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Energy scenarios: Toward a new energy paradigm

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Abstract

Primary energy sources exhibited regular long-term logistic substitution trends from the mid-19th century through the third quarter of the 20th century. This analysis, based on an extension of the Fisher–Pry substitution model, accounted for the observed historical shifts of primary energy use from sources of wood, coal, oil, natural gas, and nuclear. In the mid-1980s the substitution dynamics was replaced by a relatively constant contribution from oil, natural gas, coal, nuclear power, and hydropower. However, a major factor in energy use dynamics in this recent period was substitution of conservation and efficiency for actual fuel use. The energy efficiency is measured as the ratio of economic activity to the rate of energy use (energy intensity). To incorporate these data into the logistic analysis, a method for estimating the fraction of energy saved by the increased efficiency was used. With this interpretation, energy efficiency fits within the substitution model. Furthermore, to identify indications of future energy scenarios, as well as to test the logistic substitution analysis, another statistical approach using ternary diagrams was developed. The consistent results from both logistic substitution and statistical analysis are compared with recent energy projections, trends in decarbonization, Kondratieff waves, and other efficiency measures. While the specific future mix of renewables and nuclear energy sources is uncertain, the more general logistic dynamics pattern of the energy system seems to be continuing as it has for about 150 years now.

1. Setting the problem

The development of alternative energy sources is currently an important economic, scientific, and political topic involving environmental, growth, and sustainability concerns. These converging concerns have taken hold rapidly in the last decade because of perceptions that far-reaching change with large uncertainty is underway. Hopefully, the more this change can be understood, the better the decisions that could be made at all local, national, and global levels.

In the late 1970s Marchetti [1] demonstrated that primary energy sources exhibited regular long-term trends, which appear correlated with the Kondratieff long waves. Marchetti used logistic curves to fit the trends in the world's mix of primary energy sources (Fig. 1). His analysis, based on an extension of the Fisher–Pry substitution model, accounted for the observed historical shifts of primary energy use over a century from sources of wood, coal, oil, natural gas, and nuclear. This method, developed by him and his co-workers at the

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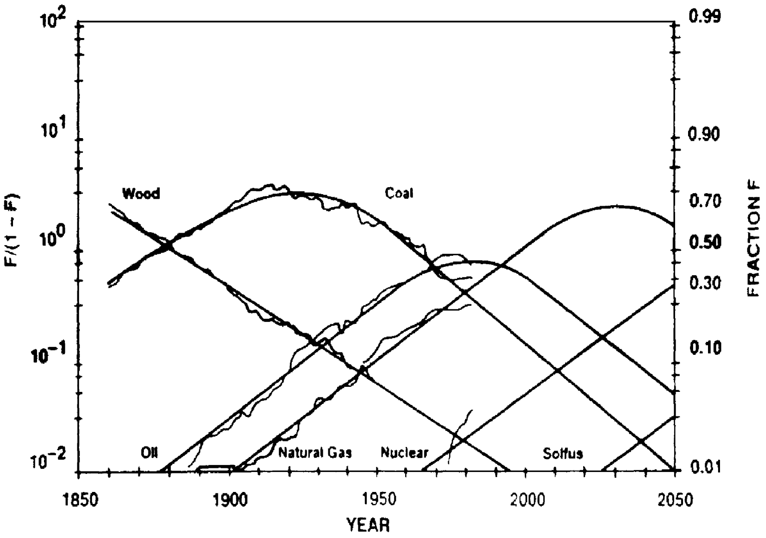

Fig. 1. Substitution dynamics of primary energy sources calculated by Marchetti [1].

International Institute of Applied System Analysis (IIASA, in Laxenburg, Austria), was very successful in analyzing thousands of time series concerning a variety of social and economic phenomena, revealing the perplexing result that a very simple logistic model can usually fit the data.

In another paper published also in the late 1970s [2] Marchetti referred to the amazing pattern found in energy systems and technology diffusion in this way: "It is as though the system has a schedule, a will, and a clock". Publishing in the 1980s in Futures [3], Marchetti has superbly coined this secular pattern as "fifty-year pulsation in human affairs". More recently, reviewing his published work for the proceedings of an international workshop on Kondratieff waves, Marchetti wrote [4]: "About 30 years ago, in an effort to solve the problem of the historical evolution of the energy markets, I came upon the idea that, the system being mostly "more of the same," primary energies might compete much as species in a biological niche, a subject well modeled by mathematical biologists in the 1920s. The idea proved extremely fruitful in the area of energy, so much so that I progressively tried to extend it to other areas, with the above argument that the system appears to be mostly more of the same. This worked beyond my expectations: magically, data time series in the most variegated social and economic areas could be fitted with simple logistic equations, the most elementary solutions of the Volterra–Lotka equations of competition".

In other words, the central aspect of Marchetti's concept is that the system is insensitive to many possible perturbations, "all perturbations are reabsorbed elastically without influencing the trend" [2]. This concept seems to apply to many "ecological" systems of competing entities: not only energy systems, but technologies as well, behave like species competing for the same niche—what we need is to observe carefully which are the competing species and what is the very niche to be filled.

One of Marchetti's followers, the American professor of economics, Berry (University of Texas at Dallas), who published vigorously on socioeconomic long waves during the 1990s, in another paper published in Futures [5] stressed the importance of this stable societal behavior for the middle- and long-range forecasting and planning: "The repetition of long-waves rhythms provides a key to what lies 25 and 50 years ahead, helping us to identify the patterns, determine the processes, and work out their logical consequences".

Within this logic and considering that a generation has passed since Marchetti's original work, it would be interesting to see if the predictions were realized or if some important aspects of the competition were overlooked. A first indication can be determined if we simply add new energy data (from 1975 onwards) on the original curve drawn by Marchetti. What is seen is an astonishing deviation from his forecasted trend, as can be observed in Fig. 2.

Apparently the pattern was broken and replaced by relative flatness from the mid-1980s to the present in many of the energy sources. Smil [6] was probably one of the first researchers proposing that Marchetti was

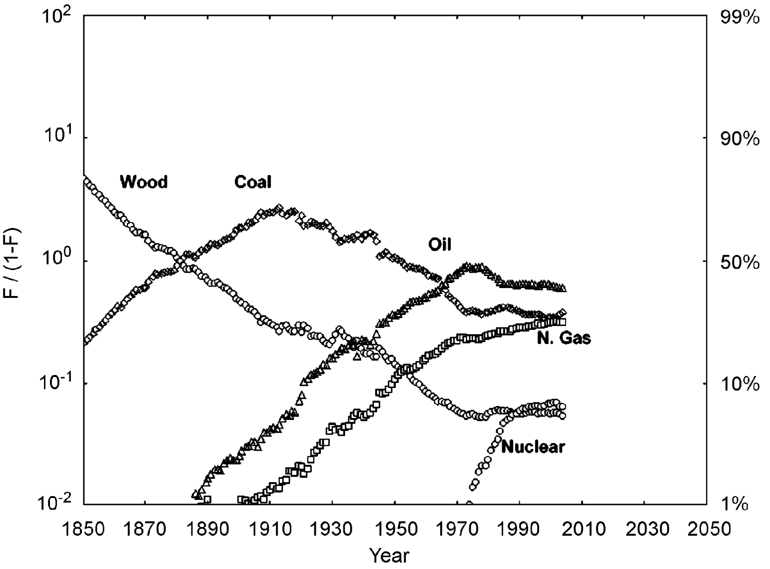

Fig. 2. Progression of actual energy use as *f*/(1−*f*) as used by Marchetti in 1977.

wrong in concluding that the system's dynamics cannot be influenced, and states: "After 1973, many forces began reshaping the system on a massive scale, and the result on the global level has been a shift from a regime of energy substitution to one of largely stable energy shares with a minimal structural change". In fact Marchetti's model and reality appear unhinged by the end of the last century, when crude oil supplied about 37% of the world's primary energy needs, well above (~50%) Marchetti's prediction of 25%, while natural gas and coal each delivered about 25% of primary energy, a pattern very distant from Marchetti's prediction of 52% and 10%, respectively. Strangely enough, this relative contribution of primary energy sources has changed only very slightly since then.

