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Turning electricity into food: the role of renewable energy in the future of agriculture

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ABSTRACT

Modern agriculture is heavily based on the energy supply obtained mainly from fossil fuels. In this sense, it can be defined as a technology that transforms fossil fuels into food. However, the available amount of fossil hydrocarbons is not infinite and climate change is creating a critical necessity of reducing their use. Therefore, it is not too early to start considering how agriculture could be adapted to sustainable sources of energy which do not cause climate change. In the present paper, we discuss how agriculture could be restructured in order to utilize the electric power provided by renewable energy technologies such as wind and photovoltaics. In this sense, the problem can be stated as the need of developing technologies able to turn electricity into food. In our analysis, we find that renewable electric power could provide some of the services for the farm produced today by fossil fuels at costs which are not outside reasonable ranges. However, not all the problems of modern agriculture can be solved simply shifting from one power source to another and the limited availability of mineral fertilizers, such as phosphates, remains a fundamental limitation. We conclude that renewable electric power in the farm should be seen as part of a more general transition that will require considerable transformations and adaptation of the current agricultural process in order to develop a truly sustainable agriculture.

1. Introduction

Modern agriculture has attained high yields per unit area in large part as the result of an external supply of energy obtained from fossil fuels. As a result, today agriculture is among the main users of fossil fuels in Western countries (Giampietro, 2009; Giampietro, 2002; Pimentel and Giampietro, 1994; Walser et al., 2012; Woods et al., 2010) and the prices of agricultural commodities fluctuate in parallel with the prices of fuels (Hendrickson, 1996). Agriculture is also one of the major emitters of greenhouse gases in the world as the result of conventional farming activities (Chefurka, 2011), deforestation (Baker et al., 2011) and direct use of fossil fuels in the agricultural process and livestock raising; which is estimated to contribute to nearly 14% of the world greenhouse gas emissions (Pimentel and Giampietro, 1994). In this paper, we will focus the discussion specifically on the agricultural process, but it is worth noting that, considering the whole chain that goes from the fields to the supermarket, one unit of energy of food appearing on the shelves of a store in the Western World requires approximately 5–10 units created from fossil fuels (Giampietro, 2009).

This situation raises fundamental problems of sustainability: fossil hydrocarbons exist on our planet in limited amounts and their production is destined to start declining at some moment in the future. Even though there is no agreement on when the decline could start (Gitz and Ciais, 2003; Campbell and Laherrere, 1998; King and Murray, 2012), rising market prices are an indication that the industry must work harder to overcome depletion (Maugeri, 2012; Bardi and Lavacchi, 2009; Murphy and Hall, 2011). Furthermore, the effect of burning fossil fuels on climate is cumulative and, despite a possible production slowdown in the near future, their continuing use is destined to worsen more and more the problem of climate change (Bardi et al., 2011) which is also causing serious troubles to agriculture.

At present, we cannot say whether the depletion of fossil fuels is a more serious problem than climate change (or vice-versa). What we can say is that, at some moment in the future, one of these two factors, or both, will force our society – and with it agriculture – to reduce the use of fossil fuels. Hence, it is important to start discussing already now how it could be possible to adapt agriculture to

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a world where cheap and abundant fossil fuels will only be a memory of the past.

It is surely possible to reduce the amount of fossil fuels used in agriculture by various methods that aim at conserving resources and use more effective cultivation techniques (Solomon et al., 2007). But these methods cannot eliminate the need of fossil fuels. In particular, a purely "organic" farm is also labor intensive and it would not be possible today, in the Western World, to return to the levels of employment which were typical of centuries ago. Besides, a completely organic farm would have a difficult task in maintaining productivity in terms of yield per unit area comparable to that of the present industrial agriculture (UNEP, 2011). Indeed, the high prices of fossil fuels are already starting to have negative effects on agriculture everywhere in the world (Ramankutty et al., 2012). An example of these negative effects can be found with North Korea, which is at the same time a poor country and a country which has applied the principles of the "Green Revolution" that is, it has transformed its agriculture into a system which heavily relies on fossil fuels; in particular for fertilizers. As a consequence North Korea is especially vulnerable to high prices in the fossil fuel market and has experienced a series of periodic famines occurring every time when the price of fossil fuels forced North Korean farmers to reduce the input of fertilizers (Haggard and Noland, 2009).

