Technology leverage and a sustainable society: a call for technology forecasting that anticipates innovation

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Abstract: We argue that economic value to society is created by converting input resources into valued outputs though the application of technology. To support this argument, the concept of technology leverage is introduced, and it is noted that the same input resource can be converted into different output values depending upon the technology employed in the conversion process and the state of technical innovation at the time the conversion occurs. This implies that through as yet unrealised innovations, future generations may create greater value for the same amount of resource than is currently possible. This difference has significant ramifications for current day resource allocation decisions. In addition to more conventional conservation arguments, technology leverage also recognises that the future value of retaining resources, especially non-renewable ones, may be evaluated using real option valuation techniques. These concepts are helpful in determining more comprehensive policies relating to resource allocation decisions.

Keywords: resource use policy; resource allocation; social value; dynamical systems; systems thinking; innovation; technology forecasting; non-renewable resources; real option valuation; sustainable society.

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1 Introduction

This article considers how we might assess the extent to which social systems might be sustainable in their resource use. We seek to measure how the level of technology used to convert a quantity of resource input into output value in the transformation process impacts the value of the outputs over time. Due to innovation, the impact that technology has on output value with respect to a given resource varies over time. However, for a given resource, output value per unit of input can also vary across both firms and industries at a point in time.

The economic benefits to society that result from applying technology to resource inputs depend upon resource productivity*,* and this varies by industry and by use. Innovation in any of these firms or industries or across several of them can increase resource productivity for each particular application. It would seem to be important, from a sustainability perspective, to measure changing trends in resource productivity across uses, especially in cases in which a single resource – petroleum, for example – is used in different technical processes in different industries each supporting its own unique purpose.

We argue that resource productivity and its impact on efficient resource allocation generates economic value to society in ways that involve complex issues that are not fully addressed by conventional economic approaches. As a result, it is possible that in the case of non-renewable resources like petroleum, society may in the future be faced with a market failure akin to 'the tragedy of the commons'. This is the famous case where a limited public good – the common pasture – was overgrazed through individual self-interest as expressed in the growth and expansion of independently 'operated' herds of sheep each grazing on a common pasture (Hardin, 1968). Since a similar squandering of non-renewable resources might be a possibility, it is worthwhile to ask whether resource allocation processes across industries might benefit from a thoughtful analysis that takes into account what might be called an objectively determined 'best use' perspective that includes forecasts about technological advances in future periods.

Toward this end, we introduce a metric that we call *technology leverage* (Hazy et al., 2008) that measures resource productivity and also anticipates future innovation in the use of those resources. In an analogous manner to the common finance practice of discounting future cash flows to ascertain present value, we advocate that analysis and decisions relating to non-renewable resources should include the opportunity cost of forgone future benefits from the use of these resources which, due to future innovation, might be obtained with greater technology leverage than is currently possible with present day technology.

Practically speaking, when applied to the resource allocation decision-making processes, our approach adds an additional factor to the calculation. In addition to recognising the value of resource conservation, we maintain that the *real-option value* stemming from the retention of a given natural resource should be added to the decision calculus when resources are consumed. Real-option valuation is a method that uses financial option valuation which seeks to quantify the value of an opportunity that exhibits significant upside potential while also limiting downside risk. By limiting downside risk this method takes advantage of statistical variance and identifies the value to be found in the low probability but high potential opportunities that are often ignored in traditional analysis. In the case of real-options, the term 'options' relates to the future use of physical entities rather than of financial instruments. The real-option value that comes from possessing a resource recognises that there is a probability that additional value may be obtained from that resource in the future, although exactly how that might happen is unknown. We believe that the concepts of technology leverage and real-option valuation when applied to resource allocation decisions will assist in the development of a more comprehensive and sustainable resource use policy.

2 Technology, resources and sustainability

In this section we look at key definitions and assumptions for the approach we propose. The notion of technology leverage was introduced by Hazy et al. (2008) to explore resource productivity within a sustainability context. The authors find the idea useful in clarifying the mechanisms of value creation within the input-to-output transformation process as was described by Hazy et al. (2010). The framing below represents a new conceptualisation of value creation with sustainability as the 'purpose' underlying human organising activity and improved resource productivity as one enabling mechanism in pursuit of that end.