Smil [6] suggests that logistic analysis of primary energy sources might not be appropriate to predict long-term energy usage, for it cannot take into account changes within the system. Surprisingly, IIASA's most recent global energy consumption forecasts [7,8] do not refer to deviations of the inevitable clockwork substitution. Nakicenovic [8] presents a *f*/(1−*f*) graph very similar to Fig. 2 (but with data only up to the beginning of the 1990s), and states: "The competitive struggle between the six main sources of primary energy—wood, animal feed, coal, oil, gas and nuclear materials—has proved to be a process with regular dynamics that can be described by relatively simple rules". A recent review, made by Rosa [9] during the above-mentioned workshop on Kondratieff waves, does not refer to a changing pattern, but analyzes the boundary conditions imposed by the limits of conventional resources, leading to a fundamental change in the historical course of the world system and to a still undecided new economic structure. Smil [6] suggests possible causes for this relatively static behavior: the massive worldwide resurgence of coal, battered and contracting nuclear fission, the fading Japanese miracle, the collapse of the Soviet Union, and the rise of a surprisingly more efficient China. This last point is important because it may indicate a key to understanding a potential clockwork dynamic again, as will be analyzed in Section 3.

This paper does not intend to disagree with the whole of Smil's analysis, but instead offers a new perspective of the current substitution process, as well as a reasonable future scenario.

2. The competition endures

Marchetti's insight into the logistic substitution of energy sources and technologies might still be at work, although not necessarily as he forecasted them. The energy system, as well as any technological regime, seems to work under competitive substitution dynamics in an environment with rapidly changing technology and uncertainty. A shift from a dynamic energy substitution regime since the mid 1970s to one of stable energy shares was not expected. The ''flatness'' observed in Fig. 2 is probably a transitory phenomenon and cannot endure forever; the exploitation of solid and non-solid fossil fuels will come to an end, and the intensive use of alternative primary energy sources is growing. In other words, the competition for market shares endures, filling ecological niches through economic pressures. Processes of growth and diffusion often follow S-shaped curves. The related logistic substitution model describes the system's dynamic stability. If a technology's market share grows, it comes at the cost of shares of others, even when the system's carrying capacity also grows [10]. Perhaps the relevant competing species of the energy system, mentioned in the first section, were not properly identified.

One seemingly inconsistent feature in Marchetti's overall substitution pattern, exhibited in Fig. 1, is the relative proximity of the last starter—natural gas (by the dawn of the 20th century)—in relation to the starting date of crude oil (1880s). Matias and Devezas [11] explored recently this issue and got a more regular (synchronized) pattern considering crude oil and natural gas as a unique primary energy source (fluid fossil fuels—FFF). Fig. 3a repeats the substitution dynamics calculated by Marchetti using data up to 1974 and considering separately oil and natural gas. Fig. 3b shows the new pattern adding the data for oil and natural gas, that is, considering both as a unique primary energy source. Some differences in the fitting of these new curves, when compared with the fitting in Marchetti's curves, are due to some (small) differences in the historical data and (mainly) to the differences in the logistic programs used to fit the data.

Considering crude oil and natural gas together as an FFF group makes sense, because they have similar geological origins and locations, are extracted with similar technologies, often by the same commercial organization, and are often transported through pipes [12]. While they both can be used to generate electricity, some main uses are complementary, providing heat through natural gas and transportation fuels from oil. Also, as seen in Fig. 2, the ratio between the contributions of oil to natural gas has been relatively constant, which suggests that the energy sources are significantly coupled and could be considered in this analysis as a single FFF source. As we can see in Fig. 3b, this consideration produces a regular pattern that seems to suggest a synchronized competition between primary energy sources, each one dominating the energy scenario for approximately two Kondratieff long waves.

The question then arises—what might have been overlooked since the mid-1970s and what might contribute to subsequent primary energy sources, completing the synchronized energy substitution process? Marchetti's forecast of a growing nuclear fission scenario since the 1970s was not realized, and his imagined projection of a SolFus scenario was very optimistic. In the next section the dynamics of both energy supply and demand will be explored to discern a possible interpretation of a current dynamic substitution process.

3. Efficiency—the new paradigm

A large factor in energy use dynamics in this recent period was the substitution of conservation and efficiency for actual fuel use [6,13]. This current wave of energy substitution with efficiency seems to be driven by both direct market mechanisms and governmental policies. The leading sector within OECD countries has been manufacturing, which indicates significant financial incentives. Governments have supported energy efficiency policies for economic, national security, and environmental reasons. For example, since the early 1970s, energy efficiency policies in the US have included vehicle, building, and appliance efficiency standards, energy efficiency labeling, cogeneration initiatives, and utility efficiency programs [14].

It seems appropriate to explore this substitution with the Fisher–Pry model. However, a unit of efficiency is not easily compared to a barrel of oil or a watt of electricity. Yet, efficiency requires technology development and capital investment to implement the technology. For example, energy efficient windows require development of materials and designs. The consumer then makes a purchase decision considering the capital investment in the windows compared to the long-term savings in heating and cooling costs. The consideration of all these commercial, residential, and industrial decisions would be very difficult to follow and attribute back to efficiency considerations compared to other factors in the purchase decision. However, a simple measure of the world's energy efficiency over this period might be constructed and incorporated into the model's data. With this extension, the model might be more consistent with historical data (including the current trends). The concept recognizes that energy efficiency or conservation is just another alternative substitute when considering energy use.

