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Further Issues in Forecasting Primary Energy Consumption

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"Le charbon blanc du noir sera chasse. . ."
Nostradamus, 1503–1566

ABSTRACT

The series of papers by Marchetti [8, 9, 10] and Graham and Senge [4] (published in this journal between 1977 and 1980) represents a useful alternative approach to the problems of energy demand forecasting and primary energy substitution. The learning system approach seems a most appropriate investigative framework, given the aggregated treatment of the energy supply-demand system. It is also interesting for its attempt to establish a link between the structure of the primary energy markets and the 50-60 year cycles of basic innovations.

This paper seeks to illustrate further conclusions from the reported research findings, by considering additional energetic criteria. These additional criteria—energy concentration (or quality) and energy accessibility—appear to reinforce the linkage between innovation waves and primary energy substitution patterns, though we modify the interpretation placed on this connection. Furthermore, the additional criteria lead to alternative conclusions about future energy supply, namely that previously discarded energy sources may be revisited and may retain some of their earlier market share.

Introduction

We wish to take up Marchetti's lead in developing a conceptual framework that may have applications in energy demand forecasting. The development of his analysis, indicated in the three reports [8, 9, and 10], represents an important heuristic exercise, the basic thrust of which we agree with. That is to say, our own thinking strongly supports the use of the logistic relationship as the most appropriate basic form for describing the long-term behavior of aggregated energy markets. Marchetti [10] makes a strong case for what may have begun as simply an intuitive analogy between the logistic behavior observed in primary energy substitution trends and that evident in numerous learning curve manifestations. His systems studies have been conducted in the context of interactions that occur between energy sources (more precisely, fluxes from energy stocks) and the societal systems they support. Insofar as these interactions can be described as the responses of societal systems to their external constraints, a "learning society" [10,

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p. 282] can be perceived analogously to a living organism growing in a physical medium (i.e., another class of phenomena amenable to logistic description).

Our analysis of the primary energy market in New Zealand during the 20th century (summarized in Figure 1) indicates energy substitution trends that are similar to those identified by Marchetti in his global analysis. However, for reasons which are discussed later, our conclusions from this analysis, which might be applied to forecasting trends for the future of the primary energy market, differ from Marchetti's.

The second important finding with which we are in substantial agreement concerns the link between the primary energy market and the innovation waves [4, 10]. This observation, along with other research [2], strongly supports the construct that societal systems and their environments "cooperate" via mechanisms, the dynamics of which are fundamentally physical-biological and thermodynamic.

Thus it is not surprising to observe what we might call the complementary trend of progressive improvement in the thermodynamic efficiency of evolving technologies, again exhibiting logistic, learning-curve behavior. What Marchetti postulates [9, 10] as "the working of deeper physical mechanisms" are, we would argue, macrosymptoms of an important design principle frequently observed in natural ecosystem development [3]. The Maximum Power Principle, first enunciated by Lotka [6] and subsequently investigated by Odum and Pinkerton [14] links efficiency in energy transformations with the physical imperatives for growth and survival within a competitive societal structure.