2.1 Technology leverage defined

Given a conversion function $r^o = \tau(r^i)$, where:

r^o = some output value

r^i = some units of input resource

we define *technology leverage* as the instantaneous rate of change of output value resulting from a change in a unit of the input. In other words, (ignoring for now the passage of time) it is the first derivative of the conversion function, or τ'.

It may be tempting to equate technology leverage to resource productivity as traditionally employed, but doing so is misleading. First, τ is not a production function (that converts input units to output units) but a conversion function that derives output *value* from resource inputs. Second, whereas the notion of resource productivity reflects the simple arithmetic relationship between input and output, technology leverage captures information and knowledge, and is itself variable, depending on the (uncertain) ways in which future discoveries might allow greater value creation from a given input resource.

Although deriving a specific mathematical model of a conversion function is beyond the scope of this article, an example of the impact that technology innovation exerts on input resources in the conversion function $\tau(r^i)$ can be illustrated by Moore's law for the growth of processing power in microcomputers in the semiconductor fabrication process. Moore's law indicates that semiconductor processing power continues to approximately double every two years (Hutcheson, 2005). In this case, the particular input resource in our conversion function, i.e., r^i, is the silicon wafer used in the fabrication process. The output value in this case would be the economic benefits that accrue to society through less expensive and more powerful electronic equipment including items like computers, medical technology equipment, telecommunications equipment, and so forth.

Additionally, τ' [specifically in this case $\tau'(r^i)$], or technology leverage, is a monotonically increasing function over time (i.e., it doubles every two years according to Moore's law). The inclusion of this technology leverage concept allows one to calculate the future value that accrues to silicon wafers and other input resources from an improving fabrication process technology in the future. This analysis could thus be used to compare current and future production capabilities and efficiencies. By forecasting technology development, it becomes possible to include the real-option value of input resources in decisions regarding the allocation of resources for either present or future consumption. We describe how this calculation might be done in a later section.

2.2 Technology leverage and labour productivity

Technology leverage is a companion metric to labour productivity, the ratio of output per unit of labour, which measures how effectively technology is used to support human effort. Labour productivity recognises the scarcity and value of labour and thus seeks to maximise the economic benefit that devolves from every labour hour. Labour productivity continues to be an important metric that captures the value created through the mechanisation of what had been traditional human labour activities. It does not, however, adequately reflect knowledge-worker contributions to the economy in areas that cannot accurately be called mechanisation. As a result, labour productivity as a metric is most significant in traditional industries and less relevant for knowledge-driven businesses.

Technology leverage, in contrast, measures the impact of knowledge and technology on the output value devolving from non-labour inputs to production. This is a direct measure of sustainability of human activity with respect to both non-renewable and renewable resources, since by measuring and maximising technology leverage, one would recognise the scarcity and inherent value in natural resources and seek to maximise the economic benefit that results from every unit of natural resources consumed.

Although technology leverage, τ', varies over time, [i.e., $\tau'(t)$, for a given firm], it can be estimated at any moment by fixing the conversion of output value to output units and assuming τ to be akin to the standard production function in economics. Under these simplified conditions, one might view τ' as the ratio of output value to units of non-labour direct inputs at the margin. It is important for us to stress here that τ' is not a simple average or marginal product but a measure of impact of knowledge and technology on the output value to society. In the next section we provide some clarifying examples of what we mean by technology leverage.

One would expect that when alternative uses exist for a given resource and different technologies are available across industries, there will be a significant difference in technology leverage across industries given the same resource input. We therefore assert that when different economic outcomes across firms depend upon the same input resource, there is a positive relationship between the market value of technological knowledge deployed and the level of technology leverage, τ', realised in the processing of the resource.

2.3 Variance in technology leverage across industries utilising the same resource

If we assume that there are differences in the use of technology to create value – with petroleum, for example, between that provided by open burning versus the internal combustion engine versus the use of its carbon molecules to synthesise pharmaceuticals – then there is also a wide variance in technology leverage deployed within the economy. Some industries would consume a resource with technology contributing relatively little to output value. Others might realise greater output value from the same resource input, owing to superior technology.