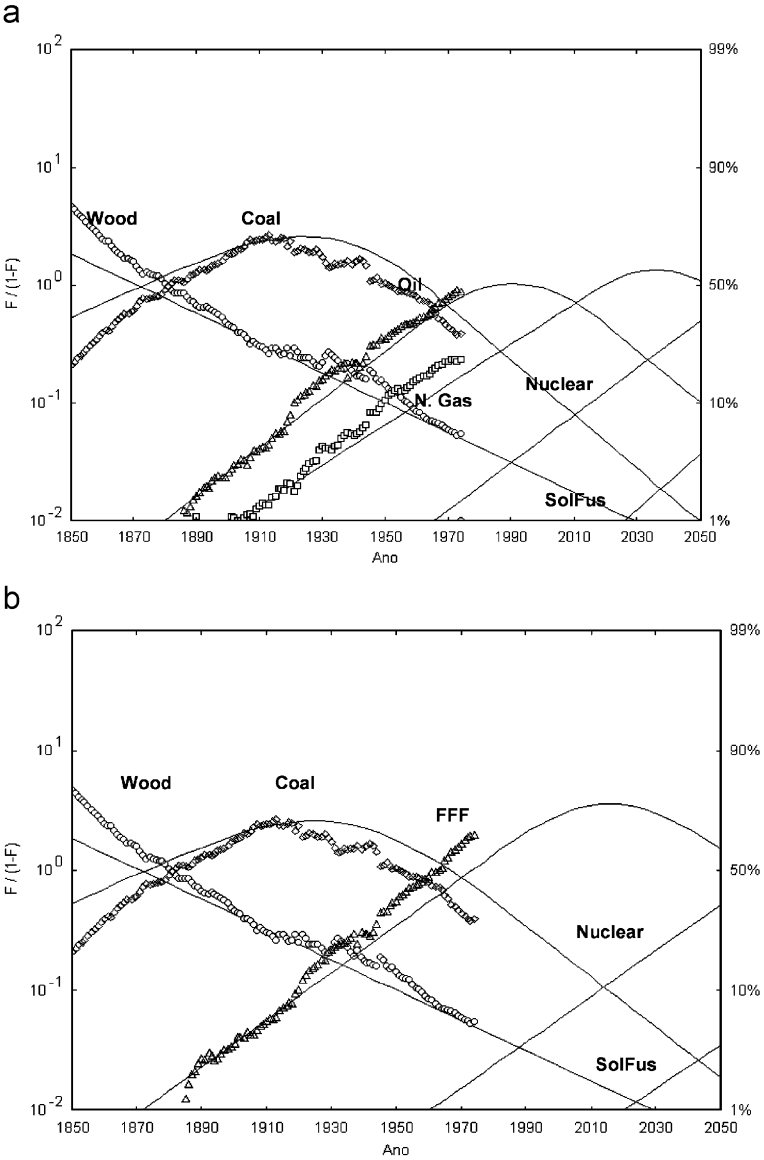

Fig. 3. (a) Progression (1860–1974) of energy use considering oil and natural gas separately. (b) Progression (1860–1974) of energy use considering oil and natural gas together as a unique primary energy source (FFF—fluid fossil fuels).

Energy efficiency is a difficult construct to measure; however, there are gross aggregated proxies that might be useful. One such measure is the ratio of economic activity to the rate of energy use (energy intensity). One analysis of this measure for the US from 1949 has been reported in a recent review of future energy use [15]. A similar world measure, shown in Fig. 4, includes uncertain market estimates of the world GNP [16]. The problem with a national measure of energy intensity is that this measure of energy efficiency is affected by not only conservation measures but also by structural changes in a regional economy, e.g., moving from the industrial sector, where high-energy inputs are required, to the service sector with lower energy requirements. However, although manufacturing might be moved outside national economies, these movements should balance out in a global energy intensity measure.

Both curves show substantial increases in this measure of efficiency. In the US, the amount of GDP generated per unit of energy increased about 60% from 1970 to 2000. The increase in the same measure for the world was a bit less at about 45%. The trends in the US data include a relatively slow change (0.1%/year)

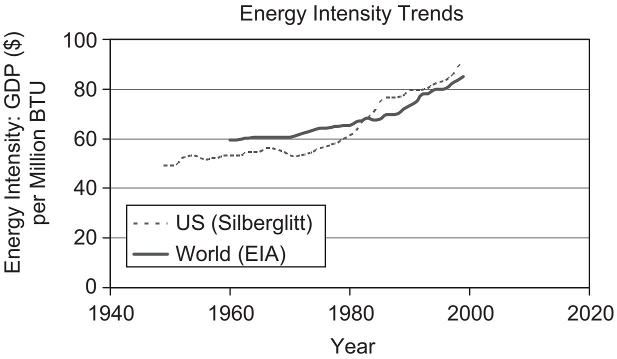

Fig. 4. Energy intensity as the ratio of GDP per million BTU for the US and the world [15,16].

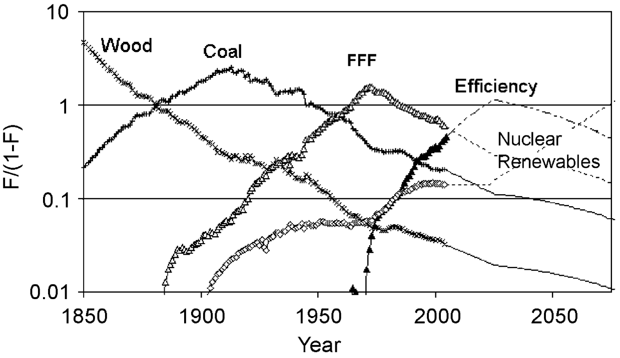

Fig. 5. Historical energy trends after accounting for energy efficiency as measured by energy intensity for the world.

before 1970, a period of rapid increase in efficiency between 1976 and 1986 of about 2%/year, and a slower growth rate of 1.2%/year since 1986. Estimates of previous energy intensity show that the few decades before this period were relatively constant [17].

To incorporate these data into the logistic analysis, a method for estimating the fraction of energy saved by the increased efficiency is needed. The energy contribution from "efficiency" is defined as the actual energy minus the energy that would have been realized from the same amount of fuel if there had been no change in energy intensity. Practically, this is equivalent to dividing the previously defined energy use fraction by the ratio of efficiency increase from some starting point (e.g., world: 1960, US 1949). For example, if the energy intensity increased by a factor of 1.5 and a fossil fuel contributed 45% to the energy standard mix, then with the above definition of efficiency, the fraction from the fossil fuels would be divided by 1.5 to obtain 30% (the amount the fuel would have contributed if the energy intensity had not changed), and the remaining 15% would be attributed to efficiency.

How long should the attribution to efficiency be applied? If the efficiency factor were applied only to fossil fuels, whose price fluctuations have driven a motivation to higher efficiency, then as the fossil fuels diminish with time, the efficiency contribution would also decay. This analysis takes this approach. Alternatively, a depreciation schedule might be followed to discount in the investments made in the past. Discount rates corresponding to depreciation schedules of 15–30 years might be considered.

For the near future (i.e., next couple of decades), the EIA predicts almost constant relative contributions from the primary energy sources of coal, oil, natural gas, and hydropower. It also predicts that the worldwide energy intensity will increase by about 2% per year [18]. The result of this energy projection is shown in Fig. 5. The trends of primary energy substitution seem to be consistent with a logistic model of the historical energy use and near-term energy predictions to 2020, with energy efficiency still continuing to be a key factor in energy substitution. This near-term projection uses the predictions by the EIA of relatively constant fractional use of the various fossil fuels with an energy intensity increasing by about 2% per year, i.e., it is a simple

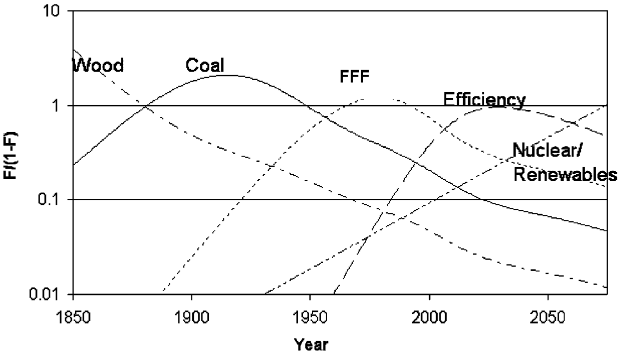

Fig. 6. Energy trends resulting from logistic substitution fits to the historical and near-term projections after accounting for energy efficiency as measured by energy intensity for the world. The near term (up to 2020) can be understood as substitution for approximately a 2% increase in efficiency as measured by the energy intensity with a corresponding 2% decrease in fossil fuels components after accounting for energy efficiency.

substitution as the efficiency (energy intensity) rises by 2% a year and the adjusted fossil fuel fractions decrease by about 2% a year. There are still quite a few technologies and options to increase the efficiency, as measured by the energy intensity [19].