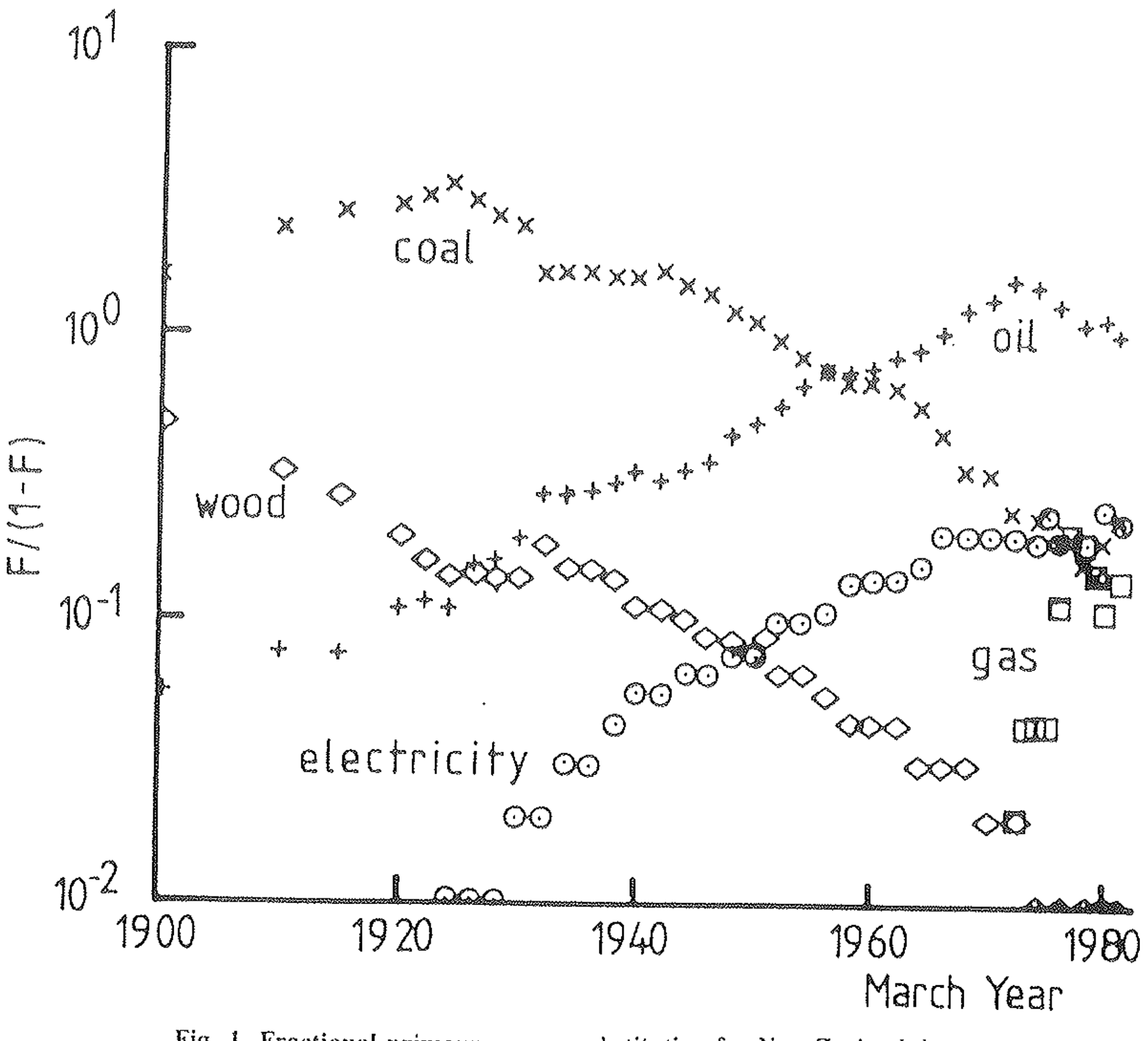

Fig. 1. Fractional primary energy substitution for New Zealand data.

Having stated the area of common conceptual ground, we now wish to question several aspects that appear to limit the heuristic possibilities of the study so far.

Limitations of the Conceptual Framework to Date

In view of Marchetti's explanation for the inclusion of wood and farm waste in his primary energy substitution model [8, p. 345] as being "necessary to get a proper basis for extrapolation . . . " (a view which we endorse), we find it inconsistent that the system boundary was not fully expanded to include direct solar and other indirect solar inputs to the societal system. Admittedly, some computational difficulties exist in arriving at a means for achieving commensurability between these "environmental energy" fluxes and those derived from what are, by arbitrary convention, normally considered as primary energy sources. Nonetheless, the problems are essentially due to data availability and are not of a conceptual nature. Classical thermodynamics makes it possible to establish equivalencies between physical flows of quite disparate qualities. Odum [13], using an ecological approach to the evaluation of energy quality differences, has established what is arguably a more universally applicable conceptual framework for defining energy equivalencies between disparate energy forms.

Irrespective of the applied numerology chosen, the fact remains that solar inputs occupy a substantial portion of the primary energy market. Part of the growth of commercial energy sources must also be attributed to technical innovations that effectively substitute for solar inputs (e.g., chemical fertilizers used to enhance agricultural yields, electrical lighting, etc.).

We argue that any framework intended to reflect the "Interaction between Energy and Society" [8] cannot afford to ignore such a substantial element. Indeed such an omission not only denies the historical evidence of centuries past but also leads to the kind of absurdity observed in Marchetti's model predictions for futures with no nuclear energy or a moratorium on nuclear development up to the year 2000. [8, pp. 351–352]

This leads to the second apparent limitation. In explanation of his experimental rationale, Marchetti [8, p. 345] refers to the need "to look at historical trends, over a century at least, and try to extract the signal out of the white noise . . ." We believe that the temporal window has not been expanded sufficiently to do justice to the concept. Once again, data availability was probably a strong determinant in the selection of an historical starting point. Nevertheless, a temporal window that begins in the middle of the 19th century suggests a regularity to the substitution pattern that may well be characteristic of the fossil fuel era, but could not be extrapolated backwards in time any further. Indeed, Humphrey and Stanislaw [5], in their analysis of energy consumption and economic growth in the U.K. between 1700 and 1975 refer back to a prolonged period of chronic wood scarcity (1550-1700) during which coal made its first significant increase in energy market share. This scarcity of wood was quite widespread in Europe at the time and provides some explanation for the entry of coal into the energy market. Clearly this particular substitution does not entirely fit the pattern that has subsequently been observed for the transitions to oil and natural gas where the diminishing energy sources have not even been approaching total depletion.

While the choice of 1850 as the beginning of the period of analysis may have been determined by data considerations or a belief that 100 years was sufficient for the purpose of observing the symptoms of some basic underlying physical mechanism, we believe that it is an unfortunate break-in point. It is historically close to what was probably an epochal turning point in the evolution of the energy-society interaction—the advent of fossil fuels and thus the first release from the constraints of a solar constant and diurnal interruptions. The period from 1850 onwards conveniently captures the societal system's response to newly accessible energy stocks. The remarkably uniform growth trend in total energy consumption and the apparently regular substitution of one dominant energy form by another during this period can hardly be considered as mere extensions of trends begun long before 1850. When energy constraints change, societal structures adapt, a phenomenon only too obvious in the last decade. How often have researchers investigating the post-OPEC behavior of economic systems been bedeviled by the relative paucity of energy information prior to 1973 and thus been unable to construct useful indicators of change?

In contrast to Marchetti's world fractional energy substitution plot, [10, p. 271] Figure 2 is intended to show the qualitative features of the same sort of sequence with extended time window and the inclusion of the solar market share. (The actual values for solar energy fraction have been chosen quite arbitrarily but are meant to indicate trends relative to the other primary energy sources.)

In addition to the foregoing comments about the significance of system and temporal boundaries, it seems to us that several assumptions are implicit in Marchetti's discussion [10] which we feel are worth questioning. They can be summarized in the following way:

1. What appears to be a unidirectional view of the innovation wave/energy substitution linkage, which seems to ignore the idea that energy availability patterns have any influence on the invention/innovation waves. This appears reminiscent of the conventional economics' perception of the energy-economy interaction that sees the system's dynamics as being internally generated (i.e., by economic factors) and ignores the effects of changing external constraints [2];
2. The assumption of continued progressive substitution of new energy sources—the "technological fix" syndrome—that sees the quality of each succeeding energy form, and indeed total energy consumption, in the framework of monotonically increasing functions of time [10, Fig. 11].

Moreover, the discussion does not appear to present satisfactory explanations for the actual introduction of a substitute energy form [4, p. 301; 10, p. 281].