Consider for example some of the varying uses for fossil fuels. As a possible example, at the low end, the energy industry burns unprocessed fossil fuels, heavy oil, natural gas and coal, to heat homes, a conversion process that would seem to have a relatively low technology leverage – it simply burns the fuel and then it is gone. Progressing up the scale, the petrochemical industry refines oil resources into more efficient fuel products such as gasoline, kerosene etc., that can be used to power transportation and other services. We might assume that this use of fossil fuels is characteristic of a higher technological leverage activity because the oil resource is being used in transportation to move people or assets and thus better utilise other resources within the economy. On the even higher end of the scale, the pharmaceuticals industry uses fossil fuel products, as an input to produce a wide variety of life-saving drugs. We argue that this use has high technology leverage since many of the organic molecules are used to directly improve the economic value that is assigned to the quality of life of individuals over many years into the future. All of these uses for the same natural resource, fossil fuels, potentially produce very different economic value within the society.

As a second example, consider some of the varying uses of fresh water. At the low end a possible example might be the value of a unit (a litre) when used to wash a car. The conversion process of hand washing with a sponge and hose exhibits low technology leverage for the water resource which through the process is partially depleted (for human use) as it is absorbed into the ground. Higher up the scale of technology leverage is the use of a sophisticated sprinkler system to water an orchard. Here water is likewise depleted, but it is more effectively distributed and contributes to the food supply. On the very high end of the technology scale might be the use of water for energy production. Here water would be used to release hydrogen (and oxygen) which can then be used to fuel vehicles. In this process, an output of the energy production process is once again water, thus replenishing the source to a degree. All of these use the same resource, fresh water, and yet as this resource is depleted, each different use produces a very different economic value to society. We also observe that, as the case of washing a car might illustrate, the application of technology leverage does not always result in what might universally be considered to be greater social value, particularly when that value is measured along some moral dimension. Greater technology leverage only means that a more highly valued output results from each unit of input resource that is used.

Perhaps a most important interpretation of variance in technology leverage deals with market pricing mechanisms, such as the pricing of fossil fuels. Pricing is based upon aggregate demand across industries (Debreu, 1959) even though demand may be quite different across different uses – with different technology leverage – of the same input resource. Market pricing does not take into account variations in the value of outputs that derive from differences in technology leverage on resources over time even though the value to society may be vastly different depending upon the specific use both currently and in the future. Within the economy, the use of resource that have low technology leverage but are also under high demand may quickly deplete scarce resources which could turn out to have very high value later on when using future technology. In these cases, as we describe in a later section, these resources have real-option value that is not currently being priced into the market. Although this option value may have little importance to a private firm in the short run, in fact these firms are likely to benefit from lower commodity prices. However, in the long run, squandered option value might carry significant costs to society.

We hope that the examples in this section provided sufficient clarification of what we mean by technology leverage. Technology leverage (τ') is much broader than mere measures of efficiency. It is a measure of the extent to which knowledge and technology enable the society to expand the frontier of the output value, enhancing the sustainability of human activity with respect to both non-renewable and renewable resources possibilities.

3 Creating economic value for society versus distributing economic value to stakeholders

The concepts of technology leverage and real option value as applied to sustainable societal social systems require that the distinction be made between economic value created for society and economic value distributed to various stakeholders. Economic value distributed is typically meant to include only the profit and cash flows that are available to shareholders. In other words, there is an implicit assumption in traditional financial theory that value is solely created when cash flow is generated for the benefit of shareholders. Contrary to this assumption, we argue that economic value is created for society when technology leverage is applied to resources to convert inputs into valued economic outputs for society. Furthermore, this value exists independently of its distribution to shareholders as well as to any other relevant stakeholders such as employees or the community. Once created, this economic value can be distributed through a variety of mechanisms to any or all stakeholders who participate in the enterprise as well as to those individuals who are part of the venture's mission.

The problem with conflating these two aspects of economic value as has been done in prior approaches is that economic analysis has been limited to the narrow perspective of the capital owner, i.e., to the value distributed to shareholders. This approach does not deal with the positive and negative values that can accrue to other stakeholders, what are known as externalities, external costs, or social costs in the economics literature (Coase, 1960; Knight, 1924). For example, while the payment of higher than market wages to employees may be considered a detriment to the economic value created for capital because of its effect on company profits, the offsetting effects may provide greater economic value to society through increases in the standard of living of employees, greater economic consumption, and the potential for increased savings. These are examples of positive externalities.