Predictions in the future require an additional assumption about a new energy source being developed at the traditional logistic substitution growth rate. Various predictions about the reemergence of nuclear power have been suggested, but even the most aggressive of these scenarios would not generate the historical logistic growth rates seen in previous substitutions. Assuming that the traditional logistic growth rate is to be maintained, another energy source, e.g., renewables, might be developed in conjunction with a resurgence of nuclear power. Alternative scenarios for this possible energy source are discussed in Section 5. An assumption with a logistic growth rate consistent with recent historical substitutions was used for predictions out to 2075. Note that the prediction does not specify the particular energy source, but instead is based on the continuation of the logistic substitution process.

Logistic substitution curves were fit to these historical and near-term projection data. These fits are shown in Fig. 6. The peak of the efficiency curve depends on the assumption of the rise of the alternative energy source, labeled “nuclear/renewables”.

4. Statistical approach

To help our search for future energy scenarios, as well as test their consistency with the previous logistic substitution analysis, another approach was developed, namely a statistical one using ternary graphs.

In 1995, Nakicenovic and Jefferson [7] published the well-known IIASA–WEC joint report “Global energy perspectives to 2050 and beyond”, in which they present six different future scenarios for world’s energy use. The six scenarios were clustered around:

- A—high economic growth (Scenarios A1, A2, and A3),
- B—middle course (Scenario B),
- C—ecologically driven (Scenarios C1 and C2).

Scenario A addressed alternative key developments in energy supply. Scenario A1 assumes an ample supply of oil and gas in the future. On the other hand, Scenario A2 assumes insufficient oil and gas resources due to technical, economic, and political reasons, resulting in a return to dependence on coal. Finally, Scenario A3 assumes that rapid change in nuclear and renewable energy technologies would result in a rapid phase out of fossil fuels for economic reasons rather than scarcity.

The middle course Scenario B was based on more cautious assumptions regarding economic growth prospects, rates of technological change, and energy availability. This scenario, characterized as “muddling through'' and pragmatic, would be reachable without relying on drastic changes in current institutions, technologies, or current perceptions of availability of fossil resources.

The ecologically driven Scenario C includes optimistic assumptions about technology and geopolitics. These two scenarios describe a future transition from the current dominance of fossil fuels towards renewable energy supply.

A few years after the release of this report, Nakicenovic et al. [20] published a book analyzing the details of the above-described IIASA–WEC's forecasts, and presented the primary energy usage (past, present, and future) in the form of a ternary graph. Each corner of the triangle corresponds to a hypothetical situation in which all primary energy is supplied by a single source: oil and gas at the top, coal in the left, and non-fossil sources (nuclear and renewables) in the right. The historical development since 1850 showed a very interesting and logistically consistent trajectory, exhibiting a spiral character, starting from the bellow of the right side, going left in direction to coal, and then upwards in direction to oil/gas, stopping almost halfway between the middle of the triangle and the complete oil/gas point at 1990. The historical data were included along with the projections to 2020, 2050, and 2100, following the six different possible scenarios (the same graph is also shown in another IIASA report by Grübler [21]).

We can now ask, after more than a decade of new data and new developments, which of these possible paths is more probably being accomplished. Trying to find this answer we have constructed ternary diagrams, using different software and adding new data. The result using data until 2004 is presented in Fig. 7.

The mixtures designs and triangular surfaces module in the software package, Statistica, was used to construct the ternary diagrams [23]. In this software, well known by materials scientists, a system can be defined comprising a number of independent size fractions (components or ingredients of a mixture—market share, in this case). The value of the property of interest (year, in this case) is experimentally determined from the historical data at a set of points. A response surface model can be derived to estimate the values at other points using the response surface methodology (RSM), a collection of statistical tools used to optimize processes. Myers and Montgomery [24] have shown the importance of this statistical tool, with important

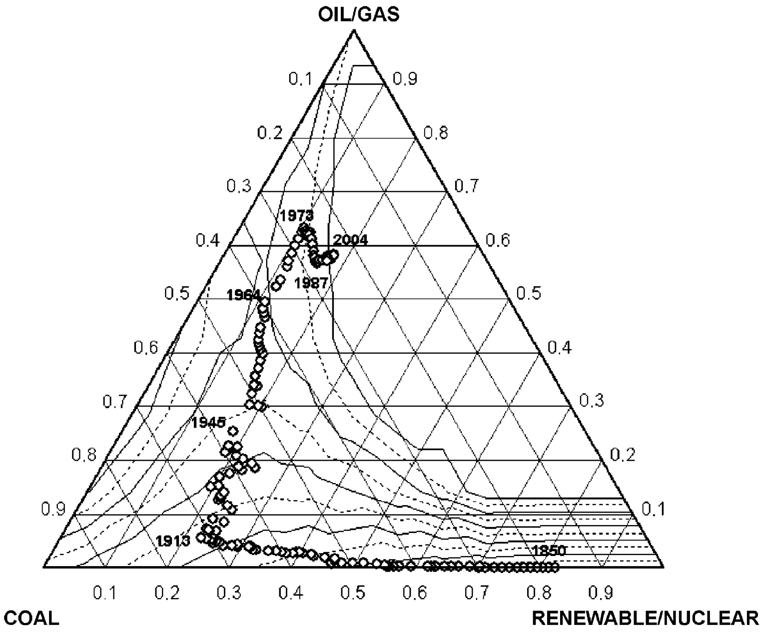

Fig. 7. Historical development 1850–2004 (open circles) for the market shares of oil/gas, coal, and renewables/nuclear. Data from 1850 to 1985 were collected from Grübler [22], p. 400, and from 1985 onward were collected from the BP Statistical Review combined with IEA Energy Statistics. The results, with a 95% confidence level, are $R^2 = 0.9976$ and $R_{\mathrm{Adj}} = 0.9975$, and a maximum error of 2.5%, $\mathrm{Year} = +1939.470*x + 1843.780*y + 1902.423*z - 57.146*x*y + 70.201*x*z + 1141.850*y*z - 1101.789*x*y*z$ where $x = $ coal, $y = $ renewables/nuclear, $z = $ oil/gas.

applications in design, in the development of new products, and in estimations of market shares based on time series.

