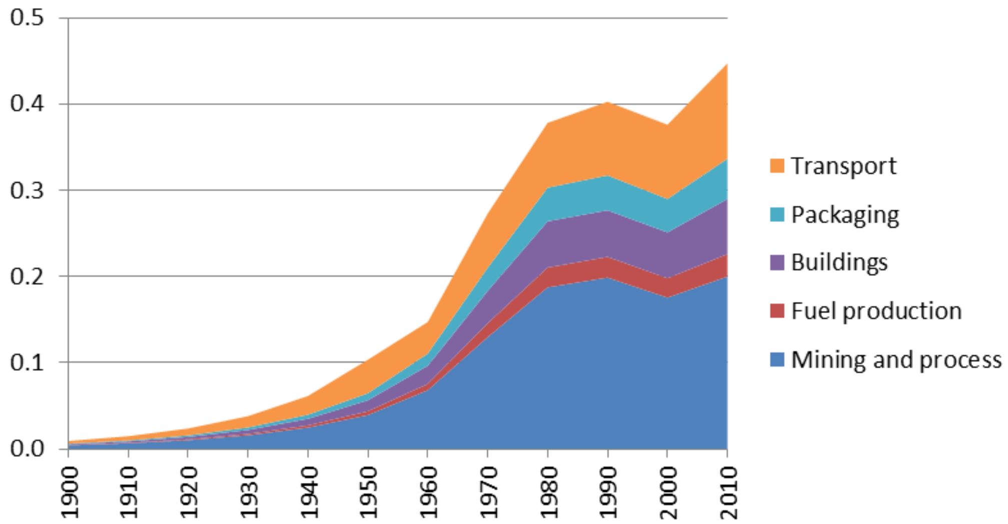


D

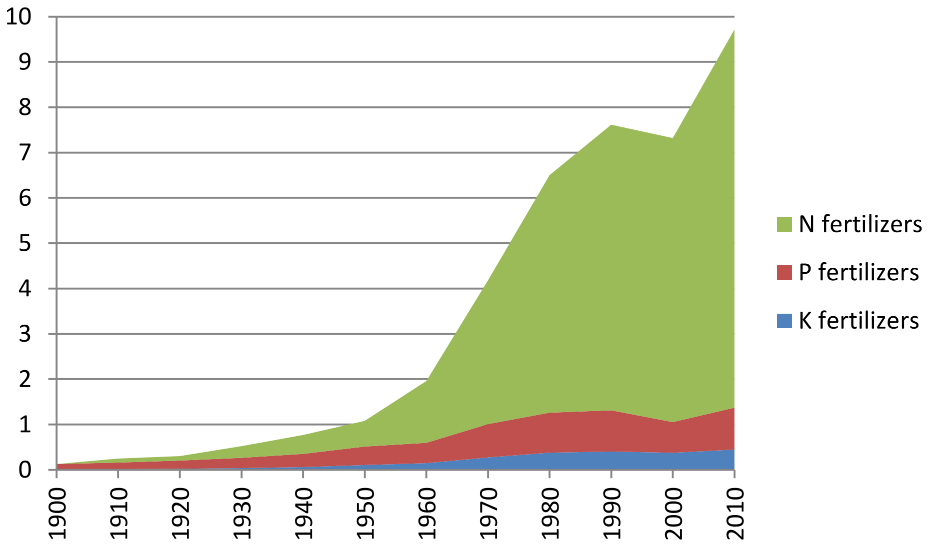
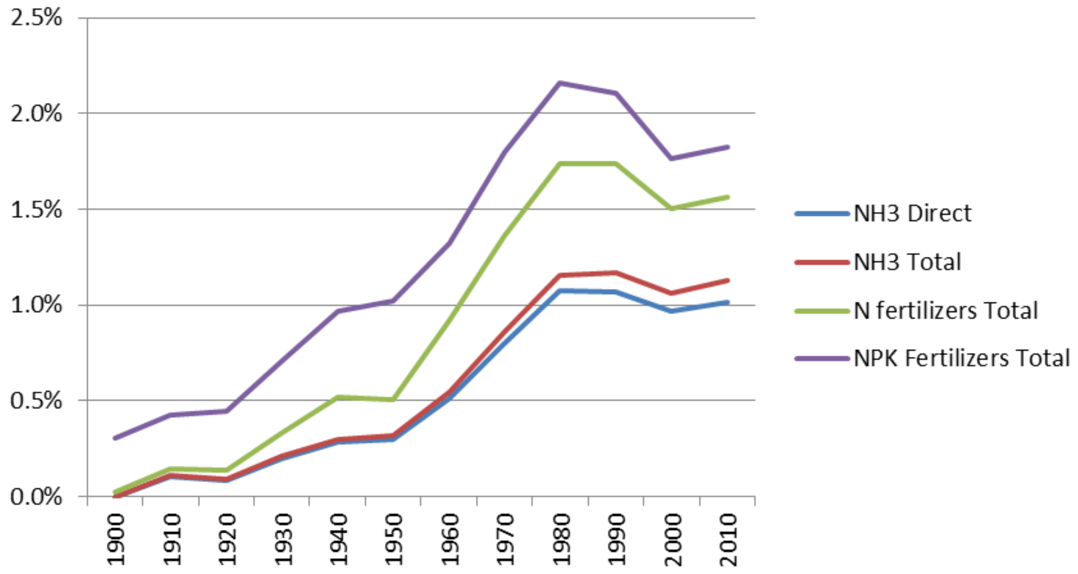


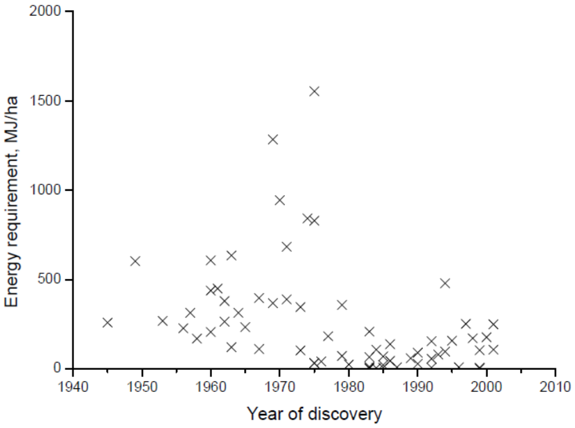
Figure 7.24. Historical evolution of the relative share of fertilizers production in world energy consumption, 1910-2010 (%). Own estimation from various sources (see text).



6.5 Pesticides

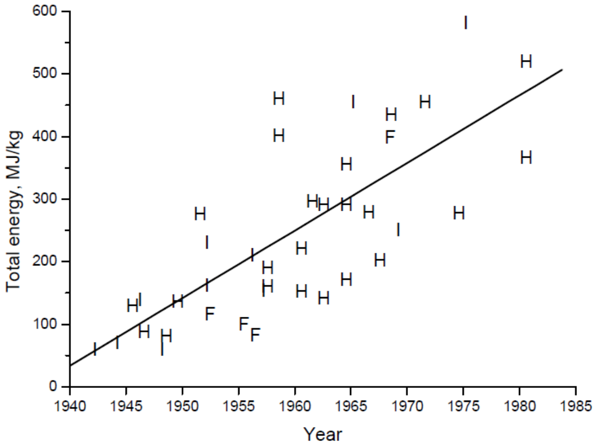
Pesticide use in agriculture has been recorded since ancient times (Taylor et al. 2007). Some of these pesticides include compounds based on sulfur, arsenic salt or plant extracts. The interest on new types of pesticides grew in the modern era. Since the 17th Century, new plant extracts such as rotenone or tobacco appeared, and in the 19th Century the interest was renewed based on new needs and on the new knowledge in biology and chemistry. Thus appeared pesticides such as pyrethrum, derris, copper sulfate solutions, Paris Green (a copper-arsenic mixture), Bordeaux mixture (a mixture of copper sulfate and hydrated lime) and petroleum oils. Stronger pesticides, such as those based in lead-arsenate or organic mercury compounds, expanded in the late 19th and early 20th centuries, triggered by the development of spraying methods. Lead arsenate was the first insecticide to be applied aerially, in 1921. The production of modern pesticides started in the 1930s with the first synthetic organic chemicals, and remarkably with the discovery and expansion of DDT use as insecticide. As Taylor et al. (2007) put it, World War II served as a spring-board for the modern agricultural-chemical industry. It became the basis for the development of a wide range of new pesticides including DDT and other organochlorine compounds, parathion and other organophosphorus compounds, and phenoxi herbicides such as 2,4-D. These were followed by a large expansion of the quantity and diversity of synthetic pesticides in the 50s and 60s. In the 60s and 70s, unintended environmental and health impacts of pesticides were discovered. During the middle decades of the 20th century, large changes occurred in the amount and types of pesticides used (Pimentel, 1987). New regulations responded to environmental and health concerns about early pesticides, particularly chlorine insecticides and phenoxi herbicides. Therefore, new pesticides were developed and rapidly adopted by farmers. These pesticides usually required more energy to be produced and were used in larger quantities per hectare. Therefore, the energy associated to pesticide use grew substantially (Pimentel, 1987). This trend, however, reversed in the 1980s: in the following decades the recommended application doses of most pesticides decreased, resulting in decreased pesticide energy consumption per hectare despite higher production energy costs of the new pesticides (Audsley et al. 2009, Figure 7.25)

Figure 7.25. Total energy requirements (MJ/ha) of pesticides active matter applied at recommended rates against year of discovery. Source: Audsley et al. (2009)



However, there is little information regarding the changes in the energy efficiency of the production of each type of pesticide, especially for new pesticides which production methods are protected by patent rights and that have been subject to little or no academic research. In fact, as noticed by Audsley et al. (2009), the works of Green (1987) and Green and McCulloch (1976) have virtually been the only basis for assessing pesticide energy use and environmental impacts; all subsequent assessments can be traced to these works (e.g. Pimentel, 1980, Bhat et al. 1994, Audsley et al. 2003, West and Marland, 2002, Alonso and Guzmán, 2010). This happens even in the widely used for LCA ecoinvent database (Nemecek et al. 2007), where the life cycle inventory of most pesticides is based on the data of Green (1987). Therefore, we also propose following Green (1987) for the calculation of pesticide energy inputs. However, all the above cited references follow an extrapolation approach for pesticides not included in Green (1987) that is based on grouping pesticides per chemical family or, if this is also absent in Green's database, based on use type (herbicide, insecticide, fungicide). Despite the wide adoption of this approach, however, Audsley et al. (2009) analyzed Green (1987) data, noticing that chemical families or use types did not explain the variability in pesticide energy requirements. They also found that steps in the production of pesticides or their molecular weights were neither good predictors of pesticide energy requirements. On the contrary, they found a good correlation ($r^2 = 0.57$) between the year of market release of the pesticide and its energy requirements (Figure 7.26). Thus, they constructed an approach for the estimation of modern pesticide energy requirements based on a regression with the date of first reporting.

Figure 7.26. Total energy requirements of pesticide active matter production (Green, 1987) versus date of first reporting. H: herbicide; F: fungicide; I: insecticide. Regression line: $E = -399 + 10.8\,(Y-1900)$, $r^2 = 0.57$. Source: Audsley et al. 2009



This approach has been followed in this work to provide a 1940-2010 reconstruction of pesticide energy requirements. All disaggregated data is shown in Appendix A8. Three series are shown in Table 7.6: one of the energy requirements of active ingredient production of new pesticides released in each period, another for new pesticides but including formulation, packaging and transport energy, and another one of the estimated total energy requirements of the pesticides actually used in each period. The latter is based on the assumption that pesticides used in a given period are an even mixture of the pesticides released in all the previous decades. An estimated energy consumption of 22 GJ/kg for formulation and packaging (Green, 1987) has been added to the energy requirements of active matter production to calculate total pesticide embodied energy. Transport energy has also been added using our own generic assumptions of distances and transport modes (Section 13), taking into account that the total transported weight does not only include the active ingredient, but also the other components of the formulation. We assumed 20% average content of active matter. For the estimation of non-renewable energy, we assumed a constant contribution of 97.5% of NRE to pesticide energy requirements (excluding transport), based on the average of NRE use of all pesticides included in ecoinvent (Nemecek et al. 2007) (Appendix A8).