Another example involves the situation where a coal mining company leaves behind a sulphur-rich slag pile that pollutes the groundwater supply of a local community. The social cost from polluting by-products destroys economic value created for society. However, unless there is a lawsuit or a large fine charged against the mining company, this reduction in economic value to society is not reflected in the 'normal' value analysis of the coal company. The perspective of the company is that this does not affect the economic value distributed to shareholders, and therefore it is not 'accounted' for in the value equation.

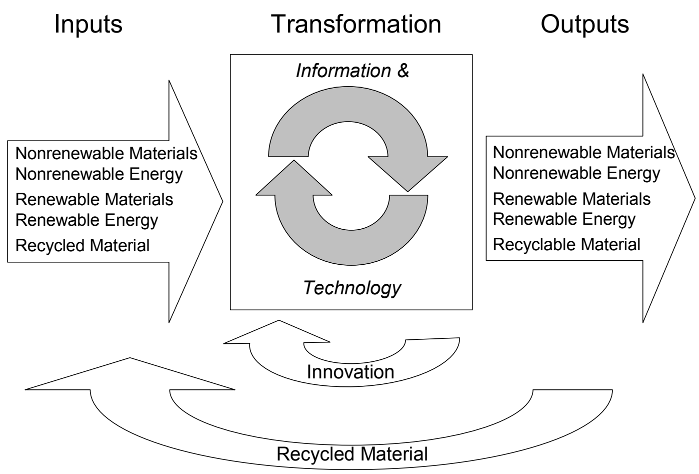
The approach in this paper maintains that economic value is not synonymous with accounting profits nor is it the cash flow that is available to shareholders. Rather, it is the sum of economic benefits to society created by technological leverage of resources, and this value might accrue to *any* or *all* stakeholders. While we recognise that the distributional question – i.e., how much value accrues to each stakeholder – is important, it is not our main focus here.

3.1 Value is created through the application of technology

As pointed out previously, traditionally it is assumed that value is created through labour and capital productivity. We argue, in contrast, that in a global economy labour is less scarce as a resource. While labour still creates value, focusing only on labour productivity is no longer sufficient. Also when credit is not being rationed, capital is generally available for 'beneficial' projects and through these projects value is created during the transformation process itself. Since natural resources over the past 150 years have grown scarce in relation to labour and capital (i.e., natural resources are increasingly the 'limiting factor' in production and value creation), the productivity of such resources is ever more important than in the past. We define 'economic value' to society as the incremental economic outcome of any conversion process where technology is applied to input resources. Under this definition, the societal value that accrues from a given organisational activity can be either positive or negative.[1] Hopefully, this tallying of economic value to society might someday drive resource allocation decisions if and when a more inclusive model is developed and used.

The perspective that the availability and use of resources creates value is not without precedent. The approach builds upon and extends the resource based view (RBV) of the firm that was originally put forth by Penrose (1959) and was expanded by Barney (1986, 1991) and others (e.g., Peteraf, 1993). In particular, the extensions to this approach that were made by Makadok (2001, 2002) strongly make the case that the sustainability of a firm's competitive position is driven by the extent of its access to scarce resources. Resources in this case include knowledge and technology which can be effectively leveraged against other resources through the firm's dynamic capabilities and operational know-how (Helfat et al, 2007; Surie and Hazy, 2006; Hazy et al., 2007; Goldstein et al., 2010b).

Figure 1 A general medium-term sustainability model



Notes: Figure 1 is a general medium-term sustainability model that depends upon technology, innovation, reuse of non-renewable material and energy, and the use of renewable materials and energy. Sustainability is only approximated and non-renewable materials and energy become depleted over time. The intent is to minimise the rate in which non-renewable resources are used up and to seek renewable substitutes for them through innovation.