The mathematical model describes the surface as a function of at least three variables (in our case three market shares). This function may be represented in a tridimensional space or through a bidimensional contour plot, i.e., a ternary diagram. The function may be of the first, second, or even of the third order, as the complete cubic model presented below:

$$f = \sum_{i=1}^{q} \beta_i x_i + \sum_{i<} \sum_{j=2}^{q} \beta_{ij} x_i x_j + \sum_{i<} \sum_{j=2}^{q} \delta_{ij} x_i x_j \left(x_i - x_j\right) + \sum_{i<} \sum_{j<} \sum_{k=3}^{q} \beta_{ijk} x_i x_j x_k.$$

The main difference between this graph and the previous one presented by IIASA's authors (constructed with data until 1990) is that a changing trend since the end of the 1980s is perceived, which clearly represents the flatness of market shares appearing in Fig. 2. Some striking aspects can be inferred from the diagram presented in Fig. 7. As IIASA's authors have pointed out, the primary energy structure has evolved clockwise in two "grand transitions": traditional renewables were replaced by coal between 1850 and 1920. Coal reached its maximum market share about 1920 and was then progressively replaced by oil and natural gas between 1920 and 1973. Since 1973, the energy system seems to be in transition, similar to that settled down after 1913, which extended until the end of WW II. These turbulent times can be easily correlated with the onset of the downturn of the third and fourth Kondratieff waves, respectively, and consequently have a change in direction of the historical points in the graph. But the trend started in 1973 (going down in the graph, or in other words, standing back from the intensive use of oil and gas) is again changing direction, going right (at least since 1987), as if avoiding following the path downwards in direction again to the right corner, renewables/nuclear. This trend could be interpreted as if the primary energy system were following the path toward Scenario B.

The question is then, what comes next? The statistical tool was used to look for the most probable path, in other words, extrapolating data using the surface model, searching for sets of market shares that resulted in an increasing sequence of dates. The result is exhibited in Fig. 8.

The correspondence of years and market shares for the extrapolated points appearing in Fig. 8 is shown in Table 1. Although the share for renewables/nuclear will significantly increase, the relevance of oil and gas will

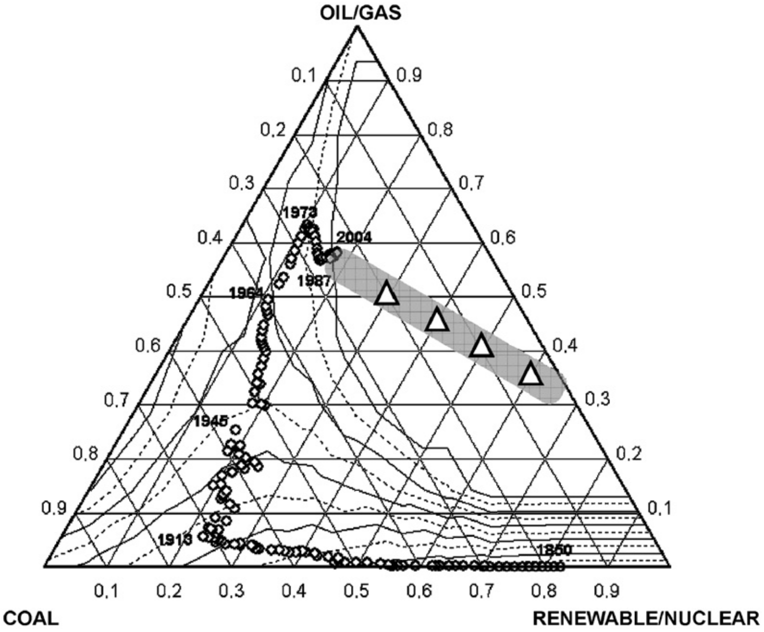

Fig. 8. Historical development 1850–2004 (open circles) for the market shares of oil/gas, coal and renewables/nuclear, now extrapolated using the equation shown in Fig. 7. The open triangles represent an increasing sequence of years, with decreasing market shares for coal and oil/gas, and an increasing market share for renewables/nuclear (see Table 1).

Table 1
Development of market shares for the extrapolated points in Fig. 8

Year	Coal	Oil/NG	Renewables/nuclear
2034	20	50	30
2060	15	45	40
2080	10	40	50
2100	4	36	60

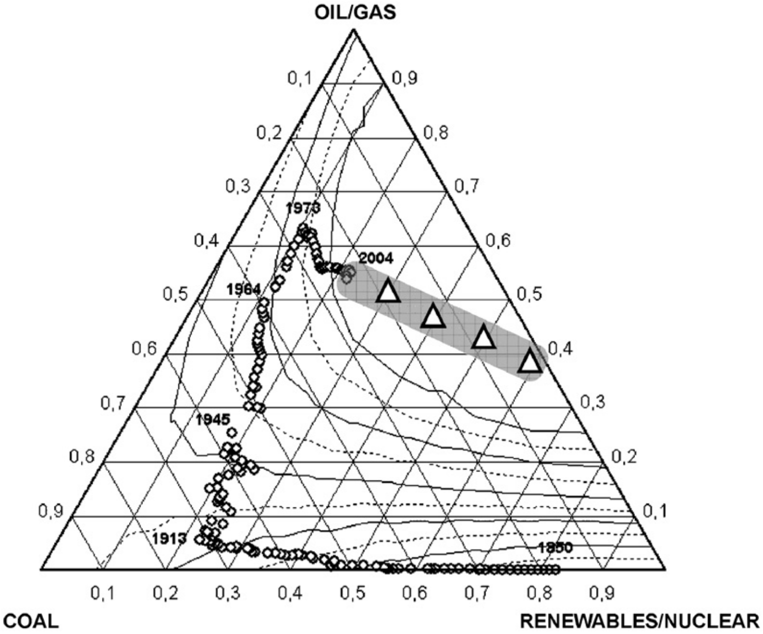

Fig. 9. Historical development 1850–2004 (open circles) for the market shares of oil/gas, coal, and renewables/nuclear, now corrected taking into account the efficiency increase since 1960 and extrapolated using the equation presented below. The open triangles represent an increasing sequence of years, with decreasing market shares for coal and oil/gas, and an increasing market share for renewables/nuclear. Results for confidence interval of 95%: $R^2 = 0.99798$ and $R_{\mathrm{Adj}} = 0.99791$, and a maximum error of 2.5%, $\mathrm{Year} = +1930.784*x+1842.092*y+1957.473*z-38.182*x*y-52.103*x*z+676.671*y*z$ where x = coal, y = renewables/nuclear, z = oil/gas.

remain for the whole 21st century. This scenario suggests a very slow transition rate from fossil fuels to renewable/nuclear.

However, things change dramatically if efficiency is considered in the same graph. In the ternary diagram presented in Fig. 9 the points from 1960 onward were corrected taking into account the increase in efficiency already presented in Figs. 5 and 6. In the same graph, four points in the future are represented. They were extrapolated from the equation shown in Fig. 9 and express the probable trend. Although Figs. 8 and 9 look similar, the transition to renewables is much quicker, giving dates for the similar mixes shown in Table 1 at 2014, 2030, 2035, and 2040, i.e., reaching a 60% fraction of renewables/nuclear about 60 years earlier than the scenario considered in Fig. 8. This is a far more optimistic scenario regarding the transition rate from fossil fuels to renewables/nuclear.