Table 7.6. Historical evolution of the embodied energy of newly released and average used pesticides (MJ/kg active ingredient). Sources: Audsley et al. (2009) (active ingredient of new pesticides), Green (1987) (formulation and packaging), and own elaboration (all other series)

	1940	1950	1960	1970	1980	1990	2000	2010
New pesticides								
Active matter	33	141	249	357	465	573	681	789
Formulation+Packaging	22	22	22	22	22	22	22	22
Transport	21	21	22	11	10	8	9	9
Total	76	184	293	390	497	603	712	820
Average used pesticides								
Active matter	33	87	141	195	249	303	357	411
Formulation+Packaging	22	22	22	22	22	22	22	22
Transport	21	21	21	19	17	15	14	14
Total	76	130	184	236	288	340	393	447

We also provide a table compiling all openly published values of individual pesticides (Appendix A8). The values are taken from Green (1987) if the compound is included in that publication. Otherwise they are taken from other references which are also based on Green (1987), in this order of preference: Bhat (1994), Pimentel (1980), Audsley et al. (2009) and Alonso and Guzmán (2010). We do not provide average values for general types of fertilizers sorted by use (herbicides, fungicides, etc.) because, as shown by Audsley et al. (2009), the type of use is not a good predictor of pesticide energy requirements. Instead, we propose that if the pesticide under study is not included in the table in Appendix A8, its energy could be estimated based on its release date, following the equation in Audsley et al. (2009) ("New pesticides" in Table 7.6). If this information is neither available, the average production values for used pesticides in each period could be used ("Average used pesticides", Table 7.6).

8. Organic inputs

8.1 Manure

Accounting for manure energy strongly depends on system boundaries. In mixed farms where all manure is used on site, this material is clearly a reuse of biomass within the system. Modern livestock production generates high quantities of manure that is stored and then exported to more or less nearby farms. Manure movements through the territory imply that it becomes an input to other farming systems. The energy employed in animal production is usually excluded from manure embodied energy, as it is allocated to the animal products (meat, milk, eggs, wool, draught work). On the other hand, transport of the manure to the farm (see Section 13 for specific coefficients) is usually very relevant due to the high quantities to be transported.

Manure, as other organic materials, is a renewable, energy-rich material, and also nutrient-rich and carbon-rich, which performs numerous ecological functions in the soils. Two methods for estimating this energy are considering the gross energy of manure or the energy value of its major nutrients (González de Molina and Guzmán Casado, 2006). The gross energy of manure is mainly dependent of its dry matter content. This value can range widely from less than 10% in liquid slurries to 80% in air-dried manures in warm areas or seasons. Gross energy content (HHV) of manure dry matter ranged 11.9-19.4 MJ/kg in a set of manures and manure mixtures of various species (Choi et al. 2014, Table 8.1)

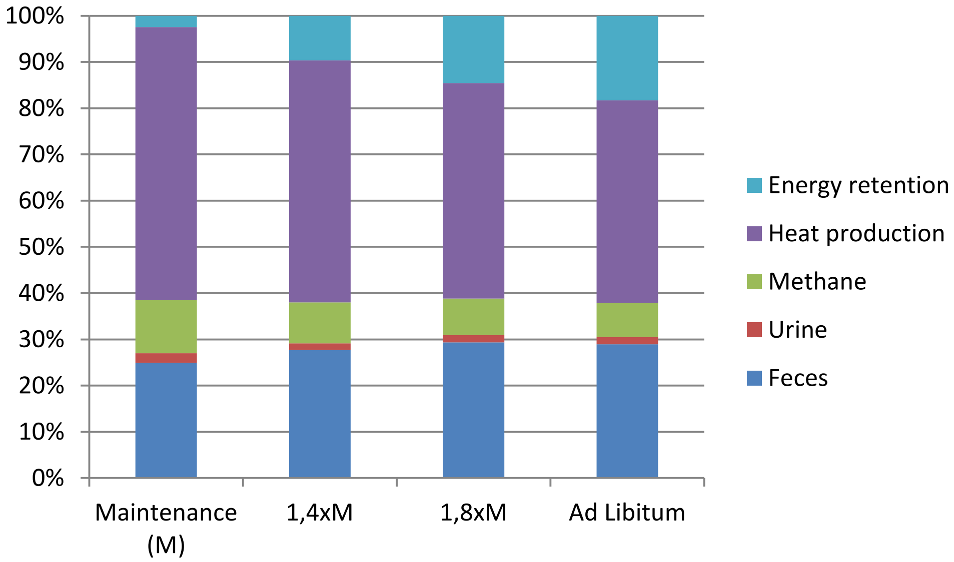
Table 8.1. Average dry matter content and gross energy (HHV) of different manure and manure mixtures. Source: Choi et al. 2014.

	% Dry matter	HHV (MJ/kg)
Beef cattle manure	24.4%	16.1
Dairy manure	26.7%	16.6
Beef cattle manure mixture	70.5%	14.9
Dairy manure mixture	70.2%	14.2
Pig manure	8.7%	19.4
Layer manure	31.4%	11.9
Broiler manure mixture	81.5%	17.9

Duck manure mixture	48.2%	12.4

Another method for calculating the gross energy of the manure is based on the energy balance partitioning of livestock animals. Starting from gross and metabolizable energies in feed, we can estimate the amount of energy that is rejected as feces (the non-metabolizable fraction of the gross energy) and methane, and the energy that is metabolized into retained energy, heat, and urine (Figure 8.1). The application of this method involves the risk of double counting. A possible solution is to calculate the energy embodied in livestock products (meat, milk, eggs, wool…) and livestock work considering just the metabolizable energy of the feed, not its gross energy.

Figure 8.1. Energy partitioning of gross energy intake by Brahman cattle in the tropics, with various levels of energy intake. Source: Chaokaur et al. (2015)



Fresh manure energy would correspond to the sum of feces and urine. If this manure is collected, it is usually subject to different types of management that affect its energy content. On the one hand, straw or other bedding materials such as rice husks or sawdust are usually mixed with the manure in solid manure management systems, adding to the energy of urine and feces. Energy contents of crop residues have been reviewed in Guzman et al. (2014).

On the other hand, different storage methods result in unavoidable losses of organic matter due to mineralization processes. These losses may account for 25-53% of the carbon, mainly as CO_2 but also as CH_4, and 17-45% of the nitrogen, mainly as NH_3 but also as N_2O (Pardo et al. 2014, Table 8.2). The most common management method, simple storage, is associated to average carbon losses of 42%. Carbon losses can be taken as a proxy for dry matter losses.

Table 8.2. Total carbon and total nitrogen losses with different waste management methods expressed as a percentage of initial element content (%). Source: Pardo et al. (2014). We have estimated total carbon as the sum of CO_2-C and CH_4-C.

	Total C	Total N

	(%)	(%)
Storage	42.0	35.7
Turned	53.3	44.6
Forced aeration	50.3	39.7
Forced aeration+Turned	39.5	33.3
Covered	25.9	16.7
Compacted	27.5	20.4

8.2 Other organic inputs

Most organic inputs to cropland soils are produced within the cropping system in the form of unharvested aboveground and belowground crop residues and weeds. These organic materials reused in the system are very important in energetic terms, and in many occasions their magnitude is much higher than that of the embodied energy of external inputs. As in the case of manure, they provide nutrients but also have other important ecological roles in the system. Therefore, it is necessary to account for them in full energy balances, and they can be used for constructing certain indicators. The estimation of the energy in crop residues usually requires the reconstruction of net primary production (NPP) from crop production data. In a previous working paper (Guzmán et al. 2014) we developed a methodology for the estimation of NPP in agroecosystems, with a compilation of literature coefficients of biomass partitioning among plant organs, dry matter content and energy content. This work also includes a description of the recommended methodology for the estimation of NPP.

Organic inputs may also include external organic residues such as agro-industry waste, municipal solid waste, sewage sludge or other. These materials are residues and therefore the energy credit for their production is usually not allocated to them but to the main process responsible for their production. For example, the energy for the production of olive mill waste is allocated to olive oil, that of municipal solid waste to food consumption and that of sewage sludge to water treatment. Only specific processes addressed to the transformation of the residue for its land application are usually included in their embodied energy, as well as the transport energy from the production source to the field. Some of these processes are drying, composting or unmanaged storing. However, it is necessary to take into account that residues have to be managed in any case. Hence, some residue management energy might be allocated to the main product.

9. Propagation

9.1 Seeds

Seeds energy includes inherent energy of seeds and the energy required to produce the seeds. The inherent energy of the seeds of grains and pulses can be equaled to the energy content of the corresponding agricultural products, which have been reviewed in Guzmán et al. (2014). The energy used in the production of seeds varies widely depending on the energy profile of the seed production system, which is often similar to the corresponding crop production system, and on the selected system boundaries. Many authors employ the energy employed in crop production as the seed production energy value. Others also use crop production energy but apply to it a more or less arbitrary factor.

In any case, seed production in modern agriculture is usually a very sophisticated process which starts with basic and applied research, continues with the cultivation of the seed under controlled conditions and goes on with further processing, packaging and distribution. Graboski (2002) studied the non-renewable energy inputs for hybrid corn seed production, estimating that it required 4.7 times the energy required for commercial corn production. The differences were mainly driven by lower yield of parent F0 plants and increased processing costs.

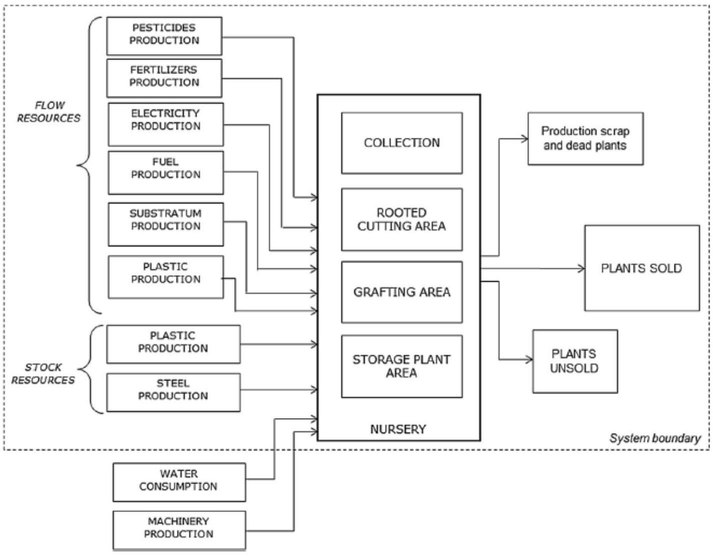
Heichel (1980) classified the methods to account for the fossil energy embodied in seeds. The first method estimates them as a multiple of the enthalpy or the digestible energy content of the seed. The second method assumes that the energy cost of producing the propagation seed is similar to the energy cost of producing the commercial product, and thus subtracts the amount of seed from the total yield of the crop. This method could only be applied when the commercial product and the propagation material are similar (e.g. seeds of grain cereals or legumes, but not seeds of vegetables or root crops, or rootstocks of woody crops). The third method is based on the economic costs of propagation materials. This method is usually applied in a simplified way, multiplying the economic costs by the energy intensity of a unit GDP (see Section 14). The fourth method reviewed by Heichel (1980) is based on a specific process analysis of the energetic costs of producing the propagation material, using a detailed inventory of its production process. Of course, this last method is the preferable option if this information can be obtained. However, this is not usually the case, so a simplified approximation might be required. The calculations of Heichel (1980), show that the third method (economic-based) is the one that yields the energy values that are most approximated to the ones obtained with the fourth (process analysis) method (39% higher), while the first method (twice the enthalpy) yields much lower values. The higher value obtained with the economic method might be justified by differences between growing regions (Heichel, 1980), but also by the energy required for the research and development of new seed varieties.

9.2 Seedlings

According to Beccaro et al. (2014) a nursery is a primary system of crop production, providing materials (seedlings and young plants in general) for use in secondary systems such as horticulture, orchards and forestry. The nursery stage of the life cycle of these crops have been usually neglected or overlooked in energy analyses and LCA studies, probably due to the lack of available information on these processes. Some studies are recently incorporating this stage with simplified methods. For example, Aguilera et al. (2014) grossly estimate greenhouse gas emissions of vegetables seedling production by quantifying the amount of peat consumed.

However, nursery production is an energy-intensive, complex process (Figure 9.1) that has been shown to represent a significant fraction of the ecological footprint of crop production systems. For example, it accounted for 17% of the ecological footprint of orchard systems (Beccaro et al. 2014). Therefore, this stage should be studied as a whole and included in the assessment of the impacts of nursery-using cropping systems.