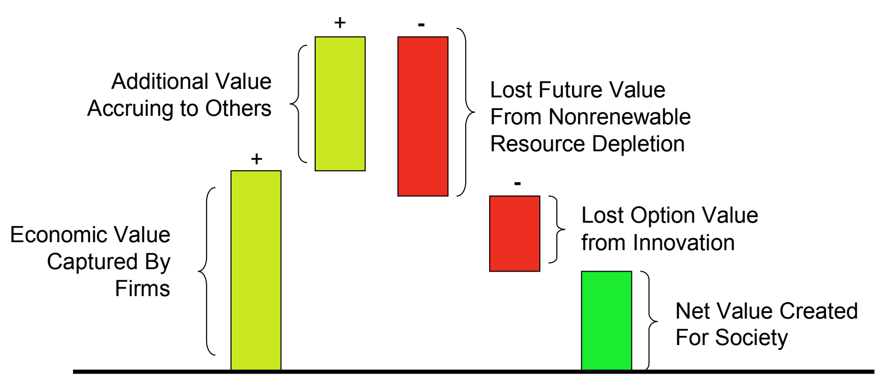
We extend the RBV beyond the firm and make a similar argument at the societal level. We state that sustainability at the societal level is driven by how the policies and norms within society position business activity with respect to its use of scarce material resources together with its capacity to use technology to leverage these resources in ways that create economic value for society. This value is created through various organisations' dynamic capabilities and operational know-how. We do not make assumptions about the material resources themselves, but instead focus on the aspects of value creation that occur during the transformation process through the application of technology. For a sustainable social system, we speak to those aspects of value creation that relate to the level of technology leverage that is occurring within an organisation during the transformation process as input resources are converted to outputs. Figure 1 shows a simple model of a transformation process that is potentially sustainable in the medium term.

We acknowledge that because some non-renewable resources are both necessary and are being depleted at a fast rate, sustaining some processes over the very long term can be problematic. The sustainability goal is to minimise the rates of depletion of non-renewable resources while still gaining appropriate benefit from their use. The minimisation of depletion can be achieved in multiple ways. The standard form is to reinvest a portion of the depletion proceeds in compensatory forms of natural capital such that the aggregate natural capital stock of a company or country is not diminished.[2] However, as we show later, the minimisation can be achieved by applying the concept of technology leverage and real-option valuation which can incentivise the company or the country overall to preserve the resource in order to consume it later when the technology for using this resource more effectively is available.

3.2 Value is distributed to various stakeholders

Once economic value to society is created (or destroyed) during the transformation of resources, it may be distributed to (or appropriated from) any number of stakeholders, including shareholders. More often than not, in practice, only part of the value created is distributed to shareholders as 'shareholder value' particularly when other powerful interests, such as professional managers and government officials, are involved in distribution decisions. These stakeholders often benefit in amounts disproportionate to their contributions. Such 'leakages' tend to go uncounted by analysts who are only interested in shareholder value, but should be included in the value equation (as noted in Figure 2).

Figure 2 An illustration of the value creation equation for a hypothetical organisation showing that the value that is captured by firms for its shareholders is only one component of the societal value impact of their activity (see online version for colours)



A second consideration is the rise of social enterprise and social entrepreneurship where a social mission expressly targets the distribution of value to stakeholders other than shareholders (Figge and Hahn, 2005; Goldstein et al., 2008; Hazy et al., 2010; Krajnc and Glavi, 2005). The mission of such enterprises does not always include the creation of shareholder value – indeed, in the case of non-profit companies no shareholder value at all is created although economic value to society is created without question (Silberstang and Hazy, 2008).

Considering stakeholders in a more comprehensive way that includes future stakeholders as well would mean that the distribution of value can still be measured using the present value of cash flows, but that it would also need to account for all of the relevant costs, including scarcity-based opportunity costs. On the other hand, when value is assumed to have already accrued in organisations through the application of technology leverage, distributions—even excess distributions to labour or management in the form of above-market compensation—do not affect value creation per se, only its distribution.

