The Grand Challenge of the Energy Transition

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Introduction

Energy is the key factor that drives the economy. Without the abundant energy coming from sources other than human and animal muscles, society as we know it would be unthinkable. Energy is needed to power all kinds of machinery, but also for the vital task of supplying the industrial system with the mineral commodities that make it function. Energy is also fundamental for the food production system which can sustain billions of people only because it makes large use of energy coming from outside agricultural sources (Giampietro, 2002).

The first to realize the importance of energy for modern society was probably William Stanley Jevons, who wrote in his "The Coal Question" (Jevons, 1866) that: "*Coal in truth stands not beside but entirely above all other commodities. It is the material energy of the country — the universal aid — the factor in everything we do. With coal almost any feat is possible or easy; without it we are thrown back into the laborious poverty of early times*." Today, we can replace the term "coal" with "fossil fuels" in Jevons' statement and obtain a good description of our situation.

Our society is based on fossil fuels and for many purposes – such as for transportation – there exist no comparable energy sources that could drive the existing infrastructures. If fossil fuels were to disappear today we would be immediately thrown back into the "laborious poverty" of old times – or much worse than that. The question that Jevons was asking in his 1866 study was “how long can coal sustain British industry?” The same question can be asked today about fossil fuels and world industry. The answer cannot be any other that: “not forever” since, for all practical purposes, the amount of fossil fuels available to humankind is finite.

But, just as Jevons had argued for coal, the problem is not the physical running out of fossil fuels; it is the fact that we are gradually running out of the low-cost energy and mineral resources that had been used to build up our industrial system. As a consequence, industry is forced to extract fuels at increasingly higher costs from resources which are deeper, more remote, less practical, and in general of lower quality. As a consequence, we need to invest increasing amounts of energy to obtain the same amounts of energy as in earlier times. This problem is normally defined in terms of a parameter termed “energy return of energy investment” EROI or EROEI (Murphy and Hall, 2011) which, for fossil fuels, usually declines as a function of the extracted quantities (Bardi et al., 2011).

The result is the generalized increase of energy costs experienced during the past decade or so; an increase that has interrupted a decreasing trend that had been lasting for more than a century (Fouquet, 2011). Even taking into account the recent collapse of oil prices, the overall trend is still one of increase and the present low prices can only be seen as a temporary phenomenon. At the same time, the Earth’s capability of absorbing the products of the combustion of fossil fuels is limited. As this text is being written, the concentration of carbon dioxide in the atmosphere has reached 400 ppm (Sweet, 2013); a value not known to have ever been reached on the Earth during the past few million years. In addition to the heating of the atmosphere generated by the greenhouse effect, there are several negative consequences of this increasing CO2 concentration: ocean acidification, sea level rise, extreme weather phenomena, and more.

Possibly the most worrisome of these effects is the release of more potent greenhouse gases: the methane trapped in the Northern Permafrost and in deep-sea hydrates. This event would then further accelerate the negative trends with truly catastrophic effects (Archer, 2007). At present, we cannot determine whether global warming or fossil fuel depletion is the more important problem we are facing, but we know that both are caused by our dependency on fossil fuels. As a consequence, it is imperative to reduce, and eventually eliminate, this dependency before it is too late. Given the situation, it is hard to think of a grander challenge for humankind than that of creating a society that can function without fossil fuels and at the same time maintain a level of prosperity and complexity comparable to the present one – and creating it in a relatively short time-span.

How are we going to meet this challenge? Whatever we decide to do, the transition is already in progress.

The Ongoing Energy Transition

The main ongoing trends can be listed as:

- The world production of oil has been basically static during the past few years (Staniford, 2013). Some areas are in an irreversible production decline (e.g., the North Sea) while others, mainly the continental US, are experiencing a true renaissance in the production of petroleum liquids owing to the exploitation of oil shales. Against this static trend of production, the consumption pattern is changing, with developing nations such as China, rapidly expanding consumption (Luft, 2007).
- Natural gas production is increasing worldwide (Zittel et al., 2013), especially in some regions of the world exploiting the so called “tight gas” resources. Coal production is rapidly growing in a trend that is not expected to slow down soon (Zittel et al., 2013). In general, energy production from fossil fuels seems to be still able to grow, although the high market prices are a clear indication that more effort is needed to keep even to rates of growth that are small in comparison to past trends.
- Worldwide mineral production is generally static for most mineral commodities; some are slowly increasing, others are declining (Brown et al., 2013). The mining industry is facing the problem of diminishing ore grades for most minerals and the consequence is the need of more energy to maintain the same levels of production. Several strategies are being pursued in order to counter depletion, e.g., recycling (Papp, 2010), mining from the seafloor (Bertram et al., 2011), and others. All these strategies, however, need large amounts of energy. These problems combined are causing a general increase in the cost of all mineral commodities (World Bank Global Economic Monitor Data, 2010; Bertram et al., 2011).
- Agriculture is facing an energy problem. The production of food and textiles is heavily dependent on fossil fuels for powering agricultural