It seems, therefore, that the gradual reduction of fossil fuel availability and their increasing costs will create enormous problems to the world's agriculture. In the present paper, we examine how these problems could be addressed by a transition involving the gradual phase out of fossil fuels and their substitution with the energy obtained from modern renewable sources such as wind and photovoltaics (similar considerations could be developed for nuclear energy, although we will not examine this possibility here). Since renewable energy sources mainly produce electricity as their output, the concept we are proposing could be termed as "turning electricity into food".

On this subject, it is obvious that renewable energy cannot provide the same services and products as fossil fuels (e.g. liquid fuels, fertilizers, and more) at the same costs. So, the subject of the present paper can be described as how agriculture can change and adapt to a new source of energy – renewables – which could expand to become quantitatively abundant, but that is likely to remain qualitatively different for the foreseeable future. One problem is that there is no simple and inexpensive way to transform electricity into liquid fuels suitable for conventional engines; another that there is no way to directly transform electricity into chemicals such as fertilizers and pesticides. Nevertheless, we argue that there is a tremendous potential in the concept of turning electricity into food as a way to "wean" agriculture from fossil fuels. That is especially true if the switch to electric power in agriculture is carried out in combination with methods of modern "conservation agriculture" which aim at conserving precious resources such as fertile soil and water.

2. Results and discussion

In this section, we will describe the problems faced by the attempt of reducing fossil fuels in agriculture and then outline possible strategies of adaptation.

2.1. Renewable energy for agriculture

The concept underlying our analysis is that the use of external energy sources allows agriculture to concentrate on optimizing yields and is therefore an element of the food production process that we should strive to maintain in the future. However, simply reducing the use of fossil fuels or swapping one kind of fossil fuel for another (e.g. using LNG or natural gas in place of diesel fuel) would only reduce costs in the short run, but it would not be a solution for the progressive depletion of fossil fuels and for the problems of climate change. Hence, we need to find new and sustainable energy sources. These sources should be able, first of all, to provide an energy supply for the farm in amounts and costs comparable to fossil fuels but, at the same time, in forms that the farm can use – either directly or by means of suitable adaptations of the agricultural process. In this section, we provide a brief assessment of the capability of renewables to provide large amounts of energy at reasonable costs.

The term "renewable energy" includes a wide variety of technologies which produce energy in different forms, with different efficiencies, with different land footprints, and at different costs. Just as agricultural products vary depending on the local environment, the best renewable technology varies as a function of the geographical location. About the spectrum of possible renewable technologies, the obvious ones are those based on wind, sun, and flowing water, which include photovoltaics (PV), wind, hydroelectric, and biomass. To these, we may add the possibility of geothermal energy.

An important factor in evaluating the efficiency of renewable technologies is the energy return for energy invested (EROI or EROEI) (Bardi et al., 2011). The EROEI is the ratio of the amount of energy that will be produced by a plant over its lifetime and the amount of energy that needs to be invested to build the plant, operate it, and finally dismantle it. An EROEI lower than one makes a technology for primary energy production useless since it generates no useful energy. EROEIs smaller than about 4–5 are considered too low for a technology to have practical applications.

Up to no long ago, the EROEI of fossil fuels was much larger than that of renewable technologies such as PV and wind and that was seen as a fundamental obstacle to a transition to renewable energy in any sector – including agriculture. However, the situation is rapidly changing. The EROEI of renewables is increasing, owing to technological progress, while that of fossil fuels is diminishing, owing to depletion (Murphy and Hall, 2011). Today, renewable technologies such as wind and photovoltaics have reached a level of EROEI efficiency high enough to be able to compete with fossil fuels in providing an abundant supply of high quality energy (Fthenakis et al., 2009; Kubiszewski et al., 2010; Muneer et al., 2003). These high EROEIs are slowly creating lower monetary costs; the process takes time because of the high costs of investment in new production plants must be recovered. However, the gap is closing with the efficiency of renewables increasing due to improved technologies and favorable scaling factors, while fossil fuels become gradually more expensive to extract and process because of their gradual depletion. It is likely that a "tipping point" that will make renewable energy more convenient than fossil energy will be reached soon and it may have already been reached in some special cases – e.g. where the vectoring of fossil fuels turns out to be expensive. Note, however, that this high efficiency of renewables does not apply to biofuels (Borjiesson, 1996; Russi, 2008; Giampietro and Mayumi, 2009; Pfeiffer, 2004), which are limited by the low yield of photosynthesis and the need of expensive processing of agricultural products.

Of course, EROEI is not the only factor involved in judging the effectiveness of an energy producing technology. Another one is the area occupied by the plants. Especially when discussing photovoltaic energy, the competition of agriculture and PV plants for land is often seen as a major problem. However, we can calculate that the area required for renewable plants to provide renewable energy for agriculture is negligible.