The critical comment we have made in this section is in no way intended to detract from the considerable advances Marchetti has made in the search for a better understanding of the energy-society interaction and its system dynamics. It merely lays some foundation for the suggestions that follow.

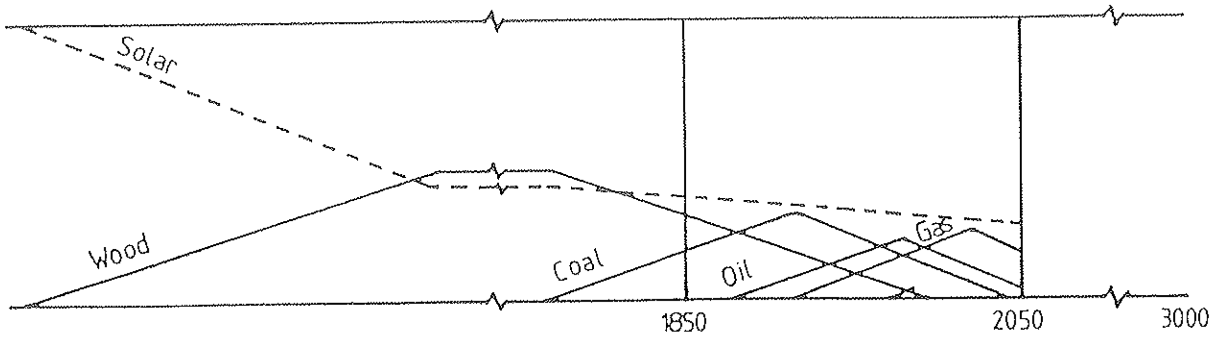

Fig. 2. Extended time window and inclusion of the solar market share.

Additions to the Conceptual Framework

We believe that the existing conceptual framework, with links between primary energy market penetration patterns, distinct invention/innovation waves, and trends for improved thermodynamic efficiency, would become even more coherent if more attention was paid to the thermodynamic dimension. This seems to us a thoroughly appropriate direction in which to look, bearing in mind the repeated claim that the investigation thus far points to the working of some deeper physical mechanisms [9, 10].

We referred above to the abstract expression of successive energy forms as having "qualities" or "intensities" that followed a monotonically increasing functional relationship with time. We have put some numbers on this in Table 1. Marchetti's "Ying-Yang plot" [10, p. 270] of evolution trends in efficiency is also a monotonically increasing function of time.

However, the societal demand for energy, which is central to these investigations, must be viewed in terms of consumable energy forms. This brings us directly to a consideration of the accessibility criterion.

All the primary energy forms have their origins in the environment, that is to say more specifically, outside the societal system. It is indeed possible to extract usable energy from a great variety of environmental sources if we devise an appropriate mechanism for doing so and if we apply sufficient resources to realize such a process. All this research and development activity itself consumes usable energy, and is only possible if such energy is available.

What we argue, in this context of building a conceptual framework, is for a continued acknowledgment of what thermodynamics says quite simply—that, in all activity, from the extraction of mineral ores from the environment to the processing of information in the brain or in a computer, useful energy in some quantity and some form is required. Of particular concern in energy supply technologies is the cumulative energy requirement for all the activities associated with accessing and delivering useful energy to consumers.

The energy requirement of energy is most frequently quantified using parameters such as energy yield ratios or net energy yields.

An energy yield ratio is the ratio between the output of an energy supply industry and the cumulative energy requirements for accessing, processing, and delivering that output. Such energy requirements include the embodied energy of material and capital inputs and, in the case of workers such as Odum [12], the embodied energy of manpower. In the context of this paper, energy yield ratios are the parameters which quantify the concept of energy accessibility.

TABLE 1
Market Saturation Dates[a] and Specific Energy Values[b] (KJ/kg)

1800	Wood	~20
1921	Coal	22–35
1980	Oil	44–48
2040	Natural Gas Components	50–55
	Liquid Hydrogen	121
~2100	Nuclear Fuel	$\sim 10^{11}$

[a]*Source:* Marchetti [10].
[b]For fossil fuels, these are based on specific enthalpies; the nuclear fuel value comes from Einstein's relationship.

Although in the economic cost-benefit ratio, economics has an analytical parameter that is analogous to the energy yield ratio, the analogy is not rigorous. Economic value and utility are based on quite different precepts from that of thermodynamic availability. Over an extended time period, changes in perceptions of value and utility make it impossible to distinguish any meaningful functional relationship between the set of economic measures and the set of thermodynamic measures.

In this paper we are concerned with constructs that derive from the energy basis of activity, which in the first instance are most appropriately analyzed in physical terms.

Odum has carried out analysis on the accessibility of a variety of primary energy sources. His graphical summary [12], reproduced in Figure 3, indicates not a monotonically increasing function but a unimodal function with a maximum. Some environmental energy sources (e.g., ocean thermal gradients) are so dilute as to be relatively inaccessible (i.e., this technology exhibits a yield ratio <1), while others (e.g., nuclear fusion) may be too concentrated, thus necessitating excessive containment technologies. In between these extremes are a variety of primary energy forms exhibiting a range of accessibilities. In physical terms, accessibility for fossil fuels will depend largely on location, grade, ease of materials handling, beneficiation or refinement requirements. Clearly, improvements in the efficiency of the associated technologies have impacts on the perceived accessibility of a primary energy source. In the same way, innovations can affect the relative accessibility of several energy sources competing for shares in the energy market.

We suggest that energy accessibility is a useful concept to add to the framework for investigating and forecasting the dynamics of energy substitution and market penetration.