Figure 9.1. Shematic representation of nursery production. Source: Beccaro et al. 2014



9.3 Replacement of livestock

Replacement of livestock is a frequent input in many agroecosystems, in a similar way as seeds or other plant reproductive material. There are different criteria to account for this input in energy balance. One option is to consider that a fraction of the herd has to be replaced every year. In the case of oxen and mules in traditional agroecosystems this fraction has been considered to be 10% (González de Molina and Guzmán, 2006). This is not a fixed percentage, and it can vary from one region to another and along history, as it depends on the work to be developed by the animals. The annual replacement fraction would be higher when the work is hard or the climate more severe. This has to be verified in historical sources. The difference between the replacement fraction and the livestock raised in the agroecosystem is the amount that had to be imported for replacement. In energy terms, the cost of these imported animals would be the reproduction and feeding costs up to their entrance in the agroecosystem. For simplification, the fraction of energy represented by these costs is considered to be equivalent to the same costs within the agroecosystem. The replacement rates of non-working livestock vary with the species and breed. The calculation of their replacement costs follows the same logic as that of working livestock in traditional agroecosystems. In industrialized livestock production (as well as in seed and seedling production), there are additional costs in the form of maintenance costs (heat, electricity, equipment) and services (veterinary, health, research, financial) that would have to be quantified in a full accounting of livestock replacement costs.

10. Irrigation

By removing water limitation, irrigation is associated to productivity increases in water deficit areas, and now contributes significantly to the overall primary productivity of global croplands. This contribution has been estimated to be about 15%, excluding other factors usually associated to irrigation such as fertilizer and pesticide application (Ozdogan, 2011). Irrigation area is still expanding but it is threatened by climate change (Hejazi et al. 2014).

The energy embodied in irrigation involves the energy required to extract the water, store it, deliver it to the farm and distribute it within the field. The origin of the water and the irrigation technology would determine specific energy requirements of each stage. In many cases, no energy is required in one or more of the stages. Thus, lowest energy requirements are achieved by gravity irrigation systems using surface water from local springs or streams. In this case, negligible external energy is applied. Highest energy consumption is observed in systems using subterranean water from deep wells or desalinized water. The industrialization and modernization of agriculture have allowed the use of less water per hectare and usually lead to the expansion of irrigated surface, if irrigated area is not constrained (Berbel et al. 2015). Modern irrigation systems are typically associated to high energy costs. In largely semiarid countries such as Spain, the modernization of irrigation has drastically increased the irrigated area and the energy requirements of the average irrigated hectare (Table 10.1, Corominas, 2010).

Table 10.1. Historical evolution of water and energy use for irrigation in Spain, 1900-2007. Source: Corominas, 2010.

	1900	1930	1940	1950	1970	1980	1990	2000	2007
Irrigated surface									
Mha	1.0	1.4	1.5	1.5	2.2	2.7	3.2	3.4	3.8
Water use									
Total (1000 Hm^3)	9.0	12.2	12.8	12.4	17.6	20.9	24.0	23.9	24.4
Average (mm)	900	900	850	825	800	775	750	700	649
Direct energy use									
Total (PJ)	0.0	0.7	0.7	1.1	3.8	7.5	12.5	17.6	21.1
GJ/ha	0.0	0.5	0.5	0.7	1.7	2.8	3.9	5.2	5.6
MJ/m^3	0.00	0.05	0.05	0.09	0.22	0.36	0.52	0.74	0.87

Modern irrigation systems such as drip irrigation or aspersion systems lower the amount of water used for irrigation but usually show increased energy demand per m^3 of water used due to pressurizing requirements and the use of more energy-intensive water sources (Daccache et al. 2014). In addition, the increased water costs of modern irrigation systems may make farmers switching to more profitable but also more water demanding crops (Fernandez Garcia et al. 2014). Thus, a tradeoff may exist between food production and water and energy uses (Hafeez et al. 2014).

10.1 Direct energy use

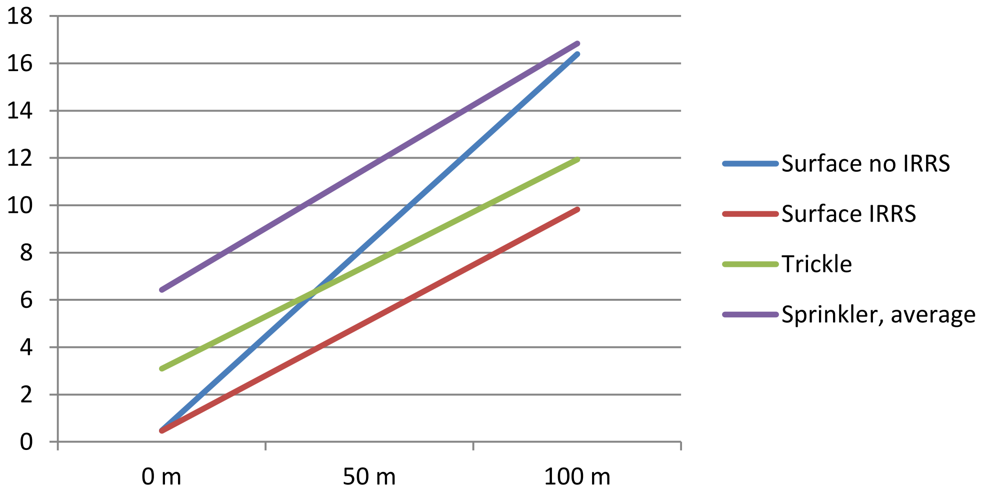
Energy is directly used in irrigation by electric or diesel pumps. Increased pressurizing needs make trickle irrigation less energy efficient when water energy cost is low, but decreased water consumption in this type of irrigation increases the overall efficiency when water energy cost is high.

This relationship can be observed in the data provided by Batty and Heller (1980), who estimated energy requirements for various types of irrigation systems taking into account the efficiency in water delivery of each system. Taking into account that Batty and Keller (1980) assumed a thermal efficiency of electricity production of 30%, we have expressed this information in direct electricity energy requirements per 500 mm net irrigation per hectare in Table 10.2 and Figure 10.1.

Table 10.2. Irrigation efficiency, water use and direct electric energy use of irrigation systems showed in Batty and Keller (1980) for three heights of water lift and 500 mm net irrigation. Data are estimated assuming a pump efficiency of 70%, and an electric motor efficiency of 88%.

		Water applied (mm)			**Direct pumping electric energy (GJ/ha)**	
	Irrigation efficiency	**Net**	**Gross**	**0 m**	**50 m**	**100 m**
Surface without return system	50%	500	1000	0.5	8.4	16.4
Surface with return system	85%	500	588	0.5	5.1	9.8
Solid set sprinkle	80%	500	625	5.3	10.2	15.2
Permanent sprinkle	80%	500	625	5.3	10.2	15.2
Hand-moved sprinkle	75%	500	667	5.6	10.9	16.2
Side roll sprinkle	75%	500	667	5.6	10.9	16.2
Center-pivot sprinkle	80%	500	625	6.0	11.0	15.9
Traveler sprinkler	70%	500	714	10.8	16.5	22.2
Trickle	90%	500	556	3.1	7.5	11.9

Figure 10.1. Direct electric energy use of irrigation systems, for 500 mm net irrigation and three heights of water lift (GJ/ha). Data are estimated using a pump efficiency of 70%, and an electric motor efficiency of 88%. Source: own elaboration from the data in Batty and Keller (1980)



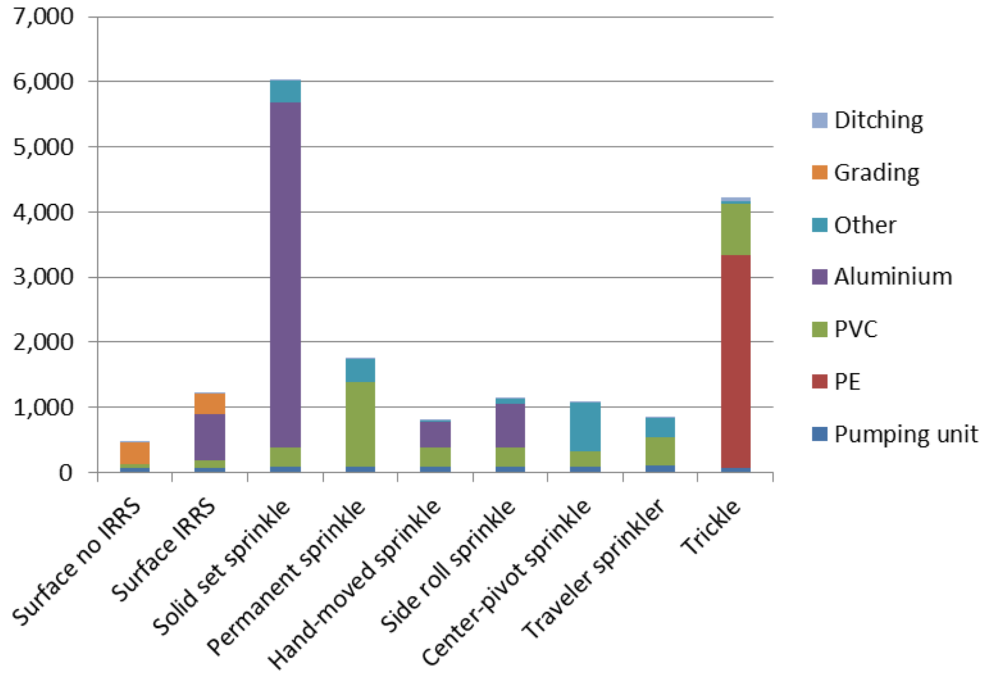
Energy used in on-farm water pumping is very site-specific, so direct information should be used when available. Otherwise, it can be estimated using data in Table 10.2 or using specific tools for energy consumption estimation. For example, the NRCS of the USDA provides energy consumption estimates for different crops, energy sources and irrigation technologies in US counties (NRCS, 2015).

Indirect energy embodied in the energy directly consumed by water pumps refers to the energy required for the production of electricity or diesel fuel. This energy should preferentially be calculated using specific information about the energy mix of electricity power generation used by the system. If this information is not available, our estimations of the global average energy efficiency of electric power generation could also be used (Section 4.3). Estimated values using these world average coefficients, as well as the estimated NRE consumption, are shown in Appendix A9.

10.2 Irrigation infrastructure

Besides direct energy consumption, the energy embodied in irrigation infrastructure is the other major component of irrigation energy requirements. This energy varies widely depending on the type of irrigation system and its particular characteristics, which has led to the exclusion of this input in some energy analyses (Alonso and Guzman, 2010). Main types of irrigation systems are surface irrigation (with or without runoff return system, IRRS), sprinkler irrigation (solid-set, permanent, hand-moved, sider-roll, center pivot and traveler) and trickle irrigation (Batty and Keller, 1980).

Figure 10.2. Energy requirements of irrigation infrastructure (MJ/ha yr). Source: Batty and Keller, 1980



The differences observed in the estimations of energy requirements of irrigation systems by Batty and Keller (1980) are mainly due to differences in their material requirements. In turn, these material requirements depend heavily on their useful lives, which can show large variations. Table 10.3 shows typical useful lives of irrigation systems components.

Table 10.3. Useful lives of irrigation systems components (years). Source: Batty and Keller, 1980.

	Useful life
Pumping unit, electric	12
Pumping unit, diesel	12
PE	10
PVC	40
Aluminum	20
Iron-based	20
Concrete	15
Grading	40
Ditching	40

According to Diotto et al. 2014, the components of an irrigation systems are pump systems, pipeline, filter system and irrigation equipment. Pumps are usually electric, but diesel fueled pumps are also common. This component usually represents a very small part in irrigation systems infrastructure (Batty and Keller, 1980).

The materials used for irrigation pipelines and equipment have changed over time from metal to plastic (Melby, 1995). First iron pipes, and then galvanized steel pipes and copper tubes were dominant in early irrigation projects, but they were expensive and their performance was limited by early corrosion (that could reduce inside pipe volume by 50% in 10-15 years) and difficult joining. Aluminium pipes were introduced in the 1940s and were rapidly adopted due to their lighter weight and improved performance. Plastic pipes were first developed in the 1940s and refined throughout time (Melby, 1995). Plastic pipes can have relatively thin walls and thus low mass per meter pipe. The development of more resistant plastic types, such as PVC-O, has allowed the construction of even thinner pipe walls (Piratla et al. 2012).

Our proposed coefficients for irrigation systems materials are the dynamic factors of metallic and non-metallic materials calculated in Section 5. We have added the energy required for manufacturing of metallic components using our own estimations of manufacture energy requirements, assuming that these components can be classified as “Machinery type C”, as defined in Section 6.2.3. We have also added energy requirements of grading and ditching, taken from Batty and Keller (1980). In the case of ditching, we assumed a use of 535 kg nonreinforced concrete per linear meter ditch, corresponding to a ditch of 1 meter bottom width and 1 meter depth (Batty and Keller 1980). We took our own values of concrete energy content (Table 10.4).

Table 10.4. Historical evolution of the energy requirements of irrigation systems materials and processes, 1930-2010 (MJ/kg). Own elaboration from various sources (see Section 5 and text in this section).