As a first round of assessment, we can estimate the land requirement for using renewables to match the amount of primary energy in agriculture used today. This assessment neglects important factors such as energy storage and energy quality, but it provides an order of magnitude value for the land area required.

In a 2002 study, agriculture was reported to consume energy in the form of fossil fuels for an amount corresponding to 18.2 EJ for vegetal production and 9.5 EJ for animal production (Giampietro, 2002). The total corresponds to 27.7 EJ per year. According to the BP statistical review of world energy (Pfeiffer, 2004) the world's total energy consumption was 513 EJ in 2012, of which 447.3 EJ were generated by fossil fuels. Hence, agriculture consumes about 6% of the world's fossil fuel energy; probably more than that considering that agricultural activity has grown from the time of the data reported in Giampietro (2002).

Today, renewable energy in its various forms (PV, wind, hydro, etc) is reported to provide about 8.2 EJ of primary energy worldwide (Pfeiffer, 2004). Expanding this amount to cover the ca. 30 EJ used by agriculture would be possible mainly by expanding the use of PV and wind. The land requirements for such an expansion would be minimal. Considering photovoltaic energy, we may assume an average irradiation of 5×10^9 J per square meter per year for tropical and equatorial land areas. Assuming 20% of efficiency in energy conversion for PV, producing 30 EJ per year would require an area of some 30.000 square km. Different assumptions would not change the fact that the area required turns out to be extremely small in comparison to the 15 million square km occupied by crop cultivations alone (Statistical Review of World Energy, 2012). Wind energy as an even smaller footprint than PV and would occupy considerably less space for the same amount of energy produced. Even less space would be occupied by hydroelectric and geothermal plants, even though both have limits to their expansion resulting from orographic and geological factors.

Different results in terms of land requirement are obtained when considering biofuels. It is true that the production of electricity from biomass would occupy no significant space as long as it is performed utilizing only waste biomass. However, biofuels, intended as ethanol and biodiesel, require specific areas for cultivation and these areas cannot be small, even in the limited assumption that these fuels would be used only for agriculture. This result can be illustrated with an example using the data reported by the University of Georgia (Ramankutty et al., 2008) which show that cultivation of peanuts requires ca. 0.015 l/m^2 of diesel fuel. This value can be compared with the yield in terms of biodiesel for peanut cultivation, which is reported to be around 0.11 l/m^2 (University of Georgia and College of Agricultural and Environmental Sciences, 2013). There follows that at least 14% of the area cultivated for peanuts must be used to provide biofuel for the agricultural machinery needed. Other kinds of biofuels may provide better results (Giampietro, 2002; Statistical Review of World Energy, 2012; University of Georgia and College of Agricultural and Environmental Sciences, 2013), but the calculation in these terms remains optimistic. First of all, biofuels pack less energy per unit volume than conventional fuel and then their production requires further energy to process the agricultural product. For some biofuels, in particular ethanol, the net energy (EROEI) is so low that the idea of using it to power agricultural machinery makes no sense (Russi, 2008; Giampietro and Mayumi, 2009). Because of the low EROEI; biofuels cannot be defined as a "renewable" source and their extensive use would only put further strain on food production and it would also worsen the climate problem (Russi, 2008).

So, in purely quantitative terms, renewable technologies can act as primary energy sources to produce large amounts of energy without negatively affecting agriculture (with the exception of biofuels). However, this primary energy is produced in a form that is not directly usable by the farm (i.e. liquid fuels) and, in addition, cannot be easily stored and utilized on demand.

Here, there are two possible solutions: 1) changing the energy carrier generated by the primary energy source that is converting electricity into liquid or gaseous fuels or 2) changing the requirements of users, e.g. irrigation, tractors and transport powered by electrical motors rather than by combustion engines.

Regarding the first possibility, transforming electricity into fuel is possible, but it is a complex and expensive process. One of the methods is to use electricity to electrolyze water and produce hydrogen, which could then be used as fuel. This is, however, a technology which brings several problems of storage, conversion and management which make it expensive and, in general, scarcely suitable for agriculture. The problem of storage could be solved by transforming hydrogen into liquid fuels in the form of ammonia or hydrocarbons by reaction with atmospheric nitrogen or carbon compounds. Again, however, we have a multi-step process which turns out to be complex and expensive.