Another interesting graph is obtained if we plot the ternary diagram using the projected points calculated for Fig. 6 (logistic substitution fit). The resulting graph is shown in Fig. 10. Graphing the scenario constructed here most closely follows the C1/C2 scenarios. The major assumption differentiating these scenarios is the relative contribution of oil and natural gas compared to coal, as both are replaced by renewables and nuclear sources. The current ratio is about 2.6. In logistic substitution this ratio would stay about the same, rising

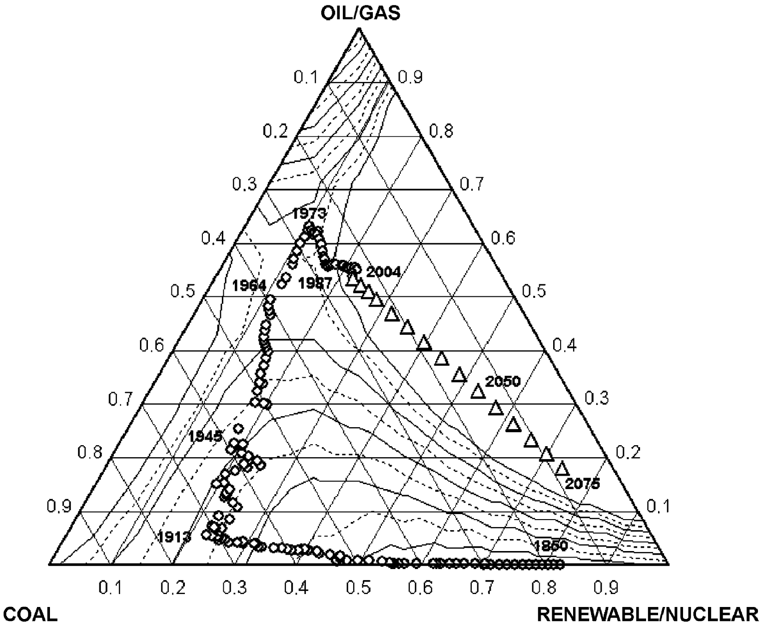

Fig. 10. Historical development 1850–2004 (open circles) for the market shares of oil/gas, coal, and renewables/nuclear, corrected taking into account the efficiency increase since 1960, and now including the projected (logistic substitution fit) points used for efficiency in Fig. 6.

slightly to about 3. Note that this trajectory does not depend on whether the analysis is done with the full four component method (coal, oil/gas, renewables/nuclear, and efficiency) or with efficiency corrections for three components. Although the trajectory would be the same, the rate of progress along the trajectory does depend on the analysis method: with the four components as shown in Fig. 6, the renewables/nuclear fraction in 2075 would be about 50%; with the alternative method of correcting the fossil fuel components for efficiency, this fraction in 2075 would be about 74%.

5. Uncertainties, alternative approaches, and interpretation

Three major areas are further explored in this analysis. First, the analysis has many uncertainties such as data classification issues and scenario construction. The uncertainty discussion includes a review of earlier energy logistic analysis criticism and an interpretation of current energy scenarios within the logistic growth framework. A second discussion concerns the perspectives from other approaches to energy and economic trends. These additional approaches include a new technique for defining system efficiency, the logistic progression of the H/C ratio, and questions concerning the potential hydrogen economy. Finally, possible longer-term trends across the logistic substitutions are discussed, and compared with new results using statistical analysis.

Uncertainties in this analysis arise from multiple sources such as data classification and scenario construction. These data sources include a variety of historic and projected estimates on energy and economic factors from governments, businesses, academia, and non-government organizations. The logistic analysis of Marchetti predicted a continuing rise in natural gas and nuclear power fractional contributions. Instead, the last quarter of the 20th century saw a relatively flat fractional contribution with seemingly little dynamics. This was pointed out by Smil [6] as a weakness in the predictive power of the logistic analysis. While the actual component of substitution seems to have been different than that identified (efficiency versus natural gas and nuclear), the prediction of a continuing dynamic seems to have been fulfilled. This substitution seems to be like it may continue its natural course if the relatively stable contribution of fossil fuels along with an approximately 2% rise in the world energy intensity is realized as predicted. There seems that there are many technologies to apply to more efficient and effective use of energy [13].

As Smil [6] has already pointed out, many notable forecasts of the US primary energy consumption in the year 2000 that were released between 1960 and 1979 ended up at least 40–50% above the actual value. Sales in electricity in US experienced a continuous fall during the last 30 years: They grew by 50% during the 1970s, expanded by 30% during the 1980s, and rose just 11% during the 1990s. Evidently forecasters greatly underestimated the cumulative contributions of mundane energy conservation and the more efficient use of fuels. Efficiency and conservation were undoubtedly the motor in the last quarter of the 20th century and surfaced as the new energy paradigm. Figs. 5 and 6 try to translate this new paradigm as the continuation of the regular dynamics already shown in the past.

In the near term, the efficiency component is expected to rise. However, the eventual decline of the efficiency component is expected due to the subsequent substitution of a new energy contributor. In the previous graphs this next energy component was identified as renewables/nuclear. While the beginning of a new logistic growth has less uncertainty, the identification of the actual energy source is fraught with many unknowns. Specifically, the assumptions that would lead to a prediction of renewables/nuclear are similar to IIASA's Scenario C: (1) The relative use of coal and oil/natural gas will remain quite constant (prediction from the logistic analysis) and (2) renewables/nuclear will substitute for them with strong growth after 2020 (discussed in the next paragraph). However, some of IIASA's other scenarios could result from slightly different assumptions. Scenarios A1 and A2 might result from changing assumption one to apply to traditional fossil fuels and assumption two to refer to non-traditional fossil fuels, such as tar sands, oil shale, and methane hydrates. Furthermore, IIASA's Scenario B might result from assuming that a mix of non-traditional energy sources (non-traditional fossil fuels, nuclear, and renewables) will substitute for traditional fossil fuels, with strong growth after 2020.

While there is an abundance of coal, the fraction of energy that it contributes may decline. In the past couple of decades coal use in absolute terms went up and is projected to continue to increase in the near term. However, the fractional supply of energy from coal (before considerations of efficiency) has remained relatively constant. At the same time the energy saved from efficiency measures has been increasing. An additional factor is the concern over carbon emissions since coal is the fuel with the largest carbon emission per energy unit. Since the Kyoto agreement has provisions for developed countries to take credit for investing in lower carbon emission plants in developing countries, either alternate fuel or more efficient coal plants might be built.

In addition to the concern about carbon emissions, the substitution of oil with other energy sources might be motivated by economics when the current reserves of oil are less than the previously extracted amount, i.e., "peak oil". This would be similar to the price jumps of oil in the 1970s motivating higher energy efficiency.

It is important to demonstrate that our present results from both logistic substitution and statistical analysis are consistent. The predicted market shares for coal, oil/natural gas, and renewables/nuclear for 2020, 2040, or 2070 are in the same range. The diagrams shown in Figs. 7 and 8 seem to suggest the development of the middle course Scenario B. However, these diagrams, when corrected to take into account the growth in efficiency, seem to point toward an approaching development of the ecologically driven Scenario C. This trend can be schematically represented as a quaternary graph shown in Fig. 11 with the extra dimension of efficiency. The historical path of the primary energy system along with the discussed projection until ~2070 is schematically shown. The dates appearing in this diagram correspond to the peaks for each market contributor resulting from the fitting presented in Fig. 6. It is interesting to note that these dates match well the peaks of previous Kondratieff waves (second, third, fourth, as well as to the predicted fifth K-wave, whose ceiling is foreseen by about 2030).