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Polytethyle (HDPE)			265	206	160	124	97	75	58
PVC		192	164	140	120	103	88	75	64
PVC-O							103	88	75
Aluminum		390	297	197	181	164	153	148	144
Iron-based	73	66	61	50	42	39	34	32	32
Manufacture	39	31	26	19	19	21	21	21	21
Concrete	1.8	1.6	1.4	1.2	1.1	1.0	0.9	0.8	0.7
Reinforced concrete	5.0	4.3	3.8	3.4	3.1	2.5	2.2	2.0	1.7
Grading (m3)	15	15	15	15	15	15	15	15	15
Ditching (m)	57	54	52	50	48	46	45	43	42

Table 10.5 shows the material requirements of typical irrigation systems studied by Batty and Keller (1980). We have used these inventories as a reference to model the changes in the infrastructure energy of 5 typical irrigation systems throughout history, taking into account the changes in the materials employed and the changes in the embodied energy of the materials.

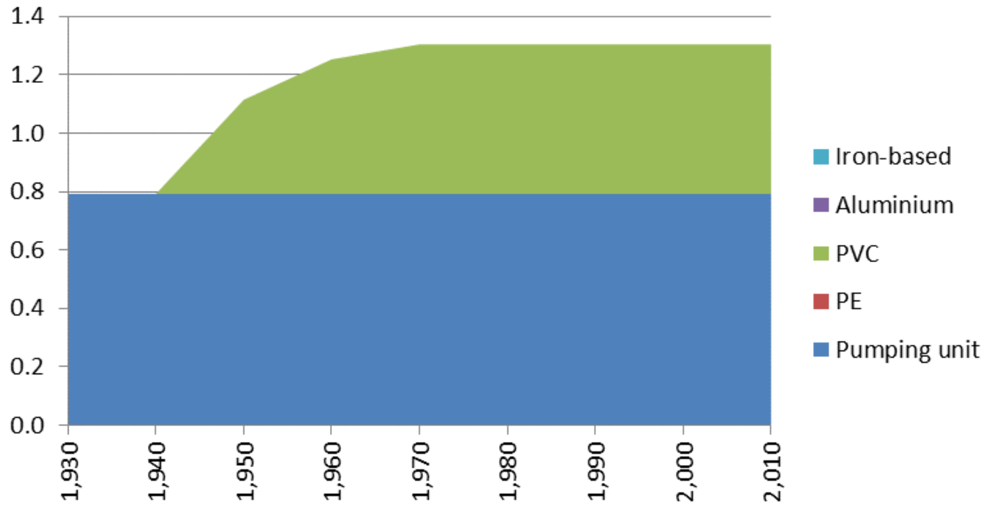
Table 10.5. Materials requirements for typical irrigation systems, per hectare of irrigated land. Source: Batty and Keller, 1980

	Materials (kg)					Earth work	
	Pumping unit	PE	PVC	Aluminium	Other (mainly steel)	Grading (1000 m^3)	Ditching (m)
Surface without return system	9.5	0	20	0	0	731	35
Surface with return system	9.5	0	35	66	0	731	35
Solid set sprinkle	11.7	0	95	506	126	0	17
Permanent sprinkle	11.7	0	404	0	140	0	66
Hand-moved sprinkle	11.7	0	95	37	9	0	35
Side roll sprinkle	11.7	0	95	63	37	0	35
Center-pivot sprinkle	10.2	0	56	0	232	0	7
Traveler sprinkler	14.6	0	129	0	110	0	23
Trickle	10.2	191	247	0	12	0	35

We have classified irrigation systems in 4 categories: surface with or without IRRS, sprinkler and drip irrigation. Sprinkler systems are modeled as the average of all sprinkler systems in Batty ad Keller (1980). Given the lack of quantitative information, we have modeled the changes in materials composition previous to 1970 taking into account the main historical hits of irrigation technology history. This means the expansion of aluminium and PVC mainly in the 1940s and 1950s. The substitution is modeled taking into account that the equivalent weight per meter of a steel pipe of a given inside diameter is approximately five times as much as the weight of aluminium and PVC pipes (Batty and Keller, 1980). In addition, the differences in useful lives among the studied materials have also been taken into account (Figure 10.3).

Figure 10.3. Historical evolution of material requirements of selected types of irrigation systems, 1930-2010, excluding earth work and concrete use (kg/ha yr). A) Surface irrigation without IRRS; B) Surface irrigation with IRRS; C) Sprinkler irrigation; D) Trickle irrigation. Source: Own estimation from various sources (see text).

A



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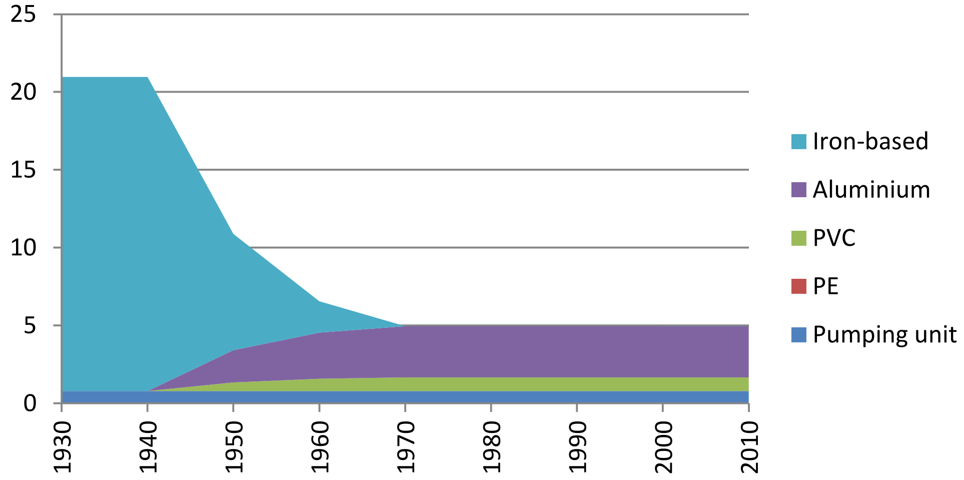

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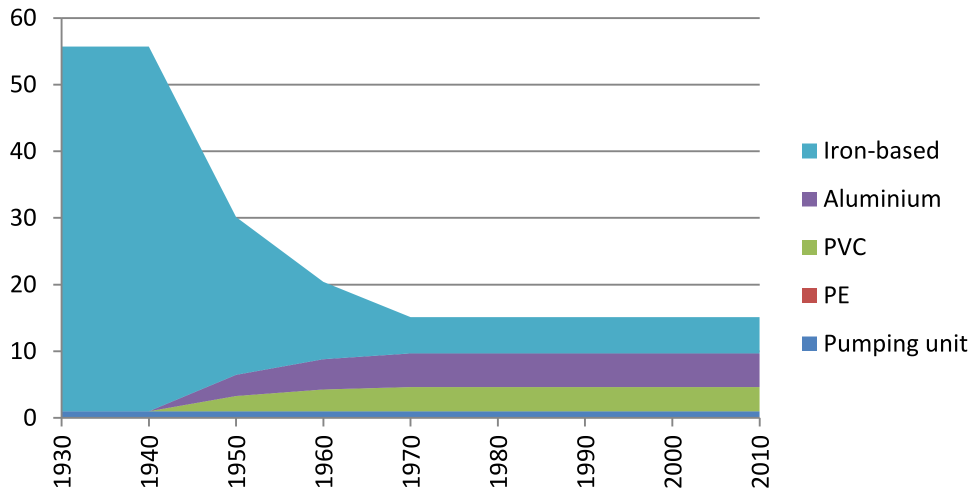

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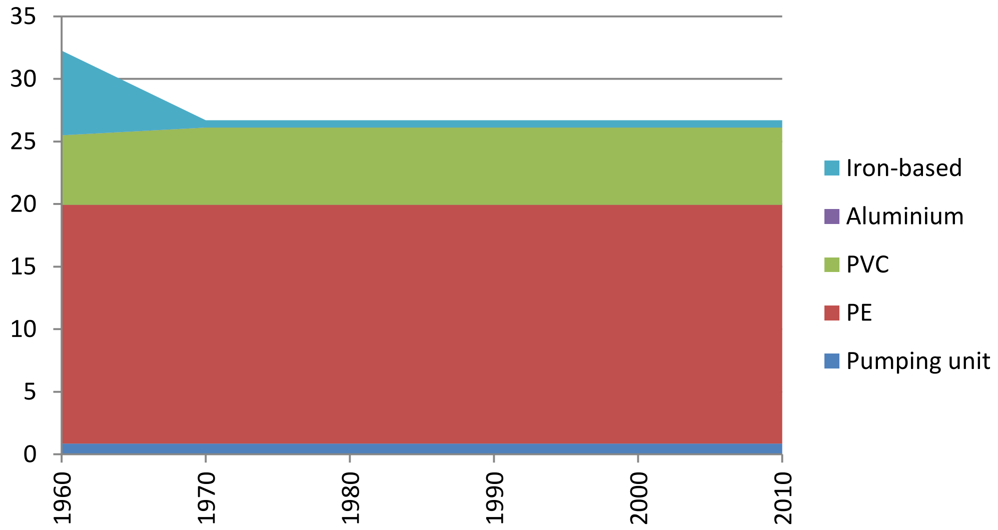
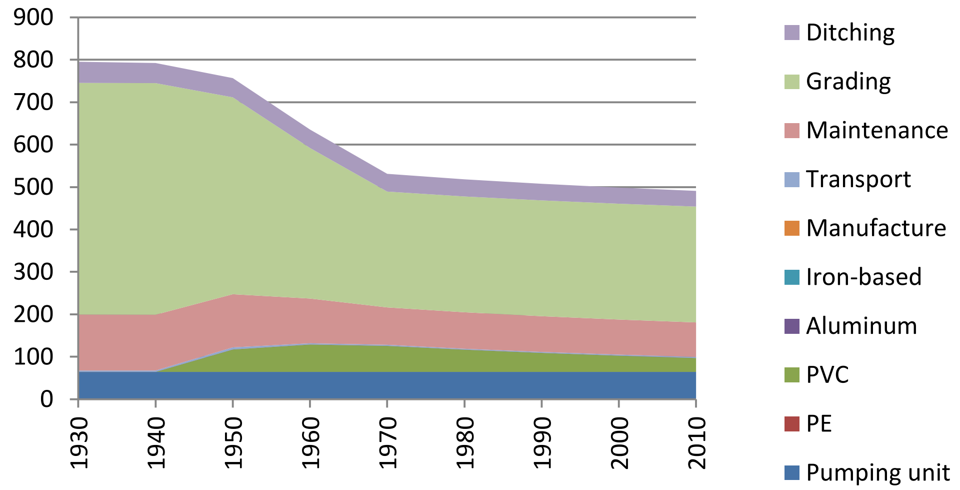


The material requirements shown in Figure 10.3 were multiplied by the embodied energy of each material in each given year (Table 10.4) to obtain the annualized energy requirements of the infrastructure for each type of irrigation system (Figure 10.4). We also added 20% maintenance energy and energy required for transport of irrigation materials to the farm, assuming our standard transport distances and modes (Section 13). All energy values and their corresponding NRE values can be found in Appendix A9.

Figure 10.4. Historical evolution of the embodied energy of the infrastructure of selected types of irrigation systems, 1930-2010 (MJ/ha yr). A) Surface irrigation without IRRS; B) Surface irrigation with IRRS; C) Sprinkler irrigation; D) Trickle irrigation. Own estimation from various sources (see text).