Hence, a more productive line of action would be to adopt the second strategy: that is adapting the agricultural process to the direct use of electricity, as much as possible. In this way, the high EROEI of modern renewables can be best exploited, without the losses caused by intermediate processing. Especially when dealing with mechanical power, the use of this approach permits to use electric motors rather than thermal engines, the latter being considerably less efficient. The consequence of this approach, however, is that the farm should learn how to directly utilize electricity for all its processes.

Adapting the farming process to using electricity as an energy source implies considering a variety of activities which, today, are mostly performed using fossil fuels, while electric power plays a minor role in the modern farm, being mainly used for activities such as lighting, heating, refrigeration, control and others. The breakdown of the various percentages of use of fossil fuels in agriculture has been reported by several authors, e.g. Pfeiffer (2004) but a more detailed evaluation of the fossil input for vegetal production was reported by Giampietro (2002) who lists the following values:

- 15% for the manufacture of agricultural machinery
- 27% fuel
- 36% for nitrogen fertilizer manufacture, 3% for phosphorous fertilizer manufacture
- 1.7% for potassium fertilizer manufacture
- 6.2% for irrigation
- 6% for pesticide production
- 3.5% miscellaneous

Similar values are reported in Giampietro (2002) for animal production and, in general, the various sets of data are consistent in

Fig. 1. RAMSES multipurpose electric vehicle for farmers.

indicating that the main inputs of fossil fuels in agriculture are for nitrogen fertilizers and for mechanical power. The requirements for other fertilizers, pesticides, irrigation and other uses are smaller, but not negligible.

Supposing now that the future farm can enjoy an abundant supply of electric power at reasonable costs, we have to discuss how it can adapt to the availability of energy in a form that is not the traditional one. That is, how can we transform electric power into food? We will breakdown the discussion according to four fundamental items.

1. Mechanical power for farm operation and transportation of products, supplies, and waste.
2. Artificial fertilizers, either from nonrenewable mineral resources (phosphates and others) or manufactured using fossil fuels (nitrates).
3. Pesticides manufactured from fossil fuels.
4. Power for irrigation and water management.

2.2. Mechanical energy for the farm

Farms make extensive use of mechanical energy for all phases of the agricultural process. Traditionally, this energy was provided by human labor and by farm animals. Hence, the introduction of fossil powered engines has been universally viewed as a major step forward for humankind in eliminating the need for the back-breaking work of the peasant. With the gradual reduction of the supply of fossil fuels, we would be facing a return to these ancient times unless we find a way to utilize different forms of energy.

Here, our discussion is based on the results obtained with the RAMSES project (Faircloth et al., 2013; Mousazadeh et al., 2009a, 2009b) of the 6th EU Framework Program that was carried out under the supervision of one of the authors of the present paper (T.E.A.) from 2006 to 2010. The fundamental idea of the project was to examine the use of renewable energy as a way to power the agricultural process. This concept was implemented by building an electric vehicle powered by on-board batteries recharged by a photovoltaic system.

From the beginning, the RAMSES vehicle (Fig. 1) was not conceived simply as an equivalent of existing conventional tractors, but it was designed with the idea of optimizing the performance of electric power for agricultural work, exploiting its advantages but also recognizing its inherent limitations. For instance, there are no problems in designing an electric vehicle with a very high torque at the wheels; able to engage in activities such as plowing. The problem is that such an activity draws a lot of energy from the batteries and cannot be sustained for a long time unless the battery pack is unreasonably large and heavy. Accordingly, the RAMSES vehicle is very different from other, existing, electric tractors. It has some of the capabilities typical of tractors, but it has been conceived as a multi-functional, mobile power station that can be used as a transportation vehicle and as a source of power for a variety of agricultural tools for such tasks as watering, spraying, fruit collecting, seeding and many others; either by mechanical or electric coupling, using the vehicle's batteries. The vehicle weighs 1700 kg, including the driver, and can carry up to a ton of load. It has a range of 70–80 km on roads at a maximum speed of 45 km/h and its battery pack allow it to work for up to 4 h in the fields before needing to be recharged. The motor works at 96 V, which can be switched to 48 V by setting the two battery packs in parallel. These relatively low voltages insure safety in the humid environment usually experienced by agricultural vehicles. Also, the traction motor is placed near the center of the vehicle, to avoid mechanical damage and contamination during operation.

The tests of the RAMSES vehicle were carried out in Lebanon, a region characterized by frequent black-outs and where the local legislation does not yet permit the sale of renewable energy to the electric grid. These conditions led to the decision of structuring the RAMSES power system as an autonomous island, where the energy was produced by PV panels located in the farm and stored in stationary batteries.