The combination of nuclear and renewables is motivated by the IIASAs scenarios, which use this grouping in their ternary diagrams. Nuclear is a potential non-fossil source that, while not quite renewable, could provide more fuel than is used (in breeder mode) for quite some time. There continue to be major issues (e.g., waste, nonproliferation/terrorism, safety, and cost) to nuclear power expansion. However, many governments, industries, and financial institutions are reconsidering options. For example, the US Global Nuclear Energy Partnership (www.gnep.energy.gov) is assessing possible reliable and safe technologies for global use with a closed nuclear fuel cycle to significantly reduce waste and extend the fuel.

Nuclear power seems to be an insurance energy source depending on how quick and how far the other renewables develop [25]. Various projections for nuclear energy point to growth in the next 25 years by up to

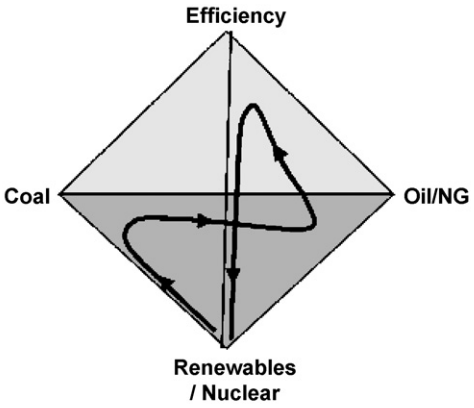

Fig. 11. Schematic quaternary diagram translating the trajectory followed by the primary energy system from 1850 to 2070. The dates correspond to the peaks for each market contributor resulting from the fitting presented in Fig. 6 and match the peaks of previous Kondratieff waves, as well as the peak of the predicted fifth K-wave.

40% [26–28]. Extended projections show that 30–50% of the world's electricity might be nuclear generated by 2050 [29]. Even with these optimistic projections for nuclear power growth, the rate of substitution would not be similar to previous logistic growths. This suggests that other energy sources from renewables might supplement the growth. Sources from renewables might include new forms of energy conversion such as wind power, geothermal, biomass, and solar power.

Besides these interpretation uncertainties, there are also differences among the historical classifications of energy sources. For example, in the IEA data there is a much larger fraction of energy derived from biofuels even in the most recent periods. The Marchetti [1,2] and the Rosa [9] data seem to neglect the energy derived from hydropower, which was very instrumental in the early expansion as a source for electrical power. These differences among the historical use of energy do not seem to significantly impact the analysis of the recent trends.

Hydropower seems to be unique. Hydropowered mills were integral to the expansion of the industrial revolution in the United States and Europe. First used to generate commercial electricity from the Niagara Falls region, hydropower continues to contribute a significant fraction of energy throughout the world mostly in the form of hydroelectric dams. Many dams were built in the first half of the 20th century, and a few large hydroprojects such as China's Three Gorges Dam continue to be constructed. The projects are known for their high capital costs that result in reliable power with low operating costs and no fuel costs. Currently, about 6% of the world's energy is supplied through hydroelectric dams, a fraction that has been relatively stable since at least 1980. Why might hydroelectric power not follow the general logistic trends of other fuels? There are many differences, but one major factor is that the potential for hydroelectric power generation is limited by geography. In developed countries most economically feasible sites have been developed. Another difference in hydroelectric power is the cost associated with substitution. Hydropower has a large investment capital cost followed by low operating and no fuel costs. The hydroelectric plant operates for a long period of time with only relatively minor decisions to upgrade turbines and generators to increase output. Therefore, the decision-making timescale for these plants is longer than one with varying fuel costs but lower capital expenditures.

Other approaches to the trends in energy and the economy might display supplementary or complementary perspectives. Two identified approaches include a recent extended efficiency analysis and the continuation of the logistic H/C growth.

In a recent paper on energy, efficiency, and CO_2, the DEA analysis was used to measure combined economic and environmental system efficiency [30]. The relative weights in this multi-criteria analysis were derived from the DEA method, also known as "frontier analysis" [31]. This makes the definition of "efficiency" in this paper [30] difficult to understand as the relative value of energy, CO_2 reduction, and GDP (or GDP/capita) are not explicitly stated. While the method is good for some applications, there are many other variables in energy analysis leading to the ranking of energy types. For example, there are capital costs, catastrophic risks, and waste management issues that do not seem to be considered. The DEA analysis looks at a bottom-up analysis of “efficiency” for each energy supply source, whereas the “efficiency” referred to here (in this paper) is a top-down approach for energy demand.

Another logistic trend has been the decarbonization of primary energy sources. The ratio of hydrogen to carbon in the primary energy sources seems to display a logistic growth trend since 140 years ago during the periods of substitution from wood to coal to oil and natural gas. The EIA projection of a relatively constant mix through 2025 would result in a constant level of the carbon to hydrogen ratio in primary fuels. It is expected that the continued growth of natural gas (methane-CH_4) would continue to replace oil (close to CH_2) and eventually lead to an economy in which renewables would supply electricity or hydrogen as carriers of fuel (no fossil carbon from primary fuels). However, if instead the H/C ratio is multiplied by the relative efficiency factor, i.e., economic activity per energy use, then the ratio would continue its decline. This could be interpreted as a zero C/H ratio for the contribution of energy from substitution of efficiency technologies, e.g., if a 50% more efficient natural gas turbine replaces an older one, the $C/H/$intensity ratio would be about 1/6 instead of 1/4 After 2025, non-fossil fuel (e.g., a mix of nuclear and renewables) is expected to climb significantly.

At first this might cause concern about carbon dioxide emissions, but the carbon dioxide release rate is dependent both on this C/H ratio and on the overall amount of energy used. While the EIA projections and historical trends forecast greater energy use, some proposals are being discussed in the EU and Japan for rapid increases in energy efficiency through use of hybrid cars and more efficient appliances [32]. Further reductions in carbon dioxide emissions might be realized through increasing efficiency in fossil fuel plants, sequestration, and use of biofuels. One plan, proposed by the European Commission in July 2005, called for a 12% renewable energy fraction by 2010 and an overall cut in energy use of 20% by 2020 [33]. These are some signals pointing toward the ecologically driven Scenario C.

The issue of the “hydrogen economy” does not play an important role in this analysis since it concerns mostly the form of energy transmission and storage, i.e., hydrogen fuel is not a primary energy source. There are many analyses comparing hydrogen with electricity as an energy carrier. Hydrogen will compete within the energy carrier market that is not addressed in this paper. However, one of the stumbling blocks for both is the ability to store the energy. This is a concern for many renewable sources that may not supply a constant flow of energy or be consistently timed with the demand for energy. Therefore, the development of more efficient transmission and storage might play a role in efficiency or facilitating renewables, but it does not contribute directly as a primary energy source.

Finally, the relative timing and heights of the logistic growth curves might suggest a larger trend: The timing of the peaks of coal to oil/natural gas to efficiency with peaks spaced about 50 years apart. These three curves are bounded in the early years by wood renewable resources and in the future by new renewables/nuclear. The relative rise of the logistic substitution seems to be similar among the growth curves. The curves show periods similar to Kondratieff cycles of innovation, deployment, and investment. In early times, while energy usage grew slowly, there was little change in the primary energy source, since it was mostly sustainable and not out of equilibrium with the environment. This leads to the question as to what would happen after the transition to nuclear and renewable energy sources. Would the logistic substitution pattern stop similar to the dominance of non-fossil fuels, such as the wood and grain biofuels, before coal was used? It seems likely to depend on the technologies being developed. For example, if fusion power were developed that was inexpensive and clean compared to renewables, its use would probably replace more expensive or unclean sources. Perhaps the relative weights of the renewable resources might show logistic patterns as new technologies enable the extraction of renewable resources more effectively.