A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1930
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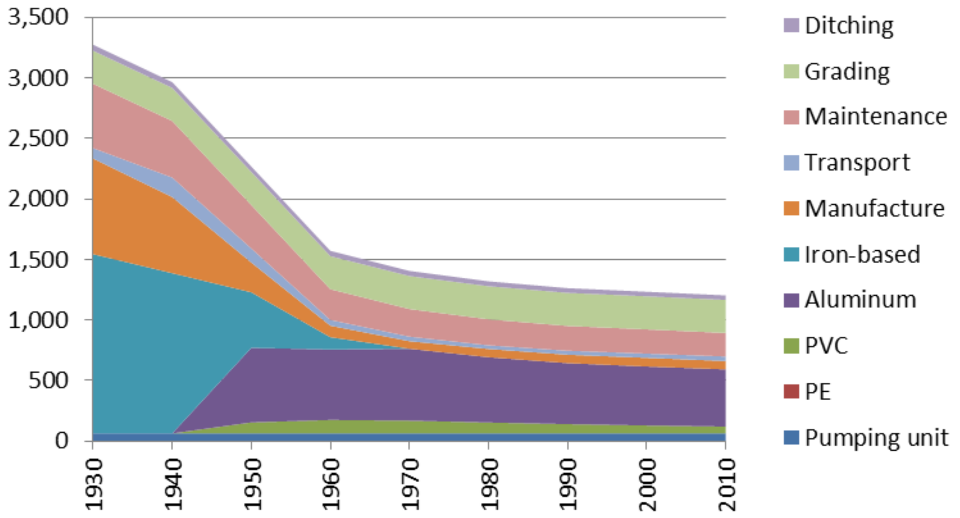
Grading
Maintenance
Transport
Manufacture
Iron-based
Aluminum
PVC
PE
Pumping unit

B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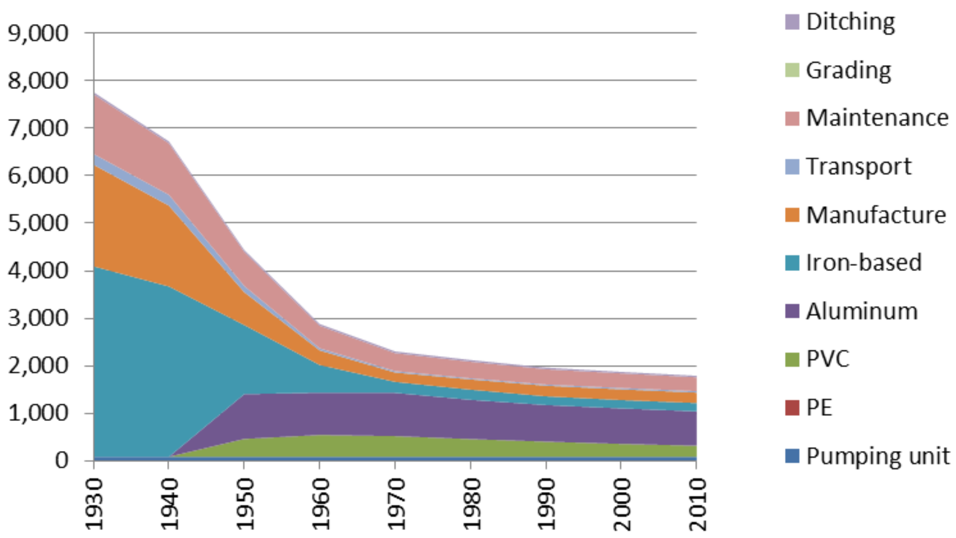
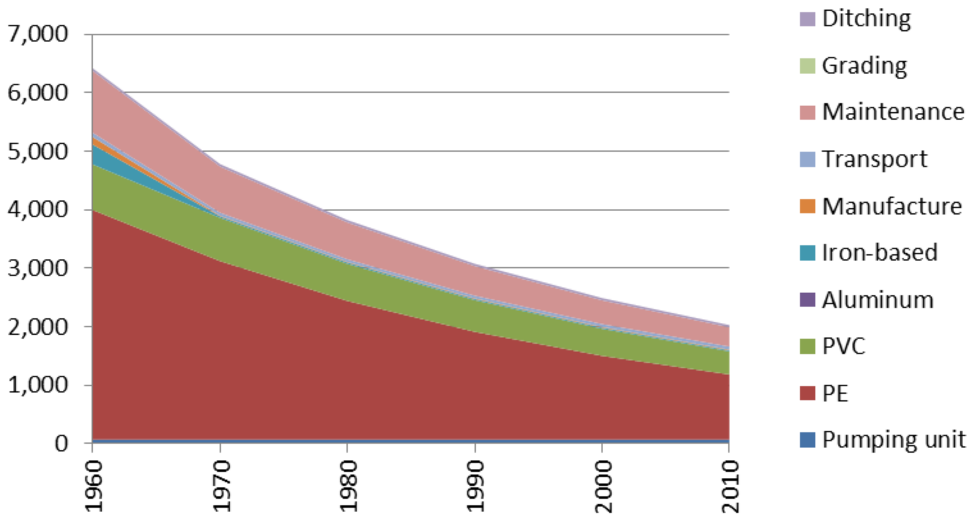


D



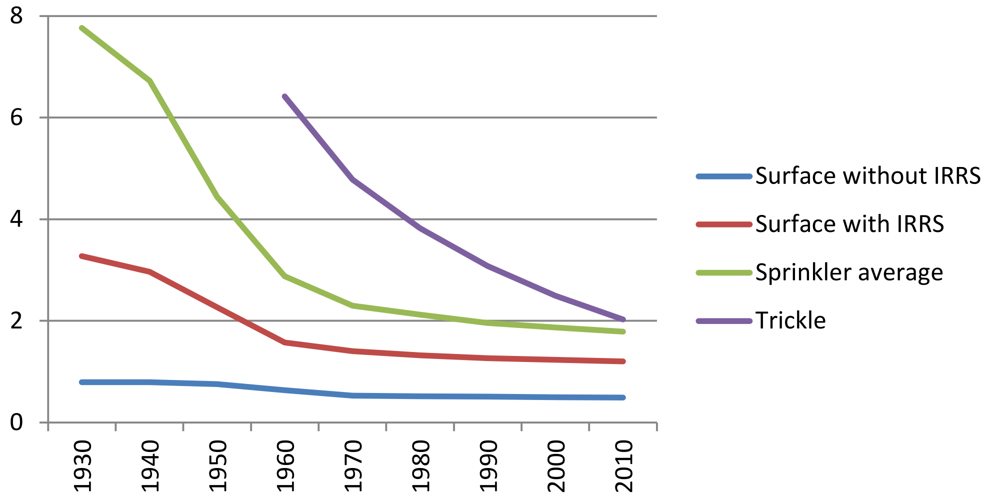
Surface irrigation systems without IRRS typically require very little infrastructure energy, mainly for earth movements and concrete ditches.

Sprinkler irrigation systems show a wide variability of material requirements, but usually PVC tubes and metal components are the major contributors to energy requirements. Components made of aluminium in Batty and Keller example can also be made of galvanized (zinc coated) steel (Diotto et al. 2014, Della Rovere et a. 2013). Premature steel corrosion has been observed with acidic irrigation water (Della Rovere et a. 2013), which could increase the energy requirements due to the reduction of the useful life.

Trickle irrigation systems are usually very energy demanding due to the high amount of polyethylene used and its relatively short lifetime (about 10 years). However, the energy consumption has decreased considerably in the studied period due to increased energy efficiency of polyethylene production.

Figure 10.5 summarizes our estimations of the historical evolution of infrastructure energy requirements for selected irrigation systems.

Figure 10.5. Comparative historical evolution of the embodied energy of the infrastructure of selected types of irrigation systems, 1930-2010 (GJ/ ha yr). Source: Own estimation from various sources (see text).

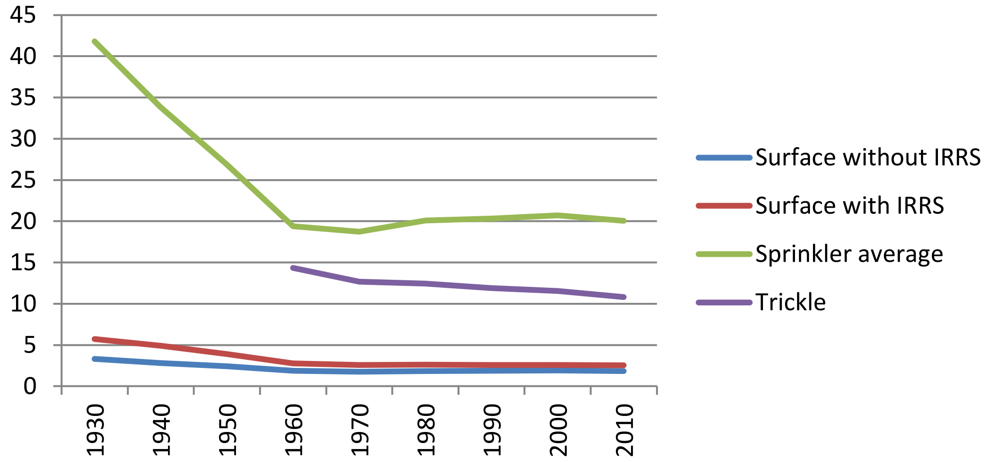


10.3 Total energy in irrigation

Total energy use in irrigation results from the sum of direct energy use, indirect energy required to produce the energy source, and embodied energy of irrigation system materials. We provide an example of total irrigation requirements for 500 mm net irrigation using water from 0, 50 and 100 m depth wells with the four types of irrigation systems studied, assuming that the energy used is electricity which is produced with the world average efficiency calculated in section 4.3. The results are shown in Figure 10.6.

Figure 10.6. Comparative historical evolution of total energy requirements for the irrigation of 500 mm in one hectare with different irrigation systems using water from 0 (A), 50 (B) and 100 (C) m wells, 1930-2010 (GJ/ha). Source: own estimation (see text)

A



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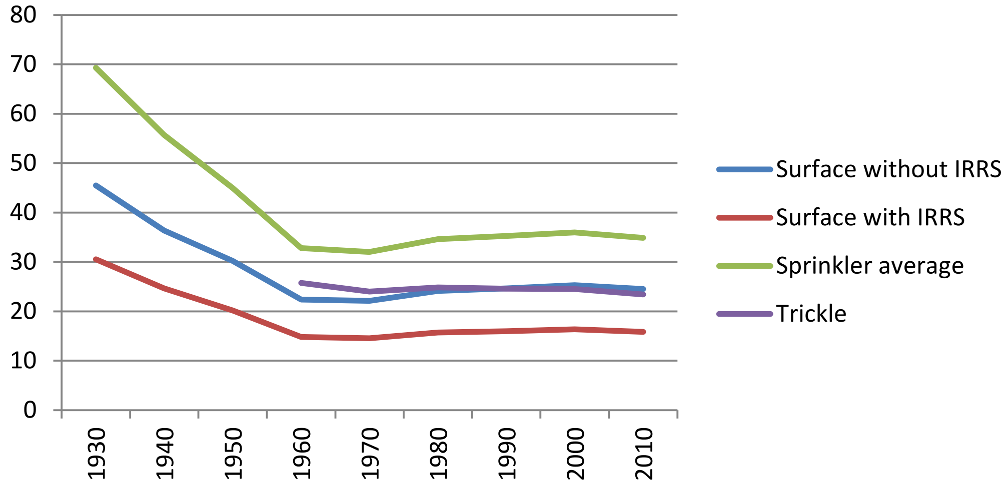

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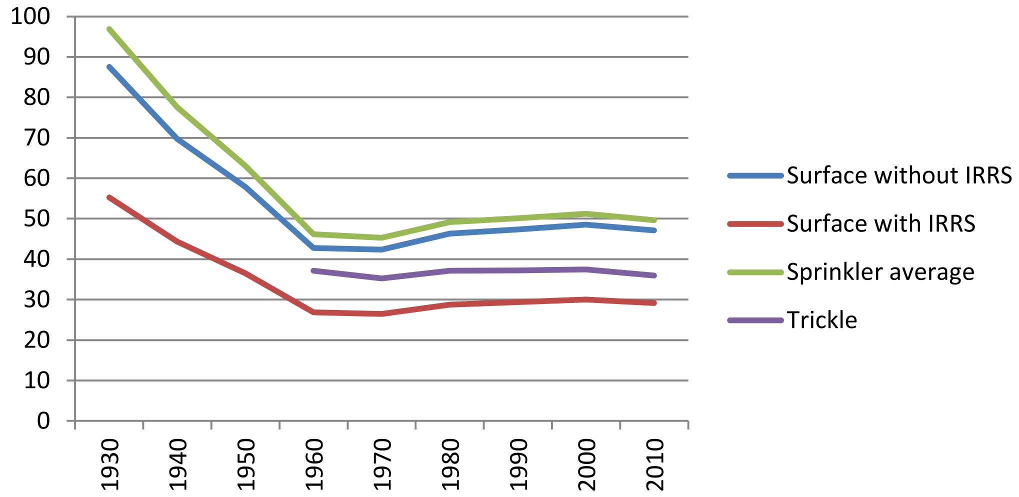

11. Other infrastructure

11.1 Buildings

The environmental impacts of buildings and other infrastructure such as industrial equipment could be relatively significant in some situations, for example in some industrial processes (Althaus et al. 2005). However, the relative importance of buildings in the overall energy balance of agricultural systems is generally very low. For example, they represented 0.1% or less of total energy consumed in a set of apple cropping systems in the US (Funt, 1980). This input is excluded from most energy assessments of agricultural systems. However, performing a comprehensive energy balance requires taking into account all the inputs involved. Therefore, buildings should ideally be included along with the rest of the required infrastructure, as we have done in the case of industrial processes involved in input production.