The RAMSES system has been tested for more than two years. It has shown good reliability and the final users reported a high degree of satisfaction. In addition to field testing, the system has been extensively evaluated for its costs and environmental parameters. The results of these tests show that the system has significant environmental advantages over conventionally powered equivalent systems (Faircloth et al., 2013; Mousazadeh et al., 2009b). However, in purely monetary costs, and until 2010, the break-even that puts the RAMSES system on a par with conventional systems has not arrived (Faircloth et al., 2013; Mousazadeh et al., 2009b). Our analysis showed that only when fuel prices reach 1.8 €/L, the RAMSES system obtains economic parity with the conventional system (Faircloth et al., 2013). As diesel fuel for agriculture is often subsidized by governments, it is clear that a competitive price advantage does not exist yet for these electric systems. However, the price differential is small and for some specific, high quality, agricultural processes, where the high price of the produced commodities would encourage investments in efficient and clean technologies. An example is the operations inside greenhouses where the lack of gaseous emissions is a major advantage. Furthermore, recent developments in the fossil fuel market, which are creating problems of availability of diesel fuel, may have already made the RAMSES system competitive.

The results of the RAMSES project show that an electric tractor can do anything that a conventional tractor of the same size the tractor of the same size can do. This opens up the possibility of replacing a variety of agricultural machinery and vehicles, which then would use only sustainable energy and generate no emissions during operation. The limits of this approach appear with large size vehicles, such as combine harvesters, which must operate continuously and at high power rates. In principle, building a combine operated by electric motors would be perfectly feasible, but if it were to be powered by conventional lead batteries the weight necessary to provide the range which is typical of conventional combines would be very large. If lead batteries were to be replaced by lithium batteries, the weight would go down, but the cost would become too high to be compatible with food production, at least at present.

Clearly, a mechanized agriculture cannot work by simply replacing diesel powered vehicles with battery powered ones. In the long run, if we do not want to return to human powered farms, the only option is to restructure the agricultural process in such a way to reduce the need of heavy vehicles and high power operations, making it compatible with electric vehicles. An agriculture which makes less use of brute power is also an agriculture that is more respectful of the environment in the sense that it causes little degradation of the soil. This could turn out to be one of the major advantages of a transition to an agriculture powered by renewable electricity, also considering that an initial phase of the transition could and should consist in starting the adaptation by means of a gradual reduction in the use of fossil fuels for the existing machinery.

2.3. Fertilizers

Modern agriculture tends to deplete the humus layer of the necessary mineral nutrients and these have to be added back to restore the fertility of the soil. The use of artificial fertilizers, in particular macronutrients such as nitrogen, phosphorous, calcium and potassium, has been a major revolution in modern agriculture.

Nitrogen is of special importance among agricultural macronutrients. It has been estimated that, without nitrogen *fertilizers*, agriculture would not be able to support more than 4 billion people on the Earth (El Asmar et al., 2009) that is little more than half of the current world population. Today, nitrogen containing fertilizers are mainly produced using the Haber-Bosch process which uses a catalytic method to obtain the reaction of atmospheric nitrogen (N_2) with hydrogen. In its most common implementation, the process does not start with pure hydrogen but it generates it from natural gas or syngas obtained from coal. Both natural gas and coal are of fossil origin, so this reaction is based on nonrenewable resources and it adds greenhouse gases to the atmosphere.

Nutrients other than nitrogen are also extremely important, in particular phosphates. Without phosphates, food production could not be kept at the present levels. Cordell et al. define this problem by saying that “we are effectively addicted to phosphate rock” (Smil, 2011). Today, phosphates are normally supplied from mines, with the mineral “phosphorite” being the main source. Phosphorite is partly the result of the accumulation of sedimentary biological materials and in part the result of inorganic hydrothermal processes.

Another important mineral macronutrient, potassium is often mined from ancient seabeds in the form of potassium chloride. The same is true for calcium and magnesium which are often obtained from such rocks as serpentinite and dolomite. All these products require mechanical energy for extraction, processing and transportation. At present, this energy is mostly provided by fossil fuels, normally in the form of diesel fuel for mining machinery and transportation vehicles. These processes are therefore sensible to depletion and generate greenhouse gases.