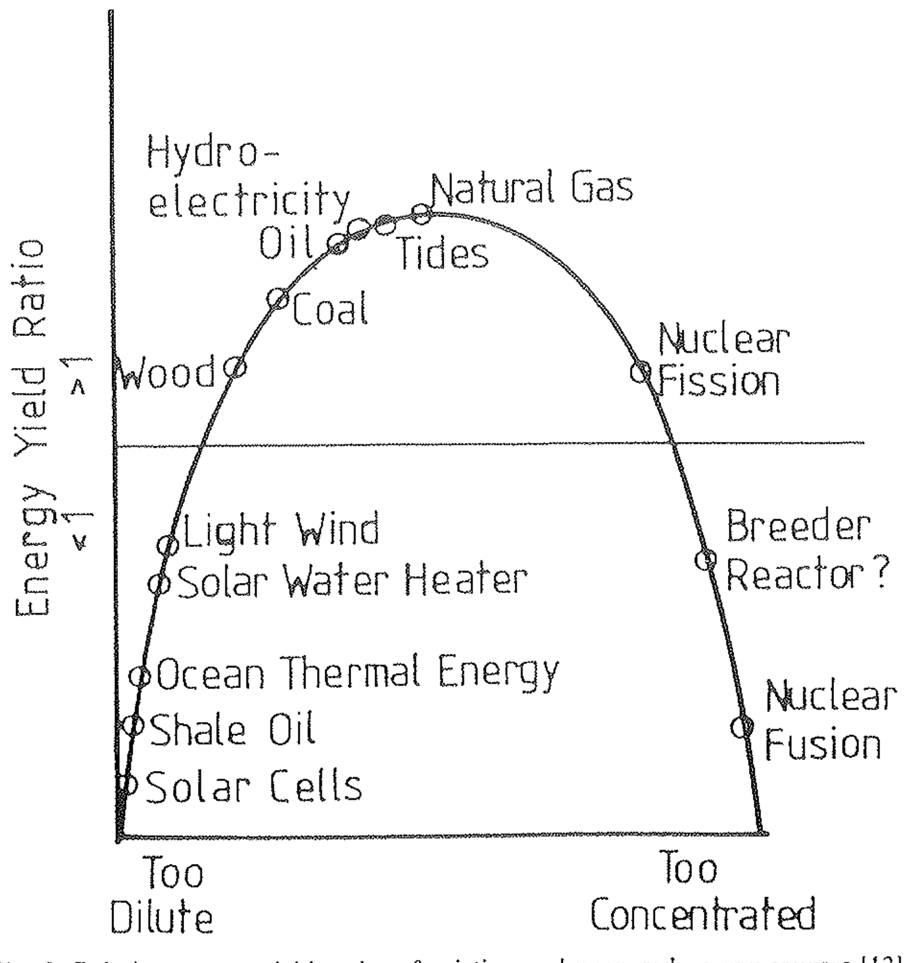

Fig. 3. Relative energy yield ratios of existing and proposed energy sources [12].

We believe that this factor—expressed in comparable energy yield ratios between competing sources at a point in time—may serve to fill the conceptual gap needed to explain in a physical way the actual introduction of a substitute energy form to the market.

In fact it would appear that these suggestions—the energy basis for all activity and the energy accessibility criterion—fit quite well the historical data and heuristic development presented by Marchetti. If we revisit Mensch's data, presented by Marchetti [10] in Figures 6-9 and Tables 1-4, it is possible to construe from this, material evidence to support our suggestions.

Coal registered at 1% market penetration during the 1770s despite the fact that it had been mined and used on a small scale domestically for several centuries previous to this [5]. The shortage of woodfuel (with the concomitant rises that occurred in firewood prices during the early part of the 17th century) can be held accountable for the early substitution of wood by coal. The technological environment was not ready to take advantage of this more concentrated energy form. Nevertheless, despite its being considered at that time a technically and environmentally inferior fuel to wood, its accessibility to widespread consumption was significantly enhanced in the late 18th century with the building of the extensive canal networks. We suggest that, because this development made coal as physically accessible as wood on a widely distributed basis, and because it is inherently a higher quality fuel, this provides a plausible explanation for the actual changeover to begin.

Not long after this (1796-1835) several innovations occurred that were to have substantial impacts for increasing coal demand: the use of coal as coke in the metal smelting trades, extensive developments in metal products, and of course the advent of steam-driven locomotives.

There is a wealth of evidence supporting this aspect of the innovation-energy substitution linkage. What appears to have been taken for granted is the fact that all this evolutionary activity (1700-1850 and earlier) was being supported by the *existing* primary energy base of the period when the dominant nonsolar energy form was wood. Marchetti estimates wood's market saturation to have occurred at about 1802, at which time coal accounted for only 2%. Marchetti makes a direct analogy to this in his discussion of the informational requirements for evolution:

> To go from structure A to structure B that better fits the external constraints, as with the diesel versus the steam locomotive, one can only proceed through stochastic exploration of possible configurations, and proper selection. In going from A to B then, the flow of information necessary is orders of magnitude larger than the difference in Shannon's information content between A and B, because of the great number of "failures" that have to be discarded. [9, p. 199]

In our construct, the new, more accessible energy form constitutes the change in external constraints; basic innovations and improvements in efficiency of use involving the new energy source provide the focus for the stochastic exploration; and the existing dominant energy source provides the negentropy basis for all the failures that precede each successful innovation.

Now a very similar sequence can be seen to have occurred again towards the end of the 19th century. Another wave of technical innovation broke during the last two decades of the century, a period when coal had begun to surpass wood and to dominate the nonsolar energy market. Oil registered 1% market penetration during the 1870s. Not only does oil exhibit a greater specific energy than coal, it is also amenable to easier extraction and distribution via pipeline networks and pumping stations. It became evident soon after the first oil strikes that an even more accessible fuel was available to society.

By 1890, the coal based innovation wave had made possible synthetic organic fibers and the gasoline motor.

Some oil fields have substantial reserves of natural gas associated with them. The proliferation of oil exploration activity soon gave rise to natural gas which registered 1% market penetration shortly after the turn of the century (when coal was reaching saturation at about 60% and oil was 4%). Again, natural gas has a higher specific energy than oil and is even more amenable to extraction and distribution under its own pressure—another improvement in accessibility.