We have not estimated the historical evolution of farm buildings energy costs, given the lack of available information and the relative low contribution of this input to total energy use. When possible, inventorying building characteristics would allow the estimation of specific buildings energy requirements. If this is not possible, some published values could be used. They do not represent specifically agricultural buildings, but could be taken as a reference. Doering (1980) provides general values for service and residential buildings, while Audsley et al. (2003) suggest that the energy cost of industrial buildings, provided by Kohler (1994) could be taken as the upper limit for agricultural buildings. We suggest applying the value of residential buildings from Doering (1980) to farm machinery buildings. This value is close to the coefficient for agricultural buildings ("Shed/CH") in ecoinvent (Kellenberger et al. 2007), estimated using the cumulative energy demand method. On the other hand, the value of industrial buildings from Audsley et al. (2003) could be applied to buildings for intensive livestock production. These values are shown in Table 11.1.

Table 11.1. Total and yearly energy cost of some types of buildings.

Type of building	GJ/m^2	MJ/m^2 year	Source
Residence	6.26	78	Hannon et al. 1977, in Doering, 1980
Service	1.71	21	Hannon et al. 1977, in Doering, 1980
Industrial	11.08	139	Kohler, 1994, in Audsley et al. 2003

11.2 Greenhouses

Greenhouses are structures that allow trapping solar heat, thus overcoming temperature limitations of certain crops in cold areas or during cold months. There is a high variety of greenhouse types, covering more or less permanent structures with more or less heat trapping capacity. Glass greenhouses are the most common ones in cold areas. Plastic greenhouses are more common in warmer areas such as the Mediterranean basin, where they allow winter cultivation of cold-sensitive vegetables, or in colder areas for cultivating these crops in the summer. Glass greenhouses typically require a very high energy investment for their construction, while plastic greenhouses typically require much lower initial energy investment. Plastic covers have a very limited useful life, of 1.5-3 years.

In this section, we provide information of the estimated historical evolution of the embodied energy of the main materials used for greenhouse construction and use. In addition, we provide some examples of the typical life cycle inventory of some greenhouse types, and the historical evolution of their estimated energy requirements. We have modeled these changes assuming constant material requirements, i.e., considering only the changes in the embodied energy of the materials.

Greenhouses, specially glass ones in cold areas, usually include a heating system. The cultivation is very intensified; hydroponic systems with artificial substrates such as rock wool, and supplemental lighting, are common. All these additional inputs will not be reviewed here, but they should be included in energy balances of agricultural systems if they are present.

Plastic and glass are the main materials for greenhouse covering. The most common plastics are plastic films made of low-density polyethylene (LDPE). We have assumed similar energy requirements for LDPE and HDPE (Hischier, 2007). Therefore, we established a single category, polyethylene (PE), which is analyzed in Section 5.2, as well as glass.

Metallic materials are another major structural component of most greenhouses. Steel is the most widely used material, and usually many components are made of galvanized steel (Alonso and Guzman, 2010). The energy requirements of the steel used in greenhouses were estimated in Section 5.1, as well as the energy required for aluminium production. We have added the energy required for manufacturing metallic components using our own estimations of manufacture energy requirements, assuming that these components can be classified as "Machinery type C", as defined in Section 6.2.3. Total energy requirements of all types of materials considered for greenhouses construction during the period 1950-2010 are given in Table 11.2.

Table 11.2. Historical evolution of total energy requirements of the materials and processes for greenhouse construction 1950-2010 (GJ/unit). Units are kg in all items except "Bulldozer", which is expressed in hours. Own estimation from various sources (See Section 5 and text in this section)

	1950	1960	1970	1980	1990	2000	2010
Plastic	265	206	160	124	97	75	58
Glass	26	21	18	16	14	12	10
Pexiglass	315	261	216	179	148	123	102
Iron-based	61	50	42	39	34	32	32
Aluminium	297	197	181	164	153	148	144
Manufacture	26	19	19	21	21	21	21
Concrete	1	1	1	1	1	1	1
Bulldozer	652	652	652	652	652	652	652

As in the case of irrigation and machinery, useful life is a key parameter in the estimation of greenhouse infrastructure energy requirements. Some common values of useful lives of the studied materials used in greenhouses are given in Table 11.3.

Table 11.3. Useful lives of the materials employed in greenhouse construction (years). Sources: Alonso and Guzman (2010), Theurl (2008)

	Alonso and Guzman (2010)	**Theurl (2008)**
Plastic	2	1.5
Glass		15
Iron-based	20	15-20
Aluminium		20
Concrete	20	15

We have compiled four examples of greenhouses from the literature: Almeria "Parral" type ("Almeria vineyard type" in Alonso ad Guzman, 2010), Glass greenhouse in Austria, Tunnel greenhouse in Austria and Multi-tunnel in Spain (Theurl et al. 2013). The material and process requirements per hectare per year of each type of greenhouse are shown in Table 11.4. The useful lives of the materials are those of the original papers. We show simplified inventories of example greenhouses. More detailed information on greenhouse material requirements can be found in specific studies, such as Torrellas et al. (2012). A recent comprehensive study (Anton et al. 2014) offers equations for calculating material requirements of the four types of greenhouses studied here, as a function the main greenhouse dimensions.

Table 11.4. Main characteristics of four types of greenhouses (unit/ha year). Units are kg for all items except "Bulldozer", which is expressed in hours. Sources: Almeria vineyard type from Alonso and Guzman (2010), Glass greenhouse, tunnel and multi-tunnel from Theurl et al. (2013)

	Almeria vineyard type	**Glass greenhouse, Austria**	**Tunnel, Austria**	**Multi-tunnel, Spain**
Plastic	1,208		406	2,624
Glass	0	6,700		
Pexiglass	0	583		
Iron-based	411	5,500	781	4,563
Aluminium	0	1,250		
Manufacture	411	6,750	781	4,563
Concrete	6,075	25,203		6,377
Bulldozer	1			
Rockwool		4,390		
Heating		7,906		

With the information of systems characteristics in Table 11.4, and the energy requirements of each material and process given in Table 11.2, we have calculated total energy requirements of each type of greenhouse during the period 1950-2010. We have included a 20% repair and maintenance rate for greenhouse infrastructure (excluding plastic). We have also included transport energy, assuming our standard farm inputs transport distances and transport modes (Section 13) for all materials except concrete, for which a 200 km road transport distance was assumed. The results are shown in Figure 11.1 and resumed in Table 11.5. All the results, including NRE use, can be found in Appendix A10.

Figure 11.1. Historical evolution of energy requirements of selected types of greenhouses, 1950-2010 (GJ/ha yr). (A) Almeria vineyard type; (B) Glass greenhouse (Austria); (C) Tunnel (Austria); (D) Multi-tunnel (Spain). Source: own elaboration (see text).

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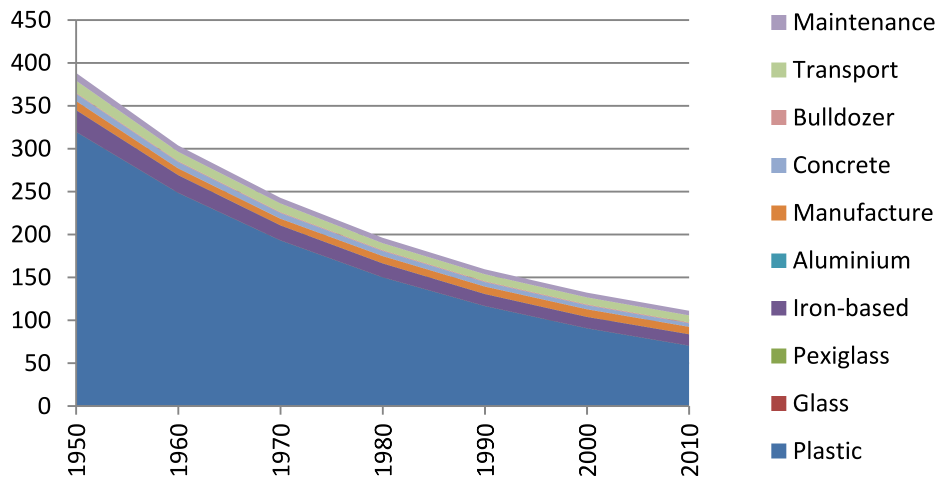

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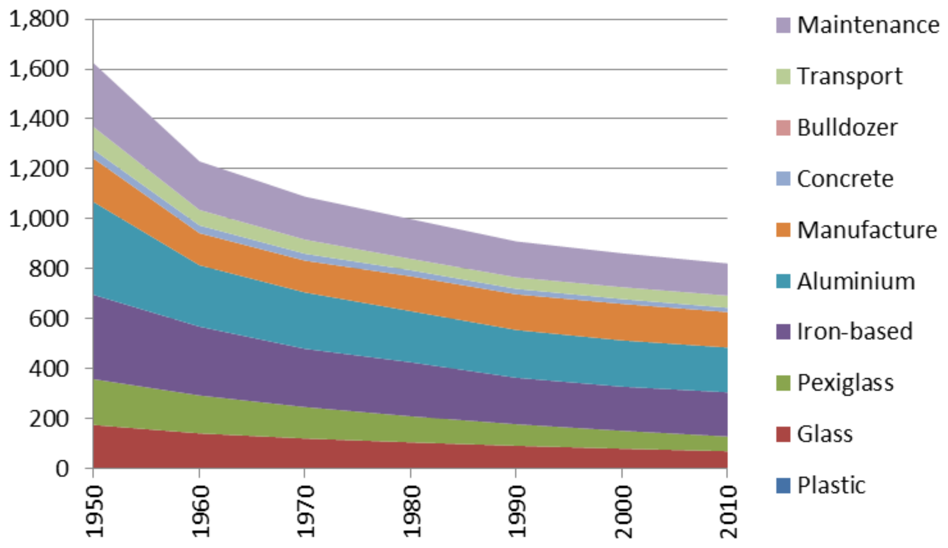

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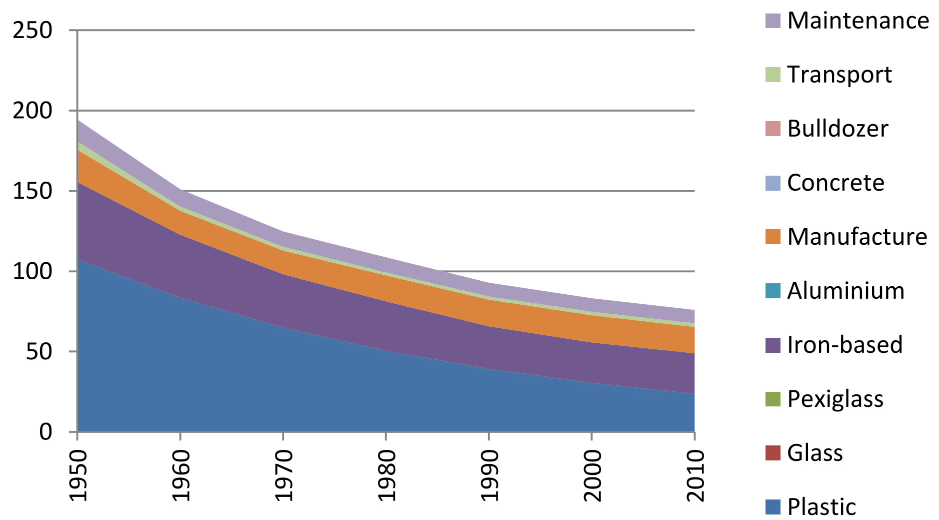

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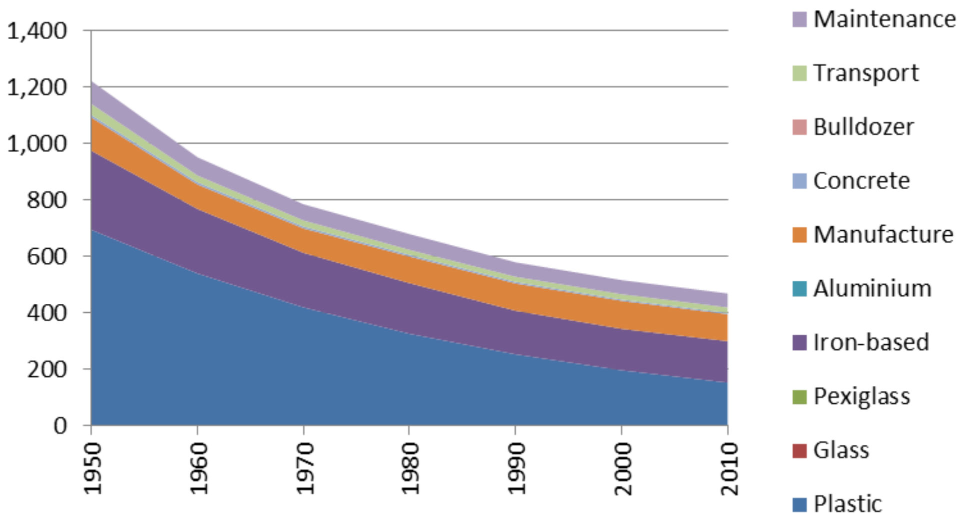


Table 11.5. Historical evolution of total energy requirements of selected types of greenhouses, 1950-2010 (GJ/ha yr). Source: own elaboration (see text).