In order to create “renewable” fertilizers, we need to consider two different areas: nitrogen and all the others. In the case of nitrogen fertilizers, traditional processes based on nitrogen fixing bacteria are possible, but their production capacity is limited. It is also possible to recover nitrogen from organic waste. However, it is possible to use renewable energy to power the Haber-Bosch process, using as feedstock renewable hydrogen, obtained by electrolysis of water. At present, electrolytic hydrogen is more expensive than hydrogen obtained from fossil hydrocarbons, but in the long run the progressive depletion of fossil fuels is destined to make renewable hydrogen more convenient and this route has the advantage that the existing Haber-Bosch plants could be kept and utilized without major modifications. An alternative is to use renewable electricity for the direct, high temperature electrolytic reaction of hydrogen and nitrogen. This method is called “solid state ammonia synthesis” or SSAS (Cordell et al., 2009; Chakraborty et al., 2009). There exist patents and known methods for this process; although at present it is not used in industrial production. It may be worth noting that ammonia may be used not just as a fertilizer, but also as fuel for conventional engines.

Regarding the other mineral macronutrients, in particular phosphates, there is no escape to the fact that they exist only in limited amounts in forms that can be economically mined (Smil, 2011). It is also true that the mineral industry makes an extensive use of diesel fuel and of energy coming from fossil fuels. In part, the latter problem can be solved by switching industrial mining equipment to machinery that uses mainly electric power. As mining machinery is not usually traveling long distances, it should be possible to substitute diesel engines with electric motors powered by batteries or by cables. However, these measures cannot change the problem of the gradual depletion of high concentration mineral sources such as phosphates and it will not be possible to maintain forever the present supply for agriculture.

The conclusion is that the supply of nitrogen fertilizers can remain abundant in the future is we are willing to invest in renewable energy, but also that agriculture will have to adapt to a reduced availability of mineral fertilizers. This adaptation will require a considerable recycling and re-using effort in the framework of conservative agriculture. In any case, a more constrained use of mineral fertilizers should at least ease the pollution problems they create, especially in terms of contamination of groundwater by phosphates (Smil, 2011) and nitrates (Amar et al., 2011).

2.4. Pesticides

Pesticides are a fundamental feature of modern, industrial agriculture, but are not without disadvantages. Pesticides kill pests, but also pest’s natural enemies and their overuse can harm farmers, consumers, and the environment. Hence, good pest management strategies need to respond to the concerns about the risks posed by pesticides to health and environment (Howden et al., 2011). Farmers often respond to pest attacks by increasing the use of pesticides. In this market, herbicides represent the largest segment, while the share of insecticides has shrunk and that of fungicides has grown over the past ten years. The excessive use of pesticides has disrupted parasite and predator populations causing the outbreak of secondary pests and contributing to the generation of a vicious cycle of pesticide resistance. That has led to further investments in pesticide development but little change in crop losses to pests, which are estimated today at 30–40%; that is, similar to those of 50 years ago. As a result, pest outbreaks caused by inappropriate pesticide use, have increased. Agriculture continues to dominate the pesticide market to the point where the pesticide market growth tends to mirror that of the agricultural market. Herbicides and insecticides will remain the largest product types. One or the other of these products is largest in essentially every national market, due to their extensive use on the major field crops. While herbicide and insecticide volumes have been affected by the use of biotechnology-derived products, fungicide usage has not (FAO, 2011).

According to Pimentel (World Pesticides, 2010) the overall energy input per hectare for the conventional US corn production is 32.6 MJ. Herbicide and insecticide contribute to this value with about 3.3 MJ; so that pesticide energy input is about 10% of the total. In terms of greenhouse emissions by arable crops, a recent study (World Pesticides, 2010) concluded that the pesticide energy input is 9% of the total. Both these estimates suffer from lack of data: most of the industrial processes for pesticide production are proprietary and, hence the evaluation of the energy content of pesticides often relies on data that go back to 1987 (Pimentel, 2006) and we can only say that 10% appears to be a reasonable estimation.

It would not be very difficult to use renewable energy to produce this amount of energy, but the problem, here is how to turn electricity into pesticides. While research is now looking at new and sustainable solutions for the synthesis of fertilizers, the same is not true for pesticides. As far as the authors of the present paper could ascertain, no approaches to pesticide synthesis other than preparation from fossil fuel derived “raw chemicals” exists. May be, in the future, we could see the rise of a new paradigm in the chemical industry entirely based on the use of biomass derived products and electrochemical processes (Food and Agriculture Organization of the United Nations, 2011). Such an approach could fill such lack of “sustainable” methods for pesticides production. However, at present, we can only conclude that a future decline of fossil fuels production will lead to a rapid increase in the cost of pesticides, forcing agriculture to move toward methods based on organic farming and a progressively smaller use of industrial chemicals.