machinery, for the supply of fertilizers, pesticides, and irrigation (Giampietro, 2002; Bardi et al., 2013). So far, food production shows no evident signs of decline. However, the increasing prices of fossil fuels are being reflected in higher prices for all agricultural products (Food Price Index, 2013); a phenomenon indicating that the problem exists and that it is growing.

- Nuclear energy faces considerable difficulties. The past decade had seen a minor renaissance in the start of the construction of new plants, although still in number insufficient to replace the old plants being retired. The trend, however, was interrupted with the Fukushima accident of 2011. At present, the production of nuclear energy worldwide is declining (Zittel et al., 2013). There are also worries about the capability of the mining industry to produce sufficient uranium if the number of plants worldwide were to be significantly increased above the present level (Dittmar, 2012).
- Renewable energy is seeing a truly explosive growth worldwide, especially with the diffusion of the “new renewables” in the form of photovoltaics (Kazmerski, 2006) and wind energy (Petersen and Madsen, 2004). The energy produced by the new renewables is still a minor fraction of the total of the world primary energy production, but it has been growing at exponential rates that, so far, show no sign of abating (Bardi, 2011). These sources can now produce electric power at prices that are nearly competitive with those of fossil fuels and have also reached EROI levels which can be considered acceptable (Raugei and Frankl, 2009), even though not on a par with those that fossil fuels had at the time of their rapid diffusion. However, even this rapid growth may not be sufficient for renewables to replace fossil fuels fast enough to avoid both depletion and disastrous climate change effects, unless either systems with much higher EROI ratios can be developed, or investments in renewable are considerably increased (Sgouridis and Csala, 2014).
- We see an evident trend toward higher efficiency in both production and end uses of energy. It is a trend particularly evident in the residential sector (Popescu et al., 2012), with buildings that reduce energy consumption by means of better insulation, passive solar heating, high efficiency lighting, and more. It is also evident in transportation with the diffusion of hybrid and purely electric road vehicles (Daziano and Chiew, 2012), as well as attempts to improve

public transportation while reducing the distance travelled by both goods and people.

Phasing Out Fossil Fuels

It is clear from the available data that an "energy transition" is in progress: we are facing more and more difficult times in maintaining the current system based on fossil fuels. The combined effects of depletion and of climate change are pushing humankind in the direction of replacing fossil fuels with cleaner and more abundant forms of energy, but the task is not an easy one. Renewable technologies could replace fossil fuels if we look at the transition only in terms of the amounts of energy that can be theoretically produced. Solar energy is ultimately limited by the solar irradiation and the amount beamed on the Earth's surface (Kambezidis, 2012) is very large in comparison to the primary energy produced by humankind.

Indeed, it has been estimated that the land area needed for the complete replacement of fossil fuels by a mix of renewable energy in terms of mainly wind and solar would be of the order of 0.5% of the total (Jacobson and Delucchi, 2011), that is of the same order of magnitude of the present footprint of human-made structures (Schneider et al., 2009). Current renewable technologies also do not use mineral resources which are likely to be in short supply in the near future (e.g. silicon and aluminium are the main components of the present generation of solar systems). In comparison, the present commercial technologies for nuclear energy generation face much more difficult hurdles in terms of fuel availability and general management (Zittel et al., 2013). Nevertheless, it is not obvious that the transition to renewable energy can be made fast enough to replace fossil fuels before their cost becomes too high for their generalized use or the damage resulting from climate change becomes truly catastrophic (Sgouridis and Csala 2014).

At the core of the problem there is the fact that, still today, no existing "alternative" energy technology can compete with fossil fuels in terms of combining a series of features that are perceived as fundamental for our energy system. These are flexibility, low cost, safety, transportability, high energy density, and high EROI. It is true that the renewables such as wind and PV do not suffer of the enormous "external costs" typical of fossil fuels in terms of environmental degradation, but the present economic system is not geared to take these costs into account. The most promising new renewable technologies, wind and photovoltaics, produce electric power and have a variable output. Hence, these technologies are not easily accommodated in an energy system built on the basis on the capability of fossil fuelled plants to produce “on demand” and on liquid fuels for transportation.