	1950	1960	1970	1980	1990	2000	2010
Almeria vineyard	388	304	243	196	159	132	111
Glass, Austria	1,623	1,231	1,088	996	904	857	817
Tunnel, Austria	194	151	125	109	93	83	76
Multi-tunnel, Spain	1,222	952	786	679	578	515	468

12. Feed

Feed production represents the majority of modern livestock production energy requirements for most animal species reviewed by Smith et al. 2014. When feed is produced within the studied system, it can be characterized using specific information on its production. On the contrary, the estimation of the embodied energy of the feed imported to the system is usually based on published coefficients. Feed energy includes the inherent energy content of the ingredients, most of which can be found in Guzmán et al. (2014) and the energy required to produce the raw agricultural commodities, transport them to the feed production facility, process them, and distribute them to the farm. The energy requirements of the different steps of this chain vary widely depending on the specific characteristics of the agro-food system.

Pelletier et al. (2014) studied the energy requirements of products used in poultry feeding in the US in 1960 and 2010. They found that, despite the embodied energy of fertilizers and other agricultural inputs had greatly decreased during the studied period, the energy used in the production of feed products (mostly agricultural products and meat industry by-products) increased over time in most cases (Table 12.1), mostly due to the increase in the amount of inputs applied to agricultural systems in relation to yields, and to the intensification of animal production systems. However the energy efficiency of egg production still increased in the studied period, due to the increase in feed conversion efficiencies of layers (Pelletier et al. 2014).

Table 12.1. Production energy of feed products used by US egg industry, 1960 and 2010 (MJ/kg). Source: Pelletier et al. (2014)

	1960	**2010**
Vegetal products		
Corn	1.4	1.8
DDGS	4.4	7.9
Soy meal	1.3	2.6
Soy oil	2.9	5.6
Wheat middlings	2.4	4.2
Animal products		
Poultry meat and bone meal	31.2	42.4
Porcine meat and bone meal	20.8	24.2
Ruminant meat and bone meal	59.6	74.1
Poultry fat	54.0	73.5
Porcine fat	41.5	48.3
Ruminant fat	119.8	149.0
Inorganic products		
Salt	2.5	3.9
Limestone	0.8	1.0
Calcium phosphate	9.3	15.2

13. Transport

Transport is a required process in many stages of the production chain of agricultural inputs, from distribution of fuels and raw materials to manufacturing plants to the final distribution of manufactured products to regional stores and finally to the farms. Freight transport energy consumption is usually measured in MJ per ton-km. It has been estimated that in 2005 the world consumed 64 EJ of primary energy to transport 46 exagrams-km of freight (Cullen and Allwood, 2010). This implies a world average energy efficiency of freight transport in 2005 of 1.39 MJ/t-km. Freight energy efficiency depends on transport mode, the efficiency of the given transport mode in the selected place and time and the efficiency of the production of the materials and energy carriers used in transport.

13.1 Direct energy consumption

The direct energy efficiency of each transport mode has usually increased along history, although there are many exceptions in certain modes, time periods or countries (e.g. Dahmus, 2014, Kamakaté and Schipper, 2009, Ruzzenenti and Basosi, 2009). On the other hand, the shift in transport modes has offset some of these efficiency gains (Kamakaté and Schipper, 2009). The relative share of road and air transport has increased in the last two decades all over the world (IEA, 2009). For simplification here we will estimate the evolution in the energy efficiency of the following transport modes: rail freight transport, road freight transport and maritime freight transport.

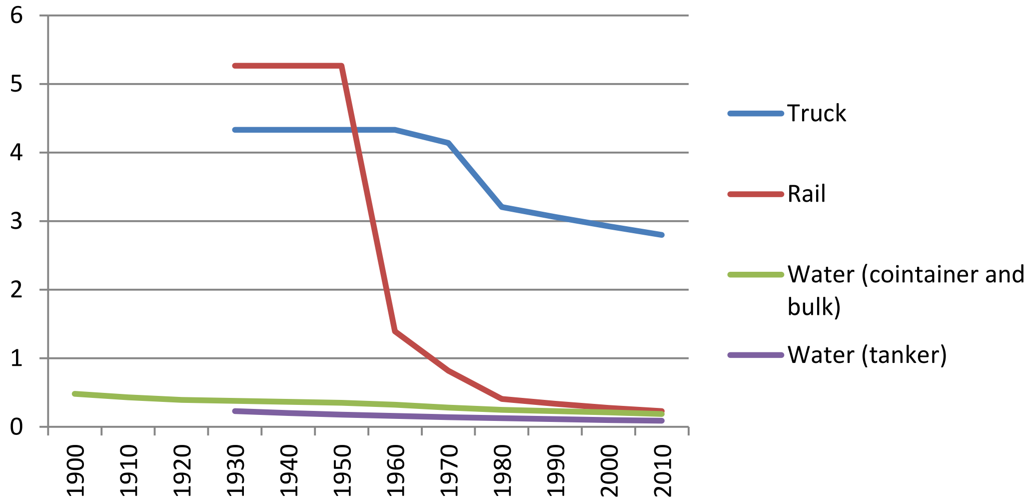
The energy efficiency of rail transport ranges between 0.2 and 0.4 MJ/t-km (IEA, 2009). However, it has experienced important historical changes. The evolution of the energy efficiency of diesel-fueled rail freight transport in the US from 1954 to 2008 was reviewed by Dahmus (2014), showing significant efficiency gains, from 0.67 to 0.25 MJ/t-km. In the 1950-1970 period, the energy efficiency of rail freight in the US had improved even more due to the substitution of coal-burning steam engines by diesel engines (Hirst, 1973). Coal-dominated rail freight in 1950 consumed more than 5 MJ/t-km. Diesel engines represented a share of 33% in 1950 and 99% in 1970.

We have constructed a series of rail freight energy consumption taking Hirst (1973) data for 1950 and 1960. For 1980 onwards, we have used Kamakaté and Schipper (2009) values for selected OECD countries in 1973 and 2005. We calculated a weighted average (weighting by total primary energy consumption in each country) of energy efficiencies in those two time points, and assumed a constant rate of efficiency gain in the period, extrapolating up to 1970 and 2010. For 1970 we have used the average of Hirst (1973) and our own elaboration of Kamakaté and Schipper (2009) data. Given the lack of information, we have assumed that the energy efficiency of rail freight transport remained constant in the decades previous to 1950 (Figure 13.1).

Ruzzenenti and Basosi (2009) studied changes in road transport efficiencies in selected EU countries between 1970 and 1998. The values ranged between 1.8-4.1 MJ/t-km, and in the majority of cases they did not show clear downward trends along the period. The IEA offers a range of 3.1-4.7 MJ/t-km for different world regions (IEA, 2009). As in the case of rail transport, we have combined the 1950-1970 US data of Hirst (1973) with the OECD 1973-2005 data of Kamakaté and Schipper (2009) to construct a 1950-2010 series of direct energy use in road freight transport. The data of 1950 and 1960 have been averaged to smooth the series (Figure 13.1). These values are average values but there is a wide disparity between different types of road freight transport. Direct fuel consumption ranged from 1.5 MJ/t-km for highest capacity lorries to about 16 MJ/t-km for delivery vans (Spielmann and Scholz, 2005, Spielmann et al. 2007). According to Ruzzenenti and Basosi (2009), there are at least three sources of biases in the estimation of road freight transport energy intensity: Uncertainty over the size of the vehicle; uncertainty over the maximum power of the engine and the method of assessment (speed, road and traffic conditions, climatic conditions, load and fuel employed).

The highest transport energy efficiency is achieved by water transport, ranging from 0.1 to more than 1 MJ/t-km in the present; tanker freight is the most energy efficient water transport type, followed by oceanic container shipping, while inland transport by barge is usually the most energy consuming (Hirst, 1973, Weber and Matthews, 2008, Spielmann et al. 2007, Kamakaté and Schipper, 2009). The evolution of the energy efficiency of water transport in the 19th and early 20th century was driven by the changes in propulsion technologies. Sail transport dominated in the 19th century and the previous human history. This was a technology that did not required direct external energy inputs, only the embodied energy of ship building and maintenance. By the end of the century, however, coal powered steamers had already substituted sail boats by a large extent due to their capacity to achieve higher speeds. The energy efficiency of steamers was very low compared to modern boats, although it greatly improved during their history. For example, coal consumption of marine steam engines dropped from 5 to 1.5 pounds per indicated horse power per hour from 1855 to 1900 (Geels, 2005). By 1910 internal combustion engines powered by oil fuel started to substitute steamers. The data offered by Stopford (2009) of fuel consumption of typical cargo ships suggest that the introduction of oil powered engines did not mean a reduction in fuel consumption per ton-km cargo. On the contrary, the increase in energy efficiency was invested in increasing the average speed of the boats. Therefore, the period of transition from coal to oil powered water transport, during the early and middle 20th century does not show very large efficiency improvements. We have constructed the series shown in Figure 13.1 using the data in Stopford (2009) for water container and bulk freight transport. The data of Stopford (2009) for around year 2000 agrees with the average Weber and Mathews (2008, based on Corbett and Koehler, 2003) average value of 0.2 MJ/t-km for international water containers and bulk freight transport. In the case of international tanker water transport, we have taken the value of 0.1 MJ/t-km for around year 2000 and assumed that its efficiency has followed the trend that can be derived from Kamakaté and Schipper (2009) data, of -1.2% yearly change (Figure 13.1).

Figure 13.1 Historical evolution of direct energy consumption for transportation modes, 1900-2010 (MJ/t-km). Own elaboration from various sources (see text).

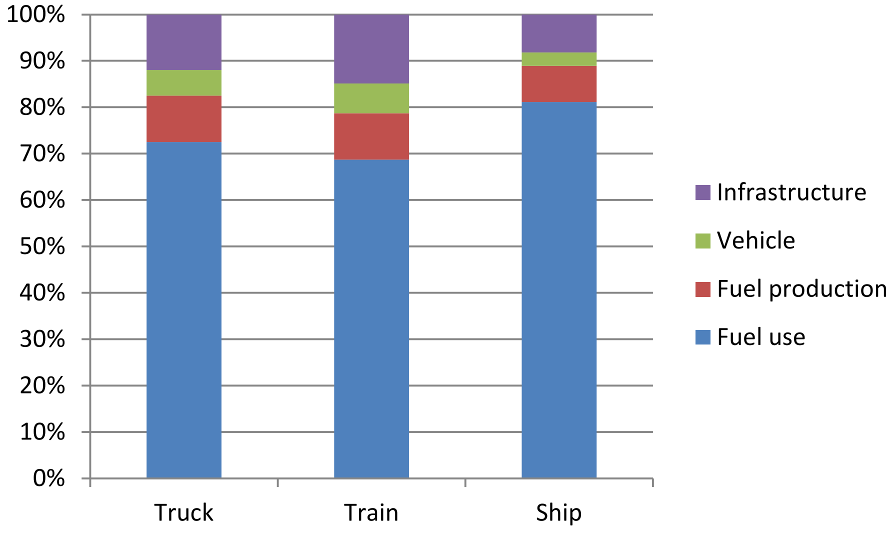


Other transport modes are pipelines and air freight. Energy consumption by pipeline transport was estimated by Hirst (1973) to be 0.73 MJ/t-km. Air freight energy consumption data published in the literature shows a large variability, from 10 MJ/t-km (Weber and Matthews, 2008, from Facanha and Hovarth, 2006), 37-71 MJ/t-km (Hirst, 1973), 16-29 MJ/t-km (Spielmann et al. 2007) or 30 MJ/t-km (European Commission-JRC, 2010).