2.5. Irrigation and water management

Over the last 50 years, land and water management has met rapidly rising demands for food and fiber. More than 40% of the increase in food production of the past decades came from irrigated areas. There remains a strong linkage between poverty and the lack of access to water (Food and Agriculture Organization of the United Nations, 2011) and water availability to agriculture is a growing constraint in areas where a high proportion of renewable water resources area already used, or where trans-boundary resource management cannot be negotiated. Groundwater extraction has provided an invaluable source of irrigation water, but it has proved to be almost impossible to regulate. Declining aquifer levels and the continued extraction of non-renewable groundwater resources present a growing risk to local and global food production.

The availability of water for irrigation is obviously related to the availability of energy. Traditionally, the energy needed to pump water out of wells was provided by human labor and by farm animals. Wind-powered pumps have a long history and they became common in the early decades of the 20th century in the United States and in many areas of Europe. Many of these old machines are still visible today, although most of them have remained unused for decades owing to the availability of low cost electricity to drive water pumping equipment. However, the decline of the cheap supply of fossil fuels may make these machine competitive again. Even though the requirements for water pumping have increased with aquifer depletion, the gearboxes of wind pumps can be adapted to produce the force needed to extract water even from deep wells. On this point, it is remarkable how wind operated pumps automatically solve the storage problem typical of renewable energy. It does not matter if wind is intermittent: what counts is the average water production accumulated in the tank. This approach would make sense also in modern times, even though it is possible that local wind pumps will remain obsolete if compared with energy production from large scale wind or PV plants.

In any case, pumping – even if done using renewable energy – cannot solve the problem of aquifer depletion which is plaguing modern agriculture. Assuming the availability of large amount of energy, we could examine the possibility of producing freshwater by desalination or by condensation of humidity from the atmosphere. At present, water produced by these methods is way too expensive to be competitive with water from traditional sources. It may not be impossible, however, to produce such water as by-product of the operation of renewable plants; that is as storage of the excess energy that plants produce in especially favorable moments of availability of light or wind. This kind of water would be, again, a way to solve the storage problem of renewable energy. However, the amounts that can be produced in this way are likely to remain limited in comparison for the demand for irrigation, so that it is conceivable to use it in agriculture only in connection with water-efficient agricultural practices.

These considerations indicate that renewable energy can ease the problem of water availability for the farm and replace fossil fuels for pumping and piping. One problem with the issue of groundwater is that the availability of low cost energy makes the problem worse, lowering the cost of water and favoring aquifer depletion. Here, government policies turn out to be (as usual) counterproductive. By subsidizing groundwater pumping, they create the same problem of wasteful over-use created by subsidies for fuels used for agricultural machinery. In this sense, an increase in the costs of energy could have beneficial effects in forcing farms to use more responsible water management policies.

2.6. Vectoring energy to the farm

We saw in the previous section how electricity produced by renewable technologies can be used by the farm. The question, at this point, is how this energy should be supplied to the farm.

The first hypothesis is that the farm should become an energy producer that is that the renewable plant should be located on farmland. This is a policy that has been followed in recent times, especially in Europe, where farms have been encouraged by governments to install wind and photovoltaic plants on their land. Medium and small wind plants can also be located on the farm. With their small footprint on land, small wind turbines can be operated with little interference with cultivation. Indeed, the use of small wind turbines as sources of power for irrigation has been a traditional agricultural technology during the first half of the 20th century. Recent results (Zhou et al., 2012) indicate that large wind parks may alter the micro-climate; in particular producing a slight increase in the average temperature at the level of the soil. The consequence of this effect may not be necessarily bad for farms located in the vicinity of these parks, but must be taken into account when deciding the location of new wind energy facilities. Farms may also have the possibility of setting up mini-hydro plants exploiting the water flow of water bodies, another traditional activity associated with farms in the past. Finally, there is the possibility of using wood, agricultural waste and animal waste as energy sources. These sources may provide a steady supply of electric energy for the farm using direct combustion or transformation into biogas to generate electricity. However, these sources ultimately rely on photosynthesis, which is an inefficient process in comparison to the direct transformation of light into electricity carried out in wind or PV plants.