Their geological proximity can to some extent explain why natural gas entered the market so soon after oil. With much of the innovative effort still directed towards the liquid fuels (improvements in liquid fuel motors, catalytic cracking of petroleum, and plastics all appeared in the period 1925-1940), it seems likely that the greater physical accessibility of natural gas played some part in its early market penetration. This was subsequently reinforced in the 1950s with the chemotechnical innovations based on polymerization reactions.

It is also interesting to observe the increasing trend in basic innovation frequency of the innovation waves [4, p. 302]. The first wave (1820) coincides with wood market saturation, the second (1890) closely precedes coal market saturation, and the third (1940) occurs when oil and natural gas have reached about 30% market penetration in total. Increasing innovation frequency and the innovation waves appear to exhibit some degree of correlation with successive dominant forms of primary energy. Similarly, the sequence of primary energy substitution has historically been characterized by increasing accessibility in each new energy form.

The search for improvement in the efficiency of energy transformation has occurred throughout history even though basic innovations (in contrast with efficiency-related innovations) have occurred in waves. As we have observed, these innovation waves can give rise to primary energy substitution. The efficiency-related innovations simply change their focus. After all, it is the combination of accessibility and efficiency that determines the proportion of an environmental energy stock that is finally converted into some consumer utility. When a more accessible energy substitute becomes available, the focus of basic innovations is redirected towards the new energy form and the impetus for further improvements in efficiency of using the old form is lost. Thus, in the early 19th century, the focus for efficiency improvements in furnace applications involved coal, not wood; at the beginning of the 20th century, the focus in motive power and synthetic fibers applications involved oil, not coal, and so on.

Implications of the Accessibility Hypothesis

Reviewing the historical sequence (including pre-1800) we have observed successional trends in increasing energy quality, increasing efficiency, and increasing energy accessibility. Even in the rate of total energy consumption the growth trend has been noticeably regular, although in prefossil fuel times this would have been much more closely linked with population growth rates.

Indeed all these energy-related parameters have displayed the characteristics of a monotonic function of time as we have evolved from solar-based hunter/gatherer societies to the fossil fuel based industrial or information society.

In looking to the future, most R & D interest has centered on even more concentrated energy sources, such as hydrogen and the various types of nuclear supply. Current understanding leads us to expect further improvements in efficiency, but we know such a trend to be asymptotically limited below theoretical thermodynamic maxima. We harbor expectations for continued growth in energy consumption for many decades to come in order to support goals for increasing the worldwide standard of living and maintaining that of the affluent nations.

In all this future-gazing, little attention has been paid to the concept of energy accessibility. Economic theory has so divorced itself from physics (if not from sociology) that we frequently ignore the evidence of changes in accessibility. But the evidence exists nonetheless and it suggests that *overall* primary energy accessibility will reach a maximum and decline thereafter. This should not disguise the fact that societies in various parts of the world have at some time already experienced declining accessibility with respect to particular energy types. Some simple examples serve to illustrate the principle.

Even though coal is generally more accessible than wood, being a higher quality energy source, some coal reserves yield more accessible energy than others (in particular, bituminous coals in well-ordered strata close to the surface). Generally, the most accessible deposits are mined first for therein lies the greater potential for financial profit, leading to reinvestment for growth. When the most acessible reserves are depleted, we must have recourse to less accessible reserves. In a similar manner, oil and natural gas that must be recovered at greater depths and distances offshore represent less accessible energy than that from land-based operations close to the consumer.

We need only look at the performance of countries whose economies relied heavily on oil imports during the 1970s to observe the impacts of reduced energy accessibility on economic growth and societal well-being.

As higher quality energy sources become less accessible, lower quality sources may be revisited and redeveloped, since their accessibility (perhaps with further improvement in technical efficiency) makes them competitive in the energy market again. This can be seen in some parts of the world already, with renewed interest in coal gasification and wood processing technologies. (The New Zealand case is discussed later in this paper).

Indeed, even cursory inspection of the development of the nuclear power industry in the United States raises some serious reservations about the real level of accessibility of nuclear energy to widespread peaceful uses. The lion's share of the R & D activity for the nuclear industry was conducted under the aegis of Federal government support. Commercial utilities took little responsibility for the necessary innovations. Even now, it appears that only part of the development costs are being counted, since the requirements (in physical terms) of radioactive waste disposal have yet to be met satisfactorily. Further innovations may overcome these difficulties. On the other hand, Ernest Rutherford's pessimistic speculation may still be proven correct.

If the accessibility concept is borne out further in the future, expectations for societal development (historically connected strongly with material consumption) may have to be revised. Furthermore, its impact on the intensity of the stochastic exploration activity that ultimately yields practical innovations may force us to review our perceptions of the energy-society interaction.

Empirical Evidence of the Accessibility Hypothesis in the New Zealand Energy Supply Trends

To support the accessibility hypothesis with further empirical data, we return to the analysis of the primary energy market in New Zealand during the 20th century as summarized (for historical data) in Figure 1. Two features in New Zealand's historical primary energy market distinguish it from the general global pattern identified by Marchetti [10].

Location, topography, and climate have combined to endow New Zealand with both a substantial input of rainfall and the natural structures that facilitate the harnessing of this source of geo-potential. It can be seen that hydroelectricity (there is a small portion of geothermal in primary electricity from 1958 onwards) had its inception as a primary energy source in 1924 and has since claimed a significant fraction in market penetration. On the world scene, hydroelectricity does not qualify as a major primary energy source.

Secondly, the inception date of natural gas, 1971, contrasts markedly with that of world gas supply, which had significant input before 1900. It was not until the late-1960s that exploration efforts located commercially viable reserves of natural gas on land and offshore. Prior to this time, all gas consumed in New Zealand was a secondary fuel manufactured from coal or petroleum.