13.2 Indirect energy consumption

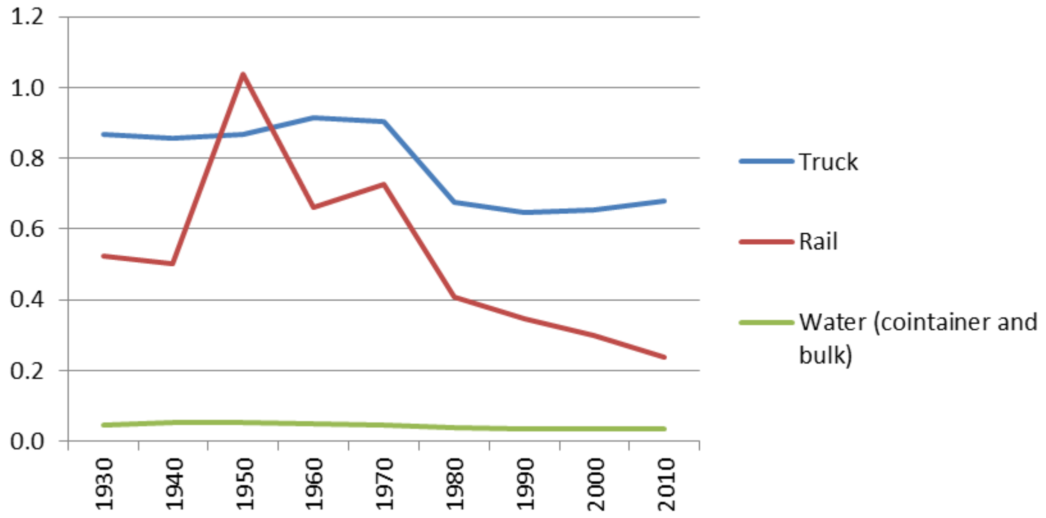
Indirect energy in transport is consumed in the production of fuels and electricity, the production and maintenance of vehicle and the construction and maintenance of infrastructure such as ports, roads and railways. As a reference case around year 2000, we have estimated the distribution of total energy requirements of different transport modes averaging the data provided by Spielmann and Scholz (2005) and Khan Ribeiro et al. (2012) (Figure 13.2).

Figure 13.2. Partitioning of total energy inputs of selected transport modes (% energy). Source: average of the data in Spielmann and Scholz (2005) and Khan Ribeiro et al. (2012). Electricity in rail transport has been converted to primary fuel equivalents.



We have estimated the historical evolution of fuel production using our own estimations of fuel production efficiencies (Section 4.3). We have assumed that trucks are fueled by diesel fuel and ships by fuel oil. In the case of trains, we have assumed that coal was the main fuel in 1930 and 1940, that it represented 70% and 50% in 1950 and 1960 and it had disappeared in 1970. It was substituted by 50% diesel fuel 50% electricity. The results are shown in Figure 13.3. In the case of vehicle and infrastructure production and maintenance, we have assumed fixed values of 0.73, 0.07 and 0.02 MJ/t-km for truck, rail and ship freight transport, respectively, resulting from the application of the above calculated percentages to direct fuel energy consumption in year 2000.

Figure 13.3. Historical evolution of energy consumption in fuel and electricity production of selected transport modes, 1930-2010 (MJ/t-km). Source: own elaboration (see text).



Truck transport fuel production required less and less energy up to 1980-1990. We can observe a peak in the energy consumption of the fuel and electricity used in rail transport due to the transition from coal to electricity. The latter required much less direct energy in train engines but more indirect energy for its production and delivery.

13.3 Total energy consumption

Total energy consumption in transport results from the sum of direct and indirect energy consumption. The results can be seen in Table 13.1.

Table 13.1. Historical evolution of total embodied energy of selected transport modes, 1930-2010 (MJ/t-km). Own elaboration from various sources (see text)

	1930	1940	1950	1960	1970	1980	1990	2000	2010
Truck	5.93	5.92	5.93	5.98	5.77	4.61	4.44	4.31	4.21
Rail	5.86	5.84	6.37	2.12	1.61	0.88	0.75	0.64	0.53
Water (cointainer and bulk)	0.55	0.49	0.44	0.40	0.36	0.32	0.28	0.26	0.24
Water (tanker)	0.27	0.24	0.22	0.20	0.18	0.16	0.14	0.13	0.12

Once we know the energy use per t-km of each transport mode, we have to estimate the distance travelled by farm inputs in each transport mode. Pimentel (1980) states that farm supplies are transported an average of 640 km, 60% by rail and 40% by truck. According to Audsley et al. (2003), farm supplies are transported 1200 km, 83% by rail and 17% by truck. In ecoinvent database (ecoinvent Centre, 2007) there is a wide variability of transport distances of agricultural inputs. For example, phosphate fertilizers are assumed to travel many thousand kilometers by sea, while the values for nitrogen fertilizers are in the range of those of Audsley et al. (2003). These differences between sources partially represent different situations in USA (Pimentel, 1980), UK (Audsley et al. 2003) and the EU (ecoinvent Centre, 2007) in the different periods and for the different products considered. The distances travelled and the transport modes differ between USA and EU and along history. In 1970, 30% of the transport was by road and 20% by rail in the EU. By 1998, these shares were 44% and 8% in the EU and 28% and 37% in the US, respectively (Caldwell et al. 2002).

We have assumed that all inputs are transported the same distance and with the same modes, except fossil fuels, for which pipelines and sea transport are more important (see Section 4.2). Given the high variability and uncertainty of the data, and given the need for simplification, we have made a conservative estimate based on the aforementioned information, taking into account the growth in distances travelled and the shift to road transport in the last decades. We have assumed a constant distance of 500 km by rail and 0 km by water. In the case of road transport, we have assumed 200 km up to 1970, and a linear growth since that date up to 400 km in 2000 (Table 13.2). In the case of refined oil products, we assumed that it was transported only by truck at a distance of 200 km during the whole period.

The results of the multiplication of total energy inputs by total distance travelled are given in Table 13.3.

Table 13.2. Historical evolution of assumed distances travelled by farm inputs, 1930-2010 (km). Own elaboration (see text).

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Farm inputs												
Truck				200	200	200	200	200	250	300	350	400
Rail				500	500	500	500	500	500	500	500	500
Refined oil products												
Truck				200	200	200	200	200	200	200	200	200
Guano and Saltpeter												
Water	16,000	16,000	12,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000

Table 13.3. Historical evolution of total embodied energy of transport of inputs to the farm (MJ/kg). Own elaboration from various sources (see text).

	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000	2010
Farm inputs												
Truck				1.19	1.18	1.19	1.20	1.15	1.15	1.33	1.51	1.68
Rail				2.93	2.92	3.18	1.06	0.81	0.44	0.38	0.32	0.27
Total				4.11	4.10	4.37	2.26	1.96	1.59	1.71	1.83	1.95
Refined oil products												
Truck				1.19	1.18	1.19	1.20	1.16	0.93	0.90	0.87	0.85
Guano and Saltpeter												
Sea	8.89	7.95	5.52	4.54	4.46	4.31	4.02	3.54	3.16	2.92	2.70	2.49

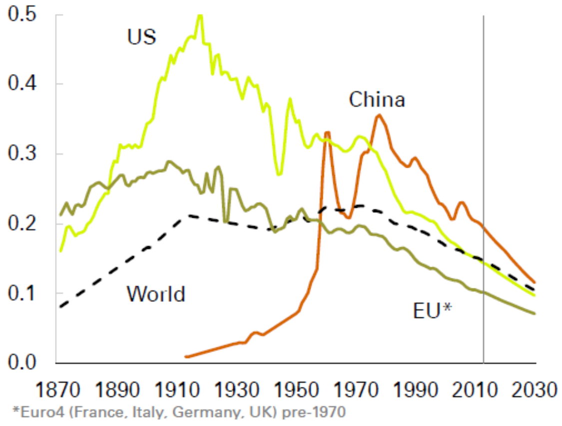
14. Auxiliary "Non material" services

Auxiliary services are fundamental for the functioning of modern cropping systems. They include financial services to make the expensive investments in machinery and other capital inputs, insurance services to assure that fixed costs are paid during years of harvest failure, administrative services to provide support including research and extension services, agricultural subsidies or market regulations. However, these services are usually excluded from agricultural energy analyses, which are usually process-based analyses focused only on physical inputs. Cleveland (1995) argued that using physical inputs to calculate indirect energy use also makes more difficult to account for temporal changes in the production efficiency of inputs.

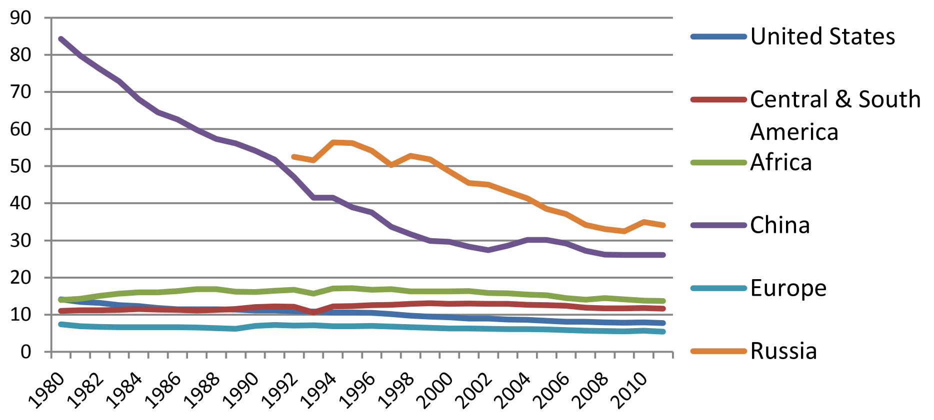
The most common approach to include non-material services in embodied energy estimations is to employ input-output models. Input-output data are based on national statistics covering the financial flows between sectors of the economy. These monetary input-output data are combined with energy statistics to develop input-output models that estimate the energy intensity of a given economic sector including all processes with an economic value. The energy intensity of the economy varies between different countries and through time (Figure 14.1) and also between economic sectors. The sector-specific coefficient of insurance and financial services in the US was 1.8 and 1.5 MJ/$ in 2002, respectively (Carnegie Mellon, 2012), versus 8.9 MJ/$ for the whole US economy (EIA, 2015b). The resulting ratios between the service sector energy intensity and the energy intensity of the economy can be applied to the economy energy intensity of the country and time period where the study is conducted (e.g. Prieto and Hall, 2013), in order to have a gross approximation of the embodied energy of these services in the agroecosystem.

Figure 14.1. Energy intensity of world regions. (A) 1870-2030 (toe/thousand $2011 GDP). Source: BP (2013); (B) 1980-2011 (MJ/$2005 GDP). Source: EIA, 2015.

A



B



Some studies estimate energy use in agriculture based mainly on input-output models. Using a monetary basis allowed Cleveland (1995), in his analysis of the evolution of energy use in USA, to incorporate in a relatively straightforward way the energy embedded in non-material services such as insurance or financial services. It also allowed him to include technological efficiency changes because the converters of dollars to energy were adjusted to each time frame.

Hybrid energy analyses (e.g. Suh et al. 2004, Crawford, 2009, Prieto and Hall, 2013) aim to fill the gaps in the production chain inventories by combining process analysis with input-output data. This way, the precision of process-based analysis is complemented by the exhaustiveness of input-output analysis.

15. Some conclusions

The energy requirements for the production of agricultural inputs have experienced some opposite trends during the historical evolution of agricultural technology. A clear, usually dominating trend towards increased energy efficiency can be identified during the majority of the studied period in most industrial processes involved in inputs production, such as electricity power generation, ammonia production, fertilizer manufacturing or iron smelting. Other technological changes have reduced the material and energy requirements at the farm, such as lighter and more fuel efficient farm machinery and more efficient fertilizers and pesticides.

In spite of these improvements, our results show that efficiency gains are slowing down in recent times. In the first place, the energy efficiency in the production of many materials is approaching the thermodynamic limit (Gutowski et al. 2013). In addition, the decreases in the EROI of primary energy sources, particularly of fossil fuels as they approach their production peaks, and the depletion of highly concentrated metal ores, have imposed an additional thermodynamic constraint to the advances in the energy efficiency of industrial processes in the last decades, in a process that is expected to become increasingly important for the energy requirements of future industrial production. At the same time, the changes towards better performing inputs have pushed the demand for more energy-intensive raw materials. This includes efficient fertilizers and pesticides, or more efficient and lighter farm machinery, but also other features not related to a reduction in energy use, such as safer fertilizers and pesticides or more powerful and more comfortable machinery. Last, the delocalization of production to countries such as China, where industrial energy efficiency is generally low, has also pushed upwards the global average energy requirements of raw materials of agricultural inputs such as ammonia and steel. Other inputs, such as human labour, have experienced a spectacular decrease in terms of units used per hectare or unit product, but their embodied energy requirements may have also sharply increased with the rise in societal energy use.

Our estimations unveil the magnitude of the changes that have taken place, underlining the need to account for them in the analysis of agricultural systems and to intensify the research on the changes in the energy efficiency of agricultural inputs. Important knowledge gaps need to be filled in order to be able to make precise energy analyses of the temporal changes in agricultural energy use, especially during socio-metabolic transitions and during the development of industrial agricultures. We have aimed to provide approximate values that could be used meanwhile information gaps are filled with specific studies.

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