In general, locating energy plants on the farm may not be the best strategy. The farm's business is farming, and farmers are rarely specialized in the task of producing electric power. Transforming the farm into a small power plant would not be the best way to maintain its productivity in terms of food. There also is no need, normally, to strive to make the farm energetically "autonomous" or "self sufficient" in the sense that it would produce all the energy it needs. Scale factors should favor firms specialized in energy production to supply the farm with renewable energy vectored through the power grid. So, whenever possible, the farm should connect to local grids or to the national grid for its energy needs. In OECD countries, these grids are already existing; providing electrical power to farms. It may be necessary to upgrade these grids to sustain a larger energy supply but, on the whole, the investment necessary and the impact on the territory are expected to be limited. The situation is different in poor countries where distributed electricity often doesn't exist or, where it exists, it is unreliable and subjected to frequent black-outs. In this case, local production and storage of energy may be the best solution, as tested with the RAMSES project (Mousazadeh et al., 2009b) in Lebanon.

2.7. Adaptation

This adaptation of the agricultural process as a way to reduce its dependency to fossil fuels is already an ongoing trend. The perception of the problems involved with unsustainable practices in agriculture has led to much effort directed to the development of technologies able to reduce the use of fossil fuels and other unsustainable resources. A term often used in this field is that of "conservation" agriculture (Friedrich, 2008; Department for International Development – DFID, 2012). This kind of agriculture aims at saving resources in agricultural production and on achieving acceptable profits together with high and sustained production levels while concurrently conserving the environment. As it is conceived today, conservation agriculture is mainly based on enhancing natural biological processes above and below the ground. In its basic implementation, conservation agriculture is mainly dedicated to improving existing cultivations. Related concepts such as permaculture ("Permanent Agriculture") take a more extensive approach in determining also what is to be cultivated on the basis of the natural productivity of the land. Among the characteristics of permaculture, we have the avoidance of all types of plowing and tilling and the reduction or the elimination of the supply of external nutrients by minimizing soil disturbance and retaining the integrity of crops residues on the soil surface. Permaculture also integrates livestock within the agricultural process (e.g. using animal manure as fertilizer) (Friedrich, 2008; Department for International Development – DFID, 2012). This approach minimizes the loss of efficiency involved with turning agricultural products into meat in traditional production practices.

The use of these conservation technologies, therefore, does not require food production to concentrate on crops only, as considerations purely based on efficiency would dictate. Instead, with proper practices it is possible to maintain a variety of processes which also include livestock raising. Conservation agriculture cannot completely eliminate the use of an external energy supply for the farm, but it can lower energy inputs requirements up to 60%, compared to conventional farming. In combination with renewable energy, conservation agriculture is the key for an agriculture completely "weaned" from fossil fuels.

3. Conclusion

In this paper, we examined the possibility of a transition where the farm will switch part of its energy needs from fossil fuels to electricity in a paradigm that we have called "turning electricity into food." We have shown that putting electricity to work at producing food is possible in several sectors of the agricultural process. In particular, electricity can produce nitrogen based fertilizers and power irrigation, completely substituting fossil fuels in these two tasks. Electricity can also power agricultural machinery, including vehicles for transportation and for field work, although the limitations of on-board energy storage place limits to their size and range. About pesticides, it is theoretically possible to develop new methods to manufacture them starting from renewable resources, but very little research and development has been done in this field up to now. Finally, about fertilizers other than nitrogen based ones (i.e. phosphorous, calcium and potassium) there is little that renewable energy can do to solve the general depletion problem of mineral resources.

These results show that it is worth doing an effort to encourage the use of electrical power in the farm, even though it is clear that it is not possible to simply replace fossil fuels with renewable energy leaving everything else unchanged. "Weaning" the farm from fossil fuels is possible only by means of a more efficient use of energy and of mineral resources, as well as an approach to farming which is more respectful to the preservation of the soil and the local resources.

At present, the problems related to fossil fuel depletion and climate change are scarcely perceived by most operators in the agricultural sector and even less by political leaders and decision makers. This lack of perception of the roots of the problem has led agricultural operators to react only with short term actions to face high fuel costs; mainly asking governments for a special taxation regimes and low cost supplies. Even though such measures may mitigate the problem in the short term, they cannot solve it; on the contrary, they may worsen it considerably in the long run.

If these trends continue, measures favoring the introduction of renewable energy in agriculture will be delayed until the prices and the availability of fossil fuels become so problematic that it will appear clear that the need of a change is imperative. At that time, it might be too late to find the financial resources needed for a rapid and significant impact of renewables on agriculture and on the food production industry. It is therefore important to start thinking of ways to favor the transition already now. In this perspective, we may think of farms that would produce most of their renewable energy locally and use energy from the grid only in amounts that can be "offset" by such activities as reforestation and biochar production. A farm that uses these methods can produce superior quality products. Such a farm will be, – among other things – a strong stimulus for the general development of renewable energy.

Conflict of interest

The authors declare no conflict of interest.

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