Historical energy yield ratios for New Zealand (1954-1979) are presented in Figure 4 [7]. Prior to 1972, the three dominant primary energy forms (oil, hydroelectricity, and coal) ranked in an order of relative accessibility that clearly supports the market penetration trends up to that time. (The data assembled thus far for energy yield ratios in New Zealand do not include distribution requirements.)

From 1973 onward, the ratio for imported oil dropped below the ratios for indigenous coal and electricity. As a consequence of this change, the fractional market penetration for oil peaked and began to decline, some seven years before the peak in world oil usage.

Also evident is the improvement during the 1970s in accessibility to coal relative to hydroelectricity to the point of virtual parity. This is a direct result of two trends: greater emphasis on open cast mining which generally exhibits higher energy yield ratios than underground operations; and coming to the end of the most suitable sites for hydro development.

Adequate data has not been available to determine the energy yield ratio for New Zealand natural gas. The value in Figure 4 is our estimate based on the literature and suggests that natural gas currently enjoys considerable advantage in accessibility over other imported or indigenous primary energy sources.

Although the relativities in yield ratios for oil, coal, gas, and electricity changed markedly only within the last decade, indicative responses in the primary energy market have already been observed: oil's share has peaked and is declining; coal's market share has ceased to decline and may possibly be increasing; hydroelectricity's market share has leveled off; indigenous natural gas has penetrated the market very rapidly.

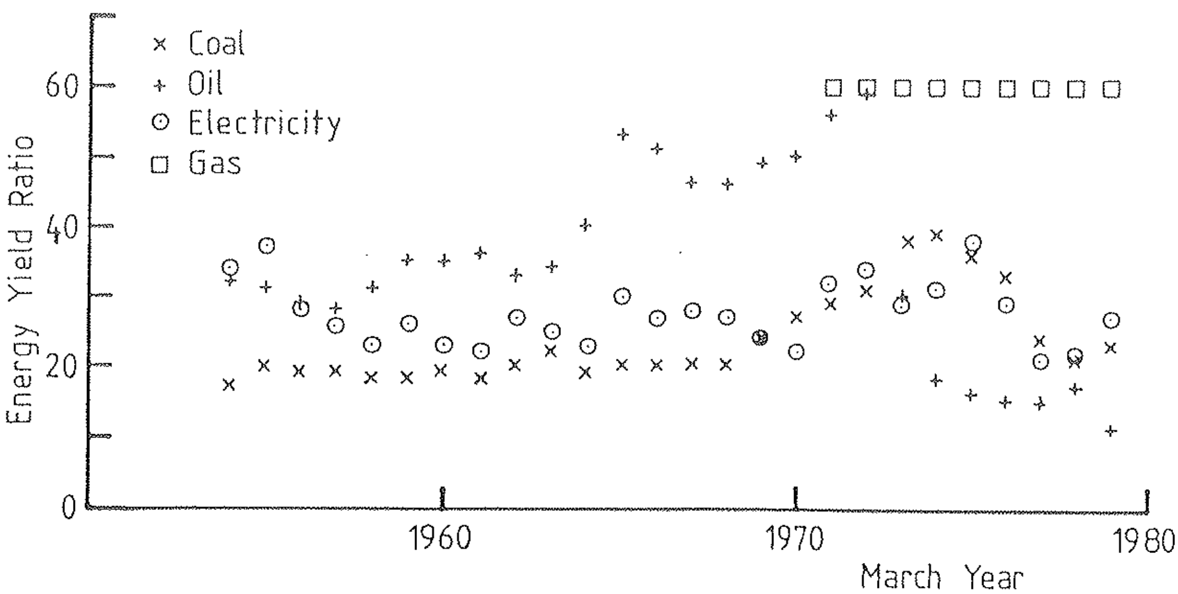

Fig. 4. New Zealand primary energy yield ratios [7].

An explanatory comment is in order concerning natural gas in the New Zealand context. At the time that natural gas became available to the New Zealand market, the existing gas distribution network (used for manufactured gas) was both rundown and of inadequate scale. Thus immediate uses for natural gas were limited largely to thermal generation of electricity where sizeable quantities could be used, accounting for the rapidity of its market penetration in the early years. It is unlikely that such rapid market penetration will continue. In fact there are already signs that a more moderate penetration rate will ensue (see Figure 1). New reticulation networks have been constructed, paving the way for greater variety in gas uses, while the profligate use of natural gas for electricity generation in any more than short-term situations has been relegated in priority.

To understand the significance of these recent developments we have projected into the future the market penetration fractions for the various primary energy sources. To make an interesting comparison, we have done this in two ways—first according to the symmetrical patterns established by Marchetti, where primary energy forms penetrate the market to peak once and then decline. These projections, up to 2020, are summarized in Figure 5. Linear extrapolation on a logarithmic scale is employed, consistent with Marchetti's logistic penetration curves. For clarity, only one set of projections is considered, based on a linear regression best fit of trends present in historical data. Thus coal continues to decline; oil continues to decline; hydroelectricity will start to decline; gas penetration increases to become the most important nonsolar fuel (at a rate commensurate with the previous primary energy penetration rate and global market penetration rate).

For each year into the future it is possible to scale off the market penetration fractions for each primary energy source. Those fractions, at five-year intervals, are listed in Table 2. It is evident that the fractions of the four energy forms do not sum to 100%. The missing fraction is also listed in Table 2.