4 New value accounting methods are needed

4.1 The traditional theory of value of the firm

There is a vast literature on value theories in economics and finance which, due to space restrictions, is beyond our present scope. Debreu's (1959) monograph is informative, however, and includes an axiomatic, mathematical treatment of the notion of value in economics. His principal results still inform much of contemporary economic theory. What is not as well-known is that Debreu also pointed out certain limitations to value analysis. Specifically, he identified the 'perfect information' assumption that pervades orthodox economic theory as an assumption that is not generally true. As he puts it:

> "One may stress here the certainty assumption made, at the level of interpretations throughout the analysis… according to which every producer knows his future production possibilities and every consumer knows his future consumption possibilities (and his future resources if resources are privately owned—otherwise only the future total resources need to be known)" [Debreu, (1959), p.11].

In our present work, we consider the implications of relaxing this assumption. In what follows, we claim that producers and consumers do not know future production possibilities that utilise these resources because they do not know what technology will be developed in the future. Certain unforeseen technologies have the potential to leverage some resources beyond what is currently imaginable. In other words, we argue that relaxing the above assumption implies that producers and consumers do not know where future technology leverage will land them on the frontier of the output value.

4.2 Resource sustainability – an alternative argument

One might argue that the notion of resource sustainability does not apply precisely in a world where human knowledge and technologies can be utilised to develop viable substitutes for resources that may have been exhausted. The accepted wisdom from economic theory is that we never literally run out of resources. Increased scarcity is reflected in a rising price, until the price chokes off further demand and a 'backstop' of technology is summoned as a substitute (so-called relative scarcity). Moreover, most 'green accounting' methodologies employed by economists assume (implicitly) that in a real life organisation, resources and fixed capital (e.g., tools, machines, etc.) are essentially substitutable. Based on this one might conclude that concern over sustainability is at best overstated and at worst pernicious insofar as it represents an attempt to appropriate company profits for the benefit of constituencies other than the owners of capital.

We have three responses to such a claim. First, the assumption that different fixed capital types are substitutable is highly questionable at best. While shifting, say, cash into an illiquid asset such as real estate may not have any obvious bearing on sustainability, the same is not true of the act of converting a standing forest to a sawmill or, for that matter, half a broadfoot of timber and some mineral ore into a saw. Saws and sawmills clearly contribute different (and narrower) types of value to society than forests or ecosystems in general.

Second, it is undeniable that in many sectors of today's economy, natural resources are a limiting factor in production. One hundred fifty to two hundred years ago, one might have reasonably argued that human impact on resource stocks and the natural environment was minimal. But such a claim would never withstand scrutiny in today's global, heavily populated, and mass-consumption-oriented world. There is increasing evidence that even the world's oceans are overfished (Coll et al., 2008; Jackson et al., 2001; Logan et al., 2008; Pauly et al., 2002). Basic economics dictates that in such a changed world we should be economising on our natural resources, not continuing to pretend that they are 'free' assets.

Third, despite seemingly limitless human ingenuity in relation to technology, we must recognise that there must be some limit to how effectively we can use our resources. To be sure, there is enormous uncertainty over when resource limits might be reached, but we must also consider the negative secondary effects associated with resource mining and other ecological consequences that remain poorly understood. With complex systems such as our natural environment, non-linearities are likely to be present; in other words, minor costs associated with environmental impact might suddenly become huge costs as an ecological threshold is breached. As these costs are eventually passed down to all participants in the economy this *is* directly relevant to value creation for society.

Consequently, we argue that exclusive focus on return on capital is unsustainable behaviour, and that such behaviour has led to shortened lives of specific organisations. We need only point to the many casualties from the banking crisis of 2008 to illustrate the point that the blind pursuit of short term financial returns can lead to the premature end of once vaulted institutions such as Lehman Brothers and Merrill Lynch, to name only a few. On the other hand, maximising economic value to society is consistent with sustainability (though even here this is probably only a necessary but not a sufficient condition). If excess returns over time can be assured by virtue of preferential positioning within resource fields – that is, continuing access to certain resources is achieved – then short-term profit maximisation can be subordinated to the goal of sustainability. While such subordination can operate against the interest of the firm's shareholders, intra-firm flexibility can be retained (and less value would be transferred to capital) when a firm establishes itself in a preferential resource or knowledge position by ownership or exclusive access to a given resource. When long term sustainability is the goal, short-term accounting profits may not be maximised since during lean times, knowledgeable people are retained for the future and excess resources are stored. Yet such flexibility supports firm sustainability.