Other renewable energy technologies do not suffer of the intermittency problem; but have their shortcomings nevertheless. The potential of geothermal and hydroelectric energy is limited (Fridleifsson, 2003), while biofuels have a low EROI and there are concerns about their impact on the environment and on the world’s agriculture (Giampietro and Mayumi, 2009). Concentrating solar power is claimed to be able to produce on demand, at least in part, but the technology is still in its early stages of diffusion (Kuravi et al., 2013). Other forms of energy such as nuclear fusion (Ward et al., 2005; Dittmar, 2012), high altitude wind power (Archer and Caldeira, 2009), enhanced geothermal systems (EGS – also “heat farming”) (Fox et al., 2013), space based solar power (SBSP) (Seboldt, 2004), and others show promise in many respects but none of these technologies has reached the industrialization stage, so far, and some are still only at the stage of theoretical possibility.

Finally, there do exist energy storage technologies that can be used to adapt the variable input from renewables to the existing infrastructure, from electrochemical batteries to hydrogen obtained by water electrolysis. All these proposed methods, however, are an additional cost that so far has prevented storage (with the exception of hydroelectric basins) to become an integral part of electrical grids worldwide.

The Role of Science and Technology for the Generation of a Smooth Transition

Clearly, the ‘magic bullet’ that allows humankind to get rid of its addiction to fossil fuels has not been found, and it doesn’t seem likely that it will be found soon, if ever.

However, we are not necessarily condemned to returning to the “laborious poverty” of old times, as Jevons surmised long ago. Renewables are a growing technology which holds the promise of being able to produce amounts comparable, and even superior, to what we are producing at present with fossil fuels (Jacobson and Delucchi, 2011). At the same time, it is possible to base at least some forms of transportation on electric power, especially with the recent development of new and more efficient batteries (Gerssen-Gondelach and Faaij, 2012).

The problem is not so much a technological one, but it lies in the fact that the infrastructure of our society is not adapted to these new forms of energy. Adapting the electric grid to a variable input is possible by means of the "smart grid" concept (Clastres, 2011) but the transition will require a major effort. At the same time, if the whole energy system is to be adapted to a larger share of electric power, e.g., for powering electric vehicles, the grid should be scaled up, which is also a major cost. So, the transition is in progress but it turns out to be difficult, complex, and expensive. If we are to move in this direction, we must accept that substantial resources have to be allocated to the task and that it can't be done without sacrifices.

What role, then, for science in this transition? Traditionally, scientists have studied and developed new and improved energy technologies: better solar conversion methods, better energy storage systems, more efficient ways to use energy, and the like.

These are all valid strategies, but as scientists we need to do more in view of the urgency of the transition. We need to evaluate the new technologies in terms of their efficiency (using factors such as EROI, life cycle assessment, and others), and their impact on the environment and on economic activity. Then we need to develop strategies to optimize their benefits and minimize their unintended negative effects. The energy transition is first of all a systemic problem, in the sense that new technologies develop within an existing energy system, and that forces change and adaptation to both the system and to the new technologies.

Adaptation takes many forms; one is higher efficiency in the final uses of energy. On this point, however, we must remember that, as Jevons pointed out in *The Coal Question*, efficiency alone is unlikely to help solve the depletion problem. This was 'Jevons' paradox', that increasing the efficiency of use makes a fuel cheaper for a consumer, and hence total consumption is likely to increase. In short, better technology will not necessarily lead to a reduction in the consumption of a resource.

The energy transition is also an economic problem, since the present financial system tends to look only toward immediate profit, discounting medium and long term advantages. So, we have policy problems in the sense that we need to allocate economic resources for the transition and to consider also the social transformations that it will cause, and we cannot neglect the need of an equitable access to energy for everyone.

We need to build good models that can tell us where we are going and what measures have to be taken if we want to plan ahead. This is possible, as was shown in the past with the seminal "The Limits to Growth" study which was the first attempt at total world system modelling (Meadows et al., 1972; Bardi 2011).

We are not blind to the future; but we need to open our eyes if we are to see it. If we can manage the energy transition by taking into account technological, economic, and systemic factors, then we will be able to eliminate fossil fuels without a 'magic bullet', and arrive to a better, cleaner, and more equitable future.

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