6. Conclusions

The consideration of energy efficiency, as measured by energy intensity, provides a continuation of logistic substitution dynamics in the primary energy sources, which had exhibited regular long-term logistic substitution trends from the mid-19th century through the third quarter of the 20th century. Substitution occurred through the sequence of primary energy sources of wood, coal, FFF (combined oil and natural gas), and efficiency with a concurrent relatively slow development of alternative energies such as hydropower and nuclear power. The sequential waves of these energy sources are similar to Kondratieff cycles of innovation, deployment, and investment. The logistic substitution pattern would continue if another primary energy source such as a mix of renewables and nuclear energy were to reach 30% of the worldwide energy market share around 2050. Furthermore, to identify indications of future energy scenarios, as well as to test the logistic substitution analysis, another statistical approach using ternary diagrams was developed. While the specific future mix of renewables and nuclear energy sources is uncertain, the more general logistic dynamics pattern of the energy system seems to be continuing as it has for about 150 years.

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References

[1] C. Marchetti, Primary energy substitution models: on the interaction between energy and society, Technological Forecasting and Social Change 10 (1977) 345–356.
[2] C. Marchetti, N. Nakicenovic, The dynamics of energy systems and the logistic substitution model, RR-79-13, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1979.
[3] C. Marchetti, Fifty-year pulsation in human affairs: analysis of some physical indicators, Futures 18 (3) (1986) 376–388.
[4] C. Marchetti, Is history automatic and are wars a la carte? The perplexing suggestions of a system analysis of historical time series, in: T.C. Devezas (Ed.), Kondratieff Waves, Warfare, and World Security, NATO Security through Science Series E: Human and Societal Dynamics, vol. 5, IOS Press, Amsterdam, 2006, pp. 173–179.
[5] B.J.L. Berry, Long waves and geography in the 21st century, Futures 29 (4–5) (1997) 301–310.
[6] V. Smil, Perils of long-range energy forecasting: reflections on looking far ahead, Technological Forecasting and Social Change 65 (2000) 251–264.
[7] N. Nakicenovic, J.M. Jefferson, Global energy perspectives to 2050 and beyond, WP-95-127, IIASA, 1995 (summary of the joint 100-page WEC–IIASA Report on Global Energy Perspectives to 2050 and Beyond).
[8] N. Nakicenovic, Technological change and diffusion as a learning process, in: A. Grübler, N. Nakicenovic, W.D. Nordhaus (Eds.), Technological Change and the Environment, RFF Press, Washington, DC, 2002.
[9] R.N. Rosa, Economic cycles in a closed finite world, in: T.C. Devezas (Ed.), Kondratieff Waves, Warfare, and World Security, NATO Security through Science Series E: Human and Societal Dynamics, vol. 5, IOS Press, Amsterdam, 2006, pp. 173–179.
[10] P.S. Meyer, J.H. Ausubel, Carrying capacity: a model with logistically growing limits, Technological Forecasting and Social Change 61 (1999) 209–214.
[11] J.C.O. Matias, T.C. Devezas, The fifth Kondratieff wave—the fossil fuels apogee?, in: IV International Workshop on Oil and Natural Gas, Lisbon, Portugal, May 2005.
[12] F. Press, S. Raymond, W.H. Earth, Freeman, San Francisco, CA, 1978.
[13] J.H. Ausubel, The environment for future business: efficiency will win, Pollution Prevention Review 8(1) (1998) 39–52 (available at ⟨http://phe.rockefeller.edu/future_business/⟩).
[14] H. Geller, P. Harrington, A.H. Rosenfled, S. Tanishima, F. Unander, Policies for increasing energy efficiency: thirty years of experience in OECD countries, Energy Policy 34 (2006) 556–573.
[15] R. Silberglitt, A. Hove, P. Shulman, Analysis of US energy scenarios: metascenarios, pathways, and policy implications, Technological Forecasting and Social Change 70 (2003) 297–315.
[16] US DOE Energy Information Administration, International statistics, ⟨http://www.eia.doe.gov/emeu/international/contents.html⟩, Web site accessed June 2, 2006.
[17] J. L. Helm, (Ed.), Energy: production, consumption, and consequences, US National Academy of Engineering, 1990 ⟨darwin.nap.edu/books/0309040779/html/24.html⟩.
[18] US DOE Energy Information Administration, International energy outlook 2005, Report No. DOE/EIA-0484, July 2005 ⟨www.eia.doe.gov/oiaf/ieo/world.html⟩.
[19] R.U. Ayres, Energy inefficiency in the US economy: a new case for conservatism, RR-89-12, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1989.
[20] N. Nakicenovic, A. Grübler, A. McDonald, Global Energy Perspectives, Cambridge University Press, Cambridge, 1998.
[21] A. Grübler, Long-term energy futures: the critical role of technology, RR-00-02, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2000.
[22] A. Grübler, Technology and Global Change, Cambridge University Press, Cambridge, 1988.
[23] Statistica (Data Analysis Software System), Version 7.0, Statsoft, Inc., 2004 ⟨http://www.statsoft.com⟩.
[24] R. Myers, D. Montgomery, Response Surface Methodology, Wiley, New York, 1995.

[25] World Nuclear Association, The Economics of Nuclear Power, April 2006. Available at: 〈http://www.world-nuclear.org/info/inf02.htm〉.

[26] US DOE Energy Information Administration, Reference case projections for electricity capacity and generation by fuel, Appendix F of international energy outlook, Report No. DOE/EIA 2005. Available at 〈www.eia.doe.gov/oiaf/ieo/pdf/ieonuclear.pdf〉.

[27] J.M. Pethokoukis, A new look at nukes, US World and News Report, September 26, 2005. Available at: 〈www.usnews.com/usnews/biztech/articles/050926/26nukes.htm〉.

[28] IAEA, Capacity building and nuclear knowledge maintenance for sustainable energy development, IAEA 2004 Annual Report. Available at: 〈www.iaea.org/Publications/Reports/Anrep2004/capacity_building.pdf〉.

[29] MIT, The Future of Nuclear Power, July 2003. Available at: 〈web.mit.edu/nuclearpower/〉.

[30] R. Ramanathan, A multi-factor efficiency perspective to the relationships among world GDP, energy consumption and carbon dioxide emissions, Technological Forecasting and Social Change 73 (2006) 483–494.

[31] T. Anderson, A data envelopment analysis home page. Available at: 〈http://www.emp.pdx.edu/dea/homedea.html〉.

[32] R.N. Elliott, A.N. Shipley, S. Nadel, E. Brown, Natural gas price effects of energy efficiency and renewable energy practices and policies, American Council for an Energy Efficient Economy, December 2003. Available at: 〈http://www.ef.org/documents/Nat_Gas_ACEEE.pdf〉.

[33] L. Brown, Plan B 2.0, W.W. Norton & Company, New York, 2006.