It should be made clear that we recognise the benefits that result from the discipline of active capital markets within the economy. Such discipline has been and will remain critical to continued economic growth and prosperity. We simply point out that as useful as a capital-centric perspective has been for defining the modern economic system, it has not acquired a thorough recognition of the concept of technology leverage. The consequences over the long run may be severe. Relying on marketplace price signals to indicate the value of resources can be misleading because individual market actors may not be aware of, or may discount the value of future uses of technology which carry higher technology leverage but will not be seen in their lifetime.

5 Technology and resource stocks

As we describe below, because of differences in τ', conservation is not simply a tradeoff between 'using the resource now or saving it for later'. Where the same resource is used in the same manner and with the same technology leverage but at different times, there is an economic argument that justifies its immediate use which is to capture the value inherent in the firm's current production function. In fact, any reasonable argument for conservation in such circumstances rests on the simple time value preference captured in the discount rate.

There is more to consider with technology leverage, however. We must also include in the analysis the efficiency with which technology is used to leverage input resources into economic value, and how that efficiency might be different between consuming scarce resources today versus consuming them at some point in the future. When technology is included, this choice does not net to the time value preference only, but implies the potential for a real value difference in present value terms. With changing technology leverage and unavoidable uncertainty, scarce resources have real-option value. Traditional approaches do not account for such value.

5.1 Technology leverage, future innovation and real-option analysis

Differences in technology leverage across industries and firms create differences in both the positive value achieved through the consumption of resources and the negative value that relates to the opportunity lost in depletion. These differences change the value equation in important ways. To be clear, the negative value for opportunity cost is created because scarce resources, when depleted, cannot be the basis for value created in the future. Furthermore, future innovation enabling greater value creation during the transformation process is also forgone. Thus the negative value attributed to the current period relates to both known and unknown future cash flows. The latter is known as the option value from conservation. Figure 2 illustrates these components of value.

Although analytical methods for valuing real-options of this type of valuation (Cox and Rubinstein, 1985) are beyond the scope of this paper, our approach will briefly highlight and potentially 'quantify' the option value that is lost to the economy from the depletion of non-renewable resources. Some of the examples include hard minerals, fresh water, clean atmosphere, fossil fuels, soil, old growth forests, species diversity, diversity in organic and biological compounds, and ecological systems. Such depletion will subsequently spread to behavioural, social and cultural systems and will eventually alter the diversity of human population. Because technology is likely to improve in the future, we can expect yet-unimagined uses for non-renewable resources and these future uses have option value in the current economy.

Assuming constant technological leverage (τ') over time and across industries it will be easier for market pricing to incorporate both the current and future value of resources. However, it is obvious that in reality $\tau'(t)$ is not constant over time and across industries. As it took humans some thousands of years to invent a vehicle powered by internal combustion engine, it took them about hundred or so years to invent a vehicle powered by a hybrid engine. Yet, presently, it is unclear how long it will take humans to create a system to support commercially feasible vehicles powered by an engine running on hydrogen energy.

We acknowledge our limited technical knowledge of the evolution of the automotive technology. However, we hope that the above example clearly shows that the automotive technology, like most other technologies, exhibits technology leverage $\tau'(t)$ that varies across time and related industries in a seemingly unpredictable fashion. Such apparently random, i.e., stochastic, fluctuation of the technology leverage is what brought us to propose the real-option valuation approach for the problem of conservation of non-renewable resources.

5.2 Including real-option value in resource allocation decisions

Practically, in order to incorporate real-option value, one would first need to ascertain the value that is inherent in the conservation of the resource, given the changing nature of the technology leverage. To do this, the analyst would first determine the function that drives the technology leverage. This family of functions driving the technology leverage would not be deterministic, but rather it would be stochastic. A Monte Carlo analysis could be used as one of the techniques to inform the distribution of the outcomes related to the value of the resource given the evolution of the technology leverage. The analyst could also adopt the binomial option pricing model or the modified Black-Sholes approach to option valuation to determine the previously unrecognised real-option value inherent in a unit of resources. These techniques use variance in historical trading of securities to forecast both the upside and downside potential associated with the underlying assets.