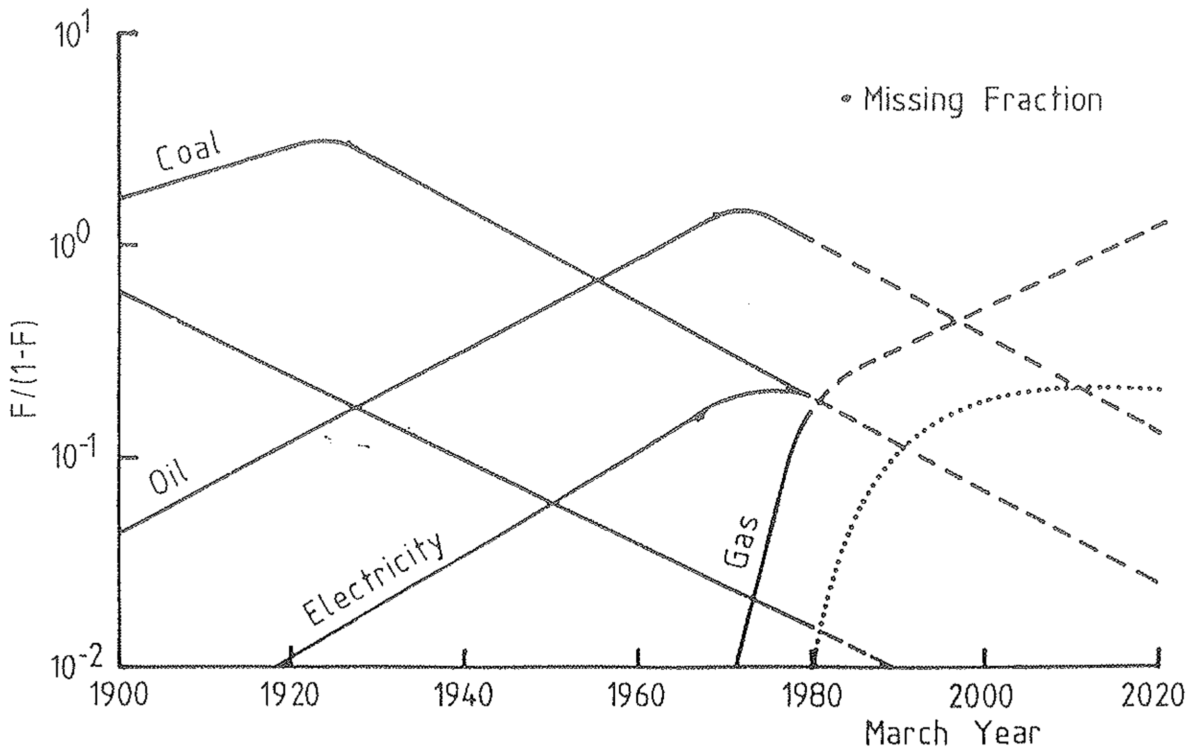

Fig. 5. Future primary energy fractional market penetrations for New Zealand based on linear extrapolation of logistical trends.

TABLE 2
Future Primary Energy Fractions for New Zealand Based On
Linear Extrapolation of Logistical Trends

Date	Primary Energy				Missing Fraction
	Coal	Oil	Electricity	Gas	
1980	.16	.51	.16	.16	.01
1985	.13	.45	.13	.20	.09
1990	.11	.38	.11	.23	.17
1995	.08	.32	.08	.28	.24
2000	.07	.27	.07	.32	.27
2005	.05	.22	.05	.38	.30
2010	.04	.18	.04	.44	.30
2015	.03	.15	.03	.50	.29
2020	.02	.12	.02	.55	.29

Worldwide, according to Marchetti [10], this missing fraction is nuclear energy (there is already a significant penetration by 1980). In New Zealand, this is highly unlikely. Nuclear power as a form of primary energy supply is not present in New Zealand, nor is it considered on the 20-year energy supply horizon [11]. Thus it will be necessary to provide the balance by redeveloping one or more of the existing energy forms.

It is unlikely that oil will make up the deficit unless significant indigenous reserves are discovered or the yield ratio for imported oil returns with stability to pre-1973 levels.

Coal reserves for future development are available in New Zealand, as they are in most countries in the world that have used this resource. It was not the exhaustion of this resource that led to the declining market share observed from 1924 onwards, so much as competition from more accessible forms of energy, namely oil, hydro, and gas. Technology is available for increased coal extraction in the short term.

Similarly, further hydroelectric potential exists, although its development would incur increasing social and environmental resistance due to land-use conflicts, as well as increasing resource requirements, since the most suitable sites are already in use.

In the longer term, the existing forestry resource (and its potentially much larger capacity) could well provide the basis for the return of wood as a substantial sustainable primary energy source, particularly as an input to biogas and alcohol fuel production.

Looking at the missing fraction (Table 2) that remains even with the successful market penetration of natural gas, it is plausible to postulate on the grounds of the energy yield ratio criterion that this would most likely be made up in the short term with additional coal and hydroelectricity. Subsequently, [1] biomass sources could become competitive again both for accessibility and strategic reasons. These postulates included in Figure 6 suggest that with coal there is a return to a primary energy source that has already peaked once in terms of market penetration, while the market penetration for hydro is sustained. Indeed the most recent figures for coal (1980, 1981 on Figure 1) may be an indicator of just such a resurgence.

The second set of projections is taken from current scenarios promulgated by the Planning Division of the New Zealand Ministry of Energy [11]. All scenarios project gas as the dominant short-term fuel, with coal returning to dominance thereafter. Only one scenario includes the use of nuclear power, with an inception date ~2000. Discussion is also made of the future of biogas. Central to these scenarios is the desire for long-term sustainable self-sufficiency in energy resources, resources which will be readily accessible to the nation.