One would expect that once this process begins to take hold, improved information regarding the possible future value of various resources would become available to markets. Just as financial markets benefited greatly from the reduced volatility after financial option became widely used, markets for non-renewable resources will benefit similarly, after real-option valuation techniques become broadly employed. The economic benefit to society will come from not only more accurate pricing of non-renewable resources but also from increased conservation. The increase in conservation will come as the result of the market participants' improved understanding of the true benefits of waiting – the option value of conservation.

6 Summary and future research directions

Value is created through the enterprising actions of organisational agents as they transform input resources into valuable outputs. To do this, technology and knowledge are used to transform resources into outputs which are valued differently across the society. The ways in which financial analyses are used in business and even in politics largely ignore the value created by the organising activities of many key stakeholders in society. The interests of stakeholders such as employees and the community are often treated as secondary to the value created for capital investors such as shareholders. This is exemplified by the convention which effectively equates shareholder value creation in particular to value creation in general. Such bias leads to the systematic exclusion of externalities like resource depletion within the value equation. It also accounts for the analysts' failure to directly count the value that might be realised by households through higher wages, to the community through improved services, and to future generations through conservation. All of these quality-of-life issues are dismissed as intangible and therefore uncountable by financial analysts. To correct this bias, we are calling for a more inclusive assessment of value, one that includes external effects and that counts the economic value that has accrued to all shareholders, capital being only one.

To further this purpose we define value creation in terms of technology leverage. Technology leverage is the extent to which the knowledge and technology enable the society to expand the frontier of the output value, making the sustainability of human activity with respect to both non-renewable and renewable resources possible. We argue that the current problem of overconsumption of non-renewable resources is the result of a diminished incentive to preserve due to a lack of sufficient understanding of the future value of these resources when a more efficient technology is available. We propose that real-option valuation technique can improve our understanding of the future value of non-renewable resources given the stochastic nature of the technology leverage. We argue that if this technique is widely adopted in the marketplace the society will benefit through not only reduced volatility in the price of non-renewable resources but also through their increased conservation.

Effectively, we advocate a new social science discipline that is dedicated to modelling and anticipating future advances in technology, particularly as these relate to the non-renewable resources that are currently being depleted. Some signs of effort in this direction, such as the analyses of the National Nanotechnology Initiative (Martin and Daim, 2008) are beginning to surface, but these are not enough. New science is needed to forecast these trends and to assess through probabilistic analysis the likely impacts of usage patterns on future generations. Just as the specific nature of the innovations in any area of entrepreneurship cannot be predicted (Goldstein et al., 2010a), so too the precise means for forecasting technology development itself cannot be predicted. But this does not mean that efforts to innovate in this area should not be attempted.

In some ways, this technology and resource depletion forecasting science would be analogous to the sciences of meteorology and climatology that seek to forecast weather patterns. Although precision is not possible and the specific scenario that unfolds can never be certain, recognising possible future patterns can be both useful and practical. When these models predict dangerous storms or the onset of climate change, for example, they can even be essential. Models of climate change are an important example of how an inherently probabilistic science can be used to influence policy for the benefit of future generations. It also highlights the challenges that complex and uncertain predictive sciences must overcome within the policy arena.

If the 22nd century is to dawn with the same promise as the twenty-first, human society must consider its probable futures in so far as this is possible. To do this, we need models of the technology 'weather', and we need new techniques for incorporating the predictions from these models into resource allocation and consumption decisions and policy. To further this vision, technology forecasting will almost certainly become a growth area in Society Systems Science over the coming decades.

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Notes

1 Of course the total value created is never independent of the distributional profile of the population. Yet since this is not our main point of emphasis we do not pursue the matter any further in this paper.

2 This idea is somewhere between the traditional ideas of *weak sustainability* – which assumes that all forms of capital are substitutable for each other so that there is nothing wrong with cutting down a rain forest as long as the proceeds are converted to some other form of capital, natural or otherwise – and *strong sustainability* – which on the contrary assumes that no substitution is possible so that there should be no type of capital for which total stock is diminished. While we believe that some forms of natural resources (perhaps tropical forests or wetlands) may be critically important and should therefore be preserved, other types might be traded off for other types of capital.