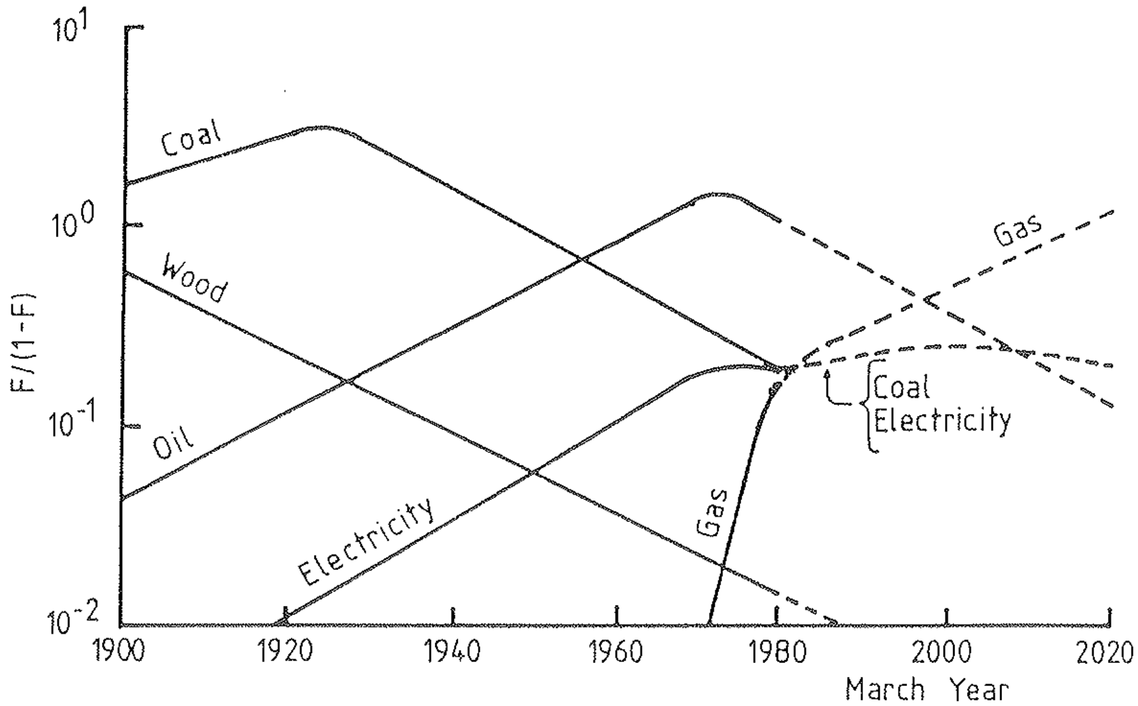

Fig. 6. Future primary energy fractional market penetrations for New Zealand with the missing fraction made up of additional coal and electricity.

It is of interest to view the projected fractional market penetration of the gas scenario in the context of the preceding historical data, as presented in Figure 7. Although derived from a completely different set of assumptions (without regard to energy yield ratios or primary energy fractional market penetration trends) the similarities between these projections and those of ours, using logistical penetration curves modified by the accessibility hypothesis, are remarkable.

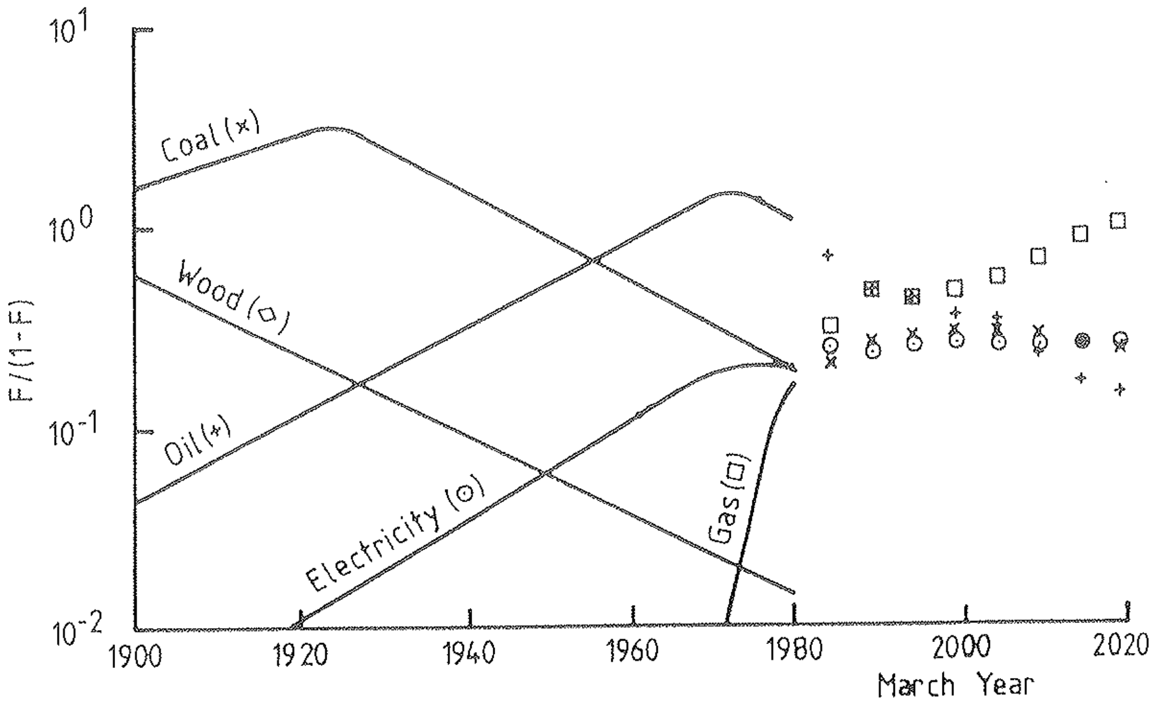

Fig. 7. Future primary energy fractional market penetrations for New Zealand, derived from the gas scenario of the Planning Division of the Ministry of Energy [11].

Conclusions

The conceptual framework postulated by Marchetti does indeed appear to be useful in understanding some of the important evolutionary trends in the energy-society interaction. Including the concept of energy accessibility and extending the interpretation placed on the innovation-energy substitution linkage seems to fill in some of the missing links in the rationale in a manner that is quite consistent with the existing framework.

In applying this expanded framework to the question of energy market forecasting, the accessibility concept provides an additional criterion against which to assess assumptions for the future, a criterion still rooted at the level of an underlying physical mechanism.

Furthermore, expanding the boundary constraints alters the framework for interpreting the evolving pattern of energy substitution. In this respect, the idea of a unimodal functional form with respect to time may offer new clues to